# IRON:

## ~~Aspects of~~ the Industry
## during the Iron Age
## and Romano-British Periods

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## M.A. (Hons)

Abstract

IRON

Aspects of the industry in the Iron Age
and Romano-British Periods

Our knowledge of the earliest methods of iron production owes a
great debt to 19th-century accounts of the bloomery technique as
still practised in parts of Africa and Asia. Inevitably, and in
common with other aspects of archaeology, many prejudices of that
period have been perpetuated up to the present day in the
literature. Additional bias has resulted from the influence of
modern metallurgy. An attempt has been made to identify and
correct these misconceptions in the light of new archaeological
evidence in conjunction with recent smelting experiments.

To enable a clearer understanding and interpretation of
archaeological field remains, the bloomery process is fully
explained in relation to furnace structures, ores and products,
and the reduction process is illustrated with appropriate
microstructures of the products.

Roasting and smelting experiments have been used to test the
viability of iron sulphide ores as ancient sources of iron.
These iron pyrites and marcasite nodules are common over large
parts of southern England. Sideritic and limonitic ores were
also smelted. The experimental products, slags and iron, were
analysed to assess the relationship between ores and slags, and
the results tabulated. The relationship between the
microstructure of the iron and slags and furnace conditions was
also evaluated. The main analytical techniques employed were
metallography, electron probe microanalyser (EPMA), X-ray
fluorescent spectrometry (XRF), scanning electron microscopy
(SEM), and inductively coupled plasma emission spectrometry
(ICP). Microstructures of both slags and iron are presented
together with backscattered electron images and X-ray element
maps.

Furnace typologies relating to iron production in both Britain
and the Continent are critically evaluated, and an overview of
the industry during these periods is presented.

The corrosion of slags and its implications for the analysis of
archaeological specimens are considered.

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# INTRODUCTION

Lucidity is found in the works
of others whose minds are in
a  similar state of chaos to ones own.
(probably Proust!)

# INTRODUCTION

Research into ancient metallurgy has a relatively short history. The 16$^{th}$-century treatises of Biringuccio and Agricola certainly referred to earlier processes, but these were largely concerned with then extant metallurgical techniques. There were passing speculations as to the nature of Roman metallurgy in the following centuries (*Gowland 1901, 362*), but it is not until the late 19$^{th}$-century, perhaps in the work of Percy (*1864*), but more concretely with the research of Gowland (*1899 etc*), a distinguished metallurgist and antiquarian, that the study of ancient metallurgy becomes a discipline in its own right. His interests were wide-ranging and involved extensive research into the metallurgy of lead, silver, gold, copper and iron.

A common thread throughout his research was the use of ethnographic analogy, and he was deeply influenced by his observations of primitive techniques practised in Japan. In all of his papers this influence is clearly seen, as he draws direct parallels between archaeological finds and analogous contemporary practises in Japan (fig. 1.1). Without such analogy our knowledge of ancient processes would therefore be impoverished, and throughout the present thesis, ethnographic information is used extensively to examine theory and to reconstruct early bloomery processes.

Ethnographic literature cannot be used without caution, as observers of 'primitive' processes have not always interpreted them correctly: for instance, Cammiade in his study of iron

smelting by the Kois, a jungle tribe from the eastern Ghats of India, describes a small shaft furnace with two vents at right angles to one another, one for blowing and the other for tapping the slag. Some time after charging, as indicated by a change in the colour of the flame, slag is tapped from one hole and molten metal form the other, the latter then being hammered on a stone anvil (*Cammiade 1931, 66*). This must be a reference to the breaking open of the mouth of the furnace to extract the white hot sponge of iron and not the molten metal, because if the metal was molten, it would be cast iron and not easily wrought.

During the preliminary research it became obvious from the contradictions in the literature that many aspects of the technology of iron were poorly understood, and that in many cases these misconceptions had been perpetuated from the 19th-century without question. Prof. J. Charles, a Cambridge metallurgist, recently warned of the dangers of the archaeologist dabbling in the field of metallurgy and the consequent errors in interpretation (*1979*). This is certainly confirmed by a survey of the archaeological literature relating to iron production.

As a typical example of the errors which have resulted, Semiatin (*1981*), suggests that one of the reasons that iron production was delayed so long after that of bronze was the absence of methods of achieving high temperatures needed to 'melt and refine iron ore', and is obviously unaware of the solid state nature of the process: that the temperatures required are no higher than those for smelting copper, and that they relate to the required

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viscosity of the slag rather than the melting point of the metal.

Others, while realising that these high temperatures are not required for reduction, similarly fail to understand the role of the slag. For instance, J.G.D. Clark in *Prehistoric Europe* posed questions which recur in the literature: '800-900 degrees are required to reduce iron ore to a malleable metal, why was this not achieved earlier?' (*1952, 199*). The explanation given by Clark is that until a technique was developed for toughening of the forged metal (i.e. repeated hammering of the carburised metal) it was too soft to be of practical use. This was also the reason suggested by Prof. J. Charles (*1979*). However, this interpretation overlooks many of the technological aspects of iron production without even beginning to account for cultural/economic factors. The first chapter looks at some of these problems and attempts to provide a comprehensive view of the bloomery process.

These 'technological' errors relate not only to the extractive processes, but are also common in physical metallurgy. For instance:

Wrought iron is a very pure form of metal, containing less than 0.5% carbon ; to turn it into steel, the carbon content has to be raised to about 1.5% (Manning in Strong et al. 1976, 149).

However, iron with carbon content from 0.2% to 0.5% is considered mild steel, which on working can achieve considerable hardness. The carbon content of wrought iron is normally less than 0.1% and many ancient artefacts have greater amounts than this. Chapter 2 examines experimental and archaeological products and examines the roles of carbon and other impurities common to iron. It also

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examines the effect of post-depositional changes on the analyses of slag remains.

One of the more specific aims of this research was to investigate the remains of smithing and smelting of iron in an attempt to find characteristics distinguishing between these processes, particularly the difference between smelting furnace bottoms and smithing furnace bottoms, for without this ability it is difficult to reconstruct the organisation of local iron industries. Mineralogical or chemical distinction is almost impossible, but evidence from both experimental and archaeological data has made it possible to draw certain conclusions regarding this material, and is discussed at length in chapter 2.

What was also evident from the literature was that while archaeologists propagated fundamental metallurgical errors, metallurgists perpetuated archaeological ones. Inevitably, some of them imposed $20^{th}$-century metallurgical knowledge onto past practices. An example has been cited above, where a metallurgical explanation for the slow transition from bronze to iron has been put forward when a socio-economic one could be considered equally viable. Such theoretical errors are discussed throughout the thesis, but particularly in the section on furnaces (chapter 4).

The basic tripartite furnace typology (bowl/dome/shaft) prevalent in the literature has been with us from the time of Gowland. At that time it was based entirely on ethnographic observations, as no prehistoric furnaces were known. When they did come to light,

their variation was recognised:

...as Weiershauser and others have shown, the furnaces in which this was carried
out [i.e. the smelting of iron] varied in construction, even though some supposed
variations were due to loss in superstructure; but even the most elaborate like
those in the Engsbachtal, Kr. Siegen, in S.W. Westphalia, were small and easily
worked (Clark 1952, 203).

Here the apparent variation noted in early furnace structures is
taken into account without any attempt to impose elaborate
typologies on material that is both fragmentary and poorly dated.
But such typologies have been attempted on numerous occasions
with the hope that they could be used as dating tools, or provide
cultural-historical information on migration and technological
development. Chapter 4 examines the development of furnace
typologies in the light of the present evidence and the soundness
of reasoning behind such classifications.

Chapter 5 deals with the analysis and interpretation of the
archaeological data. Throughout the Iron Age and up to the
medieval period iron is produced at the village or farmstead
level, as exemplified by sites such as Odell, Kestor and
Brooklands (Weybridge) but it also played a major role in local
supply and was certainly influenced by foreign trade. This
chapter examines recent archaeological evidence and questions the
validity of some early evidence and notable omissions. For
example, at the site of Gussage All Saints (Dorset), a 3-acre
enclosure of the 3rd century BC to the 2nd AD has the remnants of
a large bronze industry. In the reports, there is brief mention
of a small bowl furnace, perhaps early 1st century in date. This
thesis examines the evidence of slag from the site suggests that
iron production was at least on the same scale and probably as

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early as the bronze industry and could represent one of the largest production units of the period found to date in this country.

From re-examination of this early evidence, for example, the West Brandon furnace, it would appear that the fragmentary nature of the remains has resulted in incorrect conclusions and that statements regarding the nature of the early industry such as:

> processes involved were simple enough : the crushed ore mixed with charcoal would
> have been placed in a bowl furnace which may have then been partially covered
> with clay (Cunliffe 1978, 291)

must be reconsidered. The chapter also presents a selected survey of sites and their evidence of metallurgical activities.

Chapter 6 presents the archaeological background of the industry in both Europe and Britain and attempts to place the development of iron technology in a general and industrial perspective. This chapter will review the literature pertaining to the economic, particularly industrial, milieu of the relevent periods. This will include consideration of the evidence for iron production in continental Europe, and aspects of iron metallurgy (the transition from copper alloys, the scale of the industry, etc) from the Bronze age to the Romano-British period.

# CHAPTER 1

## THE BLOOMERY PROCESS

### Abstract

The bloomery process is outlined, using experimental and
ethnographic observation to reconstruct early iron-
smelting technology. The relationship between the ores
smelted and the technology/furnace form is examined, as
is the relationship between the smelting techniques and
the quality of the end product. The production of natural
steel is discussed, together with variations of the
process, specifically the use of crucible processes and
bowl furnaces.

# THE BLOOMERY PROCESS

## Introduction

The bloomery furnace as a means of producing iron was common until the 15th to 16th centuries in Europe, when it was superceded by the blast furnace. The transition was a gradual one, as the blast furnace was introduced around the 12th century in Scandinavia (if not earlier), but in areas such as Catalonia the bloomery was still in use well into the 19th century.

There are written accounts describing these later European processes, but the furnaces are massive in scale and therefore bear little resemblance to archaeological remains. On the other hand, bloomeries were still commonly used throughout Asia and Africa during the 19th century and a few examples have been recorded during the 20th century. Again, some of these were large furnaces, but many were small production units whose dimensions were similar to those found on archaeological sites.

It is only on rare occasions that we find almost complete furnace remains such as at Ashwicken (*Tylecote et al. 1960*), Broadfields (*Gibson-Hill 1980*), Scharmbeck (*Hingst 1983*), etc. For the most part, remains are so fragmentary as to make reconstruction difficult, e.g. Gussage All Saints (*Wainwright 1979*), Odell (*Dix forthcoming*), Garden Hill (*Money 1979*), and others, where little more than fragmentary furnace lining remains (e.g. plate 24). The remains at Laxton (Northants.) are comparatively well-preserved, but even here only the hearth level has survived intact (plates 25 and 26). This is in part due to the process itself, as in

many cases the furnace is broken open to extract the bloom at the end of a smelt, but destruction is mainly due to post-depositional activity.

Even more difficult to reconstruct than the physical remains themselves is the relationship between various aspects of the industry, such as the scale of production and the structure of the community giving rise to it. Many metallurgical sites are excavated without consideration of these broader issues, and consist of small excavations of the furnaces alone. Although often they do represent an industrial site where little or no cultural debris other than slags and vitrified clay remained.

An equally valuable source of information to complement the archaeological data is the extensive body of ethnographic literature recording many hundreds of 19th- and 20th-century observations of native bloomeries in operation. It was until the last decades our sole means of understanding the process, and even today, our knowledge would be much impoverished without it. As with experimental data, the use of such information has its problems. Ethnographic information on bloomery iron production is so varied that it is difficult to draw general conclusions and this inability to reduce ethnographic data successfully must serve as a cautionary tale to archaeologists interpreting ancient remains (see *Tylecote 1965* as an example). Assumptions such as 'the ore source will be in close proximity to the production source', for example, should be treated with care. These processes were often observed by missionaries and other travellers who only had a vague understanding of what was

occurring, resulting in simple errors such as assuming that the

tapping of slag was in fact the tapping of metal:

for many years Victorian antiquaries and travellers declined to accept the
metallurgical fact that iron could be produced from ore at a temperature less
than the melting point of iron (Robinson 1958, 276).

Naive analogy, such as equating social structures with furnace

types, must be avoided, but careful use of ethnographic sources

is essential to our understanding of these early processes (see

*Orme 1974* for a discussion of ethnographic analogy and also fig.

1.1 for the application of ethnographic information to

archaeology).

## Collection of Ores

(See appendix A for a tabulation of chemical and physical
properties of minerals (ores, slags, etc) referred to in this
thesis.)

There is no simple correlation between the nature of the

community and the type of iron production, but the most advanced

techniques are seen in small communities where all members

participate in the industry, supplying native markets over

several hundreds of miles (*Cline 1937, 31*); for example, the

Yoruban village of Olaigbi in the Omi river, a day's journey from

Oyo. Wares from this production unit go as far afield as Oyo,

Ibadan and south to Ojebuede; and the industry is such as

significant part of the community's economy that there is often a

shift of the entire village to a better ore field.
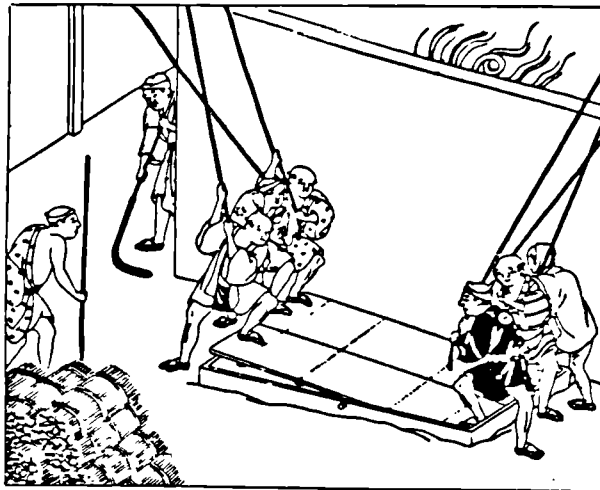
Fig. 21. Working the blowing machine (Tatara) at a blast-furnace for the extraction of iron from its ore. Japan.
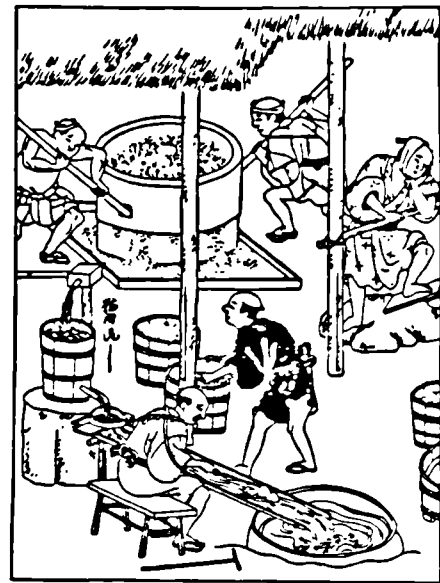
Fig 4 Grinding ore in a quern. Japan.

Fig. 6 Removing the copper in disc-shaped layers from the smelting furnace. Japan.

Fig. 7. Converting copper sulphide (regulus) into metallic copper by a blast of air. Japan.
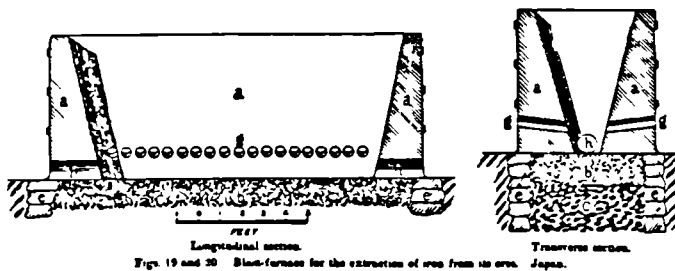
Longitudinal section. Transverse section.
Figs. 19 and 20. Blast-furnaces for the extraction of iron from its ore. Japan.
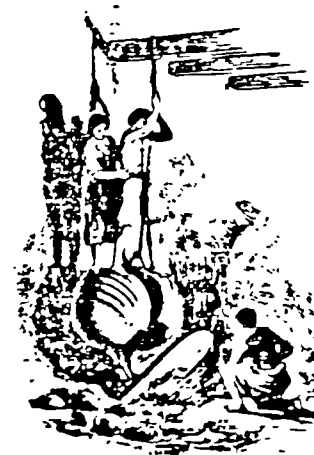
Fig 22 Iron smelting in the Khasia mountains. India.

## Fig. 1.1 Ethnographic analogy
## (from Gowland 1899)

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Of the 'Talcheer' and iron smelters from neighbouring districts in lower Bengal, Percy records:

> they are to a certain extent nomadic in their habits, remaining in one spot only
> so long as plentiful supplies of ore and wood are obtainable in the immediate
> vicinity (Percy 1864, 261).

In other instances long journeys to collect ore, such as the collection of the ores in the Belingwe district Zimbabwe, are recorded. The Manyubi of the Matapos are another group that sought their ore from great distances.

Occasionally we are fortunate to find ore on an industrial site, even more so if it is roasted and prepared for charging to the furnace, as was the case with the ore excavated at the site of Odell, Northants. But more often there is neither trace of ore nor signs of its preparation and slag is the most common trace of the past industry. There are numerous archaeological features which have been interpreted as roasting furnaces, but evidence for ore dressing is negligible. Evidence of sieving would be identified by a concentration of fine ore particles (fines), while processes of enrichment such as winnowing or hand sorting would result in concentrations of siliceous gangue material. But in many cases this would be carried out in a stream and the residue washed away:

> In order to process this ironsand, the natives conduct water over beds of granite
> sand; and as the lighter particles are washed away the remainder are removed to
> troughs, where the separation of the ore is completed (Percy 1864, 262).

In the recent past, most iron ores appear to have been used. In African iron-smelting communities there are preferences for haematite, then magnetite and limonite, but with pyrites, laterites and ilmenite also being used to some extent (*Cline*

*1937, 31)*. In India, a similar range was also utilised, including magnetite ores, haematites and limonites, but there was definitely a preference for rich ores (*Percy 1864, 255)*.

The archaeological evidence appears to suggest an equally eclectic exploitation pattern. Sideritic ores have been found on the Wealden sites (*Straker 1931)*, such as at Garden Hill, whereas sites near the Forest of Dean such as Ariconium utilised rich haematite. In North Darlarna, Sweden, magnetite sands were found on a smelting site together with roasted magnetite, and lake and bog ore (*Serning and Hyenstrand in Clarke 1979)*.

If the smelting of copper is traced through the ages, it would be generally true to suggest that exploitation began with native copper and continued with the use of the richest ores available. Initially the oxide and carbonate ores, such as malachite with 57.3% of copper, were exploited but by medieval times, with depletion of the rich ores, a lower grade of ore was accepted (c.10%) while today ores with around 0.5% copper or less are acceptable, depending on fluctuations of the market. Although it is not apparent in the current archaeological literature, it would seem equally likely that pure minerals and rich ores played an important role in the early iron industry in preference to those of poorer quality.

The Dimi (S.W. Ethiopia), for example, used an ore with iron to silica ratio of 70:8 (*Todd 1976)*, which they smelted in a conical non-tapping furnace using forced draught, 1m high with a pit extending 50cm below ground. Ore analyses from Percy (*1864, 283)* show typical ratios of 6:1, and both Percy and Cline refer to the

use of almost pure magnetite or haematite ores. No flux is recorded in the use of these materials, although they are occasionally used in conjunction with a poorer quality ore. The Dimi, for instance, often mixed pure magnetite with their limonitic ores (*Todd 1976, 27*).

Provenancing of ores and relating slags to ore types is complicated by post-collection treatment, and chemical/mineral analysis alone is inadequate for the investigation of these processes. Low-grade ores are often dismissed as not being a viable source. However, these can be treated, as at Olaigbi, where siliceous haematite was washed and charged to the furnace while still wet. The grinding and washing procedure reduced the siliceous content of the ore from 43% to 14%. Charcoal and clinker from the previous smelt was charged and tapped off at least twice before the furnace was deemed clean enough for charging. The charging of old slags, or slags from the early tappings, is frequently recorded elsewhere (*Percy 1864, 298; Todd 1976, 28*). The heavier slags are selected because they still contain retrievable iron, but the use of slags for 'cleaning' the furnace is probably a method used to assess the readiness of a furnace for charging, rather than waste good ore.

Roasting

Reduction of iron ores by reducing gases is best envisaged as being due to diffusion of the reacting gases into the ores, and the reverse diffusion of the gaseous products out of them. Therefore the influence of the porosity of the ores on reduction

is of primary importance. The presence of the gangue in the ores necessitates the reagent (CO) gaining access to the mineral through the pores of the ore, dissolving the mineral and diffusing out into the surrounding solution, and the primary reason for roasting the ore is to facilitate such reactions.

After collection, washing and sorting, i.e. the beneficiation of the ore, roasting is the the earliest part of process for which we have evidence. Roasting involves the burning of the ore in oxidising conditions, usually in a variety of pits using wood as fuel, to make the smelting process more efficient. The first effect of heating will be the expulsion of water, the bulk of which will be removed c.105$^{\circ}$C; but it will not be completed at this temperature owing to the lower vapour pressure of water when absorbed in a porous material, or contained in a colloidal mixture. Its final elimination will overlap with the dissociation of hydrates, which will occur around 550$^{\circ}$C. Carbonates in the ores will dissociate over a range of temperatures from 200$^{\circ}$C to 750$^{\circ}$C (table 1.1, 1,2 and 7). These reactions are endothermic, and hence require the input of heat, and if they occurred in the reduction furnace, which would be the case for unroasted ore, the $CO_2$ and $H_2O$ produced would lower the reduction potential of the gas. The final elimination of $CO_2$ from alkaline earth carbonates will occur and a reaction between the metal oxides and the siliceous gangue will commence around 1000$^{\circ}$C. Any sulphides present will also decompose, but with an associated loss of heat (exothermically). Below 650$^{\circ}$C, the products of oxidation will be principally sulphates, whereas above 750$^{\circ}$C they will be almost entirely oxides (table 1.1, 4 and 5).

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It has been suggested that early bloomeries would not have allowed sufficient time for the decomposition of carbonates, and hence that we have evidence for the roasting of ores at sites such as Wakerley and Stamford (Saxon) (*Fells 1983, 57*). Garden Hill (Sussex), Odell and Laxton (Northants.) could be added to this list, along with many others. Roasting would have been beneficial, but experimental evidence suggests that the process could have been accomplished in the shaft of the furnace. The absence of roasting structures at many sites, while not confirming that this was the case, suggests that ores may often have been charged directly into the furnace.

The decomposition of ore minerals is a complicated process, and effective roasting does not only depend on the height of the shaft, but also relates to the surface area of the ore (with smaller pieces of ore decomposing more rapidly); to the type of ore (some ores being denser than others, consequently reduction is slower; and the fuel to ore ratio along with blast (or burning) rate. For most of the early shaft furnaces (80cm+ in height), sufficient time would have been available to calcine the ores effectively in the upper reaches of the furnace, i.e. a relatively oxidising zone. A more pertinent reason for the roasting might be that it enabled charging of slightly larger ore pieces (note the size of the roasted ore from Odell: 4-6cm cubes), which may have been critical in nucleation of the bloom.

One of the dangers during roasting is excessive temperatures in the hearth, resulting in incipient fusion of the ore which would

inhibit diffusion of the reducing gases into the ore. This is particularly relevant to the roasting of sulphides, a reaction which is exothermic and easily generates sufficient heat to form a matte (table 1.1, 3). This was the case during roasting of the pyrites for experimental smelts (*Tylecote and Clough 1983; also chapter 3*).

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Table 1.1

Roasting reactions

```
1 MO.nH2O    =  MO + H2O  dehydration
2 M(OH)2     =  MO + H2O
3 2MS2       =  2MS + S2  matte formation
4 2MS + 4O2  =  2MSO4   ( 650°C
5 2MS + 3O2  =  2MO + 2SO2  ) 750°C  and sulphates
6 MSO4       =  MO + SO3
7 MCO3       =  MO + CO2  decomposition of carbonates
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Three will be exothermic and self sustaining (3,4 and 5), while the remainder are endothermic and require the input of energy to go to completion.

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## The Direct Process

The bloomery process is also known as the direct process because malleable iron is formed directly in the furnace, in contrast to production of liquid iron in the blast furnace which must then be refined before it can be wrought (the term 'direct reduction' is also used in modern metallurgy to describe reduction resulting from direct reduction with carbon (coke or charcoal) as opposed to indirect reduction with gaseous carbon monoxide).

The bloom, when extracted from the furnace, is a black, spongy mass of iron, with entrapped slag and charcoal (plates 19c and 21b). This product is then reheated to a temperature above the

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melting point of the slag, some of which drips into the bottom of the forging hearth. The bloom is then removed from the hearth and shingled, a process of preliminary forging which gradually compresses the bloom and squeezes additional slag from the structure. Reheating and forging is repeated until much of the slag is removed and the iron consolidated. The material is then forged into a variety of shapes, for example bars or billets which are a convenient size for trading or working up into artefacts. Such billets are commonly found on archaeological sites and have been interpreted as a form of currency: *Spitzbarren* (plate 23b)(Pleiner in: *Wertime et al. 1980; Allen 1967*).

In the blast furnace, which operates at higher temperatures (c. 1400-1600°C), the reduced metal is liquid and, being denser than the slag, forms a layer below the molten slag bath. In this process both the slag and the metal are tapped from the furnace, whereas in the direct method only the slag can be tapped, while the bloom must be removed either through the top of the furnace or by breaking open the front and destroying part of the structure. This may then be rebuilt and the furnace relined, or left in a destroyed state. Cline gives several instances, such as the Wakanogo, where the furnace is completely destroyed after a smelting operation (*Cline 1937, 47*).

The furnace is usually preheated with wood or charcoal, bringing it to a suitable temperature to begin charging with ore. This step is necessary to enable the ore and fuel, i.e. the burden, to be heated rapidly to reaction temperatures.

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## The Furnace

Understanding of the process has been greatly enhanced by the experimental work of Wynne and Tylecote (*1958*), Tylecote et al. (*1971*), Gilles (*1958 and 1960*), and Pleiner (*1965*), who, along with others, independently carried out a series of valuable simulated smelts under variable conditions, examining the effects of blast, fuel:ore ratios, furnace height, type of ore, and particle size of ore and charcoal. The effects of changing these variables are so comprehensively dealt with in these studies that it is unnecessary to consider them in the same detail here.

Probably the simplest way to approach the process is to explain these variables in terms of a single focal point - residence time - rather than to treat them as independent factors. The bloomery process is largely a diffusion-related one and therefore the residence time of an ore particle in any one zone of the furnace, determines the outcome of the smelt, affecting both the quantity and the quality of the product. Changing any one of the above-mentioned variables can be seen in terms of altering this residence time and hence affecting the product.

Table 1.2

### The effect of changing operating procedures on residence time (rt)

| Variable | Effect |
|---|---|
| increase shaft height | increases rt |
| increase blast rate | reduces rt |
| increase fuel to ore | increases rt |
| increase fuel size | alters isotherms; increases size of combustion and solution zones, therefore increases rt in these zones, but ore particles work their way through the burden at a faster rate. This decreases the relative amount of CO, therefore the reduction process slows down; overall an effective decrease of rt |
| decrease fuel size | acts to aid faster diffusion, therefore equivalent to increasing rt, but if too small will drop through the charcoal and effectively reduce rt promoting slag formation but not reduction (see function of *greillade* in catalan furnace) |
| use of a more porous ore (effected by roasting) | increases the diffusion hence reaction rate and effectively increases the rt |

To illustrate this interrelationship: one factor mentioned which increases the residence time of ore in the furnace is an increase of shaft height. Percy (*1864, 257*) observes a simple and advanced style of his type I which differ only in height. One is 0.6m high and yields 2.3-2.7kg of iron per charge while a slightly higher version of 1.2m (Deccan) gives up to 14kg per charge, thus appearing to contradict Tylecote's assertion (*in Pleiner 1981*) that furnace height has no need to exceed 0.5m. The advantages of increased height of furnace become obvious : a longer preheating and roasting period, a longer effective reduction period before slagging commences and relatively less fuel per unit of ore used.

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These advantages are put to use in the manufacture of superior iron and natural steel (see below under 'natural steel', also *Percy 1864, 259*).

The effect of residence time on the quality of the product is best illustrated by Chaudron's curves, and the Fe-O binary diagram (figs. 1.2 and 1.3), and some of the iron produced from simulated smelts during this project. For instance, smelt WH1* used a high fuel to ore ratio, and the resulting furnace conditions were exceptionally reducing and the bloom in parts had a grey cast-iron structure. These conditions also resulted in other impurities such as phosphorus and manganese being reduced into the metal (plates 5a-b and 6a-b). In contrast to this, smelt WH2 simulated bowl-furnace conditions and the ore had a very short residence time, and as a consequence very little iron was formed, and that was almost pure ferrite. The smelt using the ore from Seend (plate 21b) used a high blast, which in combination with the porous ore produced a low-viscosity slag and consequently dense furnace-bottom slag but very little iron. Some of the iron was in the form of prills at the base of the slag block. Hardness tests on a metallographic section confirmed that this metal was a white cast iron with a hardness c.500VHN and therefore had been liquid during the smelt. Bloom from the top of the same furnace bottom was ferrite.

*WH1, WH2, etc, are experimental smelt carried out in a small non-tapping shaft furnace. The codes represent the ore used: WH = West Hoathly sideritic boxstone; SE = Seend boxstone; BR = Bognor Regis pyrites nodules; WM = Wiltshire marcasite; O = roasted carbonate ore from the Saxon levels at Odell (Northants).

As illustrated (fig. 1.4), the furnace can for convenience be divided up into a number of zones. In reality there exist continuous gradients of temperature and gaseous composition and in certain conditions either oxidation (roasting, calcination, dehydration and decarburisation ) or reduction (carburisation, slagging, etc) will predominate.
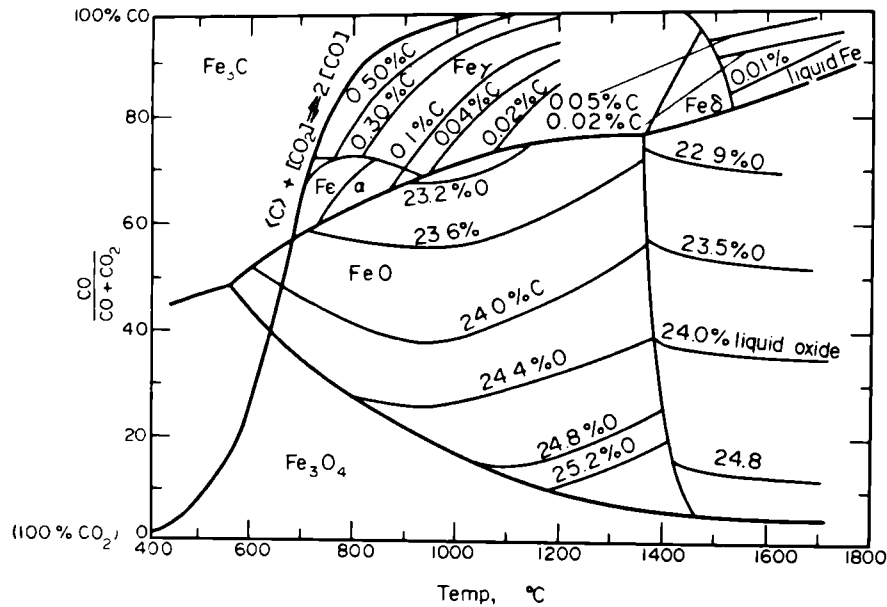


Fig. 1.2 Equilibrium C-O-Fe with the degree of carburisation of Fe and oxidation of Wustite in the presence of CO and $CO_2$.



Fig. 1.3 The Fe - O binary

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Loss of $H_2O$ and organic constituents. Carbonates begin to decompose. Morphology of original ore remains but gradually increases in porosity due to loss of water, organics and carbonates.

Conditions mildly reducing:

$Fe_2O_3 + CO = Fe_3O_4 + CO_2$

Remaining carbonates break down and porosity allows CO access to $Fe_3O_4$ and $FeO$.

$Fe_3O_4 + CO => 3FeO + CO_2$

$FeO + CO => Fe + CO_2$ (begins)

If conditions are excessively reducing, carburisation occurs: $3Fe + 2CO = Fe_3C + CO_2$

Slagging begins and slows down the reduction process. CO must now diffuse through a slag film to reach the mineral.

BLAST

Slag liquates and flows to the base of the furnace coating charcoal and forming a slag-charcoal furnace bottom (plate 4a). Small pieces of bloom and incorporated slag are exposed to welding temperatures and nucleate above this base.

TAPPING BAY

1-TUYERE
2-RACE
3-COMBUSTION ZONE    $C + O_2 = CO_2$
4-SOLUTION ZONE      $C + CO_2 = 2CO$
5-REDUCTION ZONE     (see above)
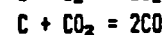
Fig. 1.4 Furnace Reactions

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The blast of air as it enters the furnace through the tuyere creates what is referred to as the race. That is, a tunnel of air with no solid present. This air hits the ignited charcoal and increases the combustion rate of the fuel. The small interface is known as the combustion zone (see reaction table 1.3) in which charcoal (C) is converted to carbon dioxide ($CO_2$). This gas then enters the solution zone where the $CO_2$ reacts with more charcoal to form the reducing gas carbon monoxide (CO), which is in the reducing zone of the furnace.

The size of these zones is dependent on both the rate of the blast and the particle size of the charcoal. The gas entering the furnace needs to travel a certain distance before it achieves a $CO/CO_2$ ratio capable of reduction. In the case of iron some 80% of CO is required. 'Oxygen in the air supply is virtually used up within 0.5"-9" (12-23cm) of the point of entry whatever its rate of supply within the range sufficient to burn coke at 1-65 lb/sqft/hr.' (*Hiles et al. 1944, 156*). Although this applies specifically to the blast furnace utilising coke, it is also an approximation of fuel combustion in the charcoal bloomery. Here, also, the production of the reducing atmosphere is dependent on the surface area of the fuel, and the larger the particle, the greater the distance will be. The oxygen is consumed within the order of 15 fuel diameters, and from this approximation, if the size of the fuel is known, the size of the reduction zone can be roughly assessed for any one furnace. For example, in the remnants of the furnace at West Brandon (*Jobey 1962*), charcoal remaining in the base of the furnace had dimensions in the range

of 2-3cm. The diameter of the base of the furnace was around 30cm

(i.e. less than 15 fuel diameters); thus, if this furnace was the

'bowl' type it was interpreted to be, then there would have been

insufficient distance for the formation of a suitably reducing

atmosphere. In this case one would conclude that the furnace

remnants represented either a forge or the base of a small shaft

furnace. Obviously, smaller fuel will produce a reducing

atmosphere in a relatively short time, but will introduce the

associated problem of greater fuel density, as a result of which

gas flow will be impeded and the isotherms lowered, leading to

incomplete reduction.

On the basis of such considerations it is possible to study some

remnants of early furnaces and suggest whether they were likely

candidates for the reduction of iron. For example, the furnaces

at Bulwick (*Jackson 1979*) had evidence of several relinings, but

a final internal diameter of 15cm, and must be interpreted as the

bases of shaft furnaces.

The 19[th]-century metallurgists Richards and Francois carried out

detailed investigations of the catalan furnace, and their

observations have been used extensively to illustrate the process

in fig. 1.4. A number of smelts were 'frozen' at increasingly

longer time intervals. The furnace was then broken open and

samples were taken for analysis, the results of which enabled a

comprehensive reconstruction of the reactions occurring at

various stages of the process and in different regions of the

furnace (*Percy 1864, 301-2*). Of interest is the information they

provided on the role of ore size, type and slag and how changing

furnace conditions affected the final product, resulting in either pure iron (ferrite), or a natural steel.

## The Reduction process

Most processes occurring in the shaft operate on counterflow principles. The burden to be heated and reduced, and the combustion gases travel through each other in opposite directions, thus leading to high thermodynamic efficiency in the heat-transfer process (*Gilchrist 1967, 167*). Applying this to the bloomery, the advantage of the higher shaft can be appreciated: :it more closely resembles a reversible process and therefore has greater efficiency because it enables time for equilibrium to be approached at any one stage before the onset of the next process.

The ore and fuel are charged into the mouth of the furnace in varying ratios, and as this burden descends the shaft it encounters gradients of increasing temperature and stronger reducing gases. In the upper levels of the furnace, conditions are oxidising and the ore, if not charged in a roasted state, undergoes reactions typical of roasting (table 1.1), such as calcination, dehydration, and the oxidation of organic matter. This process results in greater porosity (friability) in the ore and consequently easier reduction by carbon monoxide (CO), which must diffuse into the ore particles to effect reduction.

Reduction of the iron from the ore is a diffusion-related process and relies on the movement of the CO gas into the ore particle.

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From the section on furnace zones (fig. 1.4) we can see that there are progressive changes in composition of the mineral as it descends (gravitates) down the shaft. In a mildly reducing atmosphere (where the $CO/CO_2$ is low) fayalite is formed around 800°C. Baldwin (*1954*), experimenting with intimate mixtures of silica and FeO, found that no reaction occurred below 700°C but was appreciable at 800°C. Because of the lower permeability of fayalite, the rate of reduction is slowed down by cutting off the ore from direct CO contact. The process from this stage on becomes diffusion controlled, reducing the FeO in the slag. On the slag surface, iron is formed and then migrates across the fayalite film to join the Fe nucleus at the centre (plates 2 and 18e-g). As the FeO content of the slag is reduced, the viscosity increases which results in breaking of the skin, thus allowing direct reduction to be restored.

As furnace gases become enriched in carbon monoxide relative to carbon dioxide, the composition is consequently more reducing. From the free energy diagram (fig. 1.5) we can see that where the C-CO line intersects the relevant metal-metal oxide (Me-MeO) line, the lower oxide will become more stable and reduction will occur. In the case of iron, first the ferric iron (table 1.3, reaction iii), e.g. haematite or limonite, will be reduced to magnetite and the ore particles, while retaining their morphology and porosity, will display a grey-blue colour. As the descent continues, the magnetite will be further reduced to the ferrous state (reaction iv) losing more oxygen to form wustite ('FeO'), and finally this is reduced to metallic iron, ferrite (reaction

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v), and can be observed as an iron pellicle (skin) on the outside of ore particles (plate 1).

## Table 1.3

### Furnace Reactions

|       |                    |   |       |                       |                 |
|-------|--------------------|---|-------|-----------------------|-----------------|
| i)    | $C$                | + | $O_2$ | $= CO_2$              | combustion zone |
| ii)   | $CO_2$             | + | $C$   | $= 2CO$               | solution zone   |
| iii)  | $3Fe_2O_3$         | + | $CO$  | $= 2Fe_3O_4 + CO_2$   |                 |
| iv)   | $Fe_3O_4$          | + | $CO$  | $= 3FeO + CO_2$       |                 |
| v)    | $FeO$              | + | $CO$  | $= Fe + CO_2$         |                 |
| vi)   | $2FeO$             | + | $SiO_2$ | $= Fe_2SiO_4$       |                 |
| vii)  | $[FeO]_{slag}$     | + | $Fe_3C$ | $= Fe_{(m)} + CO_2$ |                 |
| viii) |                    |   | $Fe_3C$ | $= Fe + CO_2$       |                 |
| ix)   |                    |   | $Fe$  | $= [FeO]_{slag}$      |                 |
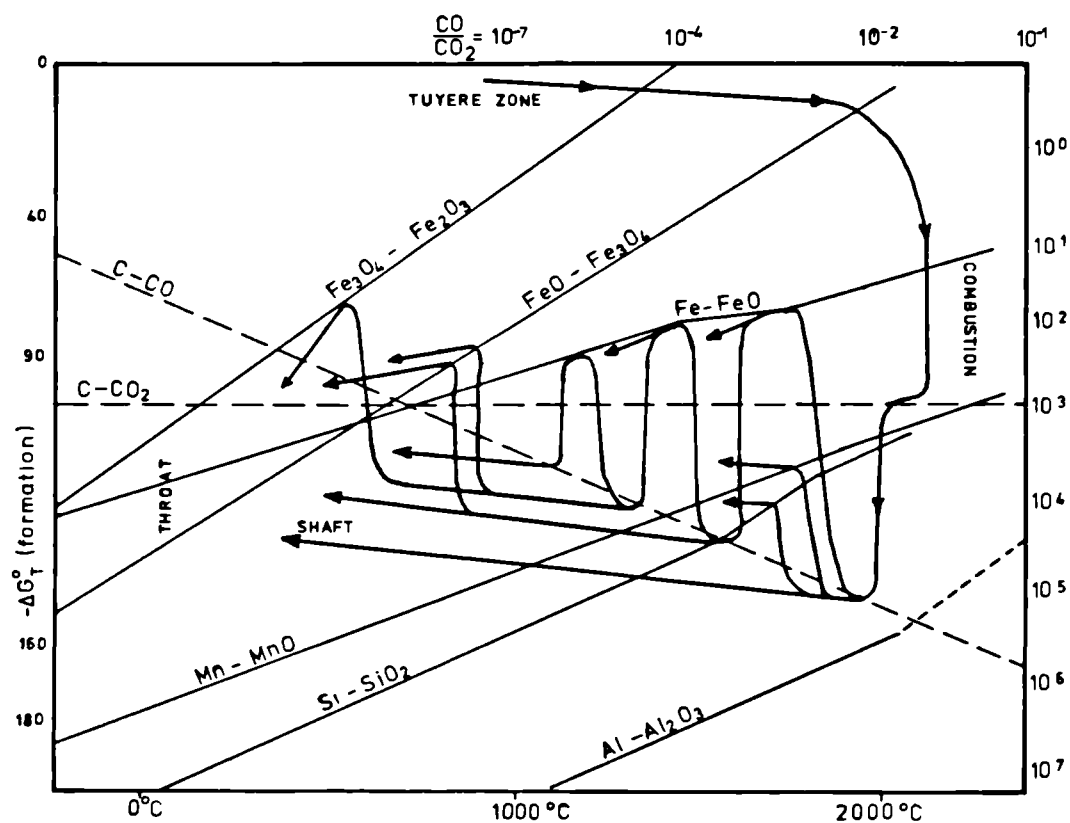


Fig. 1.5  Furnace reactions and free energy for the formation of oxides  (*from Gilchrist 1967, fig. 45*).

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Concurrent with, and part of, the reduction process is the formation of slag resulting from the reaction of most of the unwanted minerals, the gangue, with fuel ash and and flux which in the bloomery furnace is a high percentage of the iron oxide. Bloomery slags often contain as much as 60% FeO and for this reason the process is considered inefficient, as the bulk of the desired element enters the slag as silicate or oxide.

## The Formation of Slag

A slag is formed from interaction between the gangue minerals, fuel ashes, and in some cases, as the blast furnace, an intentionally added flux such as lime (CaO). To separate these minerals from the iron it is important that the slag has a relatively low viscosity and melting point, thus enabling it to interact with and flow from the iron. The most common gangue mineral is silica, along with minor quantities of alumina, lime, etc. Thus the slag is typically a complex mixture of silicates, and oxide phases in a glassy or crystalline state, but always molten at some stage of the process.

In the blast furnace the slags are usually calcium-alumino silicates, the calcium being added to flux the silica, whereas the flux (unintentional) in the bloomery process is the bulk of the FeO and reacts with the silica to form the iron olivine, fayalite ($Fe_2SiO_4$) (table 1.3, vi).

Because calcium is an important constituent in blast furnace slags, there have always been attempts to explain its absence from bloomery slags. It has been suggested that this relates to

the refractory nature of calcium and that its presence, over 5-10%, will increase the melting point and viscosity of the slag, which would be undesirable at the operating temperatures of the early bloomery (e.g. *Tylecote 1962 and Salter 1984*). However, earlier studies of the $FeO-CaO-SiO_2$ system have been overlooked, as from these it is evident that over 25% of CaO can be absorbed into bloomery slags without appreciably affecting slag properties at typical operating temperatures (*Bowen et al. 1933a and b*). This is consistent with some of the higher levels of CaO found in some of the Wealden bloomery slags, and particularly some Greek bloomery slags which are frequently calcium-rich olivines (*E. Photos pers. comm.*) (See also fig. 2.3, The $CaO-FeO-SiO_2$ ternary phase diagram for the effect of additions of lime to the $FeO-SiO_2$ system).

These silicates are forming as the reduction process continues, but if they form too early, i.e. as a result of high temperatures which lead to the formation of slag around the surface of ore particles, the diffusion of the reducing gases is inhibited and the process might fail to go to completion, as fayalite is more difficult to reduce than FeO (*Baldwin 1954*). Reduction proceeds, removing increasing amounts of iron from the slag and consequently changing its mineral composition from iron-rich olivines to pyroxenes which are poorer in iron, and then to a slag rich in quartz (fig. 1.6).

As this occurs, the melting point and viscosity of the slag increases, once again inhibiting reduction because of slower diffusion. At any stage of reduction, as soon as the ore mineral

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is slagged, carburisation of the ferrite will begin because diffusion of CO is faster in Fe than in slag. Therefore after slagging occurs carburisation of the metal proceeds more rapidly than further reduction of the slag. Obviously in a highly basic ferrous slag decarburisation of the metal will also occur, with oxygen from the slag (FeO) oxidising the carbide in the iron, forming $CO_2$ and iron (table 1.3, reaction vii). It should be noted that because of the disequilibrium prevailing in the bloomery it is not uncommon to find highly carburised iron in a basic slag, such as the metal prills in smelt SE1 (plate 2lb).
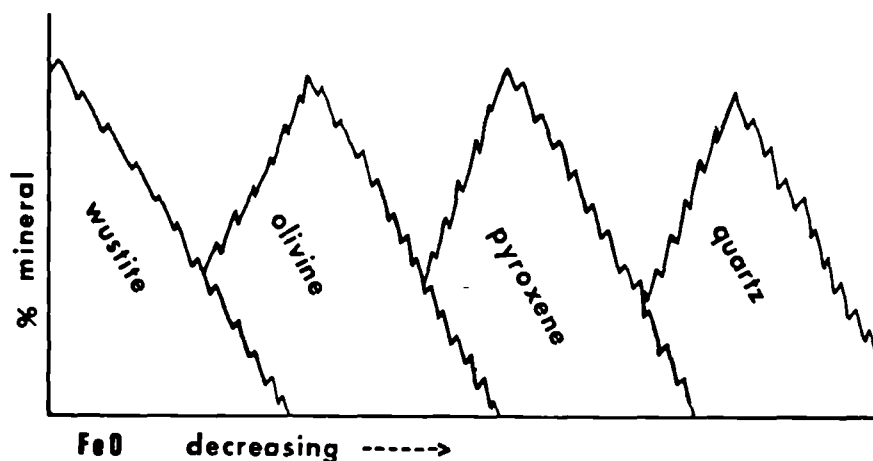


Fig. 1.6    Normative compositions: changing mineral compositions of the slag with decreasing wustite (*after Krestens forthcoming*)

When the conditions are strongly reducing, more of the impurities of the gangue, such as Si, Mn, and phosphorus, depending on the composition of the ore, can also be reduced into the metal along with carbon. As with carbon, interaction with a basic slag (e.g. of fayalite-wustite composition typical for bloomery slags) will

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remove impurities such as phosphorus and sulphur (*Coudurier et al. 1978*). However, these conditions also reduce additional iron from the slag and lead to the formation of an acid slag, for example one of pyroxene composition, in which neither decarburisation nor removal of phosphides or sulphides will readily occur. Therefore, in a highly carburised bloom or artefacts manufactured from one, we are more likely to detect these elements than in an artefact which has been carburised during refining and smithing processes.

In the tuyere zone (race + combustion zone) (fig. 1.4) the slag-coated metal undergoes little change as the residence time is too short. As the metal droplets pass through this zone of the furnace, the high temperature ($1300-1400^{\circ}C$) and oxidising atmosphere cause the slag to liquate and drop away from the metal, leaving it exposed to oxidation. If the metal is carburised, and the residence time extended, then a degree of decarburisation can occur (plate 5c); if not, then some iron is reoxidised to FeO which then enters the slag. It is in this zone that slag could act to protect the metal (e.g. plate 2). Iron of 1.7-1.8%C (c. $1400^{\circ}C$) might liquify and leave the slag (in contrast 0.6%C has a melting point of c.$1500^{\circ}C$). The particles become superheated, allowing the slag to liquify and the welding of the iron particles, resulting in formation of the bloom.

In cases where the slag is more viscous it will liquate more slowly and reduce the exposure of the iron to the oxidising conditions of the combustion and solution zones. The iron softens

and the slag liquates, falling to the base of the hearth, displacing and covering remaining charcoal to form a molten slag bath at the base of the furnace which is then tapped off (fig. 1.4). This process will continue at hearth level of the furnace where the bloom is still exposed to high temperatures. Some of the first slag to reach the base of the furnace will solidify rapidly and remain with entrapped charcoal in the furnace (plate 4a), but will form a hot base enabling subsequent slag to remain molten for tapping. This is a possible explanation for the design of the furnaces excavated at Cow Park (*Tebbutt 1980*), where the tap-hole is 15cm above the base of the hearth. A proportion of the slag adheres to the undersurface of the tuyere, leaving a structure similar to that found at Kestor (*Fox 1954*).

## The development of furnace technology as related to the ores and the process

The bulk of these reduction processes can be described within the above framework. However, there are several processes which are different and have been virtually ignored in the literature. The ethnographic literature covering observations of the iron-smelting industry of 'primitive' communities (*Percy 1864; Cline 1937; Tylecote 1965; Brown 1982; Todd 1976*) reveals considerable variation in practice, with significant differences in type of furnace, ores used and methods of charging.

Perhaps, of all the variations encountered, the use of rich-pure minerals is the most fruitful for consideration and is often overlooked in the study of ancient iron technology. This has probably been due in part to the predominance of slag on

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archaeological sites, as often little else of the process remains.

## Rich ores and small bowl furnaces

Thus there has been considerable emphasis on the role of slag in the formation of the bloom, and it is not uncommon to encounter statements suggesting that the self-fluxing ores are important because of their ability to form a fluid slag. Also encountered is the belief that some of the rich ore sources would have to be mixed with poorer quality to achieve a fluid slag. And, it is generally assumed that:

...to get low carbon metal and free running slags demanded by the bloomery process, we must have large iron losses in the slags and reduced yields (Percy 1864, 352).

Using very rich ores results in production of iron almost free of slag, while blooms of poorer ores normally contain some 30-50% of slag. The amount of slag is dependent on both the quantity of gangue minerals and the contribution from furnace lining and fuel ash.

The role of slag is threefold : primarily as a vessel for the gangue minerals (mainly silica, with some alumina and lime); as an absorber of impurities in the metal (a secondary role, but of importance in the removal of phosphorus and sulphides, and this is achieved by holding down the impurity elements in a state of lower activity); and as a protector of the bloom by preventing excessive oxidation in the combustion zone of the furnace. Or it can also play a role in the decarburisation of the bloom. To achieve such functions slags must have certain physical

properties (melting point, viscosity) and chemical properties
(basicity, oxidation potential), all of which are controlled by
variations of composition and structure (discussed earlier).

All of these functions give rise to the motto 'good slag good
steel', which is true for modern processes. But how essential is
a slag of the correct viscosity, basicity, etc, in some of the
ancient techniques? We know from free energy diagrams that
various metallic oxides can be reduced well below their melting
points (for iron see fig. 1.2), and would be advantageous
particularly by saving fuel no longer necessary to heat the
burden and maintain a liquid slag and metal. Theoretically
reduction of these rich minerals could easily be achieved, but in
practice, however, it is almost impossible to obtain significant
reduction of ores at low temperatures, because the separation of
the gangue from the desired mineral imposes formidable
difficulties as the metal itself becomes intimately mixed up with
the gangue minerals and unreduced oxide. Thus a liquid slag is
essential to enable separation of the slag and metal. However, in
a few extraordinary circumstances where the ore is a pure
compound of the metal and the reducing medium is gaseous, then
complete reduction does occur as a result of efficient diffusion
of gas into the ore.

Ethnographic observations do not always support the theory that a
liquid slag is of prime importance, as many processes are carried
out using rich magnetite or haematite sands, without the addition
of flux or blending with poorer grade ores. That is, they are
potentially slag-free processes. There are other examples where a

viscous and often untappable slag is produced along with many small pieces of bloom (*Cline 1937, 25ff* contains several references to the use of magnetite sands). In these cases the slag is either left in or raked from the furnace and the bits of bloom collected for refining operations.

One of the problems of fine pure ores, particularly in the shaft processes, is the production of 'grompie' (many small pieces of reduced sintered particles hanging up in the furnace). That is, there exists a problem of agglomeration or consolidation of the reduced particles, which is not encountered in the shaft furnace with normal ores, because apart from the roles mentioned earlier, such as fluxing the gangue, removing impurities, etc, the slag also acts as a carrier of the reduced mineral and is an integral part of the agglomeration process. These slagging processes can be seen as **dynamic**, where the slag is a fluid medium in which the reduced mineral can grow (plates 2 and 18$_{e-g}$), the slagged and reduced mineral moving down the shaft encountering changes in furnace atmosphere until it reaches the combustion zone. Here, the slag liquates and drips away from the iron, exposing it briefly to welding heat and assisting the consolidation of the bloom.

However, this is obviously not the case with pure ores and the process in this case is best described as a **static** or **slag-free** process. The term slag-free, as used here, also incorporates processes producing a low volume of slag, such as the process used by the Mashona, where little slag was produced (*Cline 1937,*

*51*). The term static is used purely to contrast it with the normal counterflow processes occurring in the shaft and the mobility of the burden in those processes. In no other sense is the process static, as the normal diffusion of carbon monoxide into the mineral and carbon dioxide away from the mineral is occurring as it would in the shaft. The nature of this process is best illustrated with reference to some ethnographic practices which, while primarily used for refining of the bloom, could have been widely used for the reduction of pure minerals.

Iron produced by the Birom on the Jos Plateau (Nigeria) is one example, and possibly representative of a widespread technique in dealing with rich ores. Tylecote (*1965*) discussed this, together with a number of related processes, under the category of forging, i.e. ways of refining the crude product. Here, the crude product was finely ground and wrapped in an envelope of clay and heated in the forge to a temperature of 900-1200°C. This was then removed from the forge, the clay envelope broken open and the bloom hot-forged into plates of low-carbon iron.

Plates similar to those from this process are also described by Tylecote from another region. In the Mandara Hills (Cameroons), crude bits of iron are hammered into thin plates, several of which are then collected together and covered with mud paste. They were then placed in the forge and brought to welding heat before forging. As with the process described at Jos, the envelope of clay or mud protects the metal from oxidation. Presumably the plates produced at Jos could have been further treated in the manner described for the Mandara Hills.

There are many examples of communities using such refining processes, such as the Southern Bantu and the Bongo (*Cline 1937, 51 and 46 resp.*). Many of these methods are related to refining of the bloom, but from knowledge of the wootz process they can also be primary reduction from the ore (*Forbes 1950, 410*). Wootz, or crucible steel, can be manufactured in a process not dissimilar to that described for the Birom (*above*), in which small pieces of crude bloom are charged into crucibles along with charcoal and organic matter. Several of these crucibles are then placed in a small furnace and heated for about four hours, by which time an ingot of homogeneous steel has formed (*Coomaraswamy 1908*). The other method involves the charging of a pure ore (e.g. magnetite sands) instead of the crude bloom, and therefore is a reduction process rather than a refining one. The Bari ironworkers at Bilinyang (S. Sudan), for instance, packed fine granular ore into special clay pots which were then packed (lidded) into a forge trench and covered with charcoal (*Russell pers. comm.*). While the production of wootz involves the use of crucibles in a small bowl furnace, there are instances, such as in the Khasia Hills, where fine magnetite sands were charged into a small bowl furnace (*Percy 1864, 265-6*; see also fig. 1.1). Reduction of very rich ores in small bowl furnaces has also been experimentally confirmed although the tests were not recorded systematically. O'Kelly (*B. Scott pers. comm.*) charged rich Cumberland haematite into a bowl furnace with a clay cover and on a number of occasions was successful in producing grey cast iron.

A recent ethnographic study in Kenya revealed tht local iron

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smelting was most commonly carried out in simple bowl furnaces: a hole in the ground, usually clay-lined, rarely more than 30-35cm in diameter and 20-30cm deep. In these, they smelt magnetite sands which are kept together and separated from the charcoal by a thick bundle of grass (*Brown 1982, 54*). It was also found that in many cases, among the coastal and highland Bantu, the ore was put into the furnace on a piece of broken pot (equivalent of a crucible?), thus preventing the fine ore from percolating down through the charcoal and enabling production of a lump of iron rather than many small pieces.

The majority of these processes of refining and smelting (of rich ores) are associated with small bowls, but rich magnetite sands have also been used in shaft and pit furnaces. In the latter process, a pit 1m x 1m is charged with layers of magnetite and charcoal and a long tuyere is inserted into the charge. As burning progresses, the tuyere is gradually withdrawn, resulting in many small pieces of bloom which require refining, no doubt by methods similar to those described above. In Niger (*Echard and Bernus 1985*) small bits of bloom were heated almost to a liquid state in a small bowl hearth. Here, many bits were welded together with the smith occasionally checking the pasty consistency of the iron. In larger dome and shaft furnaces, consolidation is at times achieved by manipulation in the smelting furnace, such as that described by Percy : 'slag is tapped and the iron is extracted through the top after being manipulated into a ball by an iron bar' (*1864, 259*).

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Thus is would appear that the bowl furnace has had a role throughout the history of iron production (as well as non-ferrous applications), for it was not only used as a smithing hearth, but for a number of refining and primary smelting applications. It is this type of furnace which is thought to be typical of the furnaces utilised during the Iron Age in Britain and Europe. Typical dimensions for such furnaces are a diameter of 30cm, and a depth of 23-30cm (*Tylecote et al. 1971, 342*). However, such a furnace is small, and its size and lack of shaft must result in an inefficient process, because, although it is not difficult to achieve a reducing atmosphere, it is difficult to prevent re-oxidation of the bloom. Apart from the lack of evidence in Britain for the use of these small bowl furnaces, a furnace of such dimensions would only support very small-scale production, because the bloom size is fixed not only by the dimensions of the furnace, but also by the ability of the furnace to remove slag. Growth of the bloom is limited by the combustion zone, where it will readily oxidise. Thus a small non-tapping hearth has a limited slag capacity and a rich ore must be used to maximise the size of the bloom. With the obvious exception of these 'crucible' or low-slag processes using rich/pure minerals (*see above*), such a furnace is is unlikely to have been used for long in the history of iron smelting for a variety of technical and economic reasons.

If a small bowl furnace can only pre-pack some 10kg ore, and operates with an assumed 20% efficiency, it should also be noted that a fuel to ore ratio of at least 2:1 would have to be

maintained. If there was 70% Fe in the ore (i.e. pure haematite), the bloom maximum would therefore be 1.4kg. Such a situation is unlikely to occur, as most ores will have a significant gangue (e.g. silica, alumina, etc.) content, and 20% efficiency is high for the bloomery process, particularly in a bowl hearth, where 10% is a much more likely figure. Another point to consider is the volume of fuel required. The volume of charcoal to ore relates to their relative densities and is in the vicinity of 10:1, which effectively means very little ore and charcoal could be charged in a small bowl furnace, and hence the result would be the production of only a few hundred grams and not kilograms of iron; in fact less than the weight of many iron currency bars.

Such a furnace could have been charged in one of three ways: by the 'catalan' method, packing the ore into the back of the furnace; by a layered charge in which a large percentage of the charge is exposed to the combustion zone which is oxidising, resulting in the production of a slagged ore, and insignificant reduction ; and with a mixed ore/charcoal charge, but this would suffer from the same drawbacks as a layered charge. Therefore without a shaft to descend, the prepacked 'catalan' method ensures that ore will not only be kept out of the oxidation zone, but also be in intimate contact for welding. Crucibles, pieces of broken pot and bundles of grass all come within this category and are associated with the smelting of rich, fine ores.

This conclusion is certainly supported by experimental evidence, as provided by Wynne and Tylecote (1958), where two types of charging were used: the catalan and the layered charge. The

latter failed to produce iron, while the catalan method was the most efficient (Richardson (*1934*) also failed to produce iron in a bowl furnace). This is to be expected, because, by maintaining the ore in a large mass, the iron is gradually reduced and the crystals of iron can weld together. This method of charging results in a characteristic structure forming in the base of the furnace (see *Tylecote 1962*, fig.44; also plate 19$_E$), with semi-reduced ore at the top, bloom in the centre and slag at the base. This is in contrast to the very different structure which would form in the shaft furnace (plates 4 and 21$_b$), with slag accreting on the underside of the tuyere. Such a structure can be seen from the furnace remains at Kestor, Devon (*Fox 1954*) and possibly in those at West Brandon, Durham (*Jobey 1962*). The remains at Kestor do not represent smelting in a bowl furnace, but possibly in a dome or small shaft furnace. In fact, the predominant use of documented bowl furnaces in the ethnographic literature is for refining or non-ferrous processes (see, for instance, *Tylecote 1965*). There are no clear examples of Iron Age or Romano-British bowl furnaces in Britain, but where they have been used for smelting, the evidence above would suggest that their presence indicates the exploitation of rich ore sources.

## Ore composition and furnace operation

Fells (*1983, 184*) questions whether it is possible to find out if ore composition had any significant influence on viscosity and whether this in turn influenced furnace type (i.e. tapping /non-tapping), or whether it was simply the ability to achieve higher

temperatures in some furnaces which allowed for tapping. From the above considerations it would seem that, within broad limits, the composition of the ore in part influenced the development of furnace structure. Perhaps the most interesting evidence comes from Kenya, where dome, shaft and bowl furnaces were all utilised; those to the east of the Rift valley, where the predominant ore was ironsand, were almost exclusively small, non-tapping bowl furnaces, while those to the west, using a lumpy ore with a higher gangue content, were the larger dome and shaft furnaces (*Brown 1982, 56*). As the gangue content of the ore increases, tapping facilities are necessary to remove the bulk of the slag. To remove the slag, it must be of low viscosity or kept at a temperature above its liquidus. If slag removal is essential, then working temperatures of the furnace must be above the liquidus of the slag, and this is best achieved by increasing the height of the shaft. Slags with small solidifying ranges resulting in a pasty state might require raking from the furnace.

Where rich ores or crucible processes are the mode of production, the slag remains will often be unrepresentative of the quantity of iron produced. There would be no massive cakes of tapped slag or furnace slags with entrapped charcoal, but instead many small pieces of slag would be produced. Such pieces of slag could easily be incorrectly identified as smithing slags. Early iron can contain some 4-5% of slag inclusions; thus it would be possible to smelt an ore with up to 10% gangue and produce these small slag pieces. With a move away from richer ore sources (resulting from depletion of rich deposits or a response to a

much greater demand) the furnace would require modification to handle greater quantities of ore, which would have to be charged in order to maintain the same production level, not only because there would be less iron per unit ore, but also because more of the iron oxide would be required to flux the higher gangue content of the ore. Hence there would be an increasing necessity to introduce slag-tapping facilities.

Once there is a significant gangue content, the slag becomes of prime importance and must achieve a certain viscosity to enable separation from the reduced iron. The shaft would require heightening to allow for the increased time for reduction and heating of the additional burden. Such changes are reflected in a late development in the history of the process, the Stucköfen, or the old high bloomery, which can be seen as a development toward the blast furnace and in part as a response to greater demand and the need to extract iron from ores of poorer quality. Operating conditions varied, resulting in a range of slag compositions from being rich in iron, 52.5% FeO, resulting in only slightly carburised blooms, to those with FeO contents as low as 10% and resulting in highly carburised blooms and occasionally being used to produce cast iron (*Forbes 1950, 391 and Harbord 1904, 246*).

**Natural steel**

There are several reasons why fine rich ores, such as magnetite sands, are preferably smelted in small furnaces, for apart from problems of consolidation of the bloom, or controlling the flow of fine particles through the burden, a more serious problem is

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the risk of extensive carburisation and the production of cast iron. As we can see from Chaudron's curves (fig. 1.2), reduction of these minerals and the formation of cementite can occur as low as 700°C (table 1.3, reaction x).

In addition, at temperatures achieved in the shaft furnace and with their greater efficiency, the formation of the eutectic between austenite and graphite is likely to occur, i.e. pig iron with a melting point of 1150°C. with 4.2% carbon (*Rosenqvist 1974, 267*). Such a product would have been the bane of the ancient smith, for without extensive refining it would have been brittle and unworkable. Several cast iron blooms have been found in Britain (table 2.2).

Even with ores less rich in iron, carburisation is easy to achieve and many recent experimental smelts in shaft furnaces have resulted in production of anything from wrought iron through steels to cast iron (*Tylecote et al. 1971*). And it has long been recognised that by controlling such factors as fuel to ore ratio, and the rate of blast to the furnace, a skilled furnaceman could produce either a ferrite bloom or a steely one at will (*Percy 1864, 307*). Plates 5a-h and 8f-h provide examples of the range of material produced in blooms from experimental smelts.

In the catalan furnace two categories of ore were charged; *greillade* (fine, pounded ore) and chunks. Richards considers that the sole object of the *greillade* is to protect the iron already reduced and carburised from oxidation and decarburisation in the tuyere zone, but this seems inconsistent with conditions listed

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for the production of natural steel, *fer fort* (*Percy 1864, 307*),
where there was less *greillade* charged in the manufacture of
steel, a carburised product, than in the production of a ferrite
bloom:

Table 1.4

Conditions required for the manufacture
of a steely bloom

less *greillade*
more charcoal
tappings more numerous,
finer ore by greater manipulation
ore often pushed towards the tuyere (gradually & slowly)
longer residence in shaft
less blast towards end of smelt than in the
case of soft iron
manganese in ore
dense charcoal
(after *ibid. 307*)

However, it was observed that even with all of these conditions
fulfilled the production of a natural steel still depends on the
skill of the furnaceman.

The fine particles, having a large surface area, were quickly
slagged and reduced. They assisted in the formation of a basic
slag bath which decarburised, rather than protecting the bloom
from decarburisation. Small particles of iron rapidly sank
through the charge and collected in a cake at the bottom (*Percy*
*1864, 300*), forming the foetus of a bloom, with occasionally more
than one centre being formed.

This ability intentionally to produce steel or high-quality iron
is of constant interest in archaeology (*Wertime 1983; Pigott et*
*al. 1982; UISPP 1982 and 1984*), no doubt inspired by classical

references to regions or peoples producing iron noted for its quality:

But for all the varieties of iron the palm goes to the Seric, sent to us by the
Seres..........The second prize goes to Parthian iron (Pliny XXXIV. XLI. 143).

Through history, different iron-producing regions have achieved such recognition:

It is said that the production of Chalybian and Amisenian iron is very peculiar;
for it grows together,...from sand that is carried down by the rivers. Some say
they simply wash this, and smelt it in a furnace;....The iron is far more
beautiful than the other kinds (Aristotle, De Mirabilibus Auscutationibus, 25-30)

Norican iron is also renowned for its quality (*Pliny, ibid.*) and the use of manganiferous ores is frequently cited as the reason for its reputation. Schubert and others have suggested that its quality relates to it being 'a natural Fe-Mn alloy' (*1957, 29*). Many authors have made the mental leap from from the presence of manganese in modern steels to suggesting that it was the manganese content of the Norican iron that was responsible for the superior quality of metal from this region. However, thermodynamically it can be shown that the presence or addition of $MnO_2$ to the smelting process does not usually result in the production of a 'natural' Fe-Mn alloy and that the manganese enters the slag replacing some of the iron in the silicate structure. This is due to the greater stability of the manganese silicate relative to fayalite (the iron equivalent). As a consequence, a greater quantity of iron is released for reduction to the bloom. Percy (*1864*) reports the use of manganiferous ore when a steely bloom is required, and from thermodynamic considerations it is evident that the addition of manganese from the ore has a similar effect to an acidic slag.

As an aid to understanding this carburisation process, consider a small particle of iron descending down the shaft. As reduction proceeds, a point will be reached when there is no longer any nucleus of the ore particle to reduce, therefore no highly basic silicate to yield a proportion of its oxygen to decarburise the iron, and carburisation of the iron increases with increasing acidity of the slag (table 1.3, reaction xi).

In an ore with a moderate percentage of $MnO_2$, the onset of carburisation will be reached earlier owing to the greater stability of the MnO in the slag. As a consequence of this, other factors being constant, the bloom will have a higher percentage of carbon and hence a steely structure.

A steely bloom can be produced simply by increasing the fuel to ore ratio in the charge, thereby extending the residence time of any ore particle in the furnace, consequently resulting in greater diffusion of carbon into the bloom. Reducing the blast towards the end of a smelt was also used to this effect, as it also results in a longer residence time and avoids the risk of extensive oxidation of the bloom. However, in many iron-producing communities, distinctions were also made between the type of furnace used to produce ordinary wrought iron as opposed to superior iron. The iron-smelting town of Tendukera (India) produced wrought iron and steely iron in two distinctly different furnaces. The latter was produced in a much taller furnace narrowing at the mouth (*Percy 1864, 258*). Production of a natural steel in this manner would have been possible during any period of ancient iron production. Certainly the steely bracelets

of the Transjordan (*Pigott et al. 1982*) represent some of the earliest, though unintentional, production of steel.


Conclusions

Experimental smelting and observations of early small-scale iron production have been invaluable in reconstructing the bloomery process and in particular providing a possible explanation for the use of small bowl furnaces. Archaeological evidence is slowly accumulating and confirms the utilisation of a wide variety of furnace structures and the full range of available ores. Understanding the role of slag enables a greater appreciation of these ancient processes. It has been demonstrated that, to some extent, the quality (texture and composition) of the ore influences the type of furnace employed (the relevance of this is further discussed in chapter 4, on furnaces): for example, the suitability of the bowl furnace for the smelting of rich ores. If rich ores had been used then only a scatter of small pieces of slag and the hearth of a small furnace would remain, which would thus be almost impossible to distinguish from smithing debris. Therefore, the volume of slag cannot be considered a reliable indication of the scale of the industry or the method employed, without additional site evidence.

Furnace morphology could be influenced by the desired product, as certain types of furnace were selected when a steely bloom as opposed to a ferritic one was required. However, the production

of both steely and ferritic blooms in the same furnace has also
been observed, and thus there is little possibility of relating
ancient furnace types to a specific product. Both ethnographic
and experimental evidence suggest that natural steel could have
been produced without intentional cementation, at almost any
stage in the history of the industry, and, as will be discussed
later, even the slag is not a reliable guide to the nature of the
product because the process is rarely in equilibrium.

# CHAPTER 2

# PRODUCTS AND BY-PRODUCTS

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## Abstract

This chapter investigates the products of the bloomery process: metal, slags and furnace materials; impurities in the metal. Slag analysis includes the distinction between smithing and smelting slags; the effect of corrosion on the analysis of slags; the products of experimental smelts; archaeological remains.

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# PRODUCTS AND BY-PRODUCTS

## Introduction

Examination of ancient metals is carried out to identify the microstructures and various phases in the structure, and from these features to deduce the nature of the changes to which the artefact has been subjected and consequently reconstruct techniques of manufacture. However, such examination is usually limited to a very small part of the artefact and an even smaller proportion of the artefacts available, and hence it is important to understand not only the processes involved in production of the bloom, but also the effect that refining, i.e. shingling and forging, has on the variable structure of the bloom.

All too often attempts have been made to impose criteria on metallographic research, which, while being correct for modern steels, are too rigid or restrictive when it comes to understanding ancient alloys and techniques. Pleiner (*1973, 18*) correctly criticises Piaskowski's (*1972*) attempt to impose such criteria on the identification of welding:

> ..one is told to be able to observe the intentional welding together of hard carbon steel and wrought iron only if: a) the welding seam is clearly visible; b) the seam is accompanied by a continuous chain of slag inclusions; c)sudden changes occur in the concentration of carbon or other elements; and d) sudden changes occur in the orientation of prolonged slag inclusions (Pleiner 1973, 22).

If such a system is adhered to, the skill of the ancient smiths will be obscured, just as the post-welding operations of

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twisting, repeated reheating and bending often obliterate such obvious means of distinguishing earlier welds (see plate 8f-g)

He illustrated this point with an experimental sandwich blade which, typical of many ancient objects, showed some decarburisation in parts and diffusion in others, during what was a quick process. Other experimental welds were difficult to detect, and there was considerable diffusion across the weld (*Pleiner 1973, 23*).

## The concept of quality

Just as attempts have been made to impose modern metallographic criteria on the study of ancient microstructures, metallurgists have also brought their prejudices to bear on other aspects of ancient metallurgy, such as the role of impurities in the metal. That phosphorus was considered detrimental was due to its effect on the metal during modern processes such as rolling. Phosphorus during certain treatments gave rise to 'cold shortness', and considerable industrial effort went into the removal of this element from iron (Thomas and Gilchrist), although, recently, phosphorus has been reintroduced into the metal for its beneficial properties, which include the toughening of the metal. Ancient smelters, however, were seemingly ignorant of the problem, as many pieces of ancient iron exhibit high phosphorus in combination with sophisticated techniques of smithing. Analysis of many early slags from Europe, of the 4[th]- 1[st] centuries BC, along with many examples from during the early centuries AD, had high $P_2O_5$

contents of 0.2-0.56%, with many of 1-2%, which is more than adequate to harden iron (*Piaskowski 1961, 264*). Therefore it can be assumed that iron containing phosphorus was as easy to work as other material, with the added benefit that the phosphorus was acting as a toughening agent. In fact there can be little doubt that iron rich in phosphorus was selected in the past as there is evidence of intentional layering of strips of high phosphorus iron with those of ferrite or rich in carbon (*Pleiner forthcoming; Crossley 1981, 33;* see also plate 22g-h).

It is worth re-emphasising aspects of bloomery iron which are pertinent to the interpretation of quality. Bloomery iron is a heterogeneous product, with carbon content varying from zero to over 1% (plates 2, 5 and 8). Also, the phosphorus content, along with other impurities, can vary considerably. Hence, the product the ancient smith manufactured or was presented with for forging had a hardness equal to many bronzes without requiring such additional techniques as quenching or heat treatment. Such material was undoubtedly adequate for manufacture of a wide range of domestic and agricultural implements and in fact agricultural tools/implements were commonly made of natural steel selected from the heterogeneous bloom on the basis of fracture (*Smith 1968*).

The recognition of quality by ancient smiths is important to any discussion of technological development. For many centuries, in fact millennia, metal workers and craftsmen have selected different qualities of material for specific tasks, e.g. high tin bronzes and leaded bronzes for casting, while a lower tin-

content was used when some forging was required. In some cases even the high-tin material was worked, requiring a considerable degree of technical skill and knowledge. Damascus steel (wootz), probably with its origins before the 1$^{st}$ century AD, also requires a highly specialised skills with precision in both the production and forging of the wootz cake (for a full discussion see Yater 1983).

There are many examples where this recognition of quality or the inherent properties of a material can be observed, demonstrating an intimate understanding of the nature of the materials best suited for the task in hand. The ability to recognise differences in a product would be quickly learned by most craftsmen, and so the transition from iron to steel, or the separation of a steely bloom from a ferrite one, could be achieved by many individual craftsmen at many periods and locations, ruling out the concept of linear progression from iron to steel. One would expect techniques of welding and the recognition of the malleability of ferrite and the hardness of steel, or the toughness of phosphorus containing iron, soon to be combined to produce a superior product. Therefore such individual developments should not be of significance in dating. (Certainly, from ethnographic examples we observe that the bloom is often in many small pieces and welding is essential to produce a bloom of workable size. Also reflected in the archaeological finds is the appearance of steel, wrought iron and welding almost simultaneously.) (see *Smith 1968, 47ff,* on the recognition of inherent qualities of

iron and steel).

Again, along with considerations of quality, one must also examine the scale of the operation, i.e. the function of the site. Seasonal production for farm or village tools need not require any great sophistication, provided that the material is adequate. For instance, the phosphorus-containing ores of Northamptonshire obviously provided an iron sufficiently hard for most purposes (see discussion of material from the site of Odell, Northants., in chapter 5).

Linear models of technological development are common to the literature on ancient technology. Piaskowski presents a familiar model for iron: an early phase represented by little control over the reduction process (*1961, 263*), resulting in a heterogeneous product; later, the ability to differentiate between iron and steel, and to produce either at will; followed by the process of welding iron and steel together (edge tools, etc). Piaskowski perhaps recognises that such a model is of little value, as 'the metallography of iron is a poor dating tool because conservative traditions [perhaps just a reflection of requirements] can last for centuries'.

## Efficiency, yield and variation in product

The variations in ore composition, product and type of production site (farm v. specialist, military v. commercial, etc), give rise to a complexity unsuited to the application of simple linear models, as iron will differ in quality, not

only from area to area, but also within one production site. Equally, specialist skills will demonstrate similar variability, e.g. between two craftsmen, or between craftsman and apprentice.

In the past the inhomogeneity of the bloom was observed and manipulated. At times, such as at Tendukera in $19^{th}$-century India, two different furnaces were used to produce steel or malleable iron. But in contrast, Francois (*Percy 1864*) observed that in $19^{th}$-century Spain, rather than two types of furnace, the same (Catalan) furnace was used to produce two different types of iron, at times even in the one process, with the steely portions dissected out while the bloom was still hot.

## Refining

The raw bloom usually contains a considerable quantity of unwanted slag, often as high as 50% (see chapter 1), and the object of refining processes is to remove a large proportion of the included slag and prepare a billet, or solid block, of iron ready for forging into a variety of objects. Shingling is one term used to describe the process of consolidating the bloom and expelling much of the intermixed slag. To do this efficiently, the slag must be pasty or liquid, in which state it can drip from the bloom in the reheating hearth or be squeezed out of the bloom during the forging. As has been discussed, the physical properties of the slag are important, for if the slag is highly viscous, and has a high melting point, then the bloom will have to be heated to a greater temperature in the forge, and in doing

so, oxidation and consequent loss of metal to the slag becomes more probable.

The overall yield of the process is low, rarely more than 20%, and often as low as 10%. To maximise production, furnaces are often charged as often as six times per day. At Arnee (Madras), smelting 44.4kg of iron sand resulted in 14.7kg of crude iron and forging 44.4kg of crude iron produced 14.7kg of bar iron, a yield of approximately 17% (*Percy 1864, 259*). In Malabar (India), 4kg of ore result in a 1kg crude bloom which was forged to approximately 0.5kg of bar iron, which is similar to the yield seen at Vizagapatam, Madras presidency (*Percy 1864, 267*). Yields, by the very nature of the process, are low as the considerable percentage of the iron used to flux the gangue pre-empts its inclusion in the final product (see chapter 1), and the most obvious effect of refining is to reduce it further. In Duson Ulu, a smelting region in Borneo, shingling and working up of the bloom often resulted in a loss of approximately one-third of the original weight (*Fairburn 1861, 47*), but this was often higher than 50%.

Refining is carried out in many types of hearth and involves a variety of anvils. Flat stones marked by heat and hammering are often found close to prehistoric iron furnaces, where they were used for the initial smithing of the bloom (*Thålin 1973, 110*). Cow Park and Pippingford in the Weald had anvils mounted on tree stumps (*Tebbutt 1980*). One of the furnaces at Hodges Wood (Crowborough, Sussex) had a large flat sandstone block set partly

beneath the slag wall of the furnace (fig. 2.1), and partly protruding into a pit. The traces of slag and possibly iron scale on the surface of the stone suggest that it was an anvil stone used for preliminary shingling of the red-hot bloom as it was removed from the furnace.
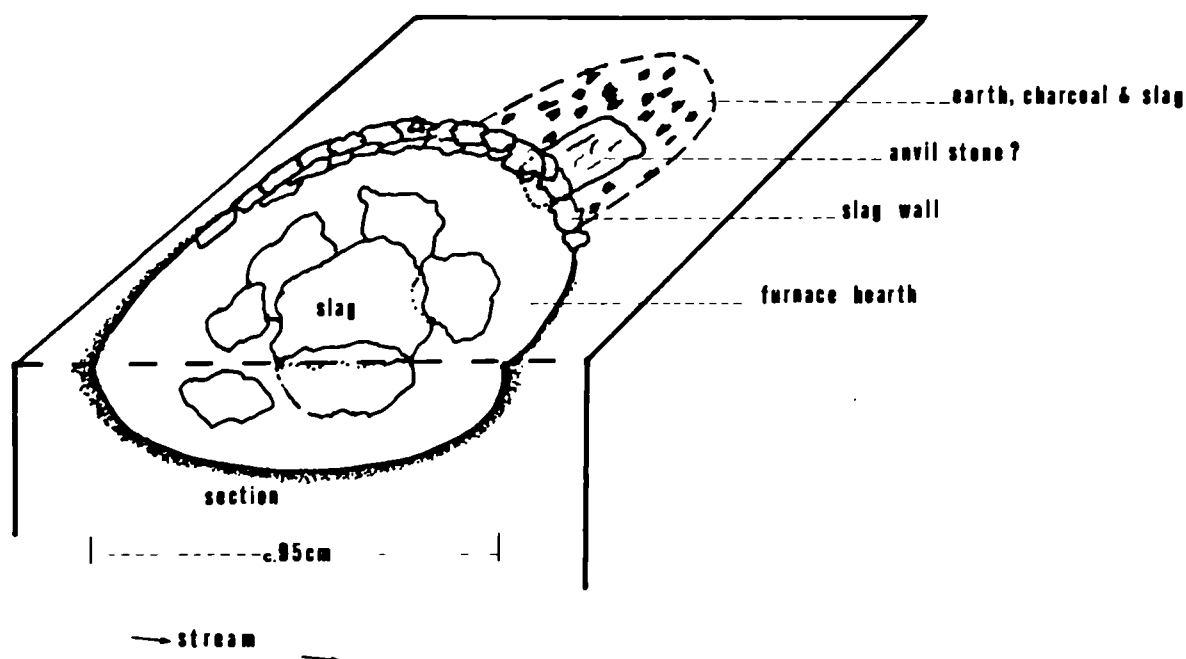


Fig. 2.1 Hodges Wood - furnace 3

At Bryn y Castell, N.W. Wales (*Crew forthcoming*), several anvil stones with adhering slag were found in slag dumps, and hammer-scale and small sphericles of slag were found associated with structures on the site which have been interpreted as forges.

This part of the process was not only the combination of shingling and welding of the solid bloom, but cases have been observed where the bloom is almost molten. In Evenstad (*1968*) there is a reference to the bloom being heated until sparking,

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at which stage it is moved to the hot zone where it melts and falls to the base of the forge. Simultaneously sand and slag are thrown into the fire to protect the molten iron. When solidified, the iron, in the form of a flat lump, is removed and broken up. In this process the distance from the tuyere is important.

Welding is an integral part of forging and often an intentional part of forming the final artefact (plates 8f-g, 17e, and 18d) and is often achieved with the aid of a flux such as sand or fine ore. To date, in prehistoric Sweden no agent other than sand has been detected (*Thålin 1973, 110*) and at one forge a vessel containing welding sand was excavated (*ibid. 108*), although in Britain no evidence has as yet surfaced. It has been suggested that welding developed first to counteract the uneven qualities of the bloom (*ibid.*). This, however, would largely have been achieved during consolidation of the bloom. In fact, rather than counteracting uneven qualities of the iron, welding and forging can give rise to variable composition. Chilton and Evans (*1955, 118*), in a study of iron corrosion, observed zones of variable composition which they concluded 'must arise from the puddling process', and the fact 'that macrohomogeneity is not obtained causes no surprise'. The enrichment zones corresponded to the weld planes of piled components, and were rich in nickel and copper and also phosphorus. This phenomenon was the result of selective oxidation of the iron which is less noble than these elements, or it relates to the re-reduction of these more noble metals from

the underlying iron:

$$Fe \ + \ NiO \ = \ FeO \ + \ Ni$$

$$FeO_{(Fe-rich)} \ + \ NiO = FeO_{(Fe-poor)} + \ Ni$$
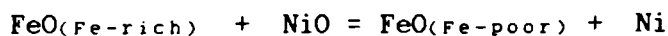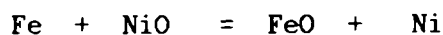
(arsenic and phosphorus are also common in these enrichment bands)

Similar enrichment zones have been observed in archaeological samples, e.g. a Malayan kris.
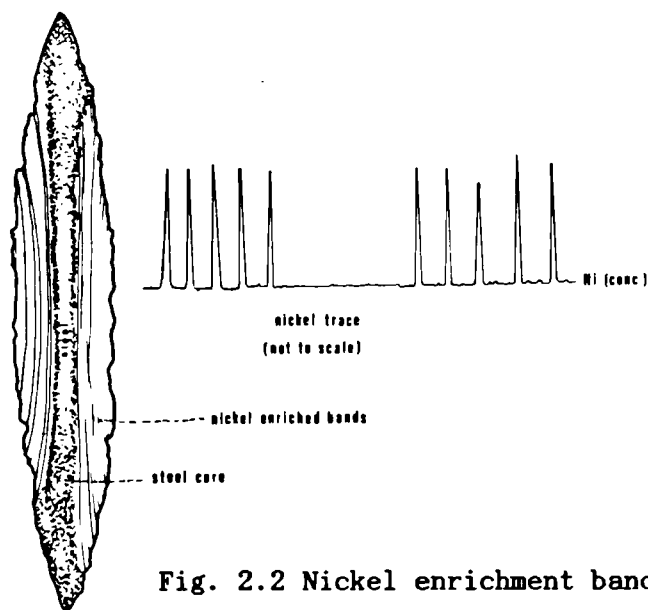


Fig. 2.2 Nickel enrichment bands in a kris

Hansson (*1973*) examined some currency bars and found that although they revealed a largely ferritic structure, they had streaks of pearlite associated with a higher nickel content, presumably demarcating the old surface prior to welding (?). The ferrite grain size varied with the distribution of the carbide and in areas with little carbide the grain size was large, in contrast to the pearlite region. This is at variance with what would be expected if the bars had been heat treated as one piece, because the critical temperature of higher carbon-iron is lower and therefore grain growth should be greater in

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the pearlite regions. Therefore, the bars had probably been formed by the piling together of strips of iron, and the enrichment had occurred during the original forging of these strips. However, if phosphorus was present in the ferrite, it would promote the growth of large grains and could explain the grain-size differences in the structure (again this might suggest piling of strips of high phosphorus iron with those low in phosphorus). The segregation bands illustrated in plate 22 (a-d) are also the result of welding, but do not appear to be enriched to a perceptible level.

Thus, not only during bloom production, but also during refining, variations in trace and minor elements are observed. The actual distribution of these impurities is influenced by the amount of forging and the skill of the smith, and thus affect the quality of the final product.

## The effect of minor constituents and natural steel

The eminent chemist Stahl, while recognising the essential identity of iron and steel, held the belief that the difference lay solely in the relative richness of the latter in phlogiston (Harbord 1904, 575).

(see also Smith 1968)

Today elements such as chromium, vanadium, titanium and many others are alloyed with iron in small quantities to produce specialist steels suitable for many purposes. Perhaps only carbon and phosphorus and slag, being the most common, are of significance in the ancient metal, but nickel, cobalt, manganese and sulphur have also been detected, though less frequently. Below, I have briefly tried to summarise the role of

these elements in iron and steel.

Carbon and phosphorus are common in ancient iron and are important because both serve to toughen the metal. They are incompatible because of their high combined solid solution pressure, and because the carbide is more mobile it diffuses into surrounding metal where there is little phosphide (*Stead 1918, 389*). Because of its mobility, the carbon content is more easily controlled, either during the smelting or forging processes, whereas the phosphorus content relates mainly to its concentration in the original ore. As a consequence, carbon is a more versatile toughener and hardener of the metal, and is a more desirable additive, particularly as it may be quench hardened.

Roesch and Kuhn (*1976*) carried out simulated smelts using high-grade Indian and German ores, the latter high in phosphorus. Ore and charcoal mixtures were heated in a gaseous mixture of $CO_2$ and $H_2$ at 1070°C. Iron was also carburised by heating with charcoal in a crucible. The outcome of these experiments confirmed the findings of an early study on the interaction of carbon and phosphorus (*Stead 1918*), in that the iron produced from the ores high in phosphorus was difficult to carburise in the 2-4% phosphorus range, in contrast to the iron from the low-phosphorus Indian ores, which easily took up carbon. While these findings accurately reflect the interaction of the two elements, simulated experiments which fail to approximate closely to the original conditions are liable to result in

spurious conclusions. For example, in many blooms it would be possible to achieve intimate mixing of phosphorus and carbon on a large scale, but with clear segregation of the phosphide at microscopic levels. For instance, the phosphide is clearly segregated in the bloom from smelt WH1 (plates 5 and 6a and table 2.1). Thus, while it may be difficult to carburise an iron high in phosphorus, it would not be suprising to find carburised iron smelted from an ore with a high phosphorus content. Also, high-phosphorus ores do not necessarily result in a high phosphorus-bloom, as a high percentage of the element could be removed by using a low fuel to ore ratio and forming a basic slag. For example, the roasted ore from the site of Odell (Bedfordshire), has 0.5% $P_2O_5$ and the slags from the same site have a similar amount (table 2.11). However, the slag from the experimental smelt (O1), using the same ore (assuming that the roasted and prepared ore found at the site was the same as that used for smelting) had phosphorus contents of c.1% (table 2.12). Even in this instance it is difficult to assess the exact fuel:ore ratio used because the charcoal ash is an unknown variable, and the Portuguese hardwood charcoal (*Quercus sp.*) used in the experimental smelt contributed greater amounts of calcium to the slag, thereby increasing its ability to remove phosphorus. However, the predominantly olivine structure of the archaeological and the experimental slags does suggest that the fuel to ore ratio employed in the ancient smelts did not differ significantly from 2:1.

Table 2.1

Analysis of regions of phosphide in experimental bloom WH1

|   | Fe | Mn | P | |
|---|---|---|---|---|
| 1 | 90.9 | n.d | 1.0 | phosphide |
| 2 | 87.5 | n.d | 6.4 | phosphide |
| 3 | 88.5 | 0.4 | 5.4 | phosphide |
| 4 | 85.7 | 0.7 | 11.4 | phosphide |
| 5 | 96.6 | 0.0 | 0.4 | pearlite adjacent to phosphide |
| 6 | 88.3 | 0.0 | 4.8 | sample 2 |
| 7 | 99.8 | 0.0 | 0.0 | ferrite |

The phosphide in a pearlite matrix can be seen in plates 5 and 6

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The movement or partitioning of phosphorus is influenced by the temperatures of the reaction:

$$P_2O_5 \text{ (slag)} + 5C = 5CO + 2P \text{ (metal)}$$
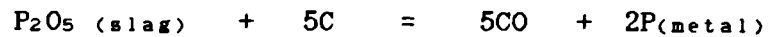
Below 1102°C the reaction right to left predominates, but above this temperature the reaction from left to right is favoured and increases with temperature (*Maréchal 1969, 281*).

An excess of phosphorus in the metal would be harmful to some applications, as although it results in increasing strength and hardness (table 2.2), it seriously effects the ductility and resistance to shock impact, and during heat treatment it increases the grain size of steel. In many early iron objects this would not be overly significant, as they were not expected to withstand modern degrees of deformation by rolling and press-forging, etc, but it would possibly affect some objects requiring considerable forging (plate 6c). The hardness of ferrite is usually around VHN 100, but hardnesses between 140 and 200 are frequently obtained and must result from low levels of phosphorus in solid solution (see table 2.2). (see

Tylecote *(1962, 204)* for the effect of phosphorus on the hardness

and strength of iron).

Table 2.2

Vickers microhardness of archaeological and experimental iron

(100g load)

| | | |
|---|---|---|
| Odell (0.4) | 157, 152, 145 | equiaxed ferrite grains |
| Jos bloom | 221, 298 | pearlitic region |
| | 197 | widmanstatten ferrite |
| | 130 | ferrite large grains |
| Jos plate | 170, 232 | surface pearlite |
| | 159, 154 | ferrite centre of plate |
| Bognor Regis | 160, 153 | ferrite in sulphide matrix |
| WM1 | 138 | massive ferrite grains |
| | 143 | ferrite with plates of carbide |
| WH1 | 253, 256, 274 | coarse pearlite |
| (see table 2.1) | 667, 700, 657 | phosphide, different regions |
| WH2 bloom | 189 | ferrite |
| | 154 | ferrite |
| | 171 | ferrite |
| Ashdown bloom | 108 | large ferrite grains |
| | 149, 143 | ferrite |
| Odell (Fiii 69) | 160 | ferrite |
| | 428, 424 | fine grained pearlite |
| Odell (Fiii 21) | 108, 97.5, 124 | ferrite with cementite as grain boundaries |

Sulphur, in a similar way to phosphorus, is another element

regarded as detrimental to iron.

It is unlikely that they [the Romans] used the sulphide group [iron pyrites]
because the presence of sulphur in it has a detrimental effect on the iron
produced (Aiano 1977, 73).

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It is important to note that it can be present in quantities up to 2% and its detrimental effects can be avoided by careful forging. If forged above 988°C the Fe—FeS eutectic is formed and coats the grain boundaries (fig. 3.1 and plate 7a-e). It then causes 'hot shortness' and weaknesses develop at the boundaries, resulting in cracking. If the forging temperature is kept below this temperature then the problem is avoided and the sulphide inclusions remain intact (plate 8c)(*Tylecote and Clough 1983;* see chapter 3 for a full discussion).

Manganese is one of those elements which today we associate with steel, and it has been discussed with respect to ancient steel in chapter 1. As we have seen, it would only enter bloomery iron under conditions of high temperature and a highly reducing atmosphere. Therefore its presence is usually associated with high levels of carbon and other impurities (table 2.1 for Mn in the bloom from smelt WH1), and such conditions were obviously responsible for the composition of the pick from Nimrud, which apparently has 1% manganese. This and picks from Khorsabad are generally low in carbon, but have some regions containing up to 1% C. From this Curtis and his colleagues conclude that there is evidence of deliberate carburisation (*Curtis 1979, 56*). However, two factors argue against such an interpretation. The heterogeneity of the artefact is consistent with microstructures which might be expected in bloomery iron, and structures show that the metal was not quenched and the 1% manganese, if correct, would suggest very strong reducing conditions during the smelt which also result in extensive

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carburisation (such as in pig iron).

## Archaeological evidence of production techniques

The archaeological evidence will always be biased. Remains of surface treatment or carburisation will often be lost in corrosion products. Also, those pieces best preserved are rarely sampled, but put on museum display. Where sampling is possible, only a small, and possibly unrepresentative, sample is taken for study. Also, most metallographic sections are taken from the edge of an artefact, and this would be the region exposed to the oxidising or carburising regions of the forge and is consequently not representative of the whole artefact (see plate 8f-g where the weld has been produced during refining of the bloom and does not relate to production of a specific artefact, and also WH1 bloom (plate 5), where decarburisation left the bloom with a clear division between ferrite and pearlite prior to forging the bloom).

The mixed product of iron and steel was certainly used in Britain prior to the Roman period (Llyn Cerrig wheel and swords; Gussage file and bronzed-steel mouthpiece; the Fiskerton and Whitcombe hammers (plate 22); Worthy Down (*Salter 1984*)), but in general, the evidence for steel remains elusive. Blooms which have been found confirm the production of natural steel, but the artefacts from this period are too few to draw sound conclusions. From Wookey Hole a 3.1kg bloom was recovered (20.3 x 8.9 x 6.4mm) (*Tylecote 1962*), too large to have originated in a traditional Iron Age bowl furnace. Although the bloom was completely

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oxidised, analysis indicated a carbon content of 0.48%, which is the equivalent of a low to medium carbon steel. At Crowhurst (Straker et al. 1938) (Iron Age or Roman) a small bloom was found. This weighed 1.2kg and had a carbon content up to 0.3%. Other sporadic finds of cast iron are listed in table 2.3.

Table 2.3

Examples of cast iron from Iron Age
and Romano-British sites

| Cast Iron | Braughing | Hengistbury | Wilderspool | Tiddington |
|---|---|---|---|---|
| total carbon | 3.3 | 3.49 | 3.23 | 3.52 |
| silicon | 2.62 | 0.39 | 1.05 | 1.92 |
| phosphorus | 0.26 | 0.18 | 0.76 | 0.77 |
| sulphur | 0.043 | 0.025 | 0.049 | 0.05 |

These finds are somewhat inconsistent with the findings from artefacts, which generally contain very little carbon, with some notable exceptions: for example, the hammer from the Whitcombe warrior burial (plate 22) and wedge from Worthy Down (*Salter 1984*) and a La Tène sword which had three distinct zones with differing carbon contents. The gradual change of carbon content across the welds suggests that the sword has been held at elevated temperatures (probably resulting from continuous hot forging). The hardness of the artefact varied as expected with microstructural changes, but was higher than the microstructure would suggest, being in the range of 320 - 450 VHN (*Stead et al. 1980*).

The inconsistency between high-carbon blooms and very little carbon in the artefact has led Tylecote to suggest that these high-carbon blooms are accidental (*1962, 204*), but the overall

picture is inconclusive as there are very few blooms of any composition, including ferritic ones, on which to base a judgement, although the number of steel finds is slowly accumulating. Also, most carburised blooms when forged could lose the bulk of their carbide, just as forging of the grey cast iron from experiment WH1 resulted in a structure with low to moderate carbide content.

**Currency bars** can be considered as an intermediate stage between the bloom and the final artefact. One particular example of a 76cm currency bar had a microstructure which, like that of blooms, varied in carbon content, in this case from 0 to 0.8% carbon (*Brewer 1976*). It displayed a Widmannstatten distribution of ferrite and slag particles, which is consistent with hot forging and fairly rapid air cooling. This is confirmed by medium lamellae of pearlite as opposed to a coarser structure which is only produced by slow cooling from the austenitic temperature. The hardness of the bars ranged from 124 to 190 VHN. According to Gilmour (*B. Gilmour pers. comm.*), the structure is made up of thin layers. In contrast to this, the Swedish bars are not considered to have been formed by any complicated welding procedure (*Brewer 1976*).

Work by Salter and Ehrenreich (*1984*) is consistent with the interpretation that currency bars are an intermediate form ready for trade and forging into artefacts. Comparable trace-element concentrations in currency bars and a wedge from Worthy Down

imply that the wedge was manufactured from one of the currency bars at the site.

The technological level of the early iron industry, in Britain, has been the subject of considerable discussion, particularly over the interpretation of forged iron artefacts which appear to have prototypes in bronze. Contrary to Manning (*et al. 1972*), Scott sees the production of these forged iron types as a considerable technological feat, and therefore indicating a developed iron industry rather than one in its 'fumbling infancy' (*Scott 1974, 12*). However, while accepting this as a technological feat, it could be an experimental one by an experienced bronzesmith, as there is growing evidence for mixed metallurgy, with smiths being competent in the manipulation of both iron and copper alloys. For example, the Gilmonby bronze hoard from Barnard Castle, Durham, contained a small quantity of iron, while Bagendon (Gloucs.) and Boxgrove (Sussex) (although late Iron Age) provided evidence for both iron and bronze smithing in the same forge. From the 3[rd] century BC both iron and bronze artefacts were being produced at the site of Gussage All Saints, with the iron industry providing the tools (e.g. punches, files) of the bronze industry (see also Danebury and Bredon Hill, chapter 5). Some of the Hallstatt swords are a combination of the two alloys and are examples of considerable forging skills (*Scott 1985*).

The number of analysed iron objects from the British Iron Age, while growing, is too small for any firm conclusions to be drawn, although there is evidence for the use of both natural steel and

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carburised steel. In Europe, however, considerably more specimens from the early periods have been analysed and it has been possible to trace the use of the following techniques between 700 and 400 BC:

Table 2.4

### Techniques of iron working in Hallstatt iron artefacts

1. Forging tools of wrought iron or low-carbon steel.
2. Forging tools of inhomogenous carburised steel reaching 0.5-0.9% carbon.
3. Forging tools of quenchable steel, )0.35% carbon.
4. Forging tools of wrought iron and carburising the edges.
5. Iron-steel welding.

Of the 111 Hallstatt specimens analysed, 67% were judged to be of poor quality, with some 78% manufactured using the techniques described in 1 and 2 (table 2.4). The quality varied depending on the artefact (*Pleiner in Wertime 1983*). Analyses of Celtic swords (*ibid. 393*) dating from the 4th to 2nd centuries BC have resulted in their being termed 'poor quality', as only a few indicated any evidence of surface carburisation or welding. Analyses of late La Tène swords from the Celtic oppida (Steinsburg, Stradonice) show them all to be of low quality, but the ironwork from the site comprised wrought iron, hard steels and evidence for quenching (*Hanemann 1922*).

Three blooms, coming from the region between the Oder and Vistula rivers (10th to the 8th centuries BC), were examined, and had a very uneven distribution of carbon. By the 6th to 4th centuries there are artefacts with extensive piling and examples of sandwiching (*Piaskowski 1961, 27, figs. 10, 18 and 19*), and some of the Hallstatt socketed axes show excellent welding skills. In

Swietokryskie (Poland) during the 7th to 6th centuries high-carbon material is utilised, but the pattern is inconsistent. However, its properties were obviously appreciated as there are examples with evidence of heat treatment (*Piaskowski 1961, 272*).

Even with a considerable number of analyses there are still far too few for any meaningful pattern to be discerned. The microstructure must be related not only to the type of artefact (function), but also the type of site, and if possible traced back to its region of production. The role of phosphorus is coming more and more into recognition, and it is evident that high-phosphorus irons were intentionally chosen and welded together with ferrite and/or high-carbon bars to produce a tough and malleable metal (*Pleiner pers. comm*). Analyses of iron objects from western Pomerania (Poland) confirm just how frequent phosphorus-containing ores were, as the 82 artefacts (from 25 sites) could be separated into three groups on the basis of their composition: high phosphorus with 0.2-1.0% and 0.2%C; low phosphorus and partly carburised, 0.2%C with up to 0.13% nickel; and steels, 0.4-0.8%C, with even carburisation and low phosphorus (*Piaskowski 1972*).

Analysis of the ubiquitous iron billets, both currency bars and the continental equivalent, *Spitzbarren* (plate 23b), shows a range of phosphorus content from 0.015% to 0.95%. Phosphorus in British currency bars (from trace to 1%) is greater in general than that in *Spitzbarren* (4-6kg), 0.015 to 0.45%, and although few iron objects from Britain have been analysed for their

phosphorus content, the levels present in currency bars (Danebury 0.1-0.9%, Gretton 0.2-0.7%, and Beckford none detected) is sufficient evidence to suggest that the toughening properties of this element were widely utilised.

Recently a large body of Iron Age (La Tène) artefacts from southern Britain has been studied metallographically (*Salter and Ehrenreich 1984*), providing an invaluable addition to the current evidence. Of the 252 artefacts sectioned, 65% had less than 0.1% carbon, 28% had between 0.1 and 0.5%, while the remaining 7% contained between 0.5 and 0.8% carbon. Overall, the breakdown is very similar to the European Hallstatt artefacts (table 2.4) and techniques 1 to 5 were all detected. This indicates that while the bulk of iron is ferritic and considered low quality, there was selection of steel and iron with phosphorus, and an awareness of heat treatment such as quenching and tempering.

## Slag: definitions and classification

Slags are by far the most obvious remnants of metallurgical processes, and even on a small production site such as Gussage All Saints there was as much as 700kg of slag excavated. A slag to metal ratio of 3:1 has been suggested for the bloomery process (*Gilles 1961, 1071; Bielenin 1974, 265*), but even this is likely to be a conservative estimate, as the use of poor ores will result in much greater volumes of slag per unit of iron produced. As a result of their frequent occurrence, archaeological slags have been the subject of several studies which attempted to define and classify them (*e.g. Sperl 1979 and 1980, Bachmann 1982, and Fells 1983*). One of the earliest studies was the

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pioneering work of Morton and Wingrove (*1969, 1972*), whose examination of the constitution of archaeological slags has provided the basis of the subject for many years and, although some of their conclusions are now in need of revision, much of their work, including their definitions of slag and cinder, are still generally applicable:

Slag: the term applied to the silicate complex formed by the combination of earthy matter agglomerated in the ore, with some of the iron oxide in the charge acting as a flux. Impurities in the fuel are molten at the completion of the smelting process.

Cinder: a drossy solid material which collects on top of the molten slag, and which when removed resembles a mass of material infusible at the working temperatures of the furnace, embedded partially in fused material. Thus cinder has never reached a molten or free flowing condition in the furnace. (*Morton and Wingrove 1969*)

## Slag composition and structure

Slag microstructure and composition are variable in both composition and texture, even from the same smelt, a fact which is consistent with the process (plate 6$_H$, see chapter 1) and the variation observed in the bloom itself. The above definition is inadequate in that slags are more than silicates, and are generally a complex mixture of silicates and oxide phases (FeO and spinels such as hercynite - plate 10$_A$). Their composition is influenced by the following:

Table 2.5

### Influences in slag composition and mineralogy

ores and gangue minerals
fluxes
furnace linings / crucible material
charcoal ash (see table 2.14)
process conditions (i.e. fuel:ore, blast rate, etc)
weathering (see below)

All of which can be significant in the interpretation of analyses, although the use of fluxes is usually not encountered in these early processes.

**Slag analysis**

Modern slags are analysed in order to understand fully the relationship between the furnace operating conditions, ore/slag composition and the quality of the end product, in order to facilitate greater control over the end product, i.e. it is a form of quality control. The analysis of ancient slags is intended initially to discover what processes they originate from, and beyond that to reconstruct the technical parameters of the early processes, such as the furnace conditions and the types of ore exploited. This involves the determination of their chemical and mineralogical composition and the relating of these to the process. The techniques used in the research for this study were X-ray fluorescence (XRF-Edax and wave dispersive), inductively coupled plasma emission spectrophotometry (ICP), X-ray diffraction (XRD), electron probe for microanalysis (EPMA), scanning electron microscopy (SEM) and metallographic examination of slag and metal microstructures. Details of these techniques have been provided in appendix B. XRF, ICP and EPMA were employed to determine bulk composition, while XRD and EPMA, along with metallographic examination and SEM, were used to examine the mineralogical structure and composition.

## Corrosion of slags

Post-depositional changes are of relevance to the selection of slags for analysis, as many of them show extensive corrosion or weathering. The most obvious indication of this is the rust-coloured surface deposits of goethite derived from the corrosion of iron minerals or metallic particles, but not present in the formation of the original structure. Goethite (FeOOH) is unstable over 250°C and not formed in any of the metallurgical processes, and therefore must be a weathering product, a sign of corrosion. Some of the slags from the Sussex site of Garden Hill, while retaining their grey-black tapped morphology, are soft and porous on the surface as a result of leaching of minerals from the structure. Both forms of corrosion can seriously distort analysis of the material and interpretations that can be drawn from such analyses. Slags weather or corrode in different ways, depending on the conditions under which they are buried (i.e. the prevailing micro-environment).

Many of the early iron-making slags are composed of three or four main phases : olivines (particularly fayalite), wustite, and a glassy phase containing silica, phosphorus, alumina, lime, alkalis and some of the other elements present. Pyroxenes and spinels also occur in these slags, with the mineral assemblage depending on the original composition of the burden (ore and fuel), the operating parameters of the furnace, and to a minor extent the composition of the furnace lining (element maps of slag phases, plates 13-15, demonstrate the partitioning of elements into the various phases).

Plates 15 and 16 exemplify slag corrosion of varying types and EPMA analysis indicates that it is, as might be expected, the glassy phases which break down first, losing the alkalis, potassium and sodium, and to a lesser degree some of the alkaline earth constituents which are leached out of the glass matrix leaving a silica-rich gel on the surface. This is certainly the case in acid conditions, whereas in alkaline conditions the gel also breaks down and the structure of the slag gradually and completely disintegrates. The microstructures in plate 15$_{g-h}$ show clearly the stages of corrosion, with an extreme example (15$_h$) where only redeposited iron oxides and wustite remain. These elements can be present in quantities of up to 5% or greater and derive mainly from the fuel ash entering the slag composition. Even in these small quantities they are powerful fluxes and it is likely that they would have a noticeable effect on the free-running temperature of the slag (and melting point). Olivines weather more rapidly than pyroxenes and from the limited investigation appear to be the next to break down in the structure, with the wustite remaining surprisingly stable (plate 15$_h$).

Many of the analytical problems arising from corrosion, metallic iron in smelting or smithing slags, etc, can be overcome if, for example, EPMA is the analytical tool used. While not ideal for bulk analysis, it is able to analyse several small areas for an approximation of the bulk composition and as a check for consistency, but more important is the ability to see the area being analysed and thereby avoid non-representative inclusions

and areas of corrosion.

## Normative calculations and phase diagrams

The term 'normative' is equivalent to the equilibrium mineral assemblage. The use of normative constituents has been an established practice in geology since the early years of this century (*Cross et al. 1903*), but it is only in the last decade that its use has become established in archaeometallurgy (*Bachmann in: Craddock 1980, 103-134 and more recently Kresten et al. 1983*). This method takes the bulk composition of a slag (usually presented as wt% or mol% oxides) and calculates the theoretical mineral assemblage which would result from equilibrium cooling. The mineral composition can then be plotted on an appropriate ternary phase diagram and its crystallisation paths and liquidus temperatures assessed (see fig. 2.3).

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**Table 2.6**

### The advantages according to Kresten

1. The comparison between various analyses is often easier when the norms are compared.

2. The contents of oxides reported in the analyses are viewed in a more many-faceted context when applying the normative calculation. For instance the CaO reported in the chemical analyses is contained in the normative constituents anorthite, calcium silicate, and wollastonite, sometimes even gehlenite. Thus, the mode of occurrence of calcium in the normative constituents depends on the relative abundance of alumina and silicon [a] in the sample, which in turn is dependent upon e.g. the total abundance of alkalis in the sample.

3. The norm makes it possible to plot the analyses into phase diagrams consisting of mineral phases, rather than pure oxides.

4. For wholly or partly glassy samples, the mineral composition of the fully mineralised equivalent is reflected by the norm.

5. The normative composition are suitable for the ultimate chemical and mineralogical classification of the samples (sic, *Kresten et al. 1983, 1*).

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The calculations are based on the free energies of formation of the minerals present in the bulk composition. Take, for example, a typical slag composition containing phosphorus, calcium, iron, alumina and silica. Theoretically calcium will first react with the phosphorus to form apatite, as this mineral has the highest free energy of formation of all the possible combinations in which CaO could react. Residual CaO will then interact with alumina and silica to form, for example, anorthite, and assuming that there is residual alumina, this will then interact with some of the FeO to form the spinel, hercynite (plates 10a and 18e). The silica is then assumed to interact with the wustite to form the olivine, fayalite ($Fe_2SiO_4$)(plate 10b,c), and any residual FeO will be present in the structure as wustite dendrites (plates 10b, 15a). This is, of course, a simplification of events, and depending on the number and quantity of oxides present a variety of minerals will form. For instance, if there are a few percent of potassium present then a potassium feldspar could form, or if there is excess silica, then the composition will move towards the silica-rich end and pyroxenes will replace the olivines (wollastonite, etc.) (see fig. 1.7).

There are, however, drawbacks to the process. One in particular relates to the use of published analyses to generate comparative norms and the problem of heterogeneity. For example, from the initial examination of the macrostructure we can gain a rough assessment of the homogeneity: a tapped slag will normally be more homogeneous than a viscous furnace-slag or a smithing slag. These general impressions can be confirmed by metallographic

examination of a thick or thin section, and such observations can then be used in conjunction with a bulk analysis. Without this dual analysis, there is a strong chance that the bulk analysis will not be representative of the slag and may include such particles as unreduced ore, quartz, metal droplets or weathered slag and corrosion products such as goethite (as seen in plates 15 and 16). If any of these were present, then the calculation of normative constituents would be invalidated and hence misleading. For instance, the slag may be largely a fayalitic one, but with some included quartz (possibly from furnace lining) which, if ground up unobserved for bulk analysis, would suggest a pyroxene slag. This would then be interpreted as resulting from much stronger reducing conditions in the furnace and the probable production of cast or steely iron.

As discussed earlier, the corrosion of slags is a common phenomenon, and it is not always visually obvious except for the presence of goethite. In certain post-deposition conditions the glassy phase is leached from the slags, leaving the macrostructure intact, and although there have been no studies directly relevant to the effect of such corrosion on the assessment of slag properties, it is certain that the calculation of mineral phases would be altered, as would reconstruction of the thermal properties of the slag/furnace.

While this is a possible weakness, it is also a method of overcoming the intrinsic heterogeneity of the process and enabling comparisons of two processes. For instance, the proportion of wustite dendrites in the slag structure has been

used to compare the efficiency of different smelting operations (*Morton et al. 1969, 1972*), but such a comparison is rendered difficult, if not invalid, when based on small samples with a mineral assemblage resulting from non-equilibrium cooling. However, with the use of normative constituents it is possible to calculate and compare the theoretical wustite contents, and hence assess the efficiency of the two processes. It has been observed that mineral textures cannot be easily explained with reference to crystallisation paths predicted from the relevant phase diagrams, which is presumably due to non-equilibrium cooling. Again, the use of normative calculations theoretically might enable this discrepancy to be overcome.

Having predicted the mineral formed from equilibrium crystallisation, the amount of each mineral phase may be calculated from the cations present (*Kresten et al. 1983*), and then plotted on appropriated binary or ternary diagrams. This is a more accurate representation of events than plotting the oxide constituents, as these are the minerals formed on equilibrium cooling and the phase diagrams represent equilibrium conditions.

Whatever the method used to analyse, classify or manipulate the slag data, the final conclusions will always be limited by the problem of sampling. The calculation of normative constituents is no exception and a full understanding of the possible processes is a prerequisite for extracting the maximum information from the slag. For instance, slag from the first run of the furnace or early tapping run is rich in iron and returned

to the furnace, while the later slag is appreciably different in

composition; slag remaining in the furnace at the end of the

smelt differs in composition from that tapped, etc:

Table 2.7

Variation in slag composition from within one smelt

|  | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 28.4 | 30.0 | 17.7 | 22.3 | 27.4 | 22.2 | 38.0 | 49.8 | 52.0 |
| Fe$_2$O$_3$ | - | - | - | - | - | - | 10.0 | 5.0 | 6.1 |
| FeO | 48.0 | 44.9 | 57.0 | 56.0 | 43.6 | 52.9 | 38.4 | 43.7 | 33.7 |
| Al$_2$O$_3$ | 7.1 | 5.8 | 3.2 | 5.2 | 7.5 | 7.0 | 7.6 | 0.2 | 2.5 |
| CaO | 2.4 | 3.7 | 8.1 | 4.4 | 7.1 | 6.3 | 1.9 | 0.6 | 3.5 |
| MnO | 2.1 | 2.2 | - | - | - | - | 0.5 | - | - |
| MgO | 2.1 | 1.9 | 0.6 | 1.1 | 2.4 | 1.9 | - | - | 0.7 |
| P$_2$O$_5$ | 0.9 | 0.9 | 0.5 | 0.7 | 1.3 | 1.0 | - | - | - |

(1) furnace slag from WM1 experiment
(2) "     " but from the base of the furnace bottom
(3) slag from experimental smelt WM1
(4) same as (3) but from base of furnace bottom
(5) top of the furnace base - Odell smelt
(6) flow slag from within the furnace of Odell smelt
(7) slag - last before furnace opened
(8) slag selected from first tapping of furnace
(9) slag sent to waste heap

(7-9) taken from Cline 1937, 33.

If the normative constituents are calculated for each of these

slag compositions, then the following results present an entirely

contradictory reconstruction of the furnace regimes, both true

for the time the slag was formed, but only the later one a more

accurate assessment of the overall thermal conditions of the

furnace.

Table 2.8

Computed Normative Compositions

| | Weight% (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| Apatite | 2.3 | 2.33 | 1.33 | 1.81 | 3.37 | 2.5 | | | |
| Ca-silicate | | | 6.91 | | | | | | |
| Anorthite | 6.62 | 13.95 | | 12.4 | 15.91 | 14.77 | 9.77 | 0.55 | 6.92 |
| Forsterite | | | | 1.2 | 2.14 | 4.69 | 3.63 | | |
| Fayalite | 60.95 | 64.09 | 51.68 | 60.57 | 68.87 | 51.09 | | | |
| Hercynite | 9.17 | 2.34 | | | | | 7.33 | | |
| Enstatite | 5.74 | 5.29 | | | | | | | |
| Rhodinite | 4.26 | 4.55 | | | | | 0.96 | | |
| Ferrosilite | 10.96 | 7.45 | | | | | 59.0 | 76.63 | 57.7 |
| Gehlenite | | | 9.88 | 3.37 | 6.91 | 6.06 | | | |
| Wustite | | | 28.99 | 19.71 | 0.26 | 21.91 | | | |
| Magnetite | | | | | | | 15.04 | 7.3 | 8.98 |
| Quartz | | | | | | | 7.9 | 14.5 | 20.17 |
| Wollastonite | | | | | | | | 1.02 | 4.47 |

Slag Classification:

AN - FeO - SiO2

| | | | |
|---|---|---|---|
| (1) | Olivine-pyroxene slag | FA 58 PX 22 | 14.3 - 57.7 - 27.9 |
| (2) | Olivine-pyroxene slag | FA 60 PX 18 | 18.9 - 53.5 - 27.6 |
| (3) | Wustite-normative | WU 27 FA 50 | 11.0 - 71.5 - 17.5 |
| (4) | Wustite-normative | WU 18 FA 58 | 16.5 - 64.8 - 18.7 |
| (5) | Wustite-normative | | 24.8 - 52.7 - 22.5 |
| (6) | Wustite-normative | WU 20 FA 48 | 22.3 - 61 5 - 16.2 |
| (7) | Quartz-normative | Q 9 PX 59 | 11.5 - 47.0 - 41.5 |
| (8) | Quartz-normative | Q 16 PX 77 | 0.6 - 46.6 - 52.8 |
| (9) | Quartz-normative | Q 21 PX 63 | 7.6 - 37.6 - 54.7 |

FA - Fayalite, PX - Pyroxene, Q - Quartz, AN - Anorthite
These figures represent coordinates on appropriate ternary diagrams.
(Calculated Kresten's method)

Another and perhaps more immediate problem in normative calculation is that its two major proponents in the field of ancient metallurgy, Keesmann (*1982*), and Krestens (*et al. 1983*), have failed to find common ground and in consequence their methods of calculating the norms result in two different predicted equilibrium assemblages for the same sample.

Morton and Wingrove also pioneered the application of such phase diagrams for the analysis of ancient slags. In particular, they made extensive use of the Anorthite–FeO–SiO₂ ternary phase diagram:

Anorthite
(1552±2°)

80
Anorthite
1370±4°
1400
60
1368±2°
1470±5°
Tridymite
1070±4
1100
Hercynite
1350
1300
1250
1200
1150
40
20
Cristobalite
1108±4°
Fayalite
1290±10°
1120±4
Two Liquids
1690±10°
1470±5°
1177±5°
1178±2°
Wustite
SiO₂
(1713±10°)
20
40
60 Fayalite 80
(1205±2°)
FeO

Fig. 2.3  Anorthite–FeO–SiO₂ ternary.

The above ternary is divided into 5 fields: anorthite, hercynite, wustite, fayalite and quartz (cristobalite, tridymite). Each field is subdivided by a series of tie-lines known as isotherms which represent compositions of equal liquidus temperatures. Where the isotherms are widely separated, such as in the hercynite field, there is a gradual rise in the liquidus temperatures of slags as they move towards the anorthite–FeO line (i.e. an increase in lime or wustite in the slag). In contrast, if the slag composition moves from the low–melting point slags of the fayalitic field towards the quartz field the greater

frequency of the isotherms reveals a rapid increase in the liquidus temperature of the slag.

If we consider the $FeO-SiO_2$ binary section of the diagram, the rise in the liquidus surface is very steep either side of the bi-eutectic, and at this point small additions of either silica or FeO rapidly increase the viscosity of the slag and the difficulty of operating the furnace. This is consistent with diffraction studies of the $FeO-SiO_2$ system, which clearly show the existence of discrete ${SiO_4}^{4-}$ tetrahedra at low $SiO_2$ content, but that at higher content the distribution of rings and chains occurs, resulting from the polymerisation of ${SiO_4}^{4-}$ anions to give simple silicate anions of chains and rings (*Waseda et al. 1978*).

In theory it should be possible to predict crystallisation paths from these phase diagrams, but as we have seen, bloomery slags are usually too complex even for quaternary phase diagrams which, with the associated fact that these slags are not equilibrium structures means that such diagrams can only be employed to predict general trends in slag behaviour.

## Smelting and smithing slags

The question 'smithing or smelting?' has often been problematic (*Bachmann 1982; Megaw et al. 1979; Cleland 1981*), particularly with respect to 'furnace bottoms', small plano-convex cakes regularly found on archaeological sites (plates 19 and 20). Various analytical techniques have been used to find a distinction, but the results are by no means conclusive because

the typical smelting slag can be chemically and mineralogically identical to a smithing slag (see table 2.9). This is hardly surprising with respect to primary smithing as the slag expelled from the bloom is the same as was tapped from, or remained in, the furnace during smelting. It should be possible to distinguish between slag deriving from the two processes, as conditions in the smelting process are more reducing, unlike the forge, where they range from reducing to oxidising. However, differences which these changing conditions give rise to are relative, and, as can be seen from the analyses below (table 2.9), the range of compositions encountered in smelting slags almost totally overlaps the range for smithing slags (diffusion in a viscous slag is very slow and as a consequence any chemical change would be minimal, because forging is often a rapid process). Thus, if we could follow the progress of one piece of slag through both the smelting and refining cycles, a compositional difference might be perceptible, as the latter cycle would see the addition of fuel ash and some hammer scale, resulting in an increased iron to silica ratio. The iron could oxidise to magnetite, which is rarely encountered in smelting slags. However, the balance could as easily be thrown in the other direction by the fine sand often used to assist the welding process, or the slag could derive from the reducing part of the forge, and so on. The outcome is that there is no easily defined relationship between smithing and smelting slags, other than that they can be of identical mineralogical composition.

A clue to the origin of such cakes of slag can be found in the

results of experimental work and primarily from consideration of the archaeological evidence. Two experiments were carried out in a small bowl furnace/forge in an attempt to simulate the forging process. As the blooms formed in the smelting experiments were too small to produce the necessary volume of slag, small pieces of slag and hammer scale were fed into the furnace during the forging process. The products of the two experiments differed in almost every respect except that they had a plano-convex shape (plate 20f). O4 was a roughly plano-convex cake of dense, grey crystalline slag with incorporated charcoal, while the second experiment produced a heterogeneous cake of slag, which in part was similar in texture to the first experiment, but other parts were light in colour and frothy (vesicular foam) in texture (plate 4b).

Foaming seen in some slags is due to rapid gas evolution and is encountered in both refining and smelting and occasionally in glass melting. This structure occurs when the entrapped gas bubbles do not readily coalesce, but instead accumulate and expand the medium, forming a honeycomb-like structure of closely packed gas bubbles separated by thin lamellae of liquid. The formation of such foam is strongly influenced by viscosity and surface tension and thus dependent on composition. Liquids with low basicity and high viscosity have low surface tensions and are therefore liable to foam (if basicity is less than 2) (*Turkdogan 1983*). The presence of undissolved oxide in the slag, such as CaO, favours foaming, presumably because of the high apparent viscosity of oxide-saturated slags. There are many examples of

this phenomenon, particulary in forge slags, for instance Silchester, and Balkerne Lane (Colchester) (table 2.9). The latter is particulary high in silica and is predominantly fuel-ash reacted with a small proportion of slag.

The texturally different parts of the experimental smithing slags were analysed and proved to have only minor differences in composition. The vesicular foam was some 2-4% higher in CaO, derived from the fuel ash. The dense slag had a composition nearer to the original 'olivine' slag, while the heterogeneous cake had c.50% silica. This high silica content increases the melting point of the slag and is consistent with its lack of homogeneity resulting from incomplete melting (table 2.9).

## Table 2.9

### Analysis of smithing slags: experimental and archaeological

|  | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total |  |
|---|---|---|---|---|---|---|---|---|---|---|
| *1 | 36.6 | 41.5 | 12.0 | 3.9 | 0.4 | 1.2 | 2.3 | 0.7 | 98.6 | light-foam |
| *2 | 27.5 | 44.3 | 10.6 | 3.6 | 0.2 | 1.2 | 1.5 | 0.7 | 89.6 | light-foam (2) |
| *3 | 36.1 | 45.1 | 8.5 | 5.1 | 0.1 | 1.0 | 1.9 | 0.6 | 98.4 | dense grey |
| *4 | 49.7 | 32.7 | 8.4 | 4.7 | 0.3 | 1.1 | 2.1 | 0.6 | 99.6 | heterogeneous |

Silchester

|  | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | 24.0 | 54.2 | 3.3 | 3.0 | 0.0 | 0.8 |  | 0.6 | 85.9 | (002) grey crystalline |
|  | 44.2 | 43.8 | 3.1 | 2.0 | 0.1 | 1.1 |  | 0.6 | 94.9 | foamy and vesicular (009) |
|  | 27.0 | 54.8 | 2.3 | 1.8 | 0.0 | 0.5 |  | 0.5 | 86.9 | furnace bottom (016) |

Bagendon

|  | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | 23.3 | 58.6 | 6.4 | 3.8 | 0.8 | 0.7 | 1.0 | 0.9 | 95.5 | plano-convex cake (18) |
|  | 20.2 | 66.5 | 5.6 | 2.5 | 0.0 | 0.7 | 1.1 | 0.4 | 97.0 | (43) |

Balkerne Lane, Colchester

|  | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | 34.0 | 51.8 | 0.7 | 3.1 | 0.0 | 0.9 |  | 0.3 | 90.8 | dense and grey |
|  | 82.5 | 14.9 | 0.0 | 0.0 | 0.9 | 1.6 |  | 0.5 | 100.4 | foamy slag |

Odell (F73 plano-convex cake)

|  | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | 50.4 | 39.8 | 1.7 | 4.9 | 0.0 | 0.5 | 1.7 | 0.4 | 99.4 | top of furnace bottom |
|  | 28.7 | 66.6 | 1.5 | 2.2 | 0.0 | 0.5 | 1.0 | 0.4 | 100.9 | base of furnace bottom |

Comparing this with the typical furnace bottoms from the smelting experiments, some characteristics emerge (see plates 4a and 21b). The furnace bottoms from the smelting experiments (non-tapping furnaces and only small charges) were larger (often weighing 60-70% of the weight of the ore charged), and incorporated larger pieces of charcoal than forging cakes. The small cakes from the forging hearth had an impression on the upper surface caused by the penetration of the blast and the upper surfaces were often vitreous, owing to a combination of fuel ash interacting with the surface and the rapid cooling caused by the blast from the tuyere. Heterogeneity was also a characteristic of these cakes, but in common with the above attributes, it cannot used in isolation as diagnostic (for instance, these cakes of slag can be large and overlap that produced in the smelting furnace), and must be used as part of an array of attributes, along with site evidence such as quantity of slag, furnace associations, etc.

Table 2.10

### Weights of plano-convex furnace bottoms

| Bagendon | 0.33 kg | Odell F73 | 0.57 |
| | 0.49 | F62 | 0.64 |
| Brooklands | 1.36 | | |
| Brooklands | 2.3 | Experimental | |
| Cow Down | 0.51 | Seend | 7.0 |
| | 0.57 | Odell.2 | 1.59 |
| Towcester | 0.55 | 0.4 | 1.2-1.4 |
| | 0.51 | 0.5 | 2.9 |
| Bussage all Saints | 0.62 | WH2 | 2.3 |

## Slag inclusion studies

Slag inclusions (using electron probe techniques) have been the subject of several studies (*Todd and Charles 1978; Hedges and Salter 1979*), with the aim of relating the composition of the inclusions to that of the original ore and thus providing a possible means of sourcing the iron object. To date, this has proved unsuccessful, although Hedges and Salter found that inclusion analyses from several groups of currency bars did form clusters which, correlating with their source, i.e. currency bars from Beckford (*Britnell 1974*), Gretton (*Jackson 1974*), and Danebury (*Cunliffe 1978*), formed separate clusters from each other (*Hedges and Salter 1979*). This suggests that each group of bars has been manufactured from a single ore source and does not derive from secondary (scrap) sources.

One of the inherent problems is that inclusions could derive from sources other than the original slag, such as the furnace lining, or from forging, or that different degrees of forging alter the composition of the inclusion (Hedges and Salter allowed for this in their statistical analysis of the results). It is known that there is often an exchange of phosphorus between the metal and the inclusion during the forging process. High-phosphorus inclusions are frequently encountered. For example, an inclusion from sample Fii 69 (Odell) contained 14.3% $P_2O_5$, surprisingly high when compared to the 1% in the experimental iron smelted from the same ore. Movement of phosphorus from the iron to the inclusion during forging (*above*) seems unlikely to explain such a discrepency because of the low mobility of phosphorus in iron

(*Stead 1918*). An explanation might be found in the typical phases encountered in bloomery slags (below). EPMA spot analyses indicate that the phosphorus partitions into the glass phase, which is also the low-melting point component of these slags. It is likely that much of the forging was carried out below the melting point of the higher m.p. phases, such as the olivines and spinels c.1200°C+, and that this resulted in differential movement of the slag phases with some separation of the glassy phase from other components. As a consequence of such events, some of the inclusions would be significantly higher in phosphorus. Such an explanation is consistent with the variation in phosphorus levels observed in inclusions from the same object, and the difference in inclusion composition between objects produced from the same ore. Similar behaviour would be expected of inclusions containing a spinel such as hercynite. A more extensive study of this phenomenon might provide a source of information regarding forging temperatures (see plates 6g-h, 8g, 17g for slag stringers/inclusions).

It seems unlikely that we will gain any knowledge of the ore source from inclusion analysis owing to the complexity of the process and the possible composite nature of some iron pieces. Mixing of ores would cause further problems, as would variation within a single ore body. However, the major obstacle is the ubiquity of iron ore sources in Britain and Europe, many of which were small by modern standards and largely worked out centuries ago.

## Typical slag phases and their characteristics

### Iron oxides

Wustite is usually represented by a lustrous dendritic phase, as illustrated in plates 3, 9$f$, 10$_{a-b}$, 11$_a$ and 12$_{f-h}$. It is thermodynamically unstable and decomposes below c.570°C into a eutectoid of magnetite and metallic iron. However, it is a slow reaction requiring long periods of heating below this temperature to reach completion. As a result it can be almost entirely suppressed by rapid cooling (*White 1943, 616*), and consequently magnetite, the stable oxide of iron below 570°C, is rarely detected in bloomery slags as a result of wustite decomposition. Its presence, therefore, is the result of incomplete reduction or re-oxidation near the end of the smelt or during tapping. A fine line of magnetite can often be detected on the freeze surface of tapped slags (plate 12$_{a,b}$). However, this should not be used to characterise tapped slags, as such chill lines have been detected in slags from the furnace (plate 12$_{d,e}$) and would form wherever a slag surface was exposed to relatively oxidising conditions.

Exsolution of wustite on cooling has been proposed as the most likely explanation for its occurrence and orientation with respect to the fayalite. As the melt begins to cool, there is a primary flush of wustite precipitation, and fayalite then nucleates on these primary wustite dendrites and surrounds them. Any excess FeO not taken up by the fayalite remains in the glass and can occasionally be recognised in this phase (plate 11$_{a-b}$) (*Fells 1983, 71*).

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**Spinels**

The spinels most commonly encountered in ancient slags are magnetite, hercynite (plate $10_a$-$_b$) and less frequently ulvo-spinel (titanium-rich). The composition of hercynites falls within a narrow range (see table 2.13), which would be expected as the operating conditions for the bloomery, irrespective of furnace type, also fall within a narrow range. There appears to be no special relationship between the proportion of $Al_2O_3$ in the bulk and the amount of hercynite observed in the structure, which would suggest that alumina forms localised nucleation centres and that the distribution of the element is uneven. This is consistent with the vanadium to chromium ratios in the spinels from experimental slags (Odell ore), which show considerable variation (table 2.13). Accordingly, no relationship could be detected between the amount of hercynite and glass in the slag. This highlights one of the problems which might be overcome by normative calculations: that proportions of the various phases have been calculated from observations on thin or thick sections, i.e. on slags not in equilibrium, and therefore the actual relationship cannot be observed. Equally, if we rely on bulk analysis alone, this role of alumina in bloomery slags would not be observed, and it would be assumed that all of this mineral was primarily available for the formation of anorthite.

Despite the rapid cooling, which one would expect to result in the formation of tiny crystals, the fayalite phase is always

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large and laths are often over 1mm long and over 2mm in furnace

slags, which is consistent with nucleation being centred on a

limited number of nuclei, and with the slag being considerably

over its melting temperature. A eutectoidal decomposition

of ferrous silicate phase to fayalite and wustite could

produce such a texture, as the two are frequently found

together. Therefore overall conditions or chemical composition do

not determine which type is formed and no special relationship

was observed between the composition of the actual mineral and

its form (*Fells 1983, 102*).

## Olivines

An olivine has the general formula $Me_2SiO_4$ and a tetrahedral

structure with the metal oxide joining the apices of $SiO_4^{(4-)}$

anion. Olivines in bloomery slags are predominantly fayalitic,

but on occasion are the calcium-rich kirchsteinite. Iron can be

continuously replaced by magnesium, manganese, and calcium, but

on the whole early bloomery slags in Britain have less than 5% of

these elements (table 2.11). Their typical structure is lath-

like (plate 10b-f), but they can also be euhedral. Probe

analysis across a large lath displays zoning, or changes in

composition, which would occur as the melt became depleted in

certain elements in the immediate environment of the forming

crystal.

## The glass phase

Morton and Wingrove (*1969, and 1972*) suggested that the glassy

phase often observed in early bloomery slags was of anorthitic

composition. However, in recent years, with increasing numbers of slags being submitted for analysis by EPMA, it has become obvious that their definitions of a standard slag, i.e. fayalite, wustite and a glass of anorthitic composition, are far from adequate. Glass is clearly an important component of bloomery slags and can be expected to vary in composition even in one area, as it is the residual liquid being continuously depleted by the forming crystalline phase in contact with it. It is important because it soaks up the alkalis (derived primarily from fuel ash - table 2.14) and phosphorus in the melt and forms a low-melting point liquid phase and thus represents the solidus of the slag (the higher-m.p. phases - e.g. spinels representing the liquidus)(plate 15). Therefore, to some extent the glass composition and quantity will dictate the viscosity and working range of the slag and be significant in such considerations as the tapping of slag from the furnace and the forging temperature required to squeeze the slag from the bloom. For instance, the overall concentration of $K_2O$ is often around 3%; however, as it concentrates in the glass phase it can be as high as 15% to 20%, which would have a melting point below 1000°C (potash feldspars with alumina) (e.g. see tables 2.11 and 2.12). This solidus point is further lowered by the presence of ferrous iron and phosphate and could be as low as 800°C (see figs. 2.4 and 2.5).

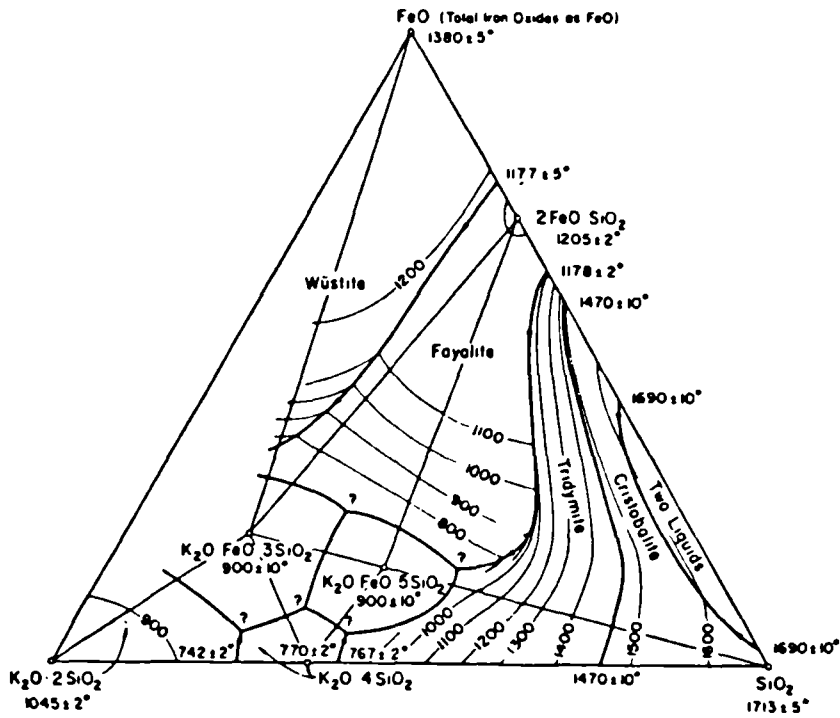**Fig. 2.4** $K_2O$-$FeO$-$SiO_2$ (*after Levin et al. 1964*)
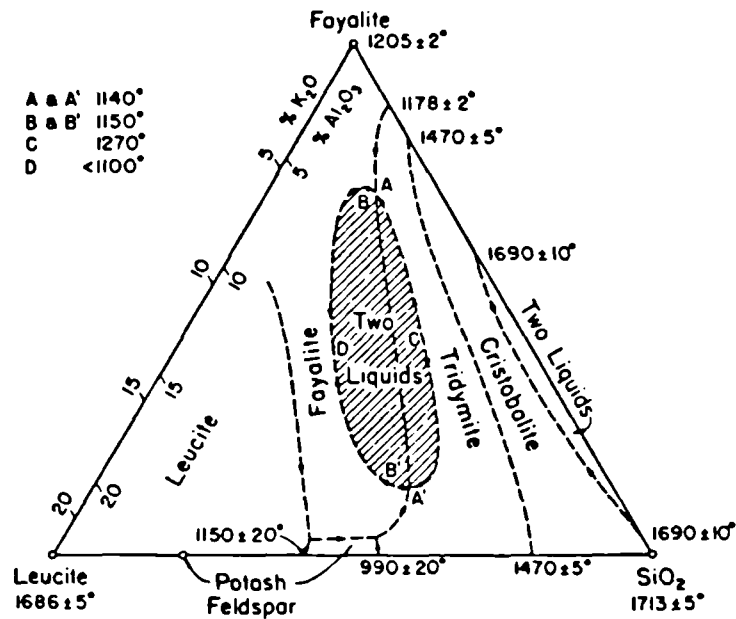
**Fig. 2.5** $K_2O$-$FeO$-$Al_2O_3$-$SiO_2$ (*after Levin et al. 1964*)

From tables 2.11 and 2.12 it can be seen that glass composition varies considerably, and optically (also SEM) is often

microcrystalline (plate 10d,f,g). On several occasions a two-phase glass structure has been observed, one calcium-rich, the other potassium-rich (table 2.12) and these are presumably immiscible liquids. One of the many compositions of the glassy phases approximates that of potassium feldspar ($K_2O.Al_2O_3.6SiO_2$) and is commonly found in slags, although possibly less common in tapped slags than slags left in the furnace, possibly because the latter have longer to interact with fuel ash and, being held at higher temperatures for a longer period of time, move closer to an equilibrium structure. Accurate analysis of the glass phase is exceptionally difficult, both because of the small areas involved and because of its microcrystalline (perhaps phase-separated) nature. It is therefore unwise to calculate liquidus temperatures from probe analyses of the glass phase.

## The value of acid/base calculations

Many texts on extractive metallurgy highlight the importance of the slag, and it is apparent that slag composition plays a major role in the quality of the final product (*Coudurier 1978; Rosenqvist 1974; Biswas 1962*). Slags are often referred to in terms of their acidity or basicity (*Gilchrist 1967; Coudurier 1978*), because they comprise predominantly acidic oxides ($SiO_2$, $P_2O_5$) which act as network formers, or basic oxides (network breakers) such as CaO, FeO, MgO, etc. Basicity is calculated as wt% basic oxides/wt% acid oxides, which in the modern blast furnace is largely equivalent to wt%CaO/wt%SiO2. If wt% basic/wt%

acidic oxides is greater than 1.2-1.3, then the slag is considered basic (*Biswas et al. 1962*). Basic and acidic slags, to some extent, behave in a predictable manner, for instance desulphurisation is most efficient in a basic slag under reducing conditions, and basic slags, particularly those high in CaO or FeO, are efficient dephosphorisers.
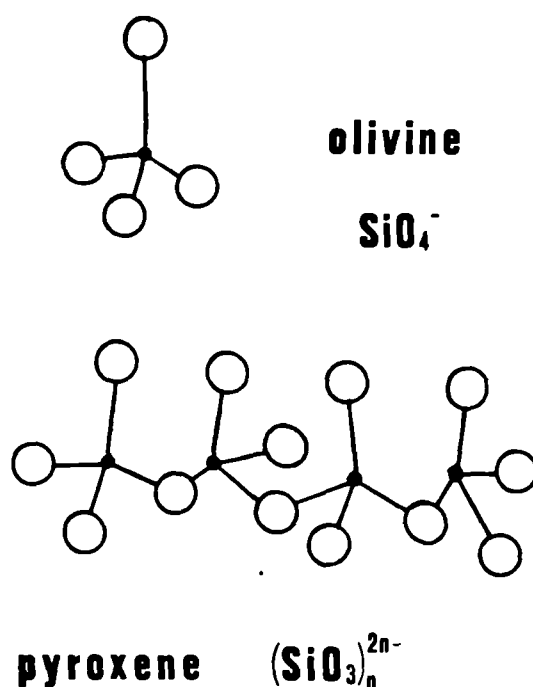
**olivine**

$SiO_4^-$

**pyroxene**  $(SiO_3)_n^{2n-}$

Fig. 2.6 Molecular structure of olivines and pyroxenes

In basic silicate melts Si is surrounded by four oxygens, forming a tetrahedral anion $\{SiO_4\}^{4-}$, typified by the fayalitic melt. As the acidity of the melt increases, e.g. an increase of silica, these tetrahedra may be further bonded together by shared oxygen atoms giving double anions $\{Si_2O_7\}^{6-}$. These can be linked to anions such as $\{SiO_3\}^{3n-/n}$ and so on until the network becomes complex and neutral silica, $(SiO_2)^n$, a gigantic 3D molecule (fig.

2.6; refer also to fig. 1.6) (*Rosenqvist 1974*). In fact, with greater degrees of polymerisation, as the slag tends towards greater acidity the slag will contain the ions: $SiO_4^{(4-)}$, $Si_2O_7^{(6-)}$, $Si_3O_{10}^{(8-)}$,——$Si_nO_{3n+1}^{2(n+1)}$, all in equilibrium with each other.

A slag of ortho-silicate composition is classed as neutral and, for example, in $Ca_2SiO_2$ two moles of lime $2Ca^{2+}$ neutralise the $\{SiO_4\}^{4-}$ anion. However, if the lime is lower than this ratio then some of the tetrahedral silica anions remain unsaturated and will link with others to form chain structures as seen in the pyroxene group (fig. 2.6). Each mole of oxide of a divalent cation added contributes one $O^{2-}$ anion to the melt, and at the composition more acid than ortho-silicate breaks one Si-O-Si linkage. Hence it is expected that oxide additions of $Ca^{2+}$, $Mn^{2+}$, $Fe^{2+}$, $Mg^{2+}$, etc, are equally effective (within certain limits relating to ion size) on a molar basis of reducing the viscosity of acid melts. Monovalent ions such as potassium are more effective in breaking up the network of silica. Therefore, when we speak of fluxing, or producing a fluid slag, this in general relates to the length or type of silicate structure predominant in the slag. Taking into account all of the components of a slag (rather than the lime to silica ratio, *above*) the basicity can be assessed by calculating the number of free oxygen anions:

$$nO^{2-} = {}_nCaO + {}_nMnO + {}_nFeO - {}_{2n}SiO_2 - {}_{3n}P_2O_5 - {}_{3n}Al_2O_3$$

And from this calculation it is possible to derive information regarding the oxygen potential of the furnace and also properties

of the slag which would affect the final product. For example,
we know that the more basic a slag is, the better is its ability
to remove sulphur from the iron.

$$[FeS]_m + (CaO)_{slag} = (CaS)_{slag} + [FeO]_{metal}$$
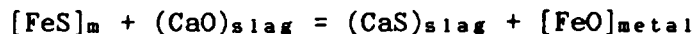
In ionic form this is represented by:

$$[S] + (O^{2-}) = (S^{2-}) + [O]$$
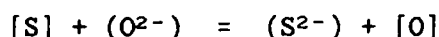
from which it can be seen that increasing the basicity (i.e. the
$nO^{2-}$) will result in lowering the sulphur content of the metal.
Similar reactions can be applied to carbon content and
phosphorus.

Constitutionally, basic slags are considerably more complex than acid slags,
since they normally contain significant amounts of CaO, P2O5, FeO, Fe2O3,
MnO, MgO, and Al2O3. Hence their phase and thermal relationships cannot be
adequately represented by a single diagram. Chemically, the outstanding
feature of such slags is that the basic oxide content is more than sufficient
to neutralise the acid oxides....as the CaO is the strongest base, it will
combine with all the acids present i.e. silica, phosphorus, and alumina in
the solid slag. Where there is a deficiency in this oxide [i.e. bloomery
slags] other oxides will combine with the acid oxides (White 1943, 665).

Apart from the roles of removing sulphur and phosphorus from the
product, these calculations also provide a rough guide to:
viscosity (of importance in tapping and removing the slag from
the bloom) and carburisation of the bloom (for instance, the more
acidic the composition, the more carburised the product).

## Conclusions

Some studies have attempted to construct a classification of
slags based on relating their morphology to the process and
furnace type. However, Sperl's (*1979*) attempt to relate
mineralogical and chemical composition to the defined slag types

proved unsuccessful (*Fells 1983*). Bachmann (*1982; and in Craddock 1980*) also attempted to relate slag types, particularly their mineralogical composition, to process and ran into equal difficulties and criticisms (*Merkel 1983*). Morton and Wingrove (*1969 and 1972*) presented a case for relating slag composition to period, suggesting that Roman slags could be distinguished from medieval ones on the basis of their mineralogy. However, this relates largely to a very small cross-section of samples and reflects rather the use of different ore sources than different processes or cultural affiliations.

Consideration of ferrous processes alone suggests that the failure of such attempts is not surprising. For example, a ropey tapped slag is the product of many furnace types and its macrostructure relates more to the temperature of tapping and to the shape of the tapping-pit than to the slag composition or furnace design. For instance, on a morphological basis it is impossible to distinguish some tapped copper slags from those of iron. Mineralogically the distinction is equally difficult because, for the process successfully to reduce the ore, the furnace must be operated within certain parameters, and naturally these similar thermochemical regimes can result in very similar slag compositions, particularly as iron oxides are used as fluxes.

Relating slags to the ores used in the smelt has proved equally difficult, being complicated by a number of factors: contribution of extraneous material during smelting (fuel ash and furnace

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lining), the effect of partitioning between the slag and the metal, variations within ore bodies, use of mixed ores, and the recharging of old slags.

Many of the conclusions drawn by Fells (*1983*) hold little promise for the field of slag studies. Statistical work failed to provide any particular pair of oxides applicable to all provenancing problems, for while some readily distinguished Wealden from Northamptonshire ores, they failed to distinguish between others. Three component plots were found to be of little value in provenancing.

Clustering analysis, K-means (*Doran and Hodson 1975*), was applied, in this study, to bulk slag and ore analyses, but was inconclusive. The original ore sources are so variable that this method can hardly be expected to produce accurate groups of ores, let alone ores and slags. However, Fells found that discriminant analysis was of value and the use of $Al_2O_3$, $MnO$, $MgO$, $TiO_2$, $V_2O_5$ was suggested. 'It is considered that weathering of slags would not significantly affect a provenance study, using these five oxides' (*Fells 1983, 183*), but from the phase analyses carried out for the present study it was observed that both the Al and Ti oxides tend to partition into the glass which is the first to leach out of the structure. However, if corroded slags are avoided this would not present a problem.

Occasionally study of an iron object will indicate furnace conditions, but only in rare cases where it is cast, or steel

from the bloom Beyond that, reconstruction of these ancient processes must rely on furnace remains and slag analysis.

Chemical and mineralogical analysis of 'plano-convex' cakes of slag failed to provide a clear-cut method for characterisation. However, with morphological information - texture, homogeneity, vitrification, and site data such as provenance, associations, quantity, etc - it is concluded that these cakes typically derive from the forge and are not a product of the smelting furnace.

Examination of slag corrosion provided a cautionary insight into techniques of slag analysis and the limitations of bulk analysis. In particular, it highlighted the value of the electron probe in slag studies.

The bulk of the metal prior to the Roman period was a mixed product of ferrite and pearlite, with evidence for the use of iron with phosphorus providing additional toughness. There is evidence, although limited, for the selection of high-carbon iron, piling, and for carburisation, but there are only a few examples with evidence of technical skills such as heat treatment (e.g. one piece from Worthy Down had incorporated a wedge of high-carbon steel in a low-carbon body; the artefact was then intentionally quenched and tempered: *Salter and Ehrenreich 1984*). Even with the valuable addition of the metallography of some 252 objects (*Salter and Ehrenreich 1984*), there is still only a small body of evidence on which to base the reconstruction of the technical skills of the Iron Age smiths. Some of these objects displayed considerable skill and had obviously been produced by a

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'seasoned blacksmith' (*ibid.*).   Where larger numbers of ancient objects have been studied, for instance continental Hallstatt and La Téne material,  the objects must be considered in respect  to their  function  and the type of site from which they  originate. That  is,  examination of metal objects will provide  an  insight into the level of skill, but, initially, this can only be related to one smith at one site.

Table 2.11

EPMA analyses of slag and slag inclusions from Odell

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|-------|---|
| **Fii69** | | | | | | | | | | | |
| 8.3 | 77.9 | 0.0 | 0.7 | 0.7 | 0.0 | 0.0 | 0.0 | 1.1 | 14.3 | 103.0 | inclusion |
| 0.1 | 100.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 100.6 | area of iron |
| **K23** | | | | | | | | | | | |
| 38.6 | 26.9 | 13.0 | 10.5 | 0.0 | 0.0 | 7.1 | 1.7 | 0.6 | + | 98.4 | glass |
| 36.7 | 35.6 | 14.6 | 8.9 | 0.0 | 0.0 | 3.4 | 1.1 | 0.2 | + | 100.5 | glass |
| 29.7 | 67.1 | 2.3 | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 99.9 | olivine |
| **K45 (mainly wustite dendrites in a massive olivine phase)** | | | | | | | | | | | |
| 29.7 | 67.9 | 2.0 | 0.3 | 0.3 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 100.1 | olivine |
| 29.9 | 65.4 | 4.2 | 0.0 | 0.0 | 0.6 | 0.0 | 0.0 | 0.0 | na | 100.1 | olivine |
| 37.7 | 39.1 | 2.0 | 14.8 | 0.0 | 0.0 | 11.3 | 0.0 | 0.0 | na | 104.9 | glass |
| 51.2 | 11.4 | 1.3 | 17.6 | 0.0 | 0.0 | 15.8 | 0.0 | 0.3 | na | 97.6 | glass |
| **K28 (contains very little glass)** | | | | | | | | | | | |
| 29.2 | 68.9 | 1.3 | 0.3 | 0.0 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 100.3 | olivine |
| 37.4 | 24.0 | 15.4 | 14.2 | 0.0 | 0.0 | 5.9 | 0.5 | 0.3 | + | 97.7 | glass |
| **K40** | | | | | | | | | | | |
| 28.4 | 69.1 | 1.0 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | na | 99.1 | olivine |
| 28.9 | 69.3 | 1.1 | 0.4 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | na | 100.1 | olivine |
| **Odell iron inclusions** | | | | | | | | | | | |
| **F30ii** | | | | | | | | | | | |
| 64.1 | 2.7 | 6.0 | 13.8 | 0.2 | 5.8 | 2.6 | 1.8 | 0.0 | na | 97.0 | inclusion 1 |
| 58.4 | 9.1 | 5.5 | 12.9 | 0.2 | 5.2 | 2.4 | 0.8 | 0.2 | na | 94.7 | inclusion 2 |
| 62.1 | 3.1 | 5.8 | 14.0 | 0.0 | 5.6 | 3.5 | 1.3 | 0.2 | na | 95.6 | inclusion 3 |
| 63.9 | 2.8 | 5.9 | 14.1 | 0.3 | 5.6 | 2.5 | 0.0 | 0.0 | na | 95.1 | inclusion 4 |
| **Fiii62** | | | | | | | | | | | |
| 19.4 | 59.3 | 2.4 | 1.5 | 3.4 | 1.5 | 0.0 | 0.0 | 0.5 | ++ | 88.0 | |
| 19.2 | 59.9 | 2.6 | 1.6 | 3.3 | 1.7 | 0.0 | 0.0 | 1.1 | ++ | 89.4 | |
| 20.3 | 63.0 | 0.9 | 0.7 | 3.3 | 2.0 | 0.0 | 1.2 | 1.3 | + | 92.7 | |
| 17.7 | 62.3 | 2.2 | 1.3 | 3.2 | 1.5 | 0.0 | 0.0 | 2.0 | + | 90.2 | |

Table 2.11 (cont.)

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | TiO2 | V2O5 | CR2O3 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17.6 | 60.5 | 3.2 | 1.1 | 3.2 | 1.6 | 0.1 | 0.0 | 2.4 | ++ | 0.4 | na | na | 89.7 |
| 20.9 | 63.3 | 1.1 | 1.3 | 3.1 | 0.9 | 0.2 | 0.0 | 0.7 | ++ | 0.5 | na | na | 92.0 |
| 0.6 | 93.1 | 0.0 | 0.4 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | + | 1.2 | 0.7 | 1.5 | 98.5 |
| 0.6 | 92.8 | 0.0 | 0.7 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | + | 1.1 | 0.4 | 1.5 | 98.1 |

Table 2.12

Experimental slags from Seend ore

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | SO | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| 36.8 | 28.7 | 13.7 | 13.7 | 0.0 | 0.0 | 3.7 | 0.3 | 2.6 | 99.5 | crystalline |
| 28.8 | 66.6 | 0.9 | 0.0 | 0.6 | 1.1 | 0.0 | 0.0 | 0.0 | 98.0 | olivine |
| 55.1 | 2.1 | 0.0 | 22.6 | 0.0 | 0.0 | 20.3 | 0.0 | 0.0 | 100.1 | K-rich glass |

Seend iron slag inclusions

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | SO | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| 44.0 | 28.6 | 1.4 | 15.7 | 0.0 | 0.0 | 11.4 | 0.0 | na | 101.1 | glass |
| 29.4 | 68.6 | 0.8 | 0.0 | 0.5 | 1.2 | 0.0 | 0.0 | na | 100.5 | inclusion 1 |
| 28.9 | 69.7 | 2.3 | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | na | 101.5 | incl 2 |
| 23.8 | 53.0 | 11.7 | 10.5 | 0.0 | 0.0 | 0.5 | 0.2 | na | 99.7 | incl 3 |
| 29.8 | 49.5 | 18.6 | 0.5 | 0.3 | 0.0 | 0.5 | 0.0 | na | 99.2 | globular phase |
| 33.9 | 40.3 | 0.0 | 15.3 | 0.0 | 0.0 | 12.4 | 0.0 | na | 101.9 | matrix of above |

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | SO | P2O5 | TiO2 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 29.4 | 68.1 | 0.7 | 0.0 | 0.6 | 2.2 | 0.0 | 0.0 | na | 0.0 | 101.0 | olivine |
| 20.5 | 18.8 | 33.6 | 4.7 | 0.0 | 0.0 | 2.2 | 0.0 | na | 0.0 | 79.8 | phase adjacent to olivine |
| 52.3 | 4.2 | 0.3 | 22.4 | 0.0 | 0.0 | 19.7 | 0.0 | na | 0.0 | 98.9 | glass (globular) |
| 20.5 | 18.8 | 0.0 | 4.7 | 0.0 | 0.0 | 2.2 | 0.0 | na | 33.6 | 79.8 | inclusion in olivine area |

Table 2.13

Odell experimental slag phases

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | SO | P₂O₅ | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| 32.0 | 37.8 | 13.8 | 9.7 | 0.6 | 0.7 | 2.6 | 0.1 | na | 97.3 | fine crystalline (01.3) |
| 30.6 | 55.6 | 6.5 | 3.8 | 1.1 | 1.9 | 1.0 | 0.2 | na | 100.7 | fine crystalline |
| 29.7 | 59.8 | 6.8 | 0.3 | 1.2 | 2.9 | 0.0 | 0.0 | 0.0 | 100.7 | olivine (01.4) |

spinels

| | | | | | | | | | V₂O₃ | Cr₂O₃ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 47.5 | 0.0 | 45.8 | 0.5 | 1.6 | 0.0 | 0.0 | na | 1.4 | 1.1 | 0.4 | 98.3 |
| 0.0 | 47.1 | 0.0 | 50.2 | 0.3 | 0.9 | 0.0 | 0.0 | na | 0.8 | 0.2 | 0.0 | 99.5 |
| 0.0 | 45.1 | 0.0 | 43.7 | 0.4 | 1.9 | 0.0 | 0.0 | na | 0.9 | 1.8 | 2.9 | 100.3 |
| 0.0 | 49.9 | 0.2 | 46.4 | 0.2 | 1.4 | 0.0 | 0.0 | na | 1.0 | 0.4 | 0.2 | 99.7 |
| 0.0 | 52.2 | 0.4 | 43.4 | 0.2 | 1.7 | 0.0 | 0.0 | na | 1.1 | 0.5 | 0.2 | 99.7 |

olivines

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | SO | P₂O₅ | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 29.6 | 58.6 | 5.5 | 1.2 | 1.0 | 3.0 | 0.0 | 0.0 | na | 99.2 | 01.4 | spot 1 |
| 29.4 | 58.9 | 6.9 | 0.4 | 1.1 | 2.4 | 0.0 | 0.0 | na | 99.1 | 01.4 | 2 |
| 26.5 | 66.1 | 4.5 | 0.8 | 1.1 | 2.9 | 0.0 | 0.0 | na | 102.4 | 01.4 | 3 |
| 29.4 | 65.2 | 3.0 | 0.8 | 0.7 | 2.0 | 0.2 | 0.0 | na | 101.7 | 01.1 | |
| 29.6 | 65.9 | 2.7 | 0.6 | 0.8 | 1.8 | 0.0 | 0.0 | na | 101.8 | 01.1 | |
| 29.6 | 63.6 | 4.0 | 0.0 | 1.1 | 1.9 | 0.0 | 0.0 | na | 100.5 | 01.3 | |

glass

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | SO | P₂O₅ | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 35.2 | 21.3 | 18.1 | 18.5 | 0.2 | 0.3 | 4.8 | 0.0 | + | 0.0 | 98.4 | 01.1 |
| 33.7 | 27.7 | 19.3 | 12.8 | 0.5 | 0.7 | 3.8 | 0.0 | + | 0.4 | 98.9 | 01.4 |
| 35.1 | 17.4 | 16.0 | 18.5 | 0.2 | 0.0 | 4.8 | 0.3 | + | 0.8 | 93.1 | 01.3 |
| 36.1 | 21.0 | 15.3 | 18.5 | 0.2 | 0.0 | 5.8 | 0.2 | + | 0.3 | 97.4 | 01.4 |

01 forged (pure ferrite)

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | SO | P₂O₅ | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 48.5 | 19.7 | 11.5 | 13.1 | 0.8 | 1.8 | 3.7 | 0.0 | 0.0 | 1.0 | 0.0 | 100.1 | inclusion 1 |
| 29.9 | 27.3 | 26.6 | 10.3 | 0.8 | 1.8 | 1.7 | 0.0 | 0.4 | 2.2 | 0.0 | 99.0 | inclusion 2 |
| 21.8 | 61.0 | 7.9 | 8.6 | 0.5 | 1.0 | 1.5 | 0.7 | 0.2 | 0.9 | 0.0 | 104.8 | area of inclusion |

Table 2.14

Analyses of charcoal ash

| Sample | $SiO_2$ | $Fe_2O_3$ | $CaO$ | $Al_2O_3$ | $MnO$ | $MgO$ | $K_2O$ | $Na_2O$ | $SO_3$ | $P_2O_5$ | $CO_2$ | Ash content of charcoal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Oak** | | | | | | | | | | | | |
| trunk | 8.1 | 0.2 | 17.9 | 0.5 | 2.6 | 4.6 | 40.3 | 1.1 | 4.7 | 0.4 | 19.5 | 1.1 |
| branch | 0.8 | 0.4 | 42.5 | 0.5 | 5.9 | 0.6 | 2.6 | 6.5 | 3.4 | 3.3 | 10.0 | 3.9 |
| **Birch** | | | | | | | | | | | | |
| trunk | 0.7 | 0.3 | 21.6 | 0.1 | 11.9 | 7.8 | 35.9 | 1.1 | 2.8 | 0.3 | 17.6 | 3.9 |
| branch | 4.8 | 0.5 | 46.4 | 7.6 | 4.4 | 0.7 | 15.2 | 17.1 | 3.3 | 3.2 | 7.3 | 2.7 |
| **Hazel** | | | | | | | | | | | | |
| branch | 2.0 | 0.3 | 54.0 | 0.8 | 0.7 | 0.8 | 13.0 | 7.4 | 1.9 | 7.3 | 11.6 | 4.3 |
| **Hawthorn** | | | | | | | | | | | | |
| branch | 1.0 | 0.2 | 56.5 | 0.8 | 0.04 | 0.3 | 6.2 | 5.5 | 5.5 | 1.0 | 22.6 | 12.5 |
| **Ash** | | | | | | | | | | | | |
| average | 2.3 | 0.3 | 38.3 | 1.8 | 5.0 | 1.7 | 26.5 | 5.3 | 3.6 | 2.8 | 12.4 | 2.6 |

# CHAPTER 3

# SULPHIDES

# AND SMELTING EXPERIMENTS

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## Abstract

Sulphidic ore (marcasite and pyrites) nodules were submitted to roasting and smelting experiments to determine whether they were a viable source of ore. Experiments were carried out in a low non-tapping shaft furnace and the slags and metal were analysed.

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# SULPHIDES AND SMELTING EXPERIMENTS

## Introduction

Communities utilising primitive techniques in the production of iron are rare today, perhaps surviving in the form of a few old men who remember taking part in a bloomery smelt some forty years ago. Thus we are forced to rely on descriptions of such techniques written mainly during last century and the earlier years of this. Unfortunately, these records are rarely thorough enough to answer the many questions posed by archaeo-metallurgists/archaeologists, and consequently the primary method of research is experimentation, simulating the ancient smelting conditions. As mentioned earlier many such experiments have been carried out over the last three decades and as a consequence a considerable body of knowledge has been added to our understanding of ancient smelting procedures, particularly of iron, copper, lead and, more recently, tin (*Tylecote et al. 1958 and 1971; Gilles 1958 and 1960; Pleiner 1965; Voss 1973; Thomsen 1963; Merkel 1983 and Heatherington 1978*). Such experiments are continuing, but are usually designed to answer specific problems, such as the use of sulphidic ores.

Possible sources of ore, which are particularly plentiful in southern England, are the deposits of marcasite (iron sulphide) nodules in the chalk. These are potentially a rich source of iron, as were the pyrites nodules weathering out of the London clays, particularly noticeable along the coast at Bognor Regis, Sussex. During the 19th century they were carried as ballast in

ships returning to Newcastle, and there were converted into sulphuric acid.

In view of the availability of material from both sources, it was decided to investigate their suitability as a source of iron ore in prehistoric times.

Several preliminary experiments were used to determine the characteristics of the furnace. However, these did not involve the use of sulphidic ores and the results have largely been incorporated in the chapters on products and processes.

## Smelting experiments

The furnace was preheated to ensure maximum efficiency in converting the fuel to carbon monoxide, oxidising and then reducing the ore, and maintaining temperatures sufficiently high to avoid freezing the slag. Maintaining a low viscosity of slag is particularly important when tapping is carried out. Temperature recordings indicated that at least two hours of preheat were required to balance heat loss through the walls of the furnaçe.

The importance of the shaft was clearly seen in experiment WH2*, when only a small quantity of charcoal was charged prior to the initial charge of ore in order to simulate bowl as opposed to shaft conditions.

* WH1, WH2, SE1, 0.1, BR, etc, are experiment numbers and directly relate to the type of ore used BR=Bognor Regis sulphide nodules, WM=Wiltshire marcasite nodules, WH=West Hoathly siderite, O=roasted ore from Odell SE=ore from Seend.

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Bowl conditions are clearly inefficient and there was a considerable amount of magnetite and unreduced ore in the final product and less than 100 grams of bloom were recovered. The residence time without the shaft had been inadequate to allow for full reduction, or any reduced material had been reoxidised in the combustion zone. When a high blast was used, such as the 300 l/m in smelt SE1 (cf 150-200 l/m in the other smelts), the charcoal at the base of the furnace was fully displaced by a fluid slag, the greater fluidity resulting from higher temperature (higher blast). The higher temperatures and blast had also resulted in higher furnace preheat and thus the slag did not freeze at the base of the furnace. However, some 83% of the charge ended up as a solid dense slag furnace bottom (plate 2b). Prills of iron can be clearly seen at the base of the slag which on analysis proved to be white cast iron with a hardness of c. 500 VHN. These result from highly carburised iron liquifying in the combustion zone and sinking through the slag bath. Thus, while the conditions had been reducing enough in the upper levels of the furnace, because of the high blast, the combustion zone temperatures had been too high and oxidising, resulting in oxidation of the bulk of the iron. Had the base diameter been larger, this would have been avoided, but with the narrow shaft, all the iron formed was channeled though the oxidising conditions of the combustion zone. Some ferritic bloom can be seen with the charcoal (plate 2b, top left), but nearer the tuyere no iron was detected. The charging ratio of charcoal to ore was 2:1.

Smelt WH1 (discussed in chapter 1) revealed the result of using a

high fuel to ore (5:1) ratio which would have led to a relatively long residence time. The product was heavily carburised and had the structure of a grey cast iron with massive phosphide inclusions (plate 6a-b).

## Smelting limonitised pyrite

Marcasite (FeS$_2$) nodules were collected from the chalk near Marlborough, Wiltshire. It took 2 man-hours to collect approximately 27kg of limonitised ore. Some of the nodules were so heavily weathered that they had lost all the original sulphur, leaving almost pure limonite (2Fe$_2$O$_3$.3H$_2$O). The following analysis was obtained on one nodule, using energy dispersive microprobe analysis:

| | |
|---|---|
| Fe$_2$O$_3$ | 93-94% |
| SiO$_2$ | 2-3% |
| S | 0.2-0.4% |
| CaO | 0.3-2% |
| MgO | 0.2-0.4% |

A radial traverse of the sample showed no significant variation in sulphur content. This analysis is by no means representative of the ore collected, as other nodules were visibly less weathered, having the typical metallic lustre of sulphides. However, this analysis does demonstrate the possibility of obtaining high grade iron ore from a source previously thought to be unusable because of its high sulphur content.

**Roasting**

Roasting was carried out on both the limonitised nodules, to try to remove the residual sulphur, and the unweathered nodules from Bognor Regis (Sussex). This was carried out by laying small firewood and charcoal on a perforated iron plate and placing the ore on top of the ignited fuel. The pieces of ore varied from about 2cm to complete nodules 10-15cm in diameter. In the case of the limonitised nodules a supply of the igniting gas was maintained, as the reaction was not sufficiently exothermic. The temperature achieved by this method was in the vicinity of 500°C-600°C. Although this is sufficient to drive off water, including the dissociation of hydrates (c.550°C) it is too low for the complete oxidation of the sulphides.

Dissociation of the sulphides takes place over a range of temperatures between 200°C and 700°C, but below 650°C the products of sulphide oxidation will be principally sulphates, while above 750°C they will be mainly oxides. The production of sulphates needs to be avoided, as they are reduced during smelting, and form sulphide impurities in the iron.

The dissociation of sulphides is normally not a problem as the reaction

$$2FeS_2 + 5O_2 = 2FeO + 4SO_2$$
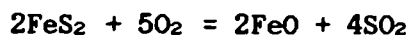
is exothermic and self-sustaining. However, these nodules were so heavily weathered, and the sulphide so dispersed, that a constant supply of energy was necessary to sustain the oxidation process. Accordingly, more charcoal was added, and an electric blower was used. In some regions of the roasting hearth, conditions became

too hot and possibly too reducing, resulting in the production of a slag. Overall, the roasting process promoted the breakdown of the nodules to a smeltable size.

The Bognor Regis nodules were unweathered and the roasting was only partially successful, as a considerable amount of matte formed. This was attempted in a small bowl structure, again with charcoal and a blower, and the reaction was self-sustaining after ignition. A second attempt at roasting proved more successful, as this was carried out on a steel plate heated from below with a wood fire. The reaction once initiated was exothermic and dense sulphur fumes were given off. On cooling, the nodules were cracked and powdery, red in colour.

A further batch of both the sulphide nodules was exposed to the atmosphere for a period of approximately one year. These were seen to weather rapidly with a yellow effluorescence of sulphur and a breakdown of the sulphide particles to a powdery state. In contrast to the Bognor Regis pyrites, the chalk marcasite nodules, while similarly losing sulphur, retained much the same nodular morphology of the original sulphide as opposed to the powdery product of the Bognor Regis ore, and thus would have been more easily charged to the furnace.

## Smelting

The smelting furnace was built to simulate a low shaft furnace, now believed to be similar to one of the furnace types in use during the Iron Age, though no tapping facility was employed because of the small scale of the smelts. The furnace employed

was cylindrical, with an internal diameter of 22cm and a height of 55cm, with a single tuyere set at 55° to the horizontal. This was set inside a square metal frame, walled with insulation board, with the area surrounding the furnace filled with sand to act as an insulator against heat loss (plate 24a). Three probe holes were drilled though the furnace walls and were connected by 1.3cm diameter steel tubing to the outside to enable temperature and gas analysis to be made from different heights of the furnace. The furnace bottom was made from insulating bricks which in turn rested on insulating board. The furnace walls and base were lined with a mixture of sand, bentonite and charcoal dust.

## Smelt WM1

The roasted limonitised marcasite was hand-crushed to 10-12mm. Charcoal (Portuguese hardwood, *Quercus sp.*) was crushed and sieved to 10-15mm. Added to 2.2kg of this ore was 0.29kg of a highly siliceous ore from Seend (Wiltshire) in order to bring the $SiO_2$ content up to approximately 20%. This allows a low-viscosity slag to form, which helps to remove the impurities from the iron and consolidate the bloom. Without the addition of the flux, the iron would be too finely divided to permit forging.

The furnace was charged with charcoal and preheated for two hours, at first with a gentle blast and gradually building up to a blast of 250 l/min. The furnace was then topped up with charcoal before the first charge of ore. Over the next hour, at approximately 10 minute intervals, the furnace was charged seven times using a total of 5kg of ore. The fuel to ore ratio was 1 : 0.81, with the first two charges being of a 2:1 ratio. After the last charge the

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first two charges being of a 2:1 ratio. After the last charge the furnace was topped up with charcoal and the blast maintained for a further 30 minutes. Throughout the smelt, the blast was 150 l/min, except while charging, when it was turned off. The furnace maintained temperatures between 1000°C and 1300°C and thus were ideal for the formation of the bloom.

On dismantling the furnace, it could be seen that all of the ore had reached the combustion zone, although there were several levels of 'grompie' (high carbon iron particles) suspended in the upper levels. The furnace bottom was a conglomerate of iron-coated charcoal, slag, and a bloom weighing about 0.25kg. The furnace bottom was 20cm in diameter x 14cm in height. At least half of the product (the top) was unburnt charcoal with a thick coating of iron (similar to plate 4a).

On examination at the tuyere level it could be seen that slag had fused around the tip, diverting the blast and hence preventing it reaching the back of the furnace, thus leaving a large proportion of uncombusted material in the base.

Some of ore charged had a tendency to break up into finer particles, and it would have been this fine ore which coated and extinguished the charcoal particles on reduction. There is an obvious need to break up the ore, perhaps to a 1-2mm size, mix it well with a flux (sand or siliceous ore) and agglomerate it into larger (c. 10mm) particles prior to charging. This would possibly avoid the coating of the charcoal and prevent the formation of 'grompie'. The weathered ore is so pure that the flux needs to be

well mixed to prevent the haematite reducing directly to a pure, porous, finely divided iron. The amount of slag produced suggested that more flux could have been added.

## Smelt WM2

This smelt was carried out in similar conditions to WM1, but with slight variation in charging ratios. After a two hour preheat the furnace was topped up with 4kg of charcoal. After this, ore and charcoal were then charged in a ratio of 1:1 in weights of 0.67kg every 10 minutes for a period of 45 minutes. A total of 2.7kg of ore was charged at a ratio of 1:1 during the smelt. However, the initial charge of charcoal charged to top up the furnace prior to the first ore would distort this actual ratio because the overall charge was small, giving an effective fuel to ore ratio of 3:1.

After the final charge the furnace was again topped with charcoal (1.8kg) and the blast was continued until the charge would have descended to the tuyere zone of the furnace. This was estimated from the descent/charging rate versus the height of the shaft above the tuyere. The furnace was covered and the contents examined on the following day. From the total charge of 2.7kg of ore, several small pieces of bloom were recovered weighing approximately 0.3kg, representing a yield of c. 10%, together with a furnace bottom of slag and entrappped charcoal weighing 2.3kg.

**Smelt BR1**

Problems with the sulphurous fumes resulted in only a small amount of roasted pyrites being charged (1.7kg). However, lumps of slag/matte and charcoal together with small pieces of bloom (c. 150gm) were recovered during furnace examination.

**The product**

The iron from the roasted marcasite smelts was low in carbon, about 0.1%, with precipitation of cementite at the grain boundaries (plate 8c-e). The slag was a typical bloomery slag, with fayalite and wustite in a glassy matrix (table 3.1). However, irregular Fe—FeS eutectic inclusions were observed in the slag, and were also present in the iron as spherical sulphide inclusions (plates 7g and 8c-d).

Overall, there is around 2-3 % sulphide included in the iron, all in the form of discrete inclusions (plate 9d). Therefore the iron produced from the weathered marcasite nodules appears to be a viable product. Problems would arise only if the metal was forged at a temperature above $1000^{\circ}C$, $988^{\circ}C$ being the melting point of the Fe—FeS eutectic. Above this, the eutectic temperature would be reached and the inclusions would melt and eventually coat the grain boundaries, forming a brittle product which would break up on forging (see Fe—S binary, fig. 3.1).

Smelting the pyrites nodules from Bognor Regis was less successful, and the furnace bottom was layered with slag overlying a matte (sulphide phase) (plate 9c). Small flecks of matte can be observed in the slag, which in other respects has a similar

structure to bloomery slags from non-sulphidic ores. The iron
retained a high percentage of sulphur (5%-10%) and as a
consequence the bloom comprised large grains of iron surrounded by
sulphide at the boundaries. Element maps for sulphur and iron
(plate 7) clearly show the sulphide distribution at the
boundaries. Even this effect would be localised, as some of the
bloom was relatively free of sulphide inclusions (plate 7b). This
distribution contrasts with the bloom from the marcasite ore,
where the sulphide remained in the form of spheroidal inclusions
(plate 7f-g). Plate 8b indicates that the sulphide at the
boundaries is two-phase, presumably FeS-FeS$_2$.
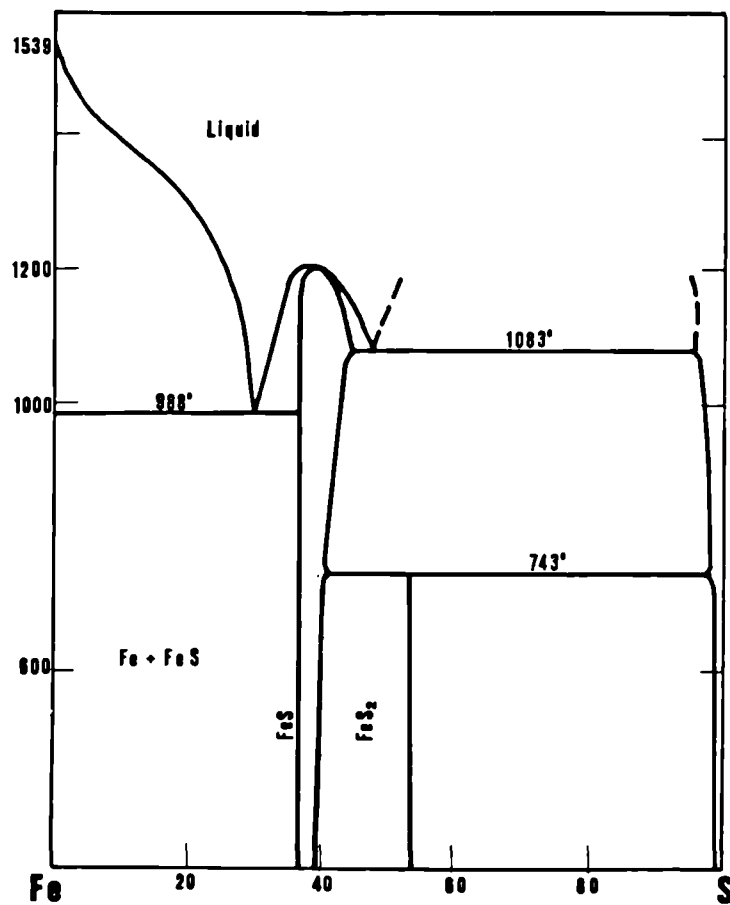


**Fig. 3.1    The system Fe -S**

Sulphide inclusions are also found in iron from non-sulphidic ores (plate 7h) and presumably derive from small deposits of sulphide or sulphate in the ore deposits. Thus, the presence of sulphide inclusions in the iron do not necessarily imply the use of a sulphidic ore source.

The iron from the WM smelts was not atypical of bloomery iron, i.e. a mixed carbon content associated with small sulphidic inclusions (plate 8c-e). The slags were fairly typical of bloomery slags, being largely fayalitic with wustite dendrites in a glassy matrix. Within one smelt, there was considerable variation in the olivine composition with notable differences in CaO content (ranging from 0.5 to 13%). The olivines at the base of the furnace bottom (f-b) were generally richer in this element than those formed at the top of the furnace bottom (i.e. slags formed later in the smelt). This could be due to variations within the ore (marcasite from the chalk), or the result of greater interaction with fuel ash accumulated at the base of the hearth. There was probably a build-up of fuel ash from the charcoal and wood consumed during the preheat and this is normally rich in CaO (table 3.1).

The slag from the Bognor nodules displayed similar variation, but the bulk of the olivine was generally richer in calcium. The major difference between the slags from these two ores was the greater frequency of matte inclusions in the Bognor slag which resulted from insufficient roasting of the sulphide nodules (plate 9).

## Conclusions

The experiments confirm that these sulphidic nodules, particularly the weathered marcasite from the chalk, are a rich source of iron and would have provided a viable source of ore for the bloomery process. Sulphide is easily broken down, either through natural weathering by exposure to the elements, or assisted by roasting prior to smelting. Sulphide nodules have been recorded on a number of sites including Cow Down (Hants), Brooklands (Surrey), Danebury (Hants) and Hambledon Hill (Dorset).

If the ore had been well roasted, iron deriving from its reduction would be difficult to characterise, because sulphide inclusions are also found in iron from non-sulphidic ores. Experimental bloom from the Seend ore had numerous inclusions with the approximate composition 64% Fe, 36% S, i.e. FeS (plate 7). In contrast, the slags might provide a means of characterisation because they have an appreciable sulphide content in the form of fine matte inclusions (plate 9).

Cluster analysis (K-means) (*Doran et al. 1975*) grouped slags and ores from these experiments together with material from Cow Down (Hants), a site on which weathered sulphide nodules were found associated with iron slag and some ores (non-sulphidic) from the Forest of Dean. This suggests that the product from such smelts falls within the general variation encountered with smelting a variety of ores and thus would be difficult to characterise.

## Table 3.1

### Analysis of products from experimental smelts

**Products from smelting Wiltshire marcasite**

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|
| * 1.88 | 90.6 | 0.4 | 0.0 | 0.0 | 0.3 | 0.1 | 0.4 | 93.6 | marcasite |
| ~22.3 | 56.0 | 4.4 | 5.2 | 0.0 | 1.1 | | 0.5 | 89.5 | furnace slag |
| ~17.7 | 57.0 | 8.1 | 3.2 | 0.0 | 0.6 | | 0.5 | 87.1 | base of f-b |
| * 8.20 | 69.31 | 14.63 | 0.52 | 0.22 | 1.33 | 0.78 | 0.5 | 95.5 | WM2 f-b |

**Analysis by microprobe - raster analyses**

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 20.5 | 63.4 | 4.0 | 7.7 | 0.0 | 0.5 | 0.8 | 1.5 | 0.0 | 1.3 | 99.7 | area |
| 30.2 | 61.5 | 6.3 | 0.4 | 0.4 | 2.1 | 0.0 | 0.0 | 0.1 | na | 101.0 | bulk phase |

**Phase analyses of slag**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.3 | 92.7 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 94.0 | wustite |
| 30.4 | 50.2 | 0.0 | 14.4 | 0.3 | 0.3 | 2.2 | 0.1 | 0.0 | 0.0 | 96.9 | grey crystalline |
| 31.8 | 64.3 | 0.5 | 1.7 | 0.4 | 0.3 | 0.8 | 0.5 | 0.7 | 0.1 | 101.1 | olivine top of f-b |

**Slag inclusions in the iron**

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 38.5 | 19.3 | 9.2 | 21.7 | 0.0 | 0.0 | 10.2 | 1.3 | 2.1 | + | 102.3 | glassy matrix of FeO |
| 30.9 | 58.2 | 9.6 | 0.6 | 0.4 | 1.3 | 0.3 | 0.0 | 0.0 | na | 101.3 | calcium-rich olivine |
| 29.7 | 67.0 | 0.4 | 0.5 | 3.3 | 0.7 | 0.0 | 0.0 | 0.0 | na | 101.6 | fayalite |
| 50.3 | 25.3 | 16.6 | 3.1 | 0.3 | 0.0 | 2.3 | 0.7 | 0.2 | na | 98.8 | glassy matrix of olivine |
| 50.0 | 6.6 | 35.2 | 3.5 | 0.2 | 0.3 | 1.8 | 0.6 | 0.0 | na | 98.2 | large area of glass |
| 29.6 | 68.3 | 1.1 | 0.0 | 0.4 | 1.0 | 0.0 | 0.0 | 0.0 | na | 100.4 | olivine top of f-b WM1 |
| 31.5 | 53.6 | 13.2 | 0.5 | 0.3 | 2.0 | 0.1 | 0.0 | 0.0 | na | 101.2 | olivine base of f-b WM1 |
| 37.9 | 24.0 | 11.5 | 16.6 | 0.2 | 0.5 | 8.1 | 1.1 | 0.6 | na | 100.5 | glass at base of f-b WM1 |

| | Fe | | | | | | | S | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.3 | 67.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 26.6 | na | 93.9 | sulphide inclusion |
| | 100.3 | | | | | | | 0.2 | | 100.5 | metal WM2 |
| | 96.2 | | | | | | | 0.3 | | 96.5 | metal WM2 |
| 8.2 | 83.1 | 5.4 | 0.8 | 0.0 | 0.3 | 0.4 | 0.0 | 5.4 | | 101.8 | raster of slag inclusion WM2 |

Table 3.1 (cont.)

Analysis of materials from experiments with sulphide nodules from Bognor Regis

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | SO | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| \ | 35.0 | 17.5 | 3.5 | 0.3 | 1.6 | 1.8 | 0.5 | na | 60.2 | slag f-b |
| ˜30.4 | 39.6 | 16.9 | 4.0 | 0.3 | 1.4 | | 0.8 | na | 93.4 | slag f-b |
| *37.5 | 40.9 | 10.1 | 4.4 | 0.2 | 1.3 | 1.3 | 0.3 | na | 96.0 | slag |

Analysis by microprobe - (raster)

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 21.3 | 61.6 | 8.2 | 4.5 | 0.0 | 0.9 | 1.9 | 0.0 | 1.2 | na | 99.6 | 200 microns |
| 30.4 | 50.2 | 14.4 | 0.0 | 0.3 | 2.2 | 0.0 | 0.0 | 0.0 | na | 97.5 | crystalline |

Phase analysis

| 34.1 | 33.7 | 22.8 | 2.4 | 0.4 | 0.2 | 3.0 | 1.6 | 0.0 | 0.0 | 98.2 | grey crystalline |
| 54.2 | 3.9 | 21.1 | 1.0 | 0.0 | 0.2 | 0.0 | 17.4 | 0.9 | 0.1 | 98.8 | glassy |
| 47.7 | 24.2 | 15.7 | 7.4 | 0.0 | 0.0 | 1.3 | 0.0 | 1.3 | 0.6 | 98.2 | crystalline |
| 33.0 | 58.3 | 1.3 | 1.4 | 0.3 | 3.2 | 0.6 | 0.0 | 0.0 | 0.3 | 98.4 | crystalline |

| Fe | | | | S | | |
|---|---|---|---|---|---|---|

sample also has spheroidal sulphide inclusions - (numerous of this composition)

| 64.4 | | | 35.8 | 100.2 | metal incl |
| 64.4 | 0.3 | 0.1 | 35.9 | 100.7 | area of inclusion |
| 65.3 | | | 35.3 | 100.6 | inclusion 2 |

Region of islands of iron in the matrix 390microns (see plate 7)

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | S | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 89.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.2 | 0.0 | 99.9 | area plate 7c |
| 1.3 | 96.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 0.0 | 99.3 | low sulphide area |
| 0.2 | 100.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 100.6 | area 2 |

Ash analyses from charcoal used in smelts

| \ | 0.1 | 42.7 | 0.1 | 0.3 | 4.0 | 12.7 | 1.1 | | 61.0 | British mixed softwood |
| ˜49.1 | 3.6 | 20.1 | 1.4 | 1.8 | 1.6 | | 0.9 | | 78.5 | Portuguese (Quercus sp.) |

\ Hydrofluoric/perchloric dissolution and ICP analysis (iron as Fe2O3
* XRF - (wave dispersive) of slags and ores (sodium borate fusions). Iron as Fe2O3.
˜ XRF (energy dispersive) with sodium borate fusion discs. Iron presented as FeO.

# CHAPTER 4

# FURNACES

## The problems of interpretation and classification of early iron-smelting furnaces

### Abstract

Archaeologists have always turned to classification as as end
in itself rather than as a means towards interpretation of
the remains, and their treatment of furnaces proves to be no
exception. The theory and reasons behind classification are
usually left undisturbed. This chapter questions some of the
underlying assumptions of furnace classification and
discusses some of the typologies that have been proposed to
explain the development and diffusion of iron technology.
Ethnographic data are used in a critical analysis of
classification and to provide possible new directions in
dealing with what is usually very fragmentary information.

# FURNACES

## The problems of interpretation and classification
## of early iron smelting furnaces

### Introduction

Up until the last two decades only been a few vestiges of ancient furnaces had been found. Thus the interpretations of Gowland through to Coghlan were severely limited and relied almost entirely on ethnographic data. Recently, the number of excavated furnace structures has increased significantly in both Britain and on the Continent, particularly in Poland and Scandinavia. An associated phenomenon has been the proliferation of furnace typologies in an attempt to rationalise the new data, but overall they represent only a small contribution towards understanding these ancient furnace structures and have in general failed to break away from the core of the earlier classifications. Martens, for example (*1978, 45*), recognises the entrenched position of the basic tripartite typology and as a consequence these types remain central to her scheme. Bowl, dome and shaft furnaces, together with their many subdivisions, therefore remain central to all typologies and represent the labels most commonly used by archaeologists to describe their furnaces. The classification has become an endpoint in itself. Once labelled, furnace distribution maps can be prepared and are then used to trace the movements of furnaces (cultures?) across Europe, and typologists are able to construct evolutionary schemes, with one type of furnace giving rise to another. Unfortunately there is greater accuracy in

tracing the development of the various classification schemes than the evolution of the furnaces themselves.

Before investigating the merits of the various furnace typologies it is necessary to consider the reasons for and methods of classification, particularly the underlying assumptions behind such schema, and beyond that to assess the manner in which they have been used by archaeologists.

## Why classify?

From the archaeological point of view there are reasons for dividing furnaces into types other than for clarifying their technical development. Traditions within different geographical areas and cross-influences between these areas dictated the shapes and details of the furnaces, involving factors which do not seem to have any technical significance. These then, have much value for cultural and historical reasons (Serning 1979, 68).

The main use of the schemes has been typical of the use of any classification in archaeology: cultural-historical reconstruction (*ibid.* and *Martens 1978, 36*), using the furnace types to define cultural horizons and to trace traditions through time. We encounter articles on the diffusion of slag-pit furnaces and their parallels (*Tylecote 1973*), and the diffusion of iron technology. Many of the archaeometallurgists (*Gowland, Coghlan, Tylecote et al.*) have their roots in the discipline of metallurgy and have understandably remained peripheral to advances in archaeological theory. As a consequence diffusion has been the predominant mode of explanation, with emphasis on the movements of furnaces or of metals across the Middle East and Europe. In British Bronze Age studies, groups of impurities found in copper alloys have been known to migrate around the country (*Northover*

*1984)*, while the slag-pit furnace appropriately chose the Migration period to move from Jutland to East Anglia (Aylesham slag block, *Tylecote 1973)* and the shaft furnace came to Britain during the unrest of the Gallic wars.

The mechanisms for such movements (distributions) remain unexamined and the material on which they are founded is usually undated. Iron smelting is rarely seen in its wider industrial or economic context, even though in one of the earliest classifications furnaces are studied within their cultural setting (see Percy's classification below). Technological reconstruction should be a primary aim, but few papers go beyond simple description of technological development seen purely in terms of increasing complexity of the furnace structures. Notable exceptions can be found in recent work from parts of Scandinavia, where iron production is considered in its industrial and social context (*e.g. Clarke 1979, Magnusson 1983*).

The use of furnace type to reconstruct cultural movement, or indeed technological development, assumes that similar form implies not only culturally similar manufacturers but also equivalent function. We have seen that similar forms often have a variety of functions (e.g. bowl furnace = forge, smelting furnace, base of shaft furnace, and melting furnace for non-ferrous metallurgy), and hence caution must be exercised in using typologies. Underlying assumptions must be examined, particularly relating to the transposition of modern values into the past. As an example:

I am of the opinion the iron furnaces of Britain before Roman times, and long

afterwards, were simple bowl hearths resembling the Catalan furnace (*Gowland*
*1899, 312*).

Here the damage is done, the bowl furnace is now the established
type for early iron production, and models since have adhered to
this tradition in spite of the inadequate evidence to support it.

Coghlan follows similar reasoning, but with a cautious proviso:

> It is natural to consider that the original iron smelting furnace was of a simple
> nature, but before we can be certain of this, we require dated examples of
> furnaces which may safely be ascribed to the earliest phases of iron smelting
> (*Coghlan 1956, 86*).

In doing so, he has highlighted two problems, everybody assumes
the simplicity of early furnaces and unfortunately all fail to
use firmly dated or stratified examples to construct not only the
typology but the cultural links with type. However, very few
persons investigating this problem have recognised the warning in
Coghlan's early work on the subject and, as a result, the
expectation became the reality, with an inversion of the above:
all simple furnaces came to be regarded as being early, a
typology from simple to complex was developed and subsequently
used to date the fragmentary remains excavated. In fact, shaft
furnaces used primarily for the production of non-ferrous metals
may have been converted to the production of iron without a
necessary reversion to a simple bowl, and also many simple
furnaces have been used throughout the history of metallurgy.

Sollas, in his classic work (*1911*), considered the aborigines of
Tasmania and Australia to be at different levels of development,
and ranked them on the basis of their primitiveness. These levels
he saw as analogous to, and, in fact, as survivals of different

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stages in the development of Palaeolithic man. In the field of ancient metallurgy similar mental processes have been applied: the basis of all classification schemes is the vast body of ethnographic material on iron-smelting communities. In the case of iron, the various methods of production, particularly the types of furnaces used, were organised into a typology on the basis of their efficiency, a rough guide to their 'primitiveness'. This synchronic distribution of furnace types is then inverted, becoming a diachronic scale, the most 'primitive' representing the earliest furnace type and so on, to the most complex representing the most modern. This simplistic linear evolutionary model is then imposed on the archaeological data with each type representing a rung on the ladder, and each rung implying progress, in contrast to an evolutionary tree model where many branches (types) are concurrently present and progress is not necessarily implied. The latter, although not particularly appropriate for furnace development, is an improvement over the simple linear model, but even here contemporary furnaces are classified and those less efficient are seen as fossil furnaces.

This then gives rise to several problems inherent in literature concerning early iron production :

a) Variation. In any one period furnace morphology will vary considerably: for example, the variation observed in Africa at the time of early European contact, seen in microcosm in parts of Africa such as Kenya, where more than three furnace types were in use over a small region. A similar level of variation is apparent during the Iron Age in Sweden (*Clarke 1979, also*

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*Magnussen pers. comm.*), where a multiplicity of furnace structures have been excavated and are contemporary. The same is true of India (e.g. Tendukera in the 19th century) and must be expected throughout the history of iron production.

b) The archaeological evidence is limited, often with only a small part of the furnace structure remaining, leaving reconstruction to the imagination of archaeologists with only a limited knowledge of furnace (bloomery) technology. As the superstructure of many furnaces is missing, the remaining structure, which is usually the hearth or base, often resembles a bowl shape. Thus interpretation is open to the above prejudices, and if it is associated with, for example, a pre-Roman site, it is seen as a bowl furnace, whereas if it is from a later period it is seen as the base of a more complex structure such as a shaft furnace. Problems arise when a considerable amount of the structure remains and must be interpreted as a furnace atypical of the period. For example, Dellfield (Berkhampstead) was assigned a date in the 1st to 2nd centuries AD on the basis of furnace type, while ceramics and other material from the site suggested a pre-Roman date (*Thompson and Holland 1976*).

The classification problems of bloomery furnaces are considerable. On one hand, the furnaces are complicated structures with a great number of typological elements ; on the other, a high percentage of them are badly preserved (Maitenz 1978, 27).

From the outset limitations are imposed by the paucity of intact furnaces (plate 24) and, apart from the bowl hearth base, we are most commonly left with a slag pit and some vitrified lining together with the ubiquitous slag. And as we shall see later in

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the chapter, many of the typologies rely on measurement of furnace dimensions, for example the diameter of the furnace mouth or the height of the furnace, both elements of which are usually absent from the field record.

In reality each furnace embodies economic, technological and traditional influences together with individual preferences. Constraints on structure are imposed by the materials utilised in furnace construction and, as we have seen, by the ores available to the smelter. These influences, together with the requirements of the community (which determine the scale of production) and tradition, are probably so intertwined that even the power of the elves would fail to unravel them. For example, are bowl furnaces designed to smelt a particular ore type, or do they merely reflect the small requirements of the community? Are slag-tapping shaft furnaces used for their efficiency, their ability to cope with poorer ore, or are they more suited to mass-production units typical of many Roman sites.

Classification is problematic. However, as we have seen in chapter 1, furnace morphology is technologically significant, and this, plus the fact that archaeologists will continue to classify, means that classifications must be considered and understood. Classification, in providing pigeon- holes for furnaces, results in minimizing variation in that no furnace exactly fits a type, but all are inevitably manipulated into one. In this process information is both lost and gained; the variation, which is trimmed, in itself provides information about

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the process and therefore must be explained, but if each furnace is treated as unique, then the ability to relate furnace morphology to, for example ores, tradition, or economy is lost.

Which aspects are governed/limited by the process, and which are cultural elements? If both archaeological and ethnographic examples are considered with respect to their wall thickness, it becomes obvious that thickness of furnace walls suggests no optimum as this varies greatly, and it could be concluded that temperatures and conditions required for reduction can be achieved within either thin or thick walls and are not difficult to attain. Therefore, thick walls must relate to other working procedures and possibly to cultural-historical preferences. For instance, the available clay may be of such a composition that it is structurally necessary to construct a thick wall to avoid collapse of the structure during fire-hardening or a smelting operation. Or thickness might relate to the desired permanence of the structure; the size of the community (availability of labour); or the seasonal nature of the work, e.g. a rainy season which would both prevent smelting and destroy a flimsy furnace; alternatively, as the furnace would require rebuilding in any event, then there is little advantage in a labour-intensive structure. If such reasoning processes are extended not only to other aspects of the furnace structure, but also to related site data such as the type and quantity of slag, then it should be possible to define the extent and nature of the industry more precisely.

## Which elements should be stressed?

Distinguishing hearths and shaft furnaces is of greater importance for classification from technological and economical points of view. Any subdividing should, I think, be subordinate to this basic scheme (*Pleiner in Martens 1978, 34*).

Opinions differ, which is understandable, since it is impractical to base a classification on every attribute of a furnace (as they are limitless). It is therefore expedient to give an empirical weighting to one or another attribute of the furnace. However, some justification or elucidation of the reasoning behind the selection used to generate the typology is necessary. The existing classification schemes referred to in this thesis stress different features of the furnace in their typologies, but often fail to explain the significance of such a selection, for example, Cleere, like others, prefers to stress the slag-tapping facility, possibly for no reason other than that he believes it to be a cultural, i.e. Roman, innovation. Such unexplained bias often elicits criticism from other quarters, particularly from originators of alternative schemes, who naturally regard their method as correct. As we shall see, some emphasise the separation of slag, while others see the elevating of the furnace hearth to ground level as an important 'evolutionary' step.

Beyond classification, there is the difficulty of interpretation, as most excavators still lack even the most elementary knowledge of the process of smelting. Even those experienced in ancient metallurgical remains often differ with regard to interpretation. For example, Martens (*1978, 36*) observed that very similar furnaces have been interpreted as both natural and artificial

draught: e.g. Salzgitter-Lobmachteisen and Hildingen have been interpreted as natural (citing *Osann 1959, 206 and Dehnke 1967, 156*) and Lodenice (with tuyere) and Ashwicken as artificial (*Pleiner 1965, 24 and Tylecote 1962, 22*).

## Classification schemes

A recurrent theme in many schemes is a tripartite division into bowl, dome and shaft furnaces. Most have further subdivisions relating to features such as slag tapping, but all fail to explain the significance of their types other than in terms of diffusion or cultural association:

> but one important fact distinguishes Roman techniques from earlier processes in which slag remained in the bottom of the furnace. By the Roman period the slag was tapped from the furnace in a fluid state as shown by the evidence from Pickworth and Ashwicken (*Tylecote 1973, 25*).

The classification schemes encountered in archaeological literature range from the all-encompassing evolutionary scheme of Forbes (*1956*) to the geographically specific typologies relating only to furnaces from a few sites, such as Gibson-Hill (*1980*), Gowland (*1899*), Coghlan (*1956*), Cleere (*1972*), Osann (*1971*), Serning (*1979*), Martens (*1978*) and others.

There has been a general consensus of opinion from the time of Gowland (*ibid.*) that in Britain and Europe the earliest form of iron furnace was the bowl furnace (defined below) or the *Rennfeuer* (*Osann 1971, fig. 1,*) and that this structure was displaced by the shaft furnace. Hybrids evolved, with the bowl furnace apparently developing into the Catalan furnace, or developed bowl furnaces, with domed furnaces playing some

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intermediate role.

Forbes differed slightly in that he saw all metallurgy beginning with, and evolving from, crucible processes (*Forbes 1950*). His classification is a general one, concentrating primarily on the evolution of furnace technology and, although iron smelting predominates, it also encompasses finery hearths, liquation hearths, smiths' forges, etc, and equates the furnace type only with a specific process, thereby avoiding the finer constructional problems or questions of ore/furnace, furnace/community relationships.

One of the earliest and perhaps the most influential studies of iron-smelting furnaces was that of Percy (*1864, 255ff*), using data primarily from South Asia. He proposed a division into three basic types which he related to the geographical areas where they are commonly found and to the type of community employing them. These he sees as analagous to historical examples from Europe. For example, those of central India resemble the simplest forms of Catalan, and those from the N.W. provinces the German *Stucköfen*, while on the west coast more primitive furnaces (i.e. equivalent to low hearth or bowls) are found.

Percy's typology comprises: i) a low hearth; ii) a small blast furnace; iii) a tall blast furnace (being greater than 3m with the smelt lasting for 2-3 days producing a bloom in the vicinity of 250kg).

Type 1 is used primarily by the hill tribes of the Ghats. The furnaces are only 60cm high, yielding some 2-3kgs of iron per charge, while in the Deccan they are often 1.2m high producing 13.5kg of iron. These are circular in form, being 25-

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38cm across the hearth and 15-30cm at the top. They are carefully built of
tempered clay, and have two openings for the blast and slag tapping or extraction
of bloom, with the lower part constantly repaired with linings of fresh clay.

In Bengal and the Carnatic, often the same hole is used for charging tapping and
bloom extraction, with two tuyeres side by side at the opening of the furnace.
The charge is layered and the smelt is complete in 4-6 hours with the majority of
slag remaining in the furnace. In these districts, there is usually no division
of labour, the same family collecting the ore and charcoal, and carrying out the
smelting and smithing. At times the smelters are itinerant, moving their
residence to new ore/fuel sources or new markets.

Type 2 is found in the Northwest provinces, where the ironmakers are united in a
village, the sites of which are determined by the proximity of ore and fuel. In
the large villages there is usually a complete sub-division of labour into
miners, charcoal burners, smelters, and blacksmiths, all forming separate
classes. The product from such an industry is often sold at considerable
distances.

Tendukera is an example of such a process. Here is a town devoted to the
production of iron, which has 50-60 furnaces. These are often built in groups of
2-3 into banks of well-tempered clay, 38-46cm in internal diameter and 64cm deep.
Slag is tapped and the iron is extracted through the top after being manipulated
into a ball by an iron bar. The furnace is often charged as many as 6 times in a
day, producing 6 blooms of 9kg each in a day of 16 hours.

In the same district, another type of furnace is used specifically for the
manufacture of superior iron and steel. Again it is made of clay built into a
mound, but here the furnace is 2.5-3.0m high on the outside and 1.8-2m within,
the hearth being 60-90cm above the ground. The interior of the furnace is 45cm
sq. The base of the furnace has a plate of ceramic with numerous holes punched in
it , and is set at an angle of 45° with the back of the furnace. These frequently
produce as much as 68-90kg of iron in a 20 hour smelt. When the object is to
produce steel, a larger fuel to ore ratio and a gentler blast are employed
(after Percy 1864, 257-259).

Before the century was out, weaknesses in this typological scheme

were highlighted in what is still a relevant criticism of most

typologies today: that in general the evidence must be distorted

to fit the classification:

All three forms of furnace are still in regular use, and though Dr Percy's
classification is a convenient one for general purposes, there are in various
localities furnaces of intermediate height, so that there is no abrupt line of
separation between the different types (Turner 1893, 166).

However, this criticism accepted, there is obviously some

significance   in   the   socio-economic   implications   of   Percy's

proposal.   It would be expected that in a larger industrial   unit

there   would   be   greater division of labour   and   hence   greater

specialisation.   Furnaces   would   be   more   uniform   in   their

dimensions   and   different types would be more likely to   have   a

functional significance.

Gowland went to Japan in 1872 as Master of the Mint in Osaka.   He

was   immediately   impressed by   the   primitive   metallurgical

techniques   still practised and his observations   influenced   all

subsequent interpretations of early metallurgy.

> A comparative study, however, of the primitive furnaces in Japan, which I have
> just described, and of others in Southern Europe and elsewhere, affords most
> valuable data for the solution of these problems, and aids us greatly in tracing
> the iron furnace of Europe back to its primitive form, and in depicting the
> various stages of development through which it must have passed in its evolution
> (Gowland 1899, 309).

His   evolutionary scheme was   entirely dependent on this   Japanese

material   and   other   ethnographic examples,   and   was   certainly

influenced by Percy (*ibid. 303*).   At that time and throughout the

following decades there were no known early remains from Britain,

and   few from the Continent.   The earliest furnaces were seen   as

equivalent   to the most primitive of modern practices,   with   the

Khasia Hills (fig. 1.1) and Kordofan (Sudan) being representative

of this stage.   They were little more than simple hearths 30-35cm

in diameter and of a similar depth.

The   second   stage   of furnace development was characterised by   a

change in the mode of introducing the blast,   which in turn   gave

rise   to an alteration in the form of the furnace superstructure.

The blast, formerly introduced through the top, was changed to entry through the base of the furnace, which enabled the extraction process to be continuous. This in turn gave rise to the development of furnace superstructure, as seen in the dome and shaft furnaces (*ibid. 314-415*). A typical example examined by Beck at Saalburg was a cylindrical shaft 90cm high, with a 35cm diameter at the base and widening towards the top (*ibid. 319*).

Coghlan's first category is the bowl furnace, exemplified by finds at the site of Hüttenberg (Austria), by the Kordofan bloomeries (Sudan), and also known from Egyptian wall-paintings (*Coghlan 1956, 88-89*). Neuberger (*1930, fig. 24*) suggests that these paintings depict a supposed bloomery, but also mentions its use for gold extraction (*ibid. 26*). This use for gold is supported by Wainwright (*in Forbes 1956, 6, 71*), who stresses that the Egyptians always depict their smiths working with crucibles on charcoal fires or hearths and that their reliefs never depict a smelting furnace.

Coghlan's second category is the domed furnace (*ibid. 89*), which in general relies on natural draught. As an example he uses the Engsbachtal furnace (*see illustrations from Weierhausen 1939, ill. 2 E25, used in Coghlan 1956 and Cleere 1972*), which was in such a good state of preservation that a reasonable reconstruction was possible, giving dimensions of 1m in both height and diameter with a 2m long wind passage. Another example given is the Aalbuch furnace (*ibid. 92*), which seems to be a typical La Tène furnace and is important as an example of an Iron Age furnace of considerable size and operated under a natural

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draught. However, the mode of operation of the Engsbachtal furnace is debated, while the lack of datable associations for the Aalbuch furnace makes it unsuitable to use in typologies, particularly as it is used in cultural-historical reconstruction. Also, this furnace was reconstructed to a height of 2.5m when the remains only survived to a height of some 25cm (*Martens 1978, 63*).

His third category, the shaft furnace, or Jura type, was represented by the Jura furnaces (*ibid. 95*) and also the Lölling furnace (*ibid 97*), which was recovered in mint condition, was over 1.26m high and 90cm in internal diameter, but was again undated. A similar furnace was excavated at Hüttenberg, Austria (*see Weierhausen 1939, fig. 43*), and has been dated to Roman times or earlier. Examination of descriptions of these structures leads to the realisation that the remains are too fragmentary for firm conclusions to be drawn as to the superstructure, but the remains could as easily be interpreted as reheating or refining hearths. Again the lack of dating for the Lölling furnace and the paucity of the Hüttenberg remains leaves type 3 as a category with little empirical backing. This type of shaft furnace was frequently used in the Middle Ages and, indeed, according to Weierhausen 'similar furnaces were still in use by the Löllingen peasant, for primitive smelting as late as the 19[th] century' (*Coghlan 1956, 99*), which rather illustrates the pitfalls of using furnace morphology for cultural-historical interpretation.

Both Coghlan's typology and technical aspects of his furnace types have been discussed at greater length by Cleere (*1972*), and

the revised edition of his work (*Coghlan 1977, 23*) although retaining the three basic types, extends it by essentially adopting the classification of Cleere (*1972, 23*), which will be discussed below. In his revision, the Hüttenberg furnaces are retained (though Martens (*1978, 29*) suggests that these are reheating furnaces), and those from Britain – Kestor (Devon), Chelms Combe (Cheddar) – are cited as good examples of Iron Age bowl furnaces. However, in each case, the interpretation of these structures as the remains of bowl furnaces is questionable.

Forbes uses the evolutionary tree to trace the development of furnace types:

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Fig. 4.1   (from *Forbes 1956*)

THE EVOLUTION OF THE METALLURGICAL FURNACE
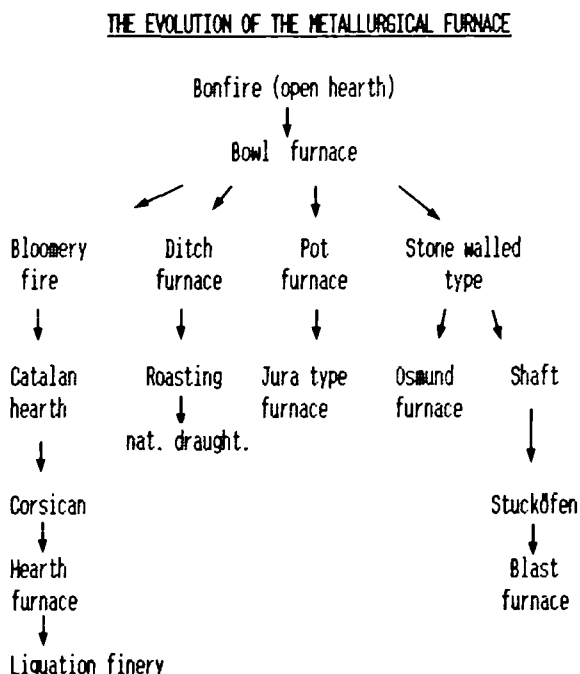


(Hearth furnaces are defined as having height less than or equal to diameter and include liquation hearths, finery fires, hearths lead from galena, and smiths hearths.)

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This model has obvious parallels with biological evolutionary schemes, without the advantage of genetic reproduction, and the underlying implication is that the development of furnace form is unrelated to function. It has been noted earlier that furnaces of similar form can have a variety of functions, which is particularly true of small bowl hearths where forging, crucible melts and smelts, ferrous and non-ferrous applications are all possible. While it is of interest to observe the variety of furnace structures through time, there is no obvious reason why, for instance, a furnace suitable for the melting of copper alloys, or for liquation processes, would develop into a Catalan furnace for smelting iron. The obvious theme in the model is the development from simple to complex.

Furnace development has a long history before the Iron Age. Not only were furnaces in use for copper smelting, but also in the extraction of most metals. Shaft furnaces were in use for production of many non-ferrous metals prior to and during the Iron Age. For example, ores from the silver mines at Laurion were smelted in shaft furnaces and were similar to those on Siphnos (*Forbes 1956, vol. 6*). Here, a model suggesting development from simple to complex seems inapplicable, as such a general model has little relevance to regional development of furnaces. Any development of furnace form must be explained in terms of several factors : function (material smelted or melted), the influence from neighbouring areas, and local traditions.

Cleere (*1972*), as Serning (see below), stresses the slag-tapping

facilities and believes that they are fundamental to the distinction between furnace types. The typology is primarily used for the identification of cultural connections and also to assess the technological progress of individual communities (*1972, 23*). The difficulties of tracing cultural associations through furnace types have already been discussed, and unfortunately very few sites provide evidence suitable for a judgement to be made on technological progress. If this scheme is closely examined, many of the sub-groups (based on morphology and operating procedure) can be seen to rely on evidence that is rarely available to the archaeologist, or at best open to debate. For example, tuyere holes are often absent and the nature of the draught must be assumed, as must be the exact shape of the superstructure. Furnaces with rectangular sections have not been considered, but are not uncommon, and Serning has certainly allowed for them (see below). Slag-pit furnaces, on their morphology, would fall into Group A2 (non-slag-tapping) (*Cleere 1972, 22, fig. 11*), but with respect to their mode of operation they must be considered slag-tapping furnaces because the function of the slag pit is similar to slag-tapping facilities in that it increases the capacity of the furnace.

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Table 4.1

Cleere's classification (from *1972, 21-22*)

GROUP A. NON-SLAG-TAPPING FURNACES

Diagnostic features. (a) No provision for tapping of molten slag
(b) Hearth below surface of surrounding ground
(c) Blown by forced draught

Sub Group 1. No superstructure (bowl furnace)
Sub Group 2. Superstructure (cylinder or truncated cone)

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Table 4.1 (cont.)

GROUP B. SLAG-TAPPING FURNACES

Diagnostic features. (a) Provision for tapping molten slag
(b) Hearth level with surface on surrounding ground
(c) Superstructure

Sub Group 1.i  Blown with forced draught. Cylindrical superstructure
Sub Group 1.ii Blown with forced draught. Conical or hemispherical
superstructure
Sub Group 2.i  Cylindrical superstructure
Sub Group 2.ii Blown with natural draught. Conical or hemispherical
superstructure

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Table 4.2

Furnace definitions based on height and diameter

| Furnace type | Coghlan | Forbes | Martens | Serning | Tylecote |
|---|---|---|---|---|---|
| bowl (or low hearth) | h (= dh | h (= dh | rW ) 100<br>rH (= 150 | h ( 1.5dh | h (= dh |
| shaft | | | rW ) 100<br>rH )= 100 | h ) 1.5dh | h ) 2xdh |
| domed | | | rW (= 100<br>rH (= 100 | dm ( 0.5xdh | |

h = height, dh = diameter at hearth, dm = diameter at mouth
rW = relative height index (h/dh)
rH = relative width index (dm/dh)

---

Martens criticises Coghlan's basic types as lacking in clarity, but is referring to his earlier 1956 edition, where he deliberately leaves the categories vague until there is a considerable body of evidence to refine them. By 1977, however,

while keeping the basic types, he largely accepts Cleere's typology, which is one based on the method used for dealing with the slag, i.e. an aspect of technical working. This is, in fact, not far removed from Martens' own stance (*1978, 29*), where the same basic types are adhered to, and extended to a system based on four groups of typological elements:

  i) proportion
 ii) shape
iii) building {material, free-standing, sunken, in
              a bank etc.}

 iv) technical working {slag tapping, location of slag
              outlet, supply of air - shape, number
              and positioning of tuyeres}

However, no simple ratios can be used as a sound basis for the classification of furnaces, as the assessment of height or the width at the mouth is for 90% of the cases impossible, partly because the structure is no longer available and also because in certain cases a full understanding of the furnace is a prerequisite for the measurement. Further complications are often introduced by structural changes resulting from working procedures, such as the distortion of the lower part of the furnace owing to temperature or slag attack, or as the result of post-depositional changes. One significant omission from her category i) is the height of tuyere to base of furnace, or tuyere to the top of the furnace, i.e. the effective working height of the furnace.

For example, one particular African type is a trench laid with ore and charcoal from which the tuyere is gradually withdrawn. Thus the application of the above ratios would be of little

significance. There are examples of in-furnace manipulation, which leads to the question of how furnaces would differ in classification from furnaces of similar dimensions but without the manipulation during the process. These are not the only problems with the scheme, as there are examples where the height of tuyere to mouth of furnace is varied in order to expand the slag storage capacity, as was possibly the case at Mucking, or even reduced to ensure a hotter hearth more able to retain a liquid slag for tapping. The Cow Park examples appear to have a hearth with a lip, the first slag solidifying on the base and providing a means of retaining temperature for the tapping of later slag. Cleere assigned these to his type l.ii and thus overlooked what was possibly a small technological innovation.

Martens runs into problems using her own scheme:

> Furnaces may have a shaft above a dome, in which case there is a clearly defined transition between the two features. The shaft is not included in the calculation of the indexes (1978, 32).

This would appear to be a basic error, because if the burden is charged down the shaft, then the residence in the shaft plays an important part in the process and therefore the structure must be regarded as a shaft furnace at least on thermodynamic grounds (See diagrams of Dysdalen and Horden Møsstrand furnaces – *Martens 1978)*. She goes on to provide an archaeological example of a furnace at Møsstrand of which the one remaining complete example is 30cm high x 32cm diameter at hearth and lies 5cm below ground level, with the walls slightly curving outwards. This furnace, which in most views would be classified as a bowl, is remarkably classified by Martens as a shaft furnace.

In vertical section walls of these furnaces curve slightly outward, and the mouths of all of them are slightly smaller than the hearths... I have classified these low furnaces as shaft furnaces because of the comparatively large diameter of the mouth and small hearth. This ratio is decisive for my classification (1978, 32).

Martens' scheme would be best used, not just as a means of classification, but as the basis of a recording technique applicable to all metallurgical sites. To such a scheme could be added further elements:

the condition and quantity of furnace remains

location of vitrification on tuyeres, furnaces, etc

presence of slag, its quality and form, i.e. whether from within the furnace or characteristic tapped slag

an assessment of the site type, such as farmstead, village, industrial, and of the volume of slag and number of furnaces.

It is particularly important to consider these additional elements together with analytical results to give empirical weighting to any one interpretation and a clearer idea of the industrial process, whether smithing, smelting, or some non-ferrous process. As Pleiner points out (*Martens 1978, 38*), the presence of ore and traces of iron sponge may be important indicators, and as discussed in chapter 1, there does appear to be a functional relationship between ore (type and texture) and furnace structure and also possibly between the ore and features such as tapping facilities.

Associated features, such as the remains within the furnace, have been related to operating conditions: 'a feature of both Iron Age and Roman bowl furnaces is that there is commonly a basal layer

of unconsumed charcoal several centimetres thick, the result of the blast failing to reach the basal levels of the charge; further, the lack of slag in this layer is an indicator that the slag had a high viscosity and therefore the operation in these cases was primitive' (*McDonnell 1983*). The use of the term primitive is too vague, as this observation could be related to both the height of the structure and the richness of the ¯ore. A rich ore would always result in a viscous slag owing to the limited concentration of gangue material. Such a layer of charcoal could also result from removing the bloom and slag from the furnace, leaving a layer of unconsumed charcoal and small pieces of slag, or relate to an inadequate preheat of the furnace, and thus using this feature as a guide to the efficiency or 'primitiveness' of the operating procedure cannot be considered reliable.

<u>Serning</u> detects several significant trends in the residual furnace evidence, the two most important phases of development being the raising of the hearth to ground level, thus making it accessible and easily maintained, and facilitating tapping; and the construction of the shaft. Serning has related this developmental sequence to iron production alone and overlooked the fact that developments such as tapping and shafts had long been established in the production of non-ferrous metals such as copper and silver. Serning's typology follows closely that of Martens (*1978*), but with modifications in that the bowl furnace has no specific form but is seen as a low shaft furnace. Raising the hearth to ground level is not a necessary development to

enable tapping. For example, the furnaces from Cow Park, mentioned above (*Tebbutt 1980*), are similar to many from the Iron Age and Romano-British periods, in that they are constructed in a pit below ground level and are slag-tapping furnaces. What is more important is the location of the tapping arch, which in these cases is some 20cm above the floor of the pit.

Table 4.3

Serning's Classification (from Serning 1979, 68)

FORM

I. Low shaft furnace; h ( 1.5 x dh; horizontal section circular to oval or rounded quadrilateral; walls almost vertical

II. Shaft furnace; h ) 1.5 x dh; other details as in I

III. Domed furnace; hemispherical to conical; horizontal section circular to oval or rounded quadrilateral; dm (= 0.5 x dh (according to Martens 1978)

POSITION

A. Sunken; hearth below ground surface
B. Constructed above ground surface; hearth at ground level

MATERIAL OF FURNACE WALLS

a. Clay
b. Stones with clay lining
c. Drystone walling
d. Surrounding earth (sunken furnace without wall lining)

SEPARATION OF THE SLAG

e. No provision for tapping slag
f. Slag collects in pit beneath superstructure
g. Slag tapped through side of furnace

AIR SUPPLY

1. Natural draught
2. With help of hand- or foot-powered bellows
3. With help of water-powered bellows

The example Serning has chosen to illustrate the low shaft (bowl) furnace, from Västergöterland (*1979, 72, fig.12*) is some 90cm in diameter at the hearth (not 30!) and could easily be interpreted as a reheating hearth, since burnt earth and charcoal were found inside the hearth with a small patch of clay and slag nearby.

In Sweden, even within one category of furnace, such as domed furnaces (*1979, 67-73*), there is considerable variation, with many different materials being used in their construction, including rectangular structures with stone slabs, clay lining, and earth structures. From the archaeological evidence certain conclusions can be drawn: domed furnaces commonly have a much greater diameter at the hearth than shaft furnaces, e.g. the Mechlin furnace (*Pleiner 1965, ill. 7,2*), and ground-level hearths were used in Sweden during the first century BC, together with the pit type of furnace, which appears to have concentrations in some districts, e.g. Ryd Parish near Skovde (*1979, 82*), where some 227 examples have been excavated.

The final typology to be considered in this thesis is centred on the Wealden iron industry and in particular the excavated furnaces from the sites of Broadfield, Holbeanwood, Pippingford Park and Minepitwood (*Gibson-Hill 1980, 21*). It does not consider the development of furnace technology in any general way, but is based on some 70 furnaces which are chronologically tied in with a series of C-14 dates ranging from c.100 BC to 300 AD.

Gibson-Hill distinguishes five types based on several 'possibly significant' variations which he observed within the groups of

cylindrical shaft furnaces (*see ibid. figs 1-6*). Each type is discussed in terms of structural advantages, reasons for technological differences and manpower required to work such furnaces. There is no obvious linear development and different types appear to be contemporaneous, e.g. types A and B were both in use during the early levels (1$^{st}$ century BC) at the site of Broadfield. This report and others concerning Broadfield (*Gibson-Hill 1975 and 1976*) provide illustrations, but these are stylised and thus removed from the original data. Unfortunately a full excavation report, with all the site data, has not been published and hence a complete assessment of the industry at this productive site is impossible.

However, having taken such a pessimistic view of furnace classification, it would seem unavoidable in the comparison of iron-smelting techniques from different sites and regions. What is required is a comprehensive method for recording the relevant data. The following is an outline of a recording scheme which could be used during the excavation and later interpretation of early smelting sites. This would not prevent classification of any furnace structure into a category such as bowl, shaft, etc, but it would enable reappraisal or use of the data at any future date (e.g. for construction of experimental furnaces). This has taken aspects from the above classification schemes and attempted to strengthen certain weaknesses. It does limit itself to remains associated with, or of value to interpretation of, ancient metallurgical processes and assumes that the site recording schemes practised by the archaeologist will give comprehensive

coverage of all the material from the site. For a more complete

characterisation of archaeometallurgical sites it is suggested

that Bachmann's 'Check List' (*Bachmann 1982, 6-7*) is referred to,

as it is a comprehensive recording scheme, although deficient

with respect to recording of furnace remains.

## Metallurgical furnace recording scheme

### General condition of remains

Furnace morphology:

>Internal and external diameter at hearth level, or if not cylindrical then internal and external dimensions associated with a plan of the remains.

>Height of the furnace walls above ground level, and height from the base of the hearth.

>Section of the furnace giving angles of walls to ground level; whether sloping in at the mouth of the furnace. A drawing of the section exposing internal and external design where possible.

>Height of tuyere or aperture for tuyere above ground level, above hearth level and where possible in relation to the rim of the furnace. Angle of tuyere to base.

>Tapping facilities, location, Size and dimensions of tapping arch, size and location of tapping pit.

>Vitrification: extent and location, description.

>Furnace lining and furnace body; colour and fabric, noting any gradation of colour; thickness of lining or walls. Quantity and location of above.

Associated remains:

>Slag; its quantity and macrostructure, e.g. ropey, plate, plano-convex cakes, small lumps, glassy, density, colour, glassy or crystalline. The structure or stratification in slag deposits. Overall quantity and the range in sizes of individual lumps, whether they include charcoal or other material. Location, e.g. whether found in the furnace, tapping pit or slag dump. Some of these observations will give additional information regarding the size and operating procedures of the furnace or may help distinguish between smithing

and smelting processes. Crucibles, moulds and other
metallurgical waste (quantity).

Relevant site information:

> Size and nature of the site, e.g. farmstead,
> industrial, town, etc. and the range of industries
> recognizable, such as ceramics, glass, agricultural,
> etc. For example, non-metallurgical evidence from the
> site will often assist in reconstructing the scale and
> nature of the iron industry. Smelting may be a seasonal
> activity, as exemplified on the Ufipa plateau, where
> professional smelters operate from May to November,
> with a master smelter directing operations. In many
> districts in W. Sudan, such as Kita, Bammako, and the
> Bakay river, only seasonal smelting was practised.
> Here, about once a year before the rainy season,
> smelting was carried out for the production and repair
> of agricultural implements. The type of furnace alone
> will not enable reconstruction of the seasonal nature
> of events, as reasonably sophisticated furnaces were
> employed (*Cline 1937, 35*).

## Furnace variation

The archaeological furnace remains from Britain and the Continent

display considerable variation, and also show that several broad

categories were in operation at any particular period. Many of

the Celts utilised a furnace with a slag pit, and from the

information available these varied significantly in most of their

characteristics (e.g. shaft 60cm-100cm, pit 30-50cm, diameter 35-

45cm at ground level with 5-10cm of lining (*Wertime and Muhly*

*1983, 398*)). In other areas, e.g. north of the Alps in the

central Celtic area, a 'more developed' type occurs : Bellaires I

(Switzerland), Engsbach and Oberdorf-Silberquelle (Siegerland),

at Tauchenweiler Württemberg, and examples from Bergenland (*ibid.*

*1983, 399*) have large furnaces without pits, built in the shape

of massive domed clay superstructures. Furnaces with slag pits

have been found at sites dating from La Tène to the Migration

periods. At the settlement of Drengsted C-14 dates suggest that

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slag-pit furnaces were in use for some 300 years, from 200 to 500 AD (*Voss 1973, 57*). During the Romano-British period similar variation can be observed, for instance, several types of furnace were in operation in the Nene Valley, including the shaft bloomery type (*Wild 1974*). In the Rockingham Forest (Northants.), recent roadworks (1985) uncovered numerous slag-tapping shaft furnaces (c.35cm internal diameter), alongside several massive smelting furnaces over 1m in diameter associated with dumps of roasted ore and charcoal and the remains of buildings (plates 25 and 26).

## Conclusions

A classification, as usually understood, allocates entities to initially undefined classes, so that individuals in a class are in some sense close to each other. This is in contrast to identification or assignment, where a new entity is placed in one of a series of pre-defined groups (*Doran and Hodson 1975, 159*).

A close examination of the classification schemes relating to early furnace technology revealed that, without exception, all of the existing schemes are merely modifications of the simplistic model of bowl, dome, shaft, and that this was never based on archaeological data, but on examples drawn from ethnographic data.

The desire to produce a unique labelled pigeon-hole into which an individual entity can be dropped (and then forgotten) is natural to the human brain, or else we have been told to do this so often that it is now a conditioned response (*Cormack 1971, 321*).

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Certainly this desire has been predominant in the field of ancient metallurgy and, for a large part, assignment or identification has been a satisfactory end-point for the archaeologist faced with ancient furnace or hearth structures.

The purpose of classification is two-fold – as a summary of data and as a means of generating fruitful hypotheses and is of little value unless it is used to generate hypotheses, i.e. there is an attempt to explain the significance of the categories. Assignment alone is a meaningless exercise, particularly when it distorts the original data. Very few hypotheses have been generated, although implicit in most schemes is the assumption that furnace morphology has cultural connotations and consequently that furnaces may be used to date sites and to trace culture history. However, furnace attributes are influenced by many variables:
time
function
culture
economy
environment
the individual

and the role of culture is difficult to assess. There is good evidence that the structure of the furnace or method of smelting can be correlated broadly with the texture and quality of the ore (*Brown 1983*). If furnace morphology is heavily influenced by functional considerations such as these (see also chapter 1), then it seems likely that a furnace type may be utilised at any period and cannot be called upon for cultural-historical or dating information.

Thus even in the 16[th] century primitive and more sophisticated methods were used
side by side in different forms of smelting furnace adapted to the peculiar
characteristics of local ores (Forbes 1950, 407).

The use of furnace ratios (*Martens 1978*) can be misleading, as
these will group furnaces which, while having similar
proportions, could greatly differ in mode of operation and often
in quality of product. For example, other factors being
constant, a tall shaft furnace is more likely to result in the
production of cast iron than a smaller one; i.e. while the ratios
remain the same, technical aspects of operation could markedly
differ. However, the main criticism of this approach must be the
paucity of the data. If only some 10-15% of ancient furnaces
remain sufficiently intact to enable the calculation of such
ratios, then its application is severely limited.

Many of the classifications have advocated weighting a particular
characteristic, e.g. slag tapping, as the basis of the
classification, because of its ability to distinguish groups in
a classification. This would appear to be a logical fallacy.
Since the purpose of employing characteristics is to establish a
classification, one cannot make assumptions as to what these
classes are and then use them to measure the diagnostic weight of
an attribute. It is also unclear what certain attributes are
associated with. For example, is slag tapping related to the the
quality of the ore, the required size of the bloom, or does it
have a cultural significance? Therefore, basing a classification
on such a characteristic can only serve to obscure further its
technical, economic or cultural significance.

From a brief survey of British and Continental furnaces several broad morphological categories emerge, and if we are to understand the significance of such categories, then classifications must be used to generate hypotheses which can be tested against the available data. For example:

> that design of furnace relates to the quality and texture of the ore (e.g. rich ores and bowl furnaces)
>
> that furnace morphology is influenced by the desired, product e.g. size, and quality of bloom (steely or ferritic)
>
> that slag tapping was introduced to increase the yield (size of bloom) or that it related to processing larger quantities of poorer ore
>
> slag pits are just another regional preference for a means of slag tapping
>
> that intermediate structures, between smelting furnaces and smithing hearths, were utilised in the course of bloom preparation

If such hypotheses are to be tested, then classification must be coupled with a comprehensive recording scheme which will enable furnace type to be seen in an overall perspective including environmental considerations such as raw materials (ores, clays, etc.), economic background (type of site, scale of production), etc, resulting in a broader assessment of the industry.

# CHAPTER 5

# ARCHAEOLOGICAL EVIDENCE

## Abstract

This section examines some recent archaeological evidence for metallurgical processes and re-evaluates earlier material. Microstructures and analyses of slags and metal objects are presented together with comparative experimental data.

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# ARCHAEOLOGICAL EVIDENCE

## Introduction

The interpretation of archaeological data changes as new ideas and data enter the discipline and force reassessment of sites excavated in past decades, particularly those from the last and early part of this century. The lake village at Meare is an example of this. Formerly interpreted as an Iron Age village, it is now clear that post-Iron Age events have had an effect on the deposits and, as a consequence, it is no longer considered as a village, but thought to represent the remains from a short-lived event such as a fair, as parts of the same pot are scattered throughout different levels of the site (*Orme and Coles 1981*). How short-lived is debatable, as there were significant residues from a number of industries, including iron, copper alloy and glass beads. Post-depositional events can as easily be used to explain a disturbed stratigraphy in a site occupied for a longer period, as to support the case for a short-lived event such as a fair. The smelting furnace at Great Casterton (*Tylecote 1962*) is now believed to be a roasting furnace, a reinterpretation only possible because the furnace was well described and illustrated.

The understanding of the early iron industry in Britain is also changing as a result of new insights from experimental work, changing perspectives, and new archaeological evidence, although the latter is still limited and slow in accumulating. In a recent survey of smelting furnaces, McDonnell (*1982*) points out that there only 8 reasonably definite smelting furnaces from Iron

Age England:

| | |
|---|---|
| Wakerley | Chelms Combe |
| Great Oakley | Kestor |
| West Brandon | Levisham More |
| Brooklands | Rowberrow Cavern |

However, some of these sites, such as Kestor and West Brandon, on close examination are of dubious date. Kestor, for example, is possibly medieval (*Salter pers. comm.*), and some of the structures, such as at Rowberrow Cavern, are difficult to interpret even though smelting certainly occurred in the vicinity. Broadfield could also be added to the list, as C-14 dates definitely suggest a pre-Roman beginning (*Gibson-Hill 1980, 21*). The list could be extended still further if smelting sites without definite furnace remains could be included. For instance, Gussage All Saints (Dorset) had a bowl furnace, but slag evidence suggests that a larger structure was also in use, and charcoal from slag dumps at Little Inwoods gave C-14 dates from 130 BC to 70 AD (*WIRG 1972, 3*).

As previously discussed, the two major problems encountered with archaeological material are dating and identification of the process. In many cases, e.g. Gretton and Wakerley, the furnace structures stand alone without associated dating material or any easily defined stratigraphy. The identification of the process is difficult, as slags and vitrified remains are the by-product of many pyrotechnological processes other than metallurgical ones. Even within the iron industry, they could relate to smelting, or to various stages of refining. Small pieces and cakes of slag are frequently found with datable associated remains on sites, but it is often difficult to relate them to a

specific process.

As discussed in earlier chapters, an overview of site data is essential to the interpretation of the metallurgical remains and, in conjunction with a cursory examination of the slags, might often allow a reconstruction without expensive, time-consuming analyses which are either difficult to interpret or contribute little towards understanding of the metallurgical processes. For instance, the material from the Iron Age hillfort of Danebury, a few small pieces of slag and vitrified material together with currency bars and iron objects, in the absence of furnace remains and tapped slag would suggest forging rather than smelting.

## Catalogue of sites examined

The sites in this catalogue are those with metallurgical remains which have been studied and analysed as part of this research.

### Garden Hill (Sussex) (*Money 1978, 1979 and 1980*)

Garden Hill is a small hillfort in Ashdown Forest with remains of all aspects of a small industry, including ore dumps, roasting hearths, smelting furnaces and associated slag dumps. which was in operation from the $1^{st}$ century BC to the $2^{nd}$ century AD. Production appears to have been a constant feature of the site, even after the destruction of the villa and bath house.

### Furnace and hearth structures

The problem of reconstructing furnaces is typified by the fragmentary nature of the remains of furnaces F2 and F3, both of which have been interpreted as shaft furnaces similar to those found at Holbeanwood (Ticehurst), but, as seen from plate 24,

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such parallels must be drawn with caution, as both furnaces had been levelled by later occupation with only the bases and the slag pits surviving. F3 (F067/434) has been reconstructed as having a 30-40cm diameter hearth and a slag-tapping bay level with the base of the furnace, whereas F2 (F433/431) is similar (30-50cm internal diameter), but with the tapping pit beginning level with the base and then sloping away. The final internal diameters can be misleading as to the original superstructure of the furnace because furnaces slump during the reduction process and the lower lining is attacked by slag and fuel ash. It is also evident from plate 24 that the furnace has been relined several times.

Feature J4/5 is another smelting furnace located near the above, but has an internal diameter of 70-80cm with a clay lining approximately 10cm thick. In contrast to F2 and F3 the floor of the furnace is below the level of the tapping bay, and has a massive agglomeration of slag still *in situ* and separated from the tapping bay by a wall, 10-15cm high. This feature, i.e. a tapping hole above the base of the furnace, can be explained in terms of efficiency: as it is a larger furnace it would be more difficult retaining a liquid slag in the base of the furnace. However, if the early slag forms the base of the furnace, then it will act as a heat reservoir and enable the slag that is following to retain its fluidity and thus be tapped more easily. A similar feature can be seen on one of the Cow Park furnaces situated near the site of Garden Hill. J4/5 has been dated archaeomagnetically to the mid 1[st] century BC and is most likely

related to the adjacent forging hearth of similar date. Forging hearth F346 in K5 has a date in the latter half of the 1ˢᵗ century BC, but not later than the end of the century, and was flattened by later occupation.

Feature 110/545(g) has residues of roasted ore and small pieces of slag and most likely represents a roasting hearth or pit. The small pieces of slag could either be intrusive from other parts of the site or represent accidental slagging of the ore (*Money 1980, 3*). Ore from another roasting hearth has been identified as iron pan (limonite) and it is suggested that this represents the main ore, if not the only one, used on this site (*ibid. 4*). However, some of the other samples of local iron-pan analysed do not contain a sufficient percentage of manganese to produce the high level of manganese found in the slags from the site (table 5.1). Therefore, it seems probable that more than one type of ore has been exploited and that ore mixing may have been practised.

The forging hearth (F346) in one area of the site (K5) gave an archaeomagnetic date in the latter half of the 1ˢᵗ century BC and not later than the end of the century. The structure was flattened by later occupation. In common with most of the metalworking on the site the waste material was dumped in the nearby rampart (Sample SL285, see table 5.1).

Iron production at Garden Hill has been discussed in the literature both with respect to the concept of production centres and satellites, i.e. small units controlled or connected in some

way with the centre, and also with respect to the spatial separation of two parts of the industry: smelting and smithing. It has been suggested that Garden Hill was a production centre and that the nearby sites of Pippingford and Cow Park were related to this centre, providing the raw blooms which were forged at Garden Hill. The fragmentary remains of the furnaces makes comparison difficult, although enough survives to suggest considerable differences between the furnaces of each site. The Pippingford furnace had an internal diameter of 60cm and had been dug into a pit, and at the front of the furnace was a channel sloping up towards ground level, which, while not suitable for tapping, could have been used to rake the slag or bloom from the furnace, thus at variance with the furnaces from Garden Hill. Similarly, Cow Park furnaces had their own idiosyncracies and the dating evidence from Cow Park and Pippingford is not good (*Tebbutt 1980, 55*).

Cleere (in: *Hanworth 1977*) in his discussion of the iron industry from the site of Brooklands, Weybridge, suggests that two areas of ironworking, an eastern and a western area, represent a division of smelting and smithing, and suggests that 'physical separation of these two processes is well attested, e.g. Pippingford Park, where the iron was taken to Garden Hill for forging because the smelting fumes were disagreeable, fire risk etc'. However, it is rather an unfortunate example to support such a hypothesis, as the settlement of Garden Hill has indisputable evidence of roasting, smelting and smithing, i.e. every aspect of iron production within the settlement and without

any apparent division of the processes. Pippingford and Cow Park have no real evidence of settlement, but again both have smelting refining, and smithing on site.

Over the past decade the concept of mother sites and satellites seems to be pervading the literature with 'empirical' backing. While the application of Central Place Theory and Locational Analysis is well established in archaeology (*Clarke 1973*), it requires contemporaneity based on accurate dating to have sound application. The proximity of one site to another provides little evidence (necessarily) as to the nature of their relationship. For instance, in some cases a production unit may have satellite units which are located nearer to another main production centre, which was either not contemporary or separated by a physical (e.g. river) or social boundary. Thus, while the concept is attractive, the interpretation of economic links between sites on the basis of their proximity alone must at best be regarded as unreliable, particularly in an area such as the Weald, where there has been continuous iron production from the Iron Age to the medieval period and beyond. Cleere is possibly on firmer ground with the example of Holbeanwood and Bardown, as these iron production sites were in operation for a longer period of time and were connected by a slag road (*Cleere 1976, 234*).

## Relationship of ore to slag

It can be seen from analyses of ores and slags (table 5.1) that many of the potential 'ores' (GE) found during the excavations at Garden Hill were far too rich in silica and alumina relative to

the iron content to be suitable for the process, except for the ore GE673 (table 5.1). The alumina content of the ore goes into the slag and it can be seen that the slags generally contain significantly less alumina. Ore mixing could have been practised on the site, but no samples of very rich ore, which might benefit from mixing, have been found (with the possible exception of GE673). Another possibility is the likely practice of ore beneficiation, that is, the removal of excess gangue minerals by winnowing or washing, thereby producing a richer ore. GE120, GE124, GE126, GE127, and GE 140 could possibly be the by-products of such a process, as could GE142, but the latter, being predominantly quartz, is a less likely candidate.

In the interest of comparison, included in the analyses are those from experimental smelts using a typical Wealden ore, a sideritic boxstone obtained from the Sharpthorne brickworks in West Hoathly. Experiments were carried out in two types of furnace: a small non-tapping shaft furnace (WH1 and WH2 smelts) and a slag-tapping shaft furnace (by Roger Adams and members of Wealden Iron Research Group in the Ashdown forest - *Adams 1979*). The slags from the WH smelts generally fit within the composition range of the Garden Hill slags, suggesting that a sideritic boxstone could have been a likely ore source.

The slags from areas K3 and K4 lacked homogeneity. Some had the typical blue-black silicate structure of bloomery slags, mixed with clay, whereas others were mixtures of furnace lining, slag and corroded pieces of iron. There were also many small lumps

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with a vitreous surface. Some of the samples analysed had bloomery slag structure of silicate (fayalite) and wustite ('FeO') in a glassy matrix. Overall, the heterogeneity and the small vitrified lumps suggest that the material is probably from a forge rather than a smelter.

Fells (*1983*) suggests that the fragments of boxstone GE126 and GE130 (i.e. the iron pan) are locally derived, coming from the Ashdown Beds sandstone. The roasted ironstone from feature I2 has the consistency and appearence of clay ironstones (e.g. from the Wadhurst clay). The assumed Ashdown Beds material (GE132,126,130) is all very lean and would have been difficult to smelt unless charged with a much richer ore, such as GE673 with 84.8% $Fe_2O_3$ as opposed to c.51% in the former samples (see table 5.1). Also, manganese, alumina and magnesium composition of the ore GE673 is more consistent with the composition of the slags.

Thus it would appear that the iron pan of the Ashdown sands is not the major source of ore unless the material sample is not representative. The iron pan had been used to level a section of the site before the ironmaking operations had ceased, making it an unlikely source of ore (*Fells 1983*).

## Slags from the site

SL124 Slag from rampart quarry, 'likely to have come from forging hearth in K5, but the smelting hearth J4/5 is also a likely origin' (*Fells 1983*). The slag is partially magretic ard fire magretite dendrites can be seen in the microstructure. The sample has a relatively high lime content and the glassy phase exhibits a eutectic formation with phases in the $SiO_2$-$Al_2O_3$-$K_2O$ ternary such as potash-feldspar. The fayalite has c. 4% MnO. The fine magretite dendrites are more consistent with a smithing than smelting process, therefore the forge at K5 is the probable origin.

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SL135 Also from the rampart quarry, as SL124 a heterogeneous slag with the products of corrosion in the structure (goethite), and deep grey corroded iron in the body of the slag. It seems probable that both of these slags, because of their lack of homogeneity and flow structure, together with detectable magnetism, would derive from the forge at K5 and not the smelting furnace.

SL285 Slag from the base of a forging hearth, comprised small pieces of slag, up to 8cm long. Some grey, crystalline and dense with charcoal inclusions together with light porous material.

SL346 The slag from the bottom of the smelting furnace (F2) lacks homogeneity and is mixed with mud and corrosion. A clean sample of the slag gave an analysis typical of a bloomery slag.

SL350 Large piece of slag from the slag heap beside furnaces F2 and F3, displaying the obvious layering and flow structure of a tapped slag. It is a dense grey silicate with some porosity and charcoal inclusions and is non-magnetic. Olivines are low in MnO (c. 0.5%), untypical of many of the Wealden ores and in fact low in comparison with other slag olivines except for FL80 (less than 0.2%). The structure had the typical olivine-wustite-glass structure; however, the glass was not of the usual anorthite composition, with calcium virtually absent, and was mainly iron-silica-alumina-potash (see analyses). Like many of the slags from the site, this sample was extensively weathered.

SL357 Slag from the base of furnace F3, heavily corroded and coated with mud. The surface of the slag was very soft and had been leached of many of its original constituents, but again is typical of bloomery slag from within the furnace.

SL361 Slag excavated from a slag pit is non-magnetic and has a flow structure typical of a tapped slag. The analysis done by ICP correlates well with another sample analysed by Fells using XRF and would have a flow temperature in the vicinity of $1000^{\circ}C-1200^{\circ}C$, well within the limits of the bloomery. The bulk of the slag was fayalite with a small quantity of glass. Corroded in parts with depletion of the glassy phase apparent.

SL477 Very corroded, like many of the slags from the site, and has large gas bubbles. Again grey and crystalline, typical of many bloomery slags and comes from the smelting furnace, J4/5. The structure has olivines and wustite and a high proportion of a glassy phase; the bulk analyses (table 5.1) indicate a high percentage of silica and alumina which could derive from the furnace lining. Such an analysis is unlikely to be representative of a bloomery smelt as it would be too viscous at the temperatures typical of the process.

SL495 Similar to SL477, this sample is extensively corroded, having a soft and porous surface. Using the element mapping facility of the electron microprobe the corroded areas can be observed (plate 15). It can be seen that potassium and calcium have been leached from the corroded surface, a fact which would distort the results of analysis if care were not taken during sampling. It would also distort the interpretation of the thermal regimes operating, in the furnace. The composition seen in the ICP is typical of the process but the phosphorus content is high, suggesting that

the iron produced in this smelt would be hardened by its phosphorus content.

SL503 Slag from a slag pit, appears to be a section of furnace bottom, grey dense structure with small gas holes and some included charcoal. No obvious corrosion of the slag on the surface, but the microstructure revealed corrosion. Both microprobe area analyses and XRF correspond closely. Slag flow temperature c.1000°C-1200°C.

SL806 Dense, fine grained crystalline slag, mainly fayalite.

GE120 These three geological samples all have the appearance of being roasted
GE124 ore, but all have unfavourable Fe : Si ratios and extraction of the Fe
GE126 would be impossible given the normal operating parameters of the bloomery furnace. They also have very high alumina contents which are not reflected in the slag analyses from the site. Most of the slags have alumina contents in the range of 1%-5%, whereas these have iron contents of 8.5%, 9.6% and 10.2% respectively.

GE127 Fine grained sandstone, with plant impressions, both unlikely as a source
GE130 of ore.

GE132 Low grade ore, ferruginous sandstone not a source of ore.

GE140 Iron content of the sample is too low relative to the silica content for it to be considered a roasted ore, but it may result from sorting and preparation of the ore.

GE142 Mainly quartz with a small goethite content. Could possibly be the by-product of ore beneficiation (?) (ore washing or winnowing), but the iron content is very low.

GE164 Ferruginous sandstone with very low iron content.

GE192 Ferruginous sandstone with large quartz grains (not analysed).

GE231 Burnt magnetic ore, but too low in iron to smelt.

FL72 Slag and vitrified furnace lining, as probe analyses show olivine crystalline phase but also numerous quartz inclusions, which is reflected in the ICP analysis of the sample (table 5.1).

FL80 This is the normal dark grey crystalline bloomery slag remaining in the furnace, the bulk of which is fayalite with some wustite and a small % of a glassy phase, i.e. a typical bloomery slag with a flowing temperature c. 1100°C. No MnO in the sample.

FL172 Very light and vitrified from the smelting furnace at J4. Magnetite in the crystalline phase but otherwise predominantly clay minerals. Analysis typical of vitrified furnace lining.

S87 The reddish material taken from the base of the furnace, mainly quartz with a small amount of iron oxide. Presumably representative of the material used to line the furnace.

## Table 5.1

### Analysis of ores and slags from Garden Hill

| Sample | SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| ~GE126 | 32.9 | 43.9 | 0.0 | 10.2 | 0.0 | 2.6 | na | 0.7 | 90.3 | boxstone |
| ~GE140 | 51.4 | 24.7 | 0.0 | 12.4 | 0.5 | 3.7 | na | 0.5 | 93.2 | |
| \GE163 | na | 7.8 | 0.1 | 1.4 | 0.0 | 0.1 | 0.2 | 0.0 | 9.8 | |
| \GE164 | na | 4.9 | 0.1 | 4.6 | 0.7 | 0.2 | 1.1 | 0.1 | 12.3 | |
| \GE214 | na | 46.7 | 0.1 | 5.0 | 0.7 | 0.2 | 0.6 | 1.4 | 55.1 | |
| \GE231 | na | 7.7 | 0.1 | 2.7 | 0.0 | 0.1 | 0.2 | 0.1 | 11.3 | |
| \GE233 | na | 14.4 | 0.1 | 4.3 | 0.1 | 0.0 | 0.1 | 0.1 | 19.6 | |
| ~GE673 (SL) | 7.4 | 66.1 | 0.0 | 4.4 | 0.5 | 0.5 | na | 0.4 | 79.3 | ore (Fe as Fe2O3) |
| ~SL135 | 27.4 | 51.6 | 0.0 | 5.4 | 0.4 | 1.6 | na | 0.9 | 87.3 | forging |
| \SL285 | na | 43.5 | 2.7 | 5.3 | 4.4 | 1.2 | 0.8 | 0.7 | 59.1 | forging hearth K5 |
| ~SL361 | 22.3 | 59.8 | 3.5 | 4.5 | 1.1 | 1.0 | na | 0.5 | 92.7 | slag pit near F2/F3 |
| ~SL385 | 45.5 | 26.9 | 0.0 | 8.1 | 0.4 | 2.9 | na | 0.9 | 84.7 | |
| ~SL503 | 20.8 | 59.2 | 0.2 | 4.3 | 1.5 | 0.9 | na | 0.5 | 87.4 | |
| ~SL631 | 25.6 | 53.9 | 0.2 | 8.7 | 1.8 | 2.3 | na | 0.9 | 93.4 | furnace slag |
| ~SL653 | 26.9 | 56.4 | 0.5 | 3.5 | 1.0 | 1.0 | na | 0.6 | 89.9 | furnace slag |
| ~SL664 | 22.0 | 55.5 | 0.6 | 4.9 | 3.1 | 1.2 | na | 0.7 | 88.0 | |
| ~SL725 | 20.6 | 60.7 | 0.1 | 3.7 | 0.5 | 0.8 | na | 0.5 | 86.9 | |
| ~SL726 | 22.6 | 57.4 | 0.9 | 4.4 | 2.2 | 1.0 | na | 0.6 | 89.1 | |
| ~SL736 | 24.9 | 56.5 | 1.2 | 5.0 | 3.4 | 1.3 | na | 0.6 | 92.9 | |
| \SL806 | na | 44.2 | 3.9 | 4.0 | 3.4 | 1.1 | 0.8 | 0.6 | 58.5 | |
| \FL172 | na | 13.3 | 0.8 | 5.3 | 0.1 | 0.3 | 1.0 | 0.1 | 21.8 | |

| Sample | SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | TiO2 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| :SL361 | 25.3 | 64.2 | 4.3 | 3.5 | 1.5 | 0.7 | 0.7 | 0.0 | 0.0 | na | 0.5 | 100.7 |
| :SL361 | 25.4 | 61.1 | 5.0 | 4.5 | 1.5 | 0.7 | 0.9 | 0.0 | 0.0 | na | 0.6 | 99.7 |
| :FL72 | 21.5 | 71.5 | 0.6 | 1.8 | 0.3 | 0.0 | 0.3 | 0.0 | 0.0 | na | 0.5 | 95.3 |
| :SL495 | 23.7 | 66.5 | 2.8 | 6.3 | 0.6 | 0.5 | 1.3 | 0.0 | 0.1 | na | 0.6 | 102.4 |
| :FL80 | 29.4 | 70.2 | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | na | 0.4 | 100.1 |
| :FL80 | 45.4 | 20.0 | 7.0 | 20.4 | 0.0 | 0.0 | 4.2 | 1.1 | 0.4 | na | 2.1 | 100.6 |
| :FL80 | 31.4 | 63.4 | 0.9 | 3.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | na | 0.6 | 99.7 |
| :SL477 | 63.3 | 16.9 | 2.4 | 8.8 | 0.5 | 0.6 | 4.9 | 1.2 | 0.0 | na | 0.4 | 99.0 |
| :FL80 | 28.9 | 69.2 | 0.1 | 0.3 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | na | 0.4 | 99.0 |
| :WH1 | 28.9 | 61.6 | 1.3 | 0.5 | 3.9 | 2.5 | 0.2 | 0.0 | na | na | 0.0 | 98.9 |
| :WH1 | 29.3 | 61.0 | 0.9 | 0.0 | 4.0 | 3.2 | 0.0 | 0.0 | na | na | 0.0 | 98.4 |
| :WH2 | 29.7 | 62.5 | 0.9 | 0.0 | 3.6 | 3.5 | 0.0 | 0.0 | 0.0 | na | na | 100.2 |
| :WH2 | 29.4 | 64.4 | 1.1 | 0.0 | 3.5 | 2.7 | 0.0 | 0.0 | 0.0 | na | 0.0 | 101.1 |

\ Hydrofluoric/perchloric dissolution and ICP analysis (silica not analysed)
* XRF (wave dispersive), sodium borate flux. Fe as Fe2O3
~ XRF (Edax), with sodium borate fusion discs
: Area analyses by EPMA-Links energy dispersive analyser

Table 5.1 (cont.)

Microprobe analyses of some typical slag phases in Garden Hill and WH experimental slags

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|

SL124

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 29.9 | 60.4 | 4.1 | 0.0 | 3.8 | 1.8 | 0.1 | 0.0 | 0.0 | na | 0.3 | 100.4 | |
| 0.5 | 96.4 | 0.0 | 0.5 | 0.8 | 0.3 | 0.0 | 0.0 | 0.0 | na | 1.1 | 99.6 | |
| 30.3 | 53.3 | 13.4 | 0.4 | 2.0 | 0.3 | 0.0 | 0.0 | 0.0 | na | 0.5 | 100.2 | matrix |
| 41.0 | 13.8 | 1.4 | 19.6 | 0.3 | 0.0 | 13.5 | 0.6 | 0.2 | na | 0.6 | 91.0 | |
| 26.6 | 47.5 | 0.8 | 10.3 | 0.8 | 0.0 | 8.3 | 0.0 | 0.0 | na | 1.1 | 95.4 | |

Following phases part of glassy eutectic

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 31.2 | 48.4 | 17.9 | 0.0 | 2.4 | 0.7 | 0.2 | 0.0 | 0.0 | na | 0.4 | 101.2 | |
| 55.4 | 1.8 | 0.0 | 24.3 | 0.0 | 0.0 | 19.8 | 0.6 | 0.1 | + | 0.3 | 101.5 | |

SL361

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 29.5 | 64.5 | 3.6 | 0.0 | 1.8 | 0.6 | 0.0 | 0.0 | 0.0 | na | 0.4 | 100.4 | olivine |
| 35.2 | 28.9 | 16.4 | 14.4 | 0.6 | 0.0 | 2.9 | 0.0 | 0.0 | + | 0.5 | 98.9 | glass |
| 35.3 | 26.3 | 16.1 | 16.2 | 0.6 | 0.0 | 3.4 | 0.0 | 0.5 | + | 0.7 | 99.1 | glass |

SL495

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 35.4 | 27.8 | 11.2 | 20.2 | 0.4 | 0.0 | 5.5 | 0.0 | 0.5 | na | 0.3 | 101.3 | glass |
| 36.6 | 22.4 | 0.5 | 34.2 | 0.0 | 0.3 | 0.2 | 0.0 | 1.7 | na | 0.2 | 95.1 | corroded area |
| 23.7 | 66.5 | 2.8 | 6.3 | 0.6 | 0.5 | 1.3 | 0.0 | 0.1 | na | 0.6 | 102.4 | uncorroded area |

SL503

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 29.8 | 65.6 | 0.3 | 0.3 | 3.4 | 1.6 | 0.0 | 0.0 | 0.0 | na | 0.3 | 101.3 | olivine |

FL172

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 77.6 | 4.1 | 2.2 | 7.4 | 0.3 | 0.0 | 4.5 | 0.0 | 0.0 | na | 0.7 | 96.8 | |
| 55.1 | 23.2 | 3.2 | 11.9 | 1.0 | 1.1 | 3.2 | 0.0 | 0.0 | na | 0.4 | 99.1 | bulk of matrix |
| 0.8 | 93.1 | 0.2 | 0.6 | 1.3 | 0.0 | 0.0 | 0.0 | 0.0 | na | 0.6 | 99.9 | (V₂O₅ 3.3) |

FL80

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 29.4 | 70.2 | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | na | 0.4 | 100.3 | fayalite |
| 41.9 | 26.4 | 6.2 | 19.8 | 0.0 | 0.0 | 3.5 | 0.0 | 0.3 | na | 2.7 | 100.8 | glass |
| 54.1 | 29.0 | 2.3 | 13.3 | 0.0 | 0.0 | 2.1 | 1.0 | 0.1 | na | 1.6 | 103.5 | glass |

SL477

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 47.4 | 39.2 | 3.1 | 6.9 | 1.4 | 0.0 | 4.5 | 0.0 | 0.0 | na | 1.7 | 104.2 | |
| 55.5 | 13.2 | 8.4 | 14.1 | 0.4 | 0.0 | 5.0 | 1.1 | 0.2 | na | 0.8 | 98.7 | |
| 31.8 | 57.0 | 0.6 | 0.6 | 2.2 | 1.2 | 0.2 | 0.0 | 0.0 | na | 0.3 | 93.9 | euhedral olivine |
| 55.8 | 11.2 | 5.7 | 15.8 | 0.5 | 0.0 | 6.7 | 0.9 | 0.0 | na | 0.9 | 97.5 | glass |
| 1.4 | 85.7 | 0.0 | 3.9 | 0.5 | 0.0 | 0.1 | 0.0 | 0.0 | na | 2.4 | 94.0 | wustite |

# Table 5.1 (cont.)

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | TiO2 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SL350** | | | | | | | | | | | | |
| 29.6 | 69.2 | 0.8 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | na | 0.5 | 100.8 | olivine |
| 33.6 | 23.9 | 0.2 | 34.1 | 0.0 | 0.0 | 9.7 | 0.8 | 0.2 | na | 0.9 | 103.4 | glass |
| 0.7 | 95.7 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | na | 1.3 | 98.7 | wustite |
| **SL346** | | | | | | | | | | | | |
| 29.4 | 65.1 | 0.7 | 0.0 | 2.9 | 1.6 | 0.0 | 0.0 | 0.0 | na | 0.4 | 98.1 | olivine |
| 36.9 | 20.7 | 10.9 | 19.6 | 0.6 | 0.0 | 8.6 | 1.1 | 0.5 | na | 0.6 | 99.5 | glass |
| 0.8 | 96.2 | 0.0 | 0.4 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | na | 1.1 | 99.3 | wustite |
| **SL135** | | | | | | | | | | | | |
| 29.3 | 67.5 | 0.3 | 0.3 | 1.5 | 1.1 | 0.0 | 0.0 | 0.0 | na | 0.4 | 100.4 | olivine |
| 36.9 | 23.4 | 9.1 | 21.5 | 0.4 | 0.0 | 6.3 | 0.9 | 0.4 | na | 0.4 | 99.3 | glass |
| 1.0 | 98.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | na | 0.4 | 99.7 | swirl (Fe2O3) |

West Hoathly experimental slag

**WH1**

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | TiO2 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28.9 | 61.6 | 1.3 | 0.5 | 3.9 | 2.5 | 0.2 | 0.0 | na | na | 0.0 | 98.9 | olivine |
| 38.1 | 19.1 | 15.0 | 17.0 | 1.0 | 0.0 | 3.7 | 0.0 | na | na | 1.9 | 95.8 | glass |

**WH2**

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | Na2O | SO | P2O5 | TiO2 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42.5 | 23.0 | 10.9 | 16.1 | 0.9 | 0.0 | 4.6 | 0.0 | 0.3 | + | 1.9 | 100.2 | matrix |
| 29.7 | 62.5 | 0.9 | 0.0 | 3.6 | 3.5 | 0.0 | 0.0 | 0.0 | na | 0.0 | 100.2 | olivine |
| 29.4 | 38.8 | 11.6 | 13.2 | 1.1 | 0.0 | 1.2 | 0.0 | 0.0 | na | 4.1 | 99.4 | glass |

| SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|
| 22.7 | 51.1 | 1.8 | 6.1 | 3.4 | 1.5 | na | 0.8 | 87.4 | core of sideritic boxstone[1] |
| 28.7 | 49.8 | 0.0 | 6.0 | 1.8 | 1.6 | na | 0.7 | 88.6 | box around ore[2] |
| na | 40.1 | 4.4 | 6.4 | 2.1 | 1.2 | 1.5 | 0.7 | 57.1 | furnace slag |
| 28.4 | 48.0 | 2.4 | 7.1 | 2.1 | 2.1 | na | 0.9 | 91.0 | furnace slag |
| na | 39.8 | 5.7 | 6.2 | 2.2 | 1.3 | 1.9 | 0.8 | 58.7 | |
| 30.0 | 44.9 | 3.7 | 5.8 | 2.2 | 1.9 | na | 0.9 | 89.4 | slag at base of f-b |

[1] Roasting decomposed the carbonate (siderite) and removed some moisture. After 1hr at 600°C it lost 12% in weight.

[2] The limonitic box around the ore lost 12% in weight on roasting.

<u>Odell</u>, (Northants.) (*Dix 1980*)

Odell is a multi-period site with settlement evidence from the late Iron Age to the Saxon periods. Evidence for iron production is small and includes pieces of furnace fabric in addition to c. 6.5kg of slag and many small iron implements. A smaller quantity was found in the mid to late 1ˢᵗ-century AD features, but may represent the waste from the same industry (*B. Dix pers. comm.*). A dump of roasted ore in a Saxon well indicates renewed iron smelting at that period and, as in the earlier period, slag was concentrated in a few features, and weighed a total of 7.5kg. The decline of the iron industry seen in the successive Roman farms could reflect economic changes during Roman occupation. Associated with the slag was some copper alloy waste.

A likely source of ore for the industry is outcropping nodular iron ore in the not too distant boulder clay, and fieldwork in that area has indicated a number of ironworking sites which are undated. The alumina content of the ore is consistent with an ore of this origin (table 5.2).

The small quantity of furnace fabric has a grey to red zoning indicative of a reducing atmosphere and provides the only evidence for a smelting furnace. However, the presence of tapped slag, though a small amount, and the roasted ore confirms that smelting operations were carried out at the site. The existence of smithing slag (K11 and K73) and iron from the site suggests that all aspects of iron production were represented.

Tapped slag came from the early levels (K34) (dated to the 1ˢᵗ

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centuries BC/AD), as well as from the Saxon levels (K66) and surface finds (K67 and K72). Analyses of the ore and slag samples from the site show that the ore (K41) would have been suitable for smelting, having a low percentage of silica relative to its iron content (table 5.2). The ore used during the Saxon period is poorer, i.e. its higher silica content would result in a less efficient process. While the iron content of an ore can usually be improved by beneficiation, it was assumed that as the analysis was carried out on roasted ore, prepared for charging into the furnace, the ore was representative and suggests that the higher-quality deposits had been exploited in the earlier period.

The Saxon ore also has a higher proportion of alumina (c.6%; cf 2% in the Iron Age sample), but this is unlikely to increase the viscosity of the slag. However, it promotes the formation of fayalite, which would reduce the efficiency of the smelt (*Baldwin 1954*). The ore analyses (table 5.2) correspond well with those of the slag and were undoubtedly representative of the ore being used during those periods. The slags were grey and crystalline, composed of the mineral phases wustite and fayalite, which are characteristic of bloomery slags. Their composition varies considerably, which is an indication not only of changing ore composition, but also variations in the furnace conditions. The lime content of the Odell ore is low (0.1-0.4%), whereas in the slags it is relatively high and variable, ranging from 0.3% to 7.1% in the experimental slags. The slags from the site have an average 2% lime, which originates from the fuel ash together with the potash. The latter is leached out of the slags during

weathering (see chapter 2 - corrosion of slags). Overall, the experimental slags are comparable in composition to those from the site (given the differences in ore composition), the major discrepancy being the level of lime (c.7%) in the experimental slags (0.1), deriving from the high lime content of the charcoal ash (table 2.14). This displaced a similar amount of iron in the slag.

One anomaly detected in the analysis of iron and slag inclusions (site and experimental) involved the phosphorus content. This was high in both the inclusions and the metal from the site, but low in the experimental products, and in fact was not detected in the experimental iron (0.1) (table 5.2). The level of phosphorus in the experimental slags and iron is not inconsistent with that in the Saxon ore used for the smelts. However, this is not the case with the ore (K41) and Iron Age slags and it must be assumed that ore with higher phosphorus levels was also in use, as fuel ash is unlikely to contribute a significant amount of phosphorus to the smelt.

Several objects of iron were sampled and studied using standard metallographic techniques. The same samples were also analysed using EPMA X-ray analysis for quantitative analyses of both the metal and the slag inclusions in the metal (table 5.2). Metallographic sections revealed a microstructure typical of bloomery iron, with slag inclusions (stringers) following the direction in which the metal had been forged (plates 17 and 18). Etching revealed heterogeneity in grain size and carbon content typical of bloomery. The metal ranged from pure ferrite to a

pearlitic structure with approximately 0.3-0.4% carbide.

In two samples (Fi 30 and Fiii 62) the grain size was small and uniform, corresponding to an equally homogeneous carbon content c.0.2%. It is possible that these objects had been intentionally carburised, as such an even structure is atypical for bloomery iron direct from the furnace. However, overall there was little evidence for sophisticated smithing techniques such as quench hardening or carburisation. The smith generally relied on the heterogeneous nature of bloomery iron, with varying grain size and carbon content, to provide iron sufficiently hard for most purposes. Hence such sophistication as carburisation and quenching were hardly necessary. In addition to the mixed carbon levels there were significant levels of phosphorus, between 0.5 and 1.0% (table 5.2), well above a desirable level by modern standards, but the metal was still extensively forged without problem (plate 17).

The overall impression from the site is that of a small iron smelting/smithing operation, probably seasonal, producing sufficient iron to meet the needs of the farming settlement. The iron is of low quality, but the mixed carbon content and the high phosphorus contents would provide an iron tough enough for most agricultural and domestic uses. Slag from the Saxon levels indicates the use of a larger furnace, but involving a similar process.

## Table 5.2

### Analyses of ores and slags from Odell

| Sample | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| * (F73) | 50.4 | 39.8 | 1.7 | 4.9 | 0.0 | 0.5 | 1.7 | 0.4 | 99.4 | top of furnace bottom |
| * (F73) | 28.7 | 66.6 | 1.5 | 2.2 | 0.0 | 0.5 | 1.0 | 0.4 | 100.9 | base of furnace bottom |
| ~ (K22) | 28.0 | 52.1 | 2.8 | 3.6 | 0.0 | 1.3 | na | 0.9 | 88.7 | |
| ~ (K23) | 21.4 | 59.2 | 2.4 | 3.5 | 0.0 | 0.9 | na | 0.8 | 88.2 | bulk olivine, some glass |
| ~ (K27) | 12.5 | 59.8 | 1.7 | 3.6 | 0.0 | 1.4 | na | 1.6 | 80.6 | |
| ~ (K28) | 18.1 | 64.2 | 1.4 | 2.6 | 0.0 | 0.5 | na | 0.4 | 87.2 | olivine, wustite, |
| ~ (K35) | 13.3 | 64.4 | 1.7 | 2.9 | 0.0 | 0.5 | na | 0.6 | 83.4 | |
| ~ (K36) | 20.4 | 59.4 | 2.2 | 3.4 | 0.0 | 0.8 | na | 0.6 | 86.8 | |
| ~ (K37) | 85.0 | 8.1 | 0.0 | 0.7 | 0.9 | 2.3 | na | 0.5 | 97.5 | magnetic |
| ~ (K40) | 28.1 | 54.0 | 2.1 | 0.9 | 0.0 | 1.0 | na | 1.3 | 87.4 | bulk olivine |
| ~ (K41) | 7.7 | 66.8 | 0.4 | 2.3 | 0.0 | 0.1 | na | 0.3 | 88.6 | ore |
| ~ (K42) | 18.8 | 61.6 | 2.3 | 2.5 | 0.0 | 0.5 | na | 0.6 | 86.3 | |
| ~ (K47) | 24.5 | 53.4 | 1.4 | 4.1 | 0.0 | 0.9 | na | 0.5 | 84.8 | |
| ~ (K54) | 19.5 | 55.4 | 4.6 | 3.0 | 0.0 | 0.8 | na | 0.8 | 84.1 | smithing |
| ~ (K63) | 13.4 | 63.4 | 0.7 | 6.1 | 0.0 | 1.1 | na | 0.6 | 85.3 | Saxon |
| * (F62) | 45.9 | 43.9 | 2.6 | 3.8 | 0.0 | 0.6 | 2.0 | 0.5 | 99.3 | |
| ~ (K64) | 15.1 | 56.8 | 0.3 | 4.2 | 0.0 | 0.8 | na | 0.7 | 77.9 | Saxon |

### Odell (archaeological and experimental slags and ores)

| Sample | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| ~ | 11.5 | 69.0 | 0.1 | 6.6 | 0.0 | 1.0 | 0.2 | 0.5 | 88.9 | Saxon ore |
| ~ 0.1 | 27.4 | 43.6 | 7.1 | 7.5 | 0.0 | 2.4 | 1.8 | 1.0 | 90.8 | top of furnace base |
| ~ 0.1 | 22.2 | 52.9 | 6.3 | 7.0 | 0.0 | 1.9 | 0.9 | 1.0 | 92.2 | flow within furnace |

~  Analysis by XRF-Edax using sodium tetraborate discs
   (In ore analyses the iron presented as Fe₂O₃
   Water and carbon not analysed for.

*  Analysis by XRF wave dispersive using borate discs

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Table 5.2 (cont.)

Iron and inclusions from Odell

| | SiO₂ | FeO | Al₂O₃ | CaO | MnO | MgO | SO | P₂O₅ | Total |
|---|---|---|---|---|---|---|---|---|---|
| Fiii 62 slag inclusions | | | | | | | | | |
| | 17.4 | 66.4 | 1.1 | 1.9 | 3.0 | 1.1 | 1.1 | 9.0 | 101.0 |
| | 19.4 | 62.5 | 1.4 | 2.4 | 3.2 | 1.1 | 1.4 | 10.5 | 101.9 |
| Fii 69 inclusions | | | | | | | | | |
| | 6.0 | 86.5 | 0.3 | n.d | 0.4 | n.d | 0.5 | 7.1 | 100.8 |
| | 10.2 | 78.9 | 0.7 | n.d | 1.0 | n.d | 1.1 | 9.5 | 101.4 |
| 0.1 (inclusions) | | | | | | | | | |
| | 48.5 | 19.7 | 13.1 | 17.5 | 0.8 | 1.8 | n.d | 1.0 | 102.4 |
| | 29.9 | 27.3 | 10.3 | 26.6 | 0.8 | 1.8 | 0.4 | 2.2 | 99.3 |

Table showing SiO₂ for iron analyses:

| | SiO₂ | | | | | | SO | |
|---|---|---|---|---|---|---|---|---|
| Fiii 62 iron | | | | | | | | |
| | 100.1(Fe) | | | | | | 0.5 | |
| Fii 69 iron | | | | | | | | |
| | 99.8 | | | | | | 1.0 | |
| | 100.4 | | | | | | 1.2 | |
| 0.1 | | | | | | | | |
| | 100.2 | | | | | | n.d | |
| | 100.6 | | | | | | n.d | |
| | 100.2 | | | | | | n.d | |
| | 100.6 | | | | | | n.d | |

(More analyses of Odell site and experimental slags can be seen in tables 2.11 and 2.13)

## Cow Down, Longbridge Deverill (Wiltshire)

Cow Down, like Brooklands (below), provides early direct evidence for the iron industry in Britain. Several typical slag cakes (plano-convex) were found in pits on the site of this small Iron Age settlement. The farm occupation spanned several hundred years and has provided a series of C-14 dates of which the later ones can be related to the slag finds and date (indirectly) the material to the 6[th]-5[th] century BC. The only ore on site, several pieces of heavily weathered pyrites, was found in one of the pits. While this could be used as a source of ore, it is a common

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find from settlements on the chalk and therefore is not necessarily indicative of smelting. In fact, the quantity and nature of the slag and the lack of associated furnace structures argue against smelting on site. Slag cakes of this size, c. 0.5kg (plates 19 and 20), are found in settlements dating from the Iron Age to the Saxon period (e.g. Cow Down, Towcester, Walton, Wanborough, etc.) and for a variety of reasons must be considered to be the product of a smithing hearth. The lack of any furnace associations, tapped slag or ore dump, and the small quantity of slag, are consistent with this conclusion (*Clough 1985*).

The cakes were heavily corroded with a considerable amount of goethite both on the surface and in the structure. The slag was dark grey and crystalline with moderate porosity (plate 20c).

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Table 5.3

Analysis of slag from Cow Down

| $SiO_2$ | $Fe_2O_3$ | CaO | $Al_2O_3$ | MnO | MgO | $K_2O$ | $P_2O_5$ | Total | |
|---------|-----------|-----|-----------|-----|-----|--------|----------|-------|---|
| \50.6 | 1.8 | 0.8 | 0.1 | 0.5 | 0.4 | 0.4 | | 54.7 | |
| * 9.9 | 84.6 | 2.2 | 0.1 | 0.1 | 0.7 | 0.5 | 0.4 | 98.1 | small cake |
| *16.3 | 79.6 | 3.8 | 1.2 | 0.2 | 1.1 | 0.9 | 0.7 | 103.1 | large plano-convex cake |

| $SiO_2$ | FeO | CaO | $Al_2O_3$ | MnO | MgO | $K_2O$ | $Na_2O$ | SO | $P_2O_5$ | |
|---------|-----|-----|-----------|-----|-----|--------|---------|----|----------|---|
| 30.6 | 49.7 | 17.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | na | glass |
| 42.2 | 21.7 | 5.4 | 9.7 | 0.0 | 0.0 | 13.0 | 1.6 | 0.0 | na | glass |
| 24.9 | 59.8 | 6.6 | 2.8 | 0.0 | 0.5 | 2.8 | 0.6 | 0.0 | na | area |
| 40.4 | 25.3 | 7.0 | 10.6 | 0.0 | 0.0 | 12.0 | 1.3 | 0.4 | na | K-rich |
| 28.9 | 61.1 | 6.8 | 0.0 | 0.0 | 1.6 | 0.0 | 0.0 | 0.0 | na | olivine |
| 36.4 | 35.4 | 11.4 | 5.8 | 0.0 | 0.0 | 6.6 | 0.8 | 0.2 | 1.2 | glassy matrix |
| 18.9 | 69.8 | 4.2 | 2.0 | 0.0 | 0.8 | 1.8 | 0.0 | 0.0 | 0.5 | raster (200m) |
| 29.6 | 62.1 | 3.9 | 0.0 | 0.0 | 2.4 | 0.0 | 0.0 | 0.0 | 0.0 | olivine |

* XRF (wave dispersive), sodium borate flux. Fe as $Fe_2O_3$
  Other analyses by EPMA-Links energy dispersive analyser

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Gussage All Saints (Dorset)

(*Wainwright 1979; Wainwright et al. 1973 and 1976; King 1984*).
Complete excavation of the site revealed a 3 acre settlement with
features suggesting buildings and internal enclosures. Dating
evidence confirmed occupation throughout the second half of the
1[st] millennium BC and, like Little Woodbury, Gussage would appear
to have been a typical Iron Age farm settlement unit based on
stockbreeding and grain cultivation, with structures suggesting a
native settlement (*Wainwright 1979*).

Apart from primary agriculture, the site has a significant
metallurgical industry with evidence for some of the most
extensive remains of a bronze foundry in Britain. The bronze
industry is unrivalled in proto-historic Europe (*Wainwright 1979,
126; Spratling et al. 1980*). A discarded link from a bridle bit
was manufactured from forged steel which was then plated with
bronze (*Wainwright 1979, 129*), demonstrating skilled techniques
and an association of copper and iron metallurgy.

Apart from over 600 crucible fragments and thousands of fragments
from clay investment moulds, pit 209 also contained quantities of
ash, charcoal, vitrified clay (possibly furnace lining) and many
parts of tuyeres together with hammer scale and iron slag (*ibid.
127*). It also contained over 1600 objects or fragments of iron
objects, including parts of four files, one complete punch,
several short-tanged tools and some punch-like small tools (*V.
Fells pers. comm.*). Associated with this evidence is the remains
of a simple iron-smelting bowl furnace (feature 2) (*Wainwright*

*and Spratling 1973*) which was dated by a fragment of early samian

ware  sealed beneath the furnace,  and is thought to date to  the

1st century AD,  while calibrated C-14 dates from pit 209 suggest

earlier dates for the bronze debris: 165 BC- 80 AD, and 355-20 BC

(Q1206 and Q1207) (*Wainwright 1979, 125*).  However,  the

association of hammer scale,  small iron implements (chisels  and

files)  and  the  bronze-coated  steel with the  residue  of  the

earlier  bronze  industry  is suggestive  of  an  iron  industry

concurrent with the bronze foundry.  This is consistent with iron

objects, particularly those associated with metalworking (punches

and files),  which are found from the earliest levels of the site

(4th century BC).

Examination  of the of the slag and ore from the site of  Gussage

highlighted an aspect of the industry which is inadequately dealt

with in the initial report:  the quantity of iron slag from  the

site  (an  estimated  700kg) makes it one of  the  earliest  iron

production  units  on this scale found in Britain to  date  (this

could  represent  the  production of some 200kg  of  iron,  which

represents a considerable number of implements).  The size of the

slag chunks (broken from larger pieces),  weighing over  4kg,  is

inconsistent  with  the  'small bowl furnace' reported  from  the

site.  Also  the  structure of the slag,  while not  having  the

characteristic rivulets of tapped slag, did display a platey flow

structure suggesting that it had been tapped or raked out of  the

furnace. Also, the chalk particles adhering to the surface of the

slag would have come from a tapping pit.  Thus,  it seems likely

that  the  small  bowl  furnace relates to forging  and  not  the

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primary production of iron; certainly the small plano-convex cake of slag (plate 20d) derives from a smithing hearth. Numerous ferruginous nodules were found on the site, but those analysed are too low in iron and possibly represent waste (table 5.4 sample 172). Sample f2c is representative of the large platey tapped slag from the site and has a composition typical of bloomery slag. The mineralogy is also characteristic, being mainly fayalitic with a small amount of glass and wustite.

Slag is found from the earliest levels of the site, together with punches and other iron implements possibly related to bronze working. Therefore it is possible that the early iron work at the site was manufactured *in situ* and not an import (*King 1984*).

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Table 5.4

Slags and ores from Gussage All Saints

| Sample | SiO2 | FeO | CaO | Al2O3 | MnO | MgO | K2O | P2O5 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| *f2c | 26.3 | 64.2 | 2.8 | 4.2 | 0.0 | 0.6 | 0.9 | 0.5 | 99.5 | fayalitic slag |
| *172 | 46.1 | 28.3 | 0.4 | 2.1 | 0.0 | 0.3 | 0.4 | 0.2 | 78.0 | ore? |
| *F205 | 14.9 | 79.8 | 2.4 | 1.0 | 0.1 | 0.6 | 1.1 | 0.4 | 100.3 | slag |
| *F442 | 56.6 | 25.8 | 4.0 | 5.4 | 0.1 | 0.7 | 2.7 | 0.6 | 95.9 | ore? |

* XRF - (wave dispersive) of slags and ores (sodium borate fusions) Fe as Fe2O3

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Abbey Homestead, Towcester (Northants.)

Four small cakes of slag were found in the fill of a ditch (F100) (plate 20e). They are plano-convex in shape, 15-20cm in diameter and approximately 10cm deep, weighing approximately 0.6kg. Such cakes of slag typically derive from smithing hearths. All four

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samples were extensively weathered, which was confirmed by X-ray diffraction, where goethite was predominant in the pattern. As a consequence, any bulk analysis can only approximate the original composition. This imposes an uncertainty on any information which can be derived from the slag, and reconstructions of the thermal conditions operating in the furnace or hearth are difficult.

The microstructures are typical of bloomery slag, with wustite dendrites, fayalite and a glassy phase together with iron corrosion products and metallic inclusions (plate 12g-h).

The analyses in table 5.5 display a wide variation in composition, with furnace bottoms B and D being typical of slag from the bloomery process. Sample A is relatively low in silica, but this could still represent a smelting with the addition of iron scale during the smithing process, or the analysis included a lot of iron corrosion.

Although the analyses are similar to those of slags from the smelting process, they are also acceptable for smithing slags, because during the early stages of smithing the iron, much of the entrapped slag is squeezed out of the iron bloom without any obvious change in composition, i.e. the distinction cannot be made on the basis of composition. The slag often fluxes some of the furnace lining, resulting in unusual compositions such as that seen in slag C (table 5.5), which must include furnace lining or similar high alumina material.

The quantity of slag from the site is small (2-3kg), but this could reflect the small area of ditch excavated. None of the

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samples exhibits any flow structure which is typical of slag tapped from a smelting furnace, and as no furnace remains were associated with the slag cakes, they almost certainly result from periodic clearing out of a smithing hearth.

Ore deposits are located to the north of Towcester, along with traces of early pit-mining dating to the medieval period, and it is possible that Romano-British smelting operations also took place in that area.

Table 5.5

Slag analyses (Abbey Homestead, feature F100)

| Sample | SiO2 | FeO | CaO | Al2O3 | MgO | SO | P2O5 | Total |
|--------|------|------|------|-------|-----|-----|------|-------|
| A | 9.4 | 60.9 | 0.8 | 3.2 | 0.8 | 0.4 | 1.2 | 76.5 |
| B | 14.4 | 57.9 | 1.7 | 3.4 | 0.8 | 0.3 | 0.9 | 79.4 |
| C | 21.2 | 43.7 | n.d | 21.9 | 4.6 | 0.2 | 0.8 | 92.4 |
| D | 26.8 | 52.6 | 5.5 | 3.0 | 1.1 | 0.1 | 0.7 | 89.8 |

Analysed by XRF-edax, using sodium borate discs
Water and carbon not analysed
Fe is presented in the ferrous state, although the corrosion products would have been in the higher oxidation, ferric state

**Brooklands, Weybridge** (Surrey) (*Hanworth and Tomalin 1977*)

Brooklands provides some of the earliest evidence of iron production, with the remains of at least twenty-one furnaces excavated. Of these, twelve had a base diameter of c.30-35cm, while another six were about 60cm in diameter. Furnace F247 from this site can be dated on the basis of pottery to the 5[th] century BC, and was the most complete furnace on the site, with a bowl-shaped base covered with a superstructure of clay. This has been interpreted as a shaft furnace, possibly with slag-tapping facilities, as there was a 1.5m long burnt trench in front of the furnace. A small amount of tapped slag was found on site, together with plano-convex cakes (plate 20b), and small pieces of slag (*Hanworth and Tomalin 1977, 177*).

The total quantity of slag recovered during the excavation was only 44kg, and obviously is not representative of the scale of the industry. Presumably, the bulk of the slag has been reused as road metal or in blast furnaces of later periods.

A pyrites nodule was found in pit 180 (*ibid. 15*) and was the only sample of ore on site. This is not thought to be the source of ore; instead the sideritic ironstone found nearby was suggested as more likely raw material (*ibid. 23*). However, there is no clear evidence for this being the case, as analyses show that the sideritic ore contained only a trace of phosphorus, whereas the slag contained over 1.6%. Therefore, if the siderite was the raw material smelted, then the ore sample was not representative of the original source exploited.

Table 5.6

Slag and ore from Brooklands

| SiO$_2$ | TiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO | CaO | K$_2$O | P$_2$O$_5$ | |
|---|---|---|---|---|---|---|---|---|
| 10.5 | 0.3 | 2.0 | 65.0 | 0.3 | 0.6 | 0.4 | 0.07 | siderite |
| 14.0 | 0.3 | 2.9 | 58.5 | 0.4 | 0.8 | 0.6 | 0.08 | " |
| 17.0 | 0.4 | 3.4 | 58.0 | 0.4 | 0.7 | 1.3 | 0.06 | " |
| 19.0 | 0.2 | 2.3 | 76.0 | 0.2 | 0.7 | 0.6 | 1.6 | Iron Age slag |

(from Hanworth and Tomalin 1977, 23)

| | SiO$_2$ | FeO | CaO | Al$_2$O$_3$ | MnO | MgO | K$_2$O | Na$_2$O | SO | P$_2$O$_5$ | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 30.0 | 9.5 | 15.5 | 15.8 | 0.0 | 0.2 | 0.0 | 12.2 | 0.0 | 0.4 | 83.4 | glass |
| 2 | 37.0 | 14.6 | 30.6 | 3.6 | 0.0 | 0.0 | 0.0 | 5.9 | 0.9 | 1.7 | 93.4 | glass |
| 3 | 39.1 | 12.8 | 1.4 | 20.4 | 0.0 | 0.4 | 0.0 | 15.7 | 0.9 | 0.6 | 91.3 | glass |
| 4 | 28.3 | 68.7 | 0.6 | 0.0 | 0.7 | 0.5 | 0.0 | 0.0 | 0.0 | na | 98.8 | olivine |
| 5 | 28.6 | 69.7 | 0.3 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | na | 99.3 | olivine |
| 6 | 29.4 | 70.1 | 0.4 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | na | 100.3 | " |

(Analyis by EPMA)

**Bagendon** (Gloucestershire) (*Clifford 1961; Trow forthcoming*)

The oppidum at Bagendon produced evidence for a variety of metallurgical activities, including the remnants of a mint (coin moulds), crucibles for casting copper alloys, haematite and a large quantity of slag (*Clifford 1961*), with smaller quantities from later excavations (10kg in 1981, *S. Trow pers comm.*) and a hoard of currency bars. The slag was broken up into many small fragments, but there were also several typical furnace bottoms (plano-convex cakes) similar to material from many sites such as Towcester, etc. These are considered to derive from smithing activities, particularly as XRF analyses of green mineralisation, evident in several places in a section of the slag cake, showed

it to be the residue of a tin-bronze, probably originating from the hot working of tin bronzes. In other words, the cakes represented an accumulation from a smithing hearth which was used for the working of both ferrous and non-ferrous artefacts (plate 19d). A small cake of bloomery slag from the site of Boxgrove, Sussex (Iron Age levels - context 182), similarly contained a prill of leaded tin-bronze.

Analyses of the slags showed them to be typical for the bloomery process, and while most of the cakes and pieces examined derive from smithing, it is likely that smelting was carried out in the vicinity.

Scrapings were taken from the coin moulds, dissolved in *aqua regia*, and the resulting solution was analysed by atomic absorption analysis for copper, gold, silver and lead. The coin moulds could be divided into two sizes (*Trow and Clough forthcoming*), which correlated well with the analyses, indicating that the larger moulds had been used for the production of gold coin blanks, while the smaller were used in the production of silver-alloy blanks.

The crucibles were manufactured from a fine paste. They had traces of vitrification on the outer surface suggesting heating from the base, while the internal surface was encrusted with copper corrosion products and some small prills of metal. The latter, when sampled and analysed by XRF, proved to be tin bronzes with a high percentage of zinc, a common alloy for the period.

Table 5.7

Analyses of Bagendon slags

| Sample | SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | P₂O₅ | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| *18 | 23.3 | 58.6 | 6.4 | 3.8 | 0.8 | 0.7 | 1.0 | 0.9 | 95.5 | slag cake |
| *43 | 20.2 | 66.5 | 5.6 | 2.5 | 0.0 | 0.7 | 1.1 | 0.4 | 97.0 | |

* XRF (wave dispersive), sodium borate flux. Fe as Fe₂O₃

## Mucking (Essex) (*Jones 1980*)

Mucking is a multi-period site occupied from the Neolithic to medieval periods, but with difficult stratigraphy. Slags have been found in late Iron Age, Roman and Saxon levels. These range from droplets found with charcoal, located a few inches from a forge(?) (*Jones 1980, 117*), to a several slag blocks weighing over 20kg (plate 21a), the earliest one of which was found as an intrusive feature of an Iron Age ditch and consequently cannot be accurately dated.

Parallels have been drawn between these blocks of slag, and those derived from the slag-pit furnaces of Jutland and Aylesham (*Tylecote 1973 and McDonnell* pers. comm.). However, there is no apparent flow structure (as seen in the Aylesham block), and the large chunks of entrapped charcoal are more reminiscent of slag forming under the tuyere. The walls of the block show clear indications of interaction with the hearth walls at the base of the furnace. Although it is impossible to reconstruct the furnace from slag remains it is suggested that these blocks of slag do not derive from slag-pit furnaces, but from a shaft furnace with

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the tuyere some 30-40cm above the base of the hearth.

Also, none of the slag blocks was found in a pit or associated with any furnace structure. Some were found in the fill of Saxon Grubenhäuse, suggesting that they may well have been excavated during the construction of such dwellings and hence date from an earlier period. Evidence for copper working and a triangular crucible were also found in a late Iron Age context.

The microstructure of the slag indicated a typical bloomery slag mineralogy, the bulk being an olivine phase and a small amount of wustite and glass (table 5.8).

Table 5.8

Slags from Mucking

| SiO₂ | FeO | CaO | Al₂O₃ | MnO | MgO | K₂O | Na₂O | SO | P₂O₅ | TiO₂ | Total | |
|------|-----|-----|-------|-----|-----|-----|------|-----|------|------|-------|---|
| 29.3 | 69.5 | 0.0 | 0.4 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 100.2 | olivine |
| 42.1 | 28.0 | 5.4 | 14.4 | 0.0 | 0.0 | 4.2 | 1.2 | 1.1 | 3.1 | 0.8 | 100.3 | glass |

Hodges Wood, Crowborough (Sussex)

The bowl-hearth remains of three furnaces (F1-F3) were revealed by stream erosion in this small valley (plate 24e-h). The stream had also cut through deposits of slag and many large cakes of tapped slag were found in the stream bed. A slag heap just behind the photographed furnaces (plate 24) was excavated by members of the Wealden Iron Research Group (WIRG), uncovering over a metre of slag deposit and a concentration of burnt clay, presumably the remains of a furnace, though no definite structure could be defined. F1 was outlined by the remainder of a stone

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wall(?) and burnt clay which is the result of high temperatures in the furnace. This large bowl-shaped structure was c. 1.2m in diameter and 50cm deep. The bowl was incomplete with one side opening out, presumably for tapping of the slag. The bowl-hearth was full rubble, comprising of burnt clay and lining, and part of a cylindrical shaft 35cm in diameter. This was incomplete and not *in situ* and it is felt that it represents part of the superstructure which has collapsed into the furnace together with a considerable quantity of furnace lining. The *in situ* clay lining was 8-10cm thick and consisted of three layers 2-3cm thick, demonstrating relining of the furnace. No slag nor ore was found inside the structure.

Furnace F2 (plate 24e,g) was also defined by reddened clay and a dark fired lining (10cm thick) and had a 75-80cm internal diameter and a remaining height of 30cm. The structure was full of blackened mud and clay together with a large slag block at the base of the hearth.

F3 was similar in size to F2 (c. 85-90cm internal diameter and 35cm in height). A tree was growing inside the remaining structure and destroyed part of the wall on removal. The hearth was filled with large cakes of slag including one large plano-convex cake weighing c. 8kg. There was evidence for relining of the furnace and blocks of slag, were used to construct part of the wall. As far as could be determined, the tapping pit was

destroyed by removal of the tree, but at 90 degrees to this pit was another pit, darkened by charcoal and small pieces of slag. A level sandstone block (30x40x10cm) extended from under the wall into the pit. On its surface was a concreted deposit of slag and scale (hammer scale?) and it is suggested that this was used as an anvil stone to carry out preliminary forging or cutting operations on the bloom as it was pulled from the furnace (fig 2.1).

It was hoped that an archaeomagnetic date could be obtained for the furnaces, but unfortunately this was not possible, nor was there any identifiable ceramic to provide a date. On the basis of other activities (mine-pits) in the area a Romano-British date has been suggested.

Laxton (Northants).

Road widening on the A43 near Laxton revealed an industrial complex with a preliminary l$^{st}$-century date based on ceramics (*D. Jackson pers. comm.*). Three types of furnaces were uncovered during excavation, but as yet it is uncertain whether they are all contemporary, although it is likely (plates 25 and 26). Associated with the furnaces were several large structures, including one end wall of a large building, stone-built, 30m long and 0.5m thick. Deposits of charcoal and roasted ore fines appeared to be both under the wall and in part of its structure. These buildings were built on a rise some 50m from a small stream. One type of furnace is unusual for this period because of its large diameter, c.1.4m. The remains were semicircular (bowl-hearth) with a heavily vitrified wall and base of the

furnace (plate 25). The walls were thick, c.20cm, and there was evidence that the furnace had been reconstructed at least four times. Burnt clay and rubble filled the furnace and was presumably part of the superstructure. Roasted ore and charcoal fines were deposited above the furnace and were the remains of dumps of ore and charcoal prepared for charging into the furnace.

The other furnaces on the site had been built into especially prepared clay platforms (banks) c.3m x 20m in area. The outline of this bank can be seen in plate 26a and the clay is particularly clear in 26b,d. A trench cut by a JCB revealed a second clay bank and the manner of construction. The section revealed that a trench had been cut into a deposit of solid slag and had then been filled with clay brought onto the site for that purpose. Furnaces were then contructed in the clay. Two types of furnace can be seen in plate 26a and enlargements in plate 26c,d. 26d is a typical shaft furnace with an internal diameter c.30cm, height c.40cm, evidence of several relinings and surrounded by fired clay. The tapping pit appears to go under the clay platform. One of the furnaces (26c) had a stone-built base but no evidence of any superstructure. It is contemporary with the slag-tapping shaft furnace (26d) and possibly represents a different aspect of the process, part of the refining operation such as shingling, welding, etc. The bulk of the slag was tapped slag with a dense grey-black fracture typical of bloomery slag.

There were massive deposits of slag and debris up to 2m deep, which, with evidence for levelling and construction of furnaces

over older slag deposits, suggests a considerable time scale for the industry and it is suggested that the site spans from the late Iron Age to the early Romano-British period. There are several explanations for the different sizes of furnace on the site, for example: that they represent different periods; they are functionally different; or there are economic reasons for the difference. It is unlikely that they represent different periods, as industry at the site seems to have been continuous and the furnaces possibly contemporary. There might be functional differences as discussed above, but an economic reason is also a strong possibility. For instance, if a large quantity of iron was required, then a larger furnace may be used to meet the demand, while during normal operation the smaller furnaces would be predominantly used. Alternatively the smaller furnaces might be used for the production of a higher-quality (steely) product, or to refine (resmelt) the crude bloom produced in the larger furnace. Many explanations are possible, but unfortunately only two weeks were available to rescue the information from this productive site and as a result it is unlikely that we will understand fully the relationship between the various furnaces and buildings at Laxton.

## Survey of sites

The following represents a brief summary of some of the metallurgical evidence typical of Iron Age and early Romano-British sites. This is not an attempt to produce a catalogue of sites, as they have has been thoroughly covered in the works of

Aiano (*1977*), Cleere (*1983*), and Tyler (*1982*).

Aldwick, Herts. (*Drury in Cunliffe and Rowley 1978, 69*) Excavations of a semicircular structure revealed considerable domestic debris except that from pit 23, which produced industrial debris related to iron working, including fragments of tuyere and several small lumps of bloom; the number of iron objects was unusually high for this period. The bulk of the pottery from the site belongs to the 3$^{rd}$ to 1$^{st}$ centuries BC, but some also derives from the 5$^{th}$ to 4$^{th}$ centuries.

Beckford, Herefords. (*McDonnell 1983, 14*), had a concentration of smithing slag from middle Iron Age contexts. One pit alone had 1.36kg out of a total of 3.6kg. A hoard of currency bars was also found on the site.

Braughing, Gloucestershire (*Tribbick 1974*). Late Iron Age to Romano-British occupation with very similar remains to Bagendon. Industrial rubbish from the LIA ditches comprised coin moulds, crucibles, slags, and vitrified fuel ash.

Broadfield, Sussex (*Gibson-Hill 1980*). At Broadfield and Holbeanwood, some 70 shaft furnaces have been excavated. 58 furnaces from Broadfield range in date from the 1$^{st}$ century BC to to the 3$^{rd}$ century AD with C-14 dates 2140 +-80bp and 2010 +-60bp. Many of the furnaces were 1.25m high, slag-tapping, and lined with fine coiled clay (see plate 12 and table 5.9)

Boscombe Down West, Wiltshire (*Richardson 1951*). A mixed-period site, with Iron Age pits, Belgic coins and Roman sherds. The site was dated by typical Iron Age pottery. Slag report by Dr A.F.Hallimond: 'sample 1 consisted chiefly of quartz grains in a glassy matrix with a little slag on one side. Possibly furnace lining and slag. Sample 2 was a typical cindery iron slag with fayalite and magnetite. Pit S3 [Roman] produced 0.5kg of slag, possibly part of a furnace bottom with encapsulated charcoal and small trickles of slag, either smithing or smelting slags' (*Richardson 1951, 165*). Re-examination of the slag suggests that the above identification is incorrect, as the structure corresponds more closely with a leached limonitised ore, where goethite would be present as the main constituent. It certainly cannot be accepted as indisputable evidence for early iron working and it is unusual for slag to be so heavily weathered as to lose all of its primary structure.

Bryn y Castell, N.W. Wales (*P. Crew forthcoming*), is a small hillfort seemingly devoted to the production of iron, as there is considerable evidence for smelting and smithing. These activities fall into two distinct periods of activity, closely dated by C-14 from 100 BC to 70 AD and 150 AD to 250 AD. There is possibly a slight improvement in the iron technology in the first phase to a stage where tapping furnaces are used, but the character of the iron working is essentially the same in both periods. Over 650kg of slag was recorded. One furnace was built into a bank of clay and built around a hollow smashed in the bedrock (30cm internal diameter and surviving to a height of 30cm). Many small hollow sphericals (1-4mm) of slag expelled from the bloom during smithing were found, together with hammer scale, roasted bog ore, and *in situ* cakes of smithing slag. A stone anvil with traces of impacted slag was excavated from a slag dump.

Bulbourne Valley, Herts. (*Fells 1983, 48*), has evidence of a flourishing iron industry dating to the late Iron Age and Romano-British periods, with remains of four slag-tapping shaft furnaces, one surviving to a height of 60cm. These furnaces are unusual in construction, having 8cm thick clay walls, 28cm internal diameter, supported and insulated by a surrounding wall, 15cm+ thick, of hard packed chalk. Fells observes that Gibson-Hill's type E (*1980, 26*) shows some similarity but has one-third of the

shaft below ground, while the Berkhampstead furnaces are built on the surface (typical of the difficulties of trying to squeeze furnace structures into narrow typologies).

Bulwick , Northants (Jackson 1979).  At Bulwick (late Iron Age to Romano-British) a clay shaft with internal diameter of 25cm and walls 15cm thick was excavated, and analysis of the tapped slag shows typical ropey structure with very little wustite, c.5% and c.10% spinel (Fells 1983).

Cow Park, Hartfield, Sussex (Tebbutt 1980), is approximately 1km from the smelting sites of Garden Hill and Pippingford. The site is dated to the 1st and 2nd centuries AD. It has been suggested that Garden Hill was an ironworking centre for both these sites, but all the furnaces differ and the dating evidence is slight. The site was well laid out for small-scale iron production, with a working floor outlined by postholes and slag and furnace debris dumped beyond this line. The ore utilised was probably from the Wadhurst Clay. In all there were three furnaces, though none surviving to the height of the tuyere. Each had an accompanying reheating hearth. Furnaces 1 and 3 were left full of slag and cinder, while the superstructure of 2 had collapsed in and around the furnace.

Furnace 1, like the others, was built at one end of a shallow pit which also served as a tapping pit, and the lower part of the furnace was supported by the walls of the pit. Roughly shaped sandstone blocks supported the open front of the furnace (similar to furnace 3). The sandstone blocks were interpreted as a solid base on which to reconstruct the front of the furnace after the bloom had been extracted, and probably have a similar function to the sandstone blocks at the site of Hodges Wood. At the latter site, slag blocks rested on the sandstone block, but here traces of slag and iron scale imply that it also functioned as a preliminary forge for working up the hot blooms as they were extracted from the furnace.

Furnace 2 is larger than the others, with a proportionately larger tapping trench. The bottom half of the filling consisted of 30cm of almost pure charcoal dust, among which were stratified layers of small pieces of clay lining, and scraps of magnetic rusty slag. Above this was another 30cm of collapsed furnace wall, with evidence of four relinings, unlike the other furnaces. The walls of the furnace were made by coiling, with some green glazing similar to the green glazing on the walls of one of my experiment furnaces.

Furnace 3 differed from 1 primarily by the tapping pit, which, when already half full with a mixture of charcoal and loose slag, had then had liquid slag run into it forming a solid layer. This presumably resulted from the initial raking of charcoal and bits of slag from behind the tapping cavity to enable the liquid slag to flow. Apart from the reheating hearth that accompanied each furnace, the site also had a forge: a smithing area where final forging operations were carried out, having up to three anvils, one of which was an iron plate placed on tree trunks which had been set into a pit. Archaeomagnetic dates AD 50-155.

Danebury, Hampshire (Cunliffe 1983). This hillfort was occupied throughout the Iron Age from the 6th century on. There is evidence for both bronze and iron working but not for the smelting of iron. Iron was used as tools in many crafts: woodworking saws, chisels, files, gouges, and adzes; agricultural ard tips, bar shares, and sickles, together with a selections of knives and weapons. The site imported all of its iron and bronze, together with stone, ceramics and salt (briquetage was found at all levels of the site). The quantity of iron found increased in the later periods and a hoard of 21 currency bars was excavated. Bronze was used in smaller quantities, including both casting (decorative fittings) and sheet-metal working (cauldrons,

bowls, etc). A recent study of the iron from the site (*Salter and Ehrenreich 1984*) clearly demonstrates the increase in the remains of iron from the initial settlement with a corresponding decrease in bronze artefacts during the early part of the Iron Age. This displacement tails off around ceramic phase 3-4 (c.450 BC), and the use of bronze is fairly consistent thereafter.

Dellfield, Berkhampstead, Herts. (*Thompson et al. 1976*). Excavation of four shaft furnaces. Furnace 1 had a shaft with a remaining height of 60cm (internal diameter 28cm, wall 8cm thick). In common with the other furnaces, the floor sloped from back to front into a tapping pit 1.5m in length. 5kg of slag and charcoal remained as infill of the shaft. Cleere assigned them to his type B.1.i and dated them to the late 1$^{st}$ or 2$^{nd}$ century AD. However, Thompson (*ibid.*) suggested an earlier date as other material from the site was pre-Roman in date (Belgic ceramics found in the tapping pit).

Footlands, Seddlescombe, Sussex (? *WIRG 9, 1976, 3-4*), Over an acre scattered with bloomery slag, and a variety of pottery sherds including samian. A recent field survey of the site showed that a considerable deposit of slag remained. In some sections of the stream over 1m of slag could be seen including large furnace remains. While the site is definitely Romano-British, it probably has late Iron Age beginnings.

Great Oakley, Northants. (*Jackson 1982*), is significant for C-14 dates c.800 BC (Har 4494 and 4064) associated with remains of a furnace (suggested shaft) and small circular hearths with a quantity of slag, though a lack of identifiable tapped slag. Similar finds come from the sites of Weldon and Corby, which are in the same region and of approximately the same date.

Hardwick Park, Northants. (*Foster 1977*). An Iron Age to Romano-British site with continuity of settlement from 100 BC to 250 AD. It is a series of non-defensive enclosures containing 'Belgic' ceramics, iron-smelting slag and ironworking slag, together with leaded-bronze dross.

Hascombe Camp, Sussex (SxAC 40 1932, 89)had an iron smelting hearth and Romano-British pottery.

Levisham Moor, Yorkshire (*Rutter 1970*), has a single furnace of 1-1.5m external diameter with the present height 0.5m. A bowl-shaped smelting zone, 30cm internal diameter x 40cm high, narrowing to 20cm at the top and having a 40cm long horizontal passage. This was originally believed to be an intact bowl-shaped furnace with a clay dome, but is now considered to be a native slag-tapping shaft furnace (*McDonnell 1983, 9*).

Little Inwoods, Sussex, *'WIRG 19??, ?' This slag heap provided C-14 dates of 170 BC to 70 AD.

Llyn Cerrig Bach, Anglesey (*McGrath 1968*). A pre-Roman site with fragmentary remains of a chariot wheel of carburised steel, and four early Iron Age swords. These have piled structures and are manufactured from a strip of low carbon steel (0.15% to 0.25% C) sandwiched between two outer layers of higher carbon content (0.3% to 0.7%). Hardness values of 150-200 Vhn. Structure suggests intentional carburisation or selection of high-carbon strips for the outer layers.

Merthyr Mawr Warren, Glamorgan. (*Fox 1927*). The dating of the site is also uncertain, as it is a multi-period site with remains from the Neolithic through to the medieval period. Material from the site indicates evidence for both bronze and iron industries, with the remains of crucibles, drops of bronze, and bronze wire, associated with

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fragments of a Glastonbury and Meare type La Tène brooch. In the mound associated with the crucibles are two clay-lined hearths.

The same site produced a 'mound of iron' with a considerable quantity of iron slag and fragments of ceramic with adhering slag. From this came two hearths very similar to those found in the other mound. Adjacent to the larger hearth (75cm) was a basin-shaped hollow lined with clay and disintegrated pot-boilers. A small piece of iron slag was associated with the small hearth. A Roman brooch was picked up near the iron working area.

**Minepit Wood**, Sussex (*Money 1974*), (Orznash furnace). A C-14 date of 1949+-43 BP (BM363) places occupation in the range mid 1st century BC to mid 1st century AD. This site has an unusual furnace constructed of small sandstone blocks built into a semicircle against which a clay lining could be plastered. The superstructure was domed and 1m high with an internal diameter of 60cm. It is unusual in having 3 tuyeres set at 90° from one another. There was a large slag heap 19.5m x 11.6m x 1m high which included a cake 34 x 32 x 6cm which seems to have broken from a larger cake.

**Oldlands**, Sussex (*Tebbutt 1982*), is probably one of the largest Roman 'factory' smelting sites in the Weald. Similar to Footlands in that it has been almost completely destroyed by use of the slags in the early part of the last century in the process of road-making. This site covered some 6 acres and was deep with slag, which included in it burials and had domestic buildings under it. Coins 1st-3rd century, but it is difficult assess how early the industry began at this site.

**Pippingford Bloomery**, Sussex (*Tebbutt et al. 1973*), produced a 50lb bear from the furnace and had standing remains of 40-50cm high. Such a furnace would apparently need more than a single tuyere to produce the necessary conditions in the furnace; internal diameter 50cm. The site also had the remains of a forge where a steel plate had been placed on a block of wood to serve as an anvil. Ceramics and a brooch date the site to the 1st century AD.

**Purberry Shot**, Surrey (*Lowther, 1946*). From this multi-period site spanning the pre-Roman to Roman period from 200 BC to 150 AD is evidence of iron working in the form of furnace bottoms and a bloom.

**Ridge Hill**, East Grinstead, Sussex (*Tyler 1982, 267*), produced pottery post-AD 100 to 300 but the lowest levels of the site are considered to be pre-conquest.

**Ructstalls Hill**, Basingstoke, Hants (*Oliver et al. 1978*). Excavation of a single pit with 32kg of slag. C-14 300-55 BC.

**Sandyden Gill**, E.Sussex (*Tyler 1982, 267*), C-14 dates from a slag tip in a stream section 220 bc +-120 (Birm 151).

**Saxonbury**, Sussex (*Winbolt SxAC 71 1930 223-236*). Excavated by Winbolt in 1929 was a late pre-Roman settlement (La Tène III) with a considerable quantity of iron slag. This was interpreted as a fortified mining camp with connections to the iron mines of the Ashdown Forest, dated 1st century BC. Possible furnace structure together with slag and charcoal. Iron slag, R-B pottery.

**Slonk Hill**, Shoreham (*Hartridge 1977*). Slag associated with pottery which suggests a date from 600 to 200 BC. Most of the remains of slag and iron objects found in pits. Iron objects include iron knife, socket, iron plough shoe, also bronze wire, crucibles and pot sherds. Cleere has suggested that the slag relates to smithing rather than smelting.

Wakerley, Northants. (Jackson et al. 1978), provides another interesting example of early iron production, (beginning during the late 2nd to early 1st century BC), with features relating to smelting being scattered over much of the settlement area but with a concentration of smelting just outside the main enclosure. Several types of furnace structure were used during the industry's life: shaft furnaces with flat bottoms, pit furnaces sunk into the bedrock without any provision for tapping and bowl furnaces which functioned as forging hearths or were the remains of shaft furnaces. It is notable that these are often in a poor state of preservation, which tends to support an argument for the latter, although there are a few structures which were obviously used for reheating the bloom. 'The absence of slag-tapping pits and the rather rudimentary nature of the structures suggest, on typological grounds at least, that the bowl or domed furnace is the earliest form in the Wakerley series. The type may well have been in use in the 1st century BC' (ibid. 163), again dating by the crudeness or simplicity of structure.

Walesland Rath, Dyfed (Wainwright 1970). The remains of a multi-period site from the 3rd century BC to the Roman period with clear evidence for both bronze and iron working, with remains of crucibles and slag from the 3rd/2nd and the 1st century BC.

Wetwang Slack, Humberside (Dent 1980, 180), is a large Iron Age burial site with remains relating to both iron and bronze working, including slag, moulds, and crucibles.

## Conclusions

The conclusions that can be drawn from archaeological remains from the last two decades, and a reassesment of earlier data, fall into several categories: the evidence is gradually accumulating to push the beginnings of primary iron production back to the 6th century or perhaps earlier; iron production was carried out on a variety of sites and on vastly differing scales and is often associated with bronze metallurgy; furnaces and hearth remains now suggest a more complex picture of the technology, not just smelting or smithing, but possibly a range of intermediate structures related to refining the bloom.

The Weald was one of the main areas exploited by the Romans for

iron, and although the sources (*Clough 1985*) refer to an intensive native iron industry, there has been little in the way of dated evidence to support the existence of such an industry. However, very few sites have been fully excavated, leaving a high probability that earlier levels of iron working have been overlooked, and one must suspect many of the coastal sites and those of the high Weald – Broadfield, Oldlands, Ridge Hill and Walesbeech, Purberry Shot, etc – of having earlier origins. In fact, C-14 dates from Broadfield suggest the 1$^{st}$ century BC if not earlier, and if there is a C-14 calibration displacement (*Cleere 1974, 174*), many sites such as this could be earlier. Saxonbury, Footlands and Crowhurst Park (*Money 1978, Tebbutt 1973*) were until recently some of the few sites with pre–Roman industry. However, over the past decade there has been a growing body of evidence for a substantial pre–Roman industry. Sites dated by ceramic evidence such as Purberry Shot (Surrey) could be as early as 250 BC, while ceramics from the site of Slonk Hill (Bromham) suggest occupation, with an iron industry, between 600 and 200 BC. Early C-14 dates come not only from Broadfield, but also Little Inwoods (130 BC – 75 AD) and Sandyden Gill (220 bc +- 120 bc), and many others such as Garden Hill and Minepit Wood, Goffs Park, Saxonbury, etc, could be regarded as transitional.

Outside the Weald the evidence for early production is not as obscurred by later industry. In Northamptonshire, Great Oakley has C-14 dates c.800 BC, certainly the earliest dates in Britain associated with iron smelting, and although the evidence from

Hunsbury is irretrievable, it also implies iron production on a major scale. From this region (Rockingham forest), sites such as Wakerley and Odell represent recent additions to the growing number of sites with evidence for a late Iron Age industry. Iron was extracted at Aldwick (Herts) from the 3rd to 1st centuries BC and possibly as early as the 5th century, while the Bulbourne valley, also in Hertfordshire, had a flourishing iron industry during the late Iron Age.

As an example of one of the larger sites, Danebury was not a primary production site and yet iron objects were forged *in situ*, and used increasingly from the early Iron Age on. It has been tentatively suggested that it was supplied from the Weald (*Cunliffe 1983*), and although this is not impossible, it is unlikely because slag inclusions in Danebury currency bars are very low in manganese, whereas many of the Wealden ores are high in this element (table 5.1). Also a recent study by Salter (*et al. 1984*) suggests that the iron from Danebury was supplied from a number of sources. Iron is also found on smaller sites in Hampshire, such as Worthy Down and Cow Down, the latter, with evidence of a small farmstead smithy, dating around the 6th to 5th centuries BC.

Another point to emerge from this study was the association of both copper alloy and iron metallurgy throughout the Iron Age. This is most evident in the later Iron Age and Romano-British sites of an urban nature such as Silchester, Colchester, Braughing, Bagendon, etc, but also occurs in both large and small

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sites earlier in the Iron Age, for instance, Danebury, Walesland Rath (3$^{rd}$ century BC on), Wetwang Slack (5$^{th}$ century BC-), Gussage All Saints (from the 3$^{rd}$ century BC), Slonk Hill (600-200 BC), Hardwick Park (IA-Romano-British transition), Merthyr Mawr Warren (IA-RB), Glastonbury lake village and other sites. The significance of this association is discussed at length in the following chapter.

The majority of reasonably complete furnace remains date to the last century BC, and although there is strong evidence for smelting before this period the remains are largely slag or the bases of furnaces whose superstructures are unknown. However, those from the late Iron Age vary considerably in structure, from the large stone-built structure (3 tuyeres) from Minepit Wood to the tall shaft furnaces at Dellfield. From the Wakerley remains, the slags from Gussage, the structures from Brooklands, etc, we can infer that there were slag-tapping shaft furnaces with hearths above or below ground, larger dome furnaces built into pits (Pippingford), hearth diameters ranging from 25cm to 90cm, furnaces for smelting, refining and forging hearths, but very little evidence for the traditional view which equates the Iron Age with bowl furnaces.

CHAPTER 6

ARCHAEOLOGICAL BACKGROUND

## Abstract

This chapter discusses previous research in the field and attempts to set out the current state of knowledge, and evaluate critically the archaeological evidence from Europe and Britain relating to the iron industry. It deals with evidence for the beginning of iron metallurgy, the scale of the industry, trade between Britain and the Continent, and iron as part of the Iron Age economy.

# ARCHAEOLOGICAL BACKGROUND

## Introduction

Iron technology in Britain, like technologies before (e.g. bronze working) and after (glass production), was originally an import from Europe. Even after its introduction, just as we see today, the industry continued to be influenced by events in, and trade with, the Continent. Evidence for such trade is manifest in many ways throughout these millennia, but it is primarily the late Bronze Age and the Iron Age which are of concern to this thesis.

Iron production has its origins in the Near East and traditionally has been regarded as the royal monopoly of the Hittites during the $2^{nd}$ millennium. However, this view is now regarded as untenable in the light of research over the past decade. Finds of iron are now known throughout the eastern Mediterranean dating from the early Bronze Age onward, with some known from the $3^{rd}$ millennium. Iron is referred to in old Assyrian texts dating from the middle of the $2^{nd}$ millennium, specifically mentioning refining (smithing/forging), and the loss of weight due to extraction of slag. Iron is also frequently referred to in Hittite texts and it is clear from both these and the Assyrian texts that iron is expensive and confined to ritual and ceremonial use, and that there is no obvious monopoly (*Champion 1980, 513; also Wertime and Muhly 1980*). There appears to be a discrepancy between these texts and the archaeological record, because iron is a common occurrence during the second half of the $3^{rd}$ millennium, being used for various tools and weapons. By the first half of the $2^{nd}$ millennium there

is an apparent drop in iron finds, but these increase
considerably from c.1600 BC on, when iron is used for the
manufacture of tools, weapons and jewellery, in many cases
copying the pre-existing bronze forms. By the 11[th] century BC it
was being applied to agricultural implements, although many of
the tool types were still exclusively of bronze (*Waldbaum in
Wertime et al. 1980, 86*).

By the 1[st] millennium production was on a considerable scale and
iron was traded widely. The currency bars from Sargon II's
palace at Khorsabad (800 BC) were very similar to the spindle-
shaped currency bars from Europe. There were 150 tons of wrought
iron bars weighing from 4 to 20kg, being 30-50cm long and 6-16cm
thick. The appearance of such large quantities of iron in a
tradable form is impressive evidence of the scale of the industry
in the Near East at this time (*Wyndham-Hulme 1938*).

## Production and scale of the industry in Europe

In Europe, iron was also produced on a considerable scale and was
an important trading commodity, together with copper and salt,
and it is generally accepted that the wealth of the Hallstatt and
La Tène worlds was based on the exploitation and trade of these
mineral resources, and their economic drive and efficiency is
certainly reflected in the iron industry. Many large hoards of
ironwork dating from these periods have been discovered,
especially in Gaul, Germany and Britain, representing scrap or
raw material for trade (plate 23b): particularly the bi-pointed
bars which have been found in striking concentrations around

Württemberg and in the middle Rhineland, i.e. the Celtic domain of the 6$^{th}$–5$^{th}$ centuries (*Pleiner in Wertime et al. 1980*).

The trading basis of the Hallstatt world is also confirmed by numerous archaeological finds indicating contact with the Mediterranean, eastern Europe and Britain. For example, the polished black ware in Heidelberg is representative of the close contacts between the Hallstatt and Mediterranean/Greek worlds (vessels for wine, herbs and spices), and the cave site of Hoehle Byciskala, Czechoslovakia, whose material finds demonstrated close contacts with the Hallstatt world (*Kromer 1982*). In Britain probable evidence of continental trade can be seen at Staple Howe, which had Hallstatt C metal types, and in the Thames valley (*Cunliffe 1978, 150*).

The site of Waschenburg provides an example of an early, well-organised iron industry during the late Hallstatt/early La Tène periods. At this site in Austria, the remains of nine open smelting hearths, lined and slagged by the smelting operations (probably the remains of small shaft furnaces), were found together with bloomery slag and sponge iron, and were dated to 500 BC (*Wertime et al. 1980, 387*; see also Hillesheim: *Haffner 1971*). Waschenburg is by no means an isolated case, as there are significant remnants of early iron production from many regions of the Continent, such as those from the Holy Cross Mountains, Poland (*Bielenin 1973*), Manching in Bavaria (*Jacobi 1974*) and Magdalensberg, Carinthia (*Alföldy 1974*). In Carinthia (Noricum), there is evidence (as there is in the Holy Cross Mountain sites)

for intensive exploitation of the rich iron resources throughout the La Tène and Roman periods, with possible beginnings in Hallstatt times. Widespread trading of Noricum iron is well attested (*Alföldy* 1974), and it has been suggested that some Hallstatt and La Tène sites were located specifically to allow control of mineral resources, being located in regions where there is no other obvious reason for settlement. For example, at Braubach on the middle Rhine, ore and slag was found in La Tène settlement sites and burials of early to mid La Tène date contained deposits of ore in quantities of up to 37.5kg (*Härke 1979*). The Hallstatt cemetery was only 45km from the rich ore deposits of Salzburg, and the rich grave goods include iron, glass, amber, gold, and bronze, with many of the swords, daggers and spearheads manufactured from iron. Siegerland in Germany, at the northern periphery of the Celtic domain, the confluence of the Danube and Altmuehl rivers, the Holy Cross Mountains (Poland), and Mukacevo in the Carpathians, all have good ores in abundance associated with mining pits and numerous bloomeries (*Pleiner in Wertime et al. 1980*).

The industry was not only extensive, but also sophisticated, as a high level of skill had been achieved by the Celtic smiths, e.g. the minute hot-working observable on certain types of fibulae and bracelets (*Pleiner in Wertime et al. 1980, 401*).

Swordsmiths appl-d technique- which created optical effects: They etched strips and wires, covered blade surfaces with minute hammered depressions, and s metim experimented with twisting and welding wire of alternating carbon and ph phorus content, thus creating what may be interpreted a: the initial stag of the pattern welding technique (ibid.).

This specialisation is reflected in the finds from Manching (Bavaria, middle La Tène), where there is evidence that the smith occupied special quarters in the oppidum. At this site iron would have been required on a massive scale, with at least 30 tons of nails needed for a single phase of construction (*Piggott 1965, 246*). There was a full range of iron implements including hammers, knives, and sickles, etc, of types normally associated with Roman sites, half-used *Spitzbarren* and what is possibly a used currency bar of a British type (*Jacobi 1974*). This impressive range of material occurred in a large Celtic oppidum, which was not a major extraction site, occupied for some 200 years during the La Tène period, terminating c.50 BC (see illustrations *Jacobi 1974*). Thus we see evidence for iron production in a part of La Tène Europe which could have been indirectly in contact with Britain. Many of the hillforts in Europe (e.g. Glauberg and Bleibeskopf in Germany, and Molpír in Czechoslovakia) were practising bronze and iron metallurgy on an extensive scale (*Champion et al. 1984, 280*).

In Italy, although the role of the Etruscans in iron metallurgy is only vaguely understood, there is a suggestion of Etruscan management of the rich ore deposits at Elba, and the west coast, traditionally known as the Etruscan domain, emerges as one of the most progressive iron-using centres of Italy with remains of millions of tons of iron slag at Baratti Bay, Populonia, other parts of the peninsula and the heavily exploited ore body on the island of Elba, confirming the massive scale of production in the region (*Pleiner in Wertime et al. 1980*).

## Trade between the Continent and Britain

Many trading links existed between Britain and the Continent in the Iron Age (*Macready and Thompson 1984*) and the changing political boundaries and fortunes of communities on the Continent and in the Mediterranean would not only have been reflected in microcosm in Britain, but would often have had a direct effect. For example, Phoenician control of the Mediterranean, largely replacing that of the Greeks and then crushed by the rise of the Roman empire (3[rd] century BC), and its growing control not only of the trade routes of the Roman world, but also extensive exploitation of the resources of its colonies, would all have affected Britain as part of the European trading network (*Frankenstein and Rowlands 1978* suggest that the decline of the late Hallstatt regional system of trade and redistribution collapsed as a result of political disturbances in the Mediterranean, while *Northover 1982* sees a change in European tin supplies reflected in Hallstatt C metalwork in Britain).

During the Bronze Age in Britain there is evidence for well-developed local industry with a complicated and extensive trading system superimposed over the local styles. The extent of the trade is indicated by the numerous bronze hoards and the suggestion that many of the bronzes during this period were imports. The bronzes and bronze trade show obvious parallels with European development in the Hallstatt B phase of the Urnfield culture (*Northover 1982*).

Throughout the Bronze Age there is considerable trade across the

North Sea, but by the late Bronze Age this is paralleled by contacts between the Atlantic coasts of Iberia and France and Britain. The Atlantic trade is manifest in the hoards of the Carp's Tounge Sword Complex and was maintained throughout the 7th century and well into the 6th (*Cunliffe 1978, 148*). For example, the Ile Guenoc hoard, Finistere, of c.643 BC (C-14), consisted of large numbers of non-functional axes with rectangular sockets and unprepared cutting edges, known as Breton or Armorican axes. This type is also found widely in south-east Britain, and in Armorica alone 188 hoards have been discovered containing 20,000 specimens. The implication is that this was a currency type used for both local and long-distance trade, which is consistent with organised trade, and well-defined exchange rates and trading mechanisms. There is thus evidence for two separate routes of contact : from central and northern Europe across the North Sea, and from Iberia and the Mediterranean, by way of the Atlantic to south-west Britain and the Irish Sea.

These Bronze Age approaches are maintained throughout the Iron Age and recur in the 5th-6th centuries (*Cunliffe 1978, 137*). From c.600 to 120 BC there is evidence for long-distance trade in tin and probably other metals possibly related to the foundation of the Greek colony at Masilia. At this point in time there is evidence to suggest that the Etruscans were also trading metal and other materials. c.120 to 50 BC witnesses the intrusion of Roman merchants into Atlantic trade routes, seen in the distribution of wine amphorae and north-western French pottery together with the development of ports-of-trade such as Alet and

Hengistbury (*Cunliffe 1982*). Fibulae from the burial sites of Aylesford, Swarling and Deal indicate late La Tène links with northern France, while two of the richest vessels at Aylesford and Welwyn are imported Italian bronzes.

And while most clearly seen in burials, similar material recurs at settlement sites in the same areas, e.g. Wheathampstead, Prae Wood, Colchester and Canterbury (*Hodson 1964, 102*).

## The beginning of iron in Britain

Because of the evidence for long-standing trade routes and contacts between Britain and the Continent, the transition, in Britain, from copper alloys to iron, must be considered against this background. It is with the Hallstatt period that we associate the growth and spread of iron metallurgy in Europe, and similarly the earliest iron artefacts in Britain are Hallstatt in type.

This is not to suggest that the process was one-way and that all new ideas came from the Continent, as throughout the Bronze and Iron Ages there is continuous evidence for inventive craftsmanship, provided, for example, by the finds of swords and daggers from the river Thames region, where they are so densely distributed that there can be little doubt of their local origin. During the late 2nd and early 1st millennia, these craftsmen are copying continental Hallstatt types and producing distinctive local variants. Later in the 1st millennium there is evidence for specialist craftsmen, skilled in the art of bronze-working and enamelling, producing brooches, mirrors, tankards, bowls and

harness gear for the aristocratic market of the 5th-4th centuries (*Cunliffe 1978*).

Until the late 19th and early 20th centuries little was known about the beginnings of iron in Britain, but from early in this century excavations began to produce evidence of the early industry, such as the sites of Glastonbury, excavated 1892-1907 (*Bulleid and Gray 1911*), Wookey Hole (1908-1912), and the site of All Cannings Cross (1911-1922), which produced iron, slag, and furnace bottoms, while Hengistbury Head (1912) revealed considerable evidence for a range of metallurgical activities, including iron, copper alloys and cupellation (*Bushe-Fox 1915*).

It is during the late Bronze Age - Iron Age transition that we find the appearance in both Europe and Britain of hoards with mixed bronze and iron types (*Cunliffe 1978, 144*). One of the frequently cited examples is that of the Llyn Fawr hoard, Glamorganshire, which produced five socketed axes, four being a distinctive Welsh type (in bronze), while the fifth one was manufactured from iron. Together with these axes was a socketed iron spearhead identical to continental forms (*Champion 1980*). The typically Welsh axe type and a local type of iron sickle from the same hoard suggest that local production of iron was under way (*Cunliffe 1978, 146*). The site of Cold Kitchen Hill, Hants, also had iron from the 7th-century levels (*Cunliffe in Crittall 1973, 408*). A second hoard showing an association between late Bronze Age types and iron comes from Sompting, Sussex, where the remains of a class 2B cauldron were discovered (*Cunliffe 1978, 146*). The Gilmonby Hoard, Teesdale, had two pieces of heavily

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corroded iron and some iron socketed spearheads in an otherwise predominantly bronze assemblage.

The presence of socketed axes manufactured in iron rather than the traditional bronze (*Cunliffe in Crittall 1973, 408*), i.e. the concept of new technology/old typology, is often seen as indicative of the transition. However, recent research tends to suggest that socketed iron axes are a phenomenon which recurs throughout the Iron Age and cannot therefore be seen as an indication of the debut of late Bronze Age smiths in new technology (*Manning et al. 1972*).

The earliest evidence of furnaces and slag (forging?) comes from Great Oakley, Northamptonshire, where slag and the remains of a (shaft?) furnace and small circular hearths were associated with two semicircular structures and a number of pits. C-14 dates from the site (Har 4046, and 4494) date the material to c.800 BC Similar material has been reported from the neighbouring sites of Weldon and Corby (*Jackson 1982*).

The change from bronze to iron seems not to be a dramatic one, but more a matter of the gradual acceptance of a new material and the development of techniques to produce and manipulate the metal. At present it is uncertain what effect its introduction had, though it has been suggested that:

> The appearance of iron in the 7[th] century and its gradual increase and replacement of bronze, led to a breakdown of old established exchange patterns...
> (*Cunliffe 1978, 331*).

However, this appears to assume that the networks existing at the

time of its introduction were static, and that bronze production was completely divorced from that of iron. Neither is likely to be the case, as throughout the preceding Bronze Age social and economic boundaries were dynamic and there is growing evidence to suggest continued association of bronze and iron technology. The extractive metallurgy of copper alloys (in Britain) is concentrated in a few localities in the west of Britain. As a consequence, networks would have been used to distribute this commodity. However, by the late Bronze Age the bulk of trade in copper alloys was confined to the recycling of scrap metal, much of which appears to have come from the Continent (*Northover 1984*), and thus the movement of such material, being divorced from the regions of primary production, is less likely to have been dramatically affected by the introduction of the new metal.

Cunliffe also suggests that iron production, being on a local scale, did not need the complexity of trading networks known for the bronze industry. In theory this is probable, but the site evidence for such localised production, prior to the late third century BC, is limited and throughout the period trade networks continued to circulate such items as Cornish ceramics (ceramic analyses by Peacock reveal the trading of clays/ceramics from west Cornwall to Hampshire and Somerset during the Iron Age (*Megaw and Simpson 1979, 385*)), Dorset shale, beeswax, salt and other commodities. The Kimmeridge shale trade extended as far as All Cannings Cross, associated with the trade in glass beads and a wide range of bronze objects (*Cunliffe in Crittall 1973, 414*). By the 2nd century it appears that iron, in the form of currency

bars, was also being extensively traded. From the early Iron Age, throughout its occupation, Danebury (Hampshire) relied on imports for its supply of iron. Even by the third century, when there is evidence for localised iron production, at Gussage All Saints it is associated with a significant bronze foundry requiring trade in raw materials such as copper, tin, and beeswax (*Spratling in Wainwright 1979, 141*), and no doubt supplies of charcoal and iron ore. The association of copper/bronze and iron industries might be expected, as both can employ similar and tools and expertise, e.g. hammers, tongs, anvils and punches. Even where they do contrast in technique, such as in the casting of bronzes, iron tools (punches, files, and presumably hammers) have been used to finish the cast product, as, for example, at Gussage All Saints, where bronze (bronze plating) had also been used to finish a steel mouthpiece (*for alternative view see Manning in Strong and Brown 1976, 143*).

Therefore, the adoption of iron appears to have been so gradual that any breakdown or change in trading networks or other aspects of the economy could be related to other factors and merely reflect the dynamic nature of trade in general. Certainly there appears to be a continuation of European trade:

> Thus the documentary and archaeological evidence together emphasise the continuance of well-established patterns of trade along the Atlantic sea routes from the 5th to 2nd centuries (*Cunliffe 1978, 156*).

That is, not necessarily a breakdown/reduction of trade concurrent with the transition from bronze to iron, but continuing contact with fluctuations throughout the Iron Age (*Cunliffe 1978, 337*).

The dramatic changes in pottery styles, once interpreted as cultural diffusion (invasion), now are thought, almost certainly, to reflect changes in the distribution patterns (trade) rather than socio-cultural boundaries. Such distributions were not limited to ceramics and the products of individual craftsmen can be distinguished: e.g. a Wessex workshop produced a distinctive local version of the La Tène I fibula, 15 of which were found within a 30 mile radius of Salisbury. Similarly, finds of horse-bit 'links' of the Llyn Cerrig Bach type among material from Gussage All Saints, Bredon Hill, Glastonbury, Ham Hill and Meare could also reflect distribution from one production centre. These are all manufactured from forged iron or steel, with the exception of Llyn Cerrig Bach no.50, which was of cast bronze. Several were of bronze plate (e.g. Gussage, and Glastonbury, LLyn Cerrig Bach 47-49) or tin (Bredon Hill no.2)(*Spratling in Wainwright 1979, 129*).

This new perspective on ceramics, metals, etc, is consistent with the pattern of bronze manufacture and distribution in the preceding period, i.e. a complexity of small networks overlaid by long-distance ones. Just as trade would have continued (albeit with fluctuations), the subsistence economy of the Iron Age can also be seen as a:

continuation of traditions already deeply rooted in the preceding Bronze Age (Cunliffe in Crittall 1973, 408-411).

A possible interpretation of the pattern emerging from subsistence and trading patterns is that the role of iron has been overemphasised and that it should be seen as a new addition to a growing repertoire of valuable trade items, of which

communities controlling the resources or the trade routes would become influential (Hallstatt, Manching, Danebury, Hengistbury, Hunsbury(?), etc). Its importance was possibly exaggerated by the 'more apparent than real' disappearance of bronze, as hoards of bronze smiths continue, and are associated with Iron Age sites (e.g. Stanton, Polden Hill, etc), and bronze working is commonly found together with iron at many hillforts (e.g. Bredon Hill, South Cadbury, Carloggas, and Danebury) (*Megaw and Simpson 1979*).

## The scale of the industry in Britain

It has been suggested that the distinction between iron production during the Roman Iron Age and the preceding period was one of scale, and that this stems from the development of improved techniques such as the bellows-blown draught furnaces, and a move away from induced draught and bowl furnaces (*Tylecote 1962 and 1976*). However, there is considerable evidence to support the use of such furnaces prior to the Roman period in both Britain and the Continent.

Certainly the civil and, particularly, military requirements of the Romans in Britain were large, e.g. 90,000 nails (from a single deposit) were found at Inchtuthil (*Angus et al. 1962*), but the numerous currency bar hoards (*Allen 1967*), and pre-Roman iron finds also suggest that production was already on a significant scale prior to the Roman period. For instance, for the Veneti, iron was not only common in the construction of the *murus gallicus* defences common to Gaulish tribes, but also used

extensively in their boats, which were built of iron-bolted timbers, with iron chains and anchors (*Piggott 1965, 247*). And an iron anchor from was found at Bulbury, Dorset (*Cunliffe 1972*).

Its usage prior to the Roman period also suggests that it was both abundant and cheap, since it was being used for slave chains on such sites as Bigbury (Kent) and Colchester (Essex) (*Tylecote 1962, 202*). The archaeological evidence thus supports a developed local industry, and finds such as hoards of currency bars suggest production in excess of local requirements and trade. This is in accordance with Strabo, writing c.1[st] AD, who described an intensive iron industry which was exporting to the Continent (*Geography* 4.5.2.). Fifty years earlier, Caeser (*BG 5.12*) had observed an industry on a limited scale, but this was by Roman standards and probably only took into account the maritime industry in the south-east.

## Currency Bars

The occurrence of large hoards of currency bars (e.g. Meon Hill, Gloucester, 394 bars, and two hoards of 150 bars each from Malvern, Worcester (*Clark 1952, 203*)) from the 2[nd] century suggests that production was not only on a reasonable scale, but also that it was organised and supplied more than local needs, being traded over considerable distances, if not to Europe (bar at Manching??). As over 80% of the bars have been found within a 40 mile radius of the rich haematite supplies in the Forest of Dean, this has been suggested as a possible production centre (*Fox 1940, 427*), even though no bars have been found in the Dean

itself. The ore may have been supplied by this source, but smelted in the surrounding districts (*ibid. 430*), and Manning found that, in some cases, the bars were of different types (e.g. Malvern and Meon Hoards) (*1972, 231*). Tylecote suggests that the Dean was not the centre of production because the phosphorus content of one of the bars from Salmonbury was significantly higher than could originate from the ores of the Dean (*Tylecote 1962, 209*). However, as discussed earlier, analysis of three hoards of bars from Gretton, Danebury and Beckford (*Hedges et al. 1979*) indicates that these bars were manufactured at more than one centre and that the phosphorus content ranged from undetected (Beckford) to greater than 1% (Gretton), so that some, at least, were quite likely to have been manufactured from ores of the Dean. The location of currency bars was by no means limited to the west of Britain, as Hunsbury, Northants., also yielded currency bars together with what were possibly the richest iron finds (and slag) from any prehistoric site in England (*Clark 1952, 202*). Currency bars have also been recorded from such easterly locations as Gretton (Northants.), and Lincoln. As with currency bars, iron-pokers are common in Europe and Britain. And just as there are several types of currency bars, there are also various forms of poker. During the La Tène period three types are commonly found (e.g. at Manching, Mt Beuvray and Stradonice), occasionally in burials, but also in hoards which include currency bars (e.g. Madmarston) (*Rodwell 1976*).

While there is ample evidence for the scale of production, the level of achievement is more difficult to assess because there

have been very few iron objects from the Iron Age examined metallographically. Certainly the chariot wheel from the site of Llyn Cerrig Bach attests to a high level of skill. This piece was made of steel with a very uniform carbon content of 0.74-0.96%. The wheel was composite in structure, consisting of numerous pieces of carburised iron. The site is dated from 200 BC to AD 50 (*Tylecote 1962, 202*). The remains of four swords from this site were also examined and deliberate carburisation of the piled structure is inferred (*McGrath 1968*). Also, from the site at Gussage All Saints, associated with the 3rd - 2nd century bronze foundry, was a finely manufactured and carburised file used in finishing the bronze castings. Through all phases of Gussage occupation punches were found, suggesting that a specialist iron tool kit was manufactured as part of the bronze industry. Phase I of the site also produced a steelyard weight (or anvil?) (*V. Fells pers. comm.*).

## Settlement, trade and economy in the South and East

Throughout the Bronze and Iron ages there is evidence for the location of sites primarily to facilitate and control trade. For instance, west of the 'Belgic' settlements, we see independent tribal development, contact with the Armorican tribes, and important continental trading ports, the best example being the site of Hengistbury Head:

> within the protection of double dykes which cut off the neck of the promontory, there developed a complex entrepot provided with spacious anchorage and controlling the river routes into the heart of Wessex (*Cunliffe 1978, 107*).

The abundance of copper-silver coins (cast and struck) suggests a local mint. And there is considerable evidence for an extensive

metal industry: a cake of copper–silver alloy weighing 4kg, waste from copper casting, and the remains of two cupellation hearths for the extraction of silver from either argentiferous copper or argentiferous–cupriferous lead; and evidence for the extraction of iron and importation of crude glass.

To assess the scale of the industry it is important to establish the size and type of sites and their requirements. There is no shortage of sites from the Iron Age, with some 3000 structures loosely classed as hillforts, ranging in size from 1.2 ha. (enclosed homesteads) up to 33 ha. Some of the larger settlements, such as Chalbury, Dorset, one of the earliest, had over 70 huts, and Hod Hill, in its last pre–Roman phase, must have been even more populous. With their associated agricultural lands and activities they must have had considerable metallurgical requirements (agricultural implements, domestic and horse gear, together with weapons) (*Cunliffe 1978*).

Danebury, Hants, is one of the few hillforts extensively excavated in recent years and is consequently a good example for demonstrating the role and requirements of hillforts. The material retrieved during excavation showed the extent of trade networks in southern Britain: ceramics of a type appearing to have a production centre in Salisbury, imported stone, bronze, shale from Kimmeridge, and iron. Briquetage indicating salt imports was found at every Iron Age level of the site. Iron was used in many crafts, such as woodwork (saws, chisels, etc), and for agricultural tools (ard tips and iron shares), knives and

weapons and in a hoard of currency bars. Forging slag was found scattered throughout the site together with more limited evidence for bronze casting and sheet-metal work (*Cunliffe 1983*).

Bredon Hill (Gloucestershire), although occupied later in the Iron Age, had a similar range of material:

> a great many miscellaneous iron objects...including iron wedges, nails, rods, flat bars of iron, broken knife blades, flat pieces with holes ... generally speaking there is an unexpected amount of this junk iron, and it may have been collected at Bredon as part of tinkers' hoards...(*Hencken 1938, 87*).

There were also iron mouthpieces of horse-bits (3-link type), awls, box bindings, handles, saws, hammers and files. Also in common with Danebury, Bredon had evidence for bronze working and numerous bronze objects such as rings, dagger chapes, etc.

There were many enclosed farmsteads, e.g. Tollard Royal (Wilts.) Cranborne Chase (Wilts.), or Cow Down (Hants), likely to support a smithy or even a small seasonal smelting installation. Small production units are a greater possibility in some of the more extensive settlements such as Worthy Down (Hants), Owslebury (Hants), and Casterley Camp (Wilts.). And a more permanent smithy must have been required at some unenclosed sites regarded as villages, such as Hog Cliff Hill (Dorset), and Boscombe Down West (Wilts.), the latter consisting of an area unenclosed of occupation spreading over more than 16 acres.

Later in the period, from c. the $2^{nd}$ to $1^{st}$ century BC, there is a general trend towards greater urbanism, with the development of oppida and a decline in the use of hillforts, particularly in the South-East, for example, Quarrywood Camp (Kent), a 12 ha. enclosure on sloping ground overlooking a stream; and Winchester,

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a valley side defended on 3 sides. A few hillfort locations continued to develop, such as Oldbury and Bigbury in Kent, and, in common with oppida, were settlements with urban character. However, the sites of Verulamium, Canterbury, and Braughing (Herts.), had no obvious boundaries or defences, while others such as Silchester, Bagendon, and Camulodunum were often delimited at a considerable distance from the nucleus of the settlement. All of these sites have produced evidence for a multiplicity of metallurgical activities including coining, smithing, and casting of bronzes.

Hillforts and large enclosures have always been evident, but only recently has the considerable spread of Iron Age settlement slowly been revealed. For instance, Wakerley (Northants.), where ironstone quarrying has exposed a settlement in excess of 500m in length, is a good example of a settlement with a pastoral/agricultural economy and an associated iron industry. There are numerous Iron Age settlements in the Rockingham and Salsey and Whittlewood Forests, many of which were uncultivated in medieval times. It has been suggested that these sites do not necessarily imply large agricultural centres, but could be iron-working centres, as iron slag is a recurring material at them. They were not solely industrial, as the querns and bone remains suggest a mixed agricultural economy (*Brown and Taylor 1978*).

These recent finds and the massive iron finds at Hunsbury (*Fell, C. 1937*) begin to reveal the extent and scale of the Iron Age iron industry, even though the bulk of the evidence (slag) must

have been removed for road metal, or for use in blast furnace in recent centuries. Certainly, evidence for large-scale early iron production in the Forest of Dean has been largely obliterated by later iron working, particularly by the 17$^{th}$-18$^{th}$ centuries:

by 1717 Lancashire ore was being brought into the area suggesting that the local supplies were running low; matters would have been even more serious if there had not been abundant bloomery slag still available (Hart 1968, 8).

Bloomery slags were put to further use, in the production of 'Bristol Black Bottles'.

Discussing the iron industry during the Romano-British period, Cleere has suggested a division of settlement types: major industrial, minor industrial, military, urban, and iron-making in villas. For example, representative of the first type in the Weald would be the sites of Bardown, Beauport Park, Broadfield, Chitcombe, Crowhurst Park, Footlands, etc. (*Cleere 1983, 107*). During the pre-Roman Iron Age such a distinction is, as yet, difficult to apply and would require modification. There are no identifiable major industrial units, although at least three of the Romano-British sites in the Weald have pre-Roman beginnings (e.g. Broadfield), but the later industry has obscured the evidence. Other categories of settlement would be necessary, as many of the earlier sites are not as specialised. Wakerley, for instance, could be classed as minor industrial, but that would overlook its large-scale agricultural activities. Sites such as Odell are primarily farming settlements, but with smelting and smithing installations possibly used on a seasonal basis. Hillforts such as Danebury, and later sites such as Silchester, are essentially urban in character with associated craft

specialisation, and while they may produce a considerable quantity and range of iron and bronze artefacts (though not primary production), cannot be considered as industrial settlements.

## Conclusions

Iron appears in Europe during the $2^{nd}$ millennium BC (e.g. Gânovce, northern Slovakia, *Pleiner in Wertime et al. 1980*) and by the early part of the first millennium there is growing trade in iron together with other commodities. The new technology spread rapidly throughout the Continent, as is consistent with the extensive trade networks apparent in the Bronze Age. Iron ore deposits probably influenced the siting of some Hallstatt and La Tène settlements and trade in iron was certainly responsible for the wealth of many settlements.

Evidence provided by bronze and ceramic artefacts suggests that Britain was part of the Bronze Age trading network, which was interlaced with complex local trading systems. This trading pattern continued throughout the Bronze Age into the Iron Age, with fluctuations and changes in direction. The advent of iron is not seen to have a dramatic effect on the trading networks of Britain, which continued, though not without changes. While its appearance undoubtedly influenced the applications of bronze, the latter was still widely used and the production of bronze artefacts was often associated with iron on many hillforts and other Iron Age sites.

The scale of the industry is difficult to assess, particularly in the absence of many early production sites. However, if we assess the volume of iron required by Iron Age sites as widely differing in character as Danebury and Wetwang Slack and assume that their requirements were supplied by production within Britain, then the industry by this time must have been on a considerable scale and specialised production sites must have been in operation. Many sites show the extensive use of iron. Danebury, for example, was a settlement site in which iron was widely used, for a great variety of tools, implements, and weapons, from the $6^{th}$ century with increasing frequency throughout the Iron Age. In contrast, Wetwang Slack was an extensive burial site used from at least the $3^{rd}$ century BC and comprised over 250 burials in which iron was a common material, being put to many uses including weapons such as swords, iron bindings on shields, and chariot wheels. Other grave goods reveal the extent to which Iron Age society was based on complex trading networks with evidence for the exchange of artefacts manufactured from bronze, glass, amber, jet, and limestone in addition to iron. Certainly by the end of the $3^{rd}$ century BC iron was being manufactured as billets (bars) suitable for trade and ready for conversion into a variety of artefacts.

# CONCLUSIONS

CONCLUSIONS

This research has covered many aspects of early iron production in Britain against the background of Europe and has investigated both technical and theoretical aspects of the subject. Its conclusions are wide-ranging though tentative, owing to the slow accumulation and paucity of the data.

Interpretation of archaeological data is to a large extent dictated by the prevailing theoretical models of the period. This is certainly true of Iron Age studies in Britain and, in particular, of Hawkes' ABC of the Iron Age (1930s), which stimulated and strongly influenced archaeological thinking for several decades. This model explained major changes in the archaeological data in terms of invasions, and gave the impression that various ceramic and metal assemblages (e.g. brooches, swords and daggers) could be identified with late Hallstatt and La Tene invasions or immigrations from Spain and Gaul. Early metallurgy did not escape the trend, and thus Late Hallstatt or early La Tene invaders were assumed to have brought with them the bowl furnace:

the Hallstatt immigrants who arrived in Britain, were familiar with bellows
driven bowl furnaces ... (Tylecote 1962, 175).

This was followed by the 'Belgic invasions', and later of course the Romans, who were seen to bring with them the efficient slag-tapping shaft furnace. However, when the complexity of the archaeological data began to be revealed, these simple models were abandoned, being no longer capable of explaining the changes in the archaeological record, and replaced by economic

explanations (or those inspired by systems theory), such as distribution centres and complex trading networks. Although this change in thinking occurred two decades ago, it is only in recent years that changing perspectives coupled with new information have enabled a reassessment of the early iron industry in Britain.

One of the conclusions reached in this study is that there is no simple correlation of culture with furnace type, nor between furnace type and period, and that various furnace types occur contemporaneously in each period. As a consequence, it is not possible to assign a date to a furnace type or to use furnaces to trace cultural movements - particularly as the shaft, dome and slag-pit furnace are all found in Britain and Europe from the earliest stages of iron production. An important reason why furnaces should not be used for dating or to provide a basis for cultural-historical reconstruction is that, in part, their designs originate from functional considerations. For instance, the texture and richness of the ore can influence the type of furnace, and where this is the case, such a furnace could be employed at any period of the industry's history. It would therefore seem logically unsound to assume that Mucking and the Aylesham slag blocks date to the Migration period because they belong to that period in Jutland, particularly as similar remains have been found from other parts of Europe (e.g. Poland) dated as early as the La Tene period.

Furnace remains, as we have seen, are fragmentary and reconstruction is difficult. An overview of new evidence and a

rethink of earlier remains suggests a modification of previous interpretations, in particular the view that the pre-Roman industry was on a very small scale and based on small, non-tapping bowl furnaces. Re-examination of 'classic' bowl-furnaces, for example, Chelms Combe or West Brandon, shows them to be structures which could as easily be interpreted as small shaft furnaces. Levisham, Wakerley, Gussage, Broadfield and others also confirm the existence of slag-tapping shaft furnaces prior to the Roman period. Further confusion arises, no doubt, from the many possible functions of the bowl structures found on archaeological sites, such as non-ferrous metallurgy, and forging.

There is no easily discernible pattern of furnace (technological) development or cultural association in the available evidence for the iron industry in Britain, but, in the Iron Age, there is clear evidence for variation in furnace morphology, and apart from the evidence for shaft furnaces, there are no indisputable examples of bowl furnaces being used for smelting in Britain, although the low shaft furnaces from Bryn y Castell (N. Wales) come close. If the bowl furnace was used for smelting, it is suggested here that their use relates to the reduction of rich ores and is, in a sense, a crucible process. Similarly, in the early Romano-British period there is also evidence for a diversity of furnaces (e.g. Laxton).

In contrast to the fragmentary nature or absence of furnace structures, slag is ubiquitous and the most common residue of

metallurgical processes. Consequently, there have been attempts to relate slag to furnace type. However, these have failed as slags varying considerably in texture and composition can originate from a single smelt. Alternatively, they can be very similar but derive from different processes. For example, tapped slag comes from a number of processes and from a variety of furnaces. This is because the conditions necessary for the reduction of iron can be attained in a range of structures. Smelting experiments not only confirmed the variation in slag, but also the variation in the quality of the bloom. Even from the same smelt, given appropriate ore and conditions, it is quite possible to produce anything from ferrite to steel to cast-iron.

## Smelting of sulphidic ores

These were generally thought to be an unlikely source of ore owing to the detrimental effects of sulphur in iron. However, from limited investigation, analyses of the products from the smelting of sulphidic ores suggests that pyrites, particularly the marcasite nodules from the chalklands, are not only a viable, but also a readily available source of rich ore. It is essential that the ore is either left to weather, or roasted to drive off excess sulphur, but it was possible to produce iron with only 1-2% sulphide with very little effort (even then, the sulphide was localised and absent from many areas). Where sulphide inclusions did occur, providing the metal was forged below 1000°C, they remained spheroidal and isolated, thus having little effect on the mechanical properties of the iron. The main distinction between iron from sulphidic and non-sulphidic ores was not the

inclusions in the metal, as they occur both, but the small flecks of matte dispersed throughout the slag. Small deposits of these nodules have been excavated in association with slag at a number of sites (e.g. Cow Down).

## Smithing and smelting

The distinction between smelting and smithing slags is usually self evident, as the latter activity is generally represented by many small pieces of heterogeneous slaggy material (often vitreous), in the region of hundreds of grams rather than the kilograms of waste typical of smelting. However, problems arise when attempting to determine the origin of plano-convex cakes of slag found on many sites, as to whether they were products of smithing or smelting operations. Mineralogical or chemical composition alone failed to distinguish satisfactorily between the two. The shape of the cakes results from the accumulation of slag at the base of the furnace/hearth beneath the tuyere zone and thus technically they could derive from either process. The conclusion reached in this study was that the bulk of these slag cakes, particularly those weighing 0.5 to 1kg, were the result of refining operations rather than smelting. Several other features in combination with site information assisted in interpretation. Slag cakes from smelting furnaces are generally larger (although some of the slag-cakes from hearths of the 18th and 19th centuries could easily weigh 10-20kg). Furthermore, archaeological evidence suggests that these plano-convex cakes of slag originate from smithing hearths. One of the cakes from the site of Bagendon (Gloucs.) and a smaller example from Boxgrove

(Sussex) contained inclusions of tin-bronze, suggesting that the forge had dual applications.

Distinctions between smithing and smelting are clear as far as the typical plano-convex slag cakes are concerned, but site evidence of furnace remains suggests more than one level of refining, at times using the same furnace for different tasks, while on other occasions, such as at Cow Park, different structures were employed for smelting, refining and smithing.

## Aspects of the industry

One important point to emerge from this research was the limitations of analysing slags, or iron, or interpreting furnace remains in isolation, and the importance of interpretation of the archaeometallurgical data in the context not only of the site (type) and its full range of information, but also of the general industrial and economic activity of the period. An attempt to understand a furnace structure without knowledge of the ores used, and the slags and iron produced, is perhaps as futile as reconstructing the scale of the industry without dated and provenanced finds. Even with the many iron objects analysed from La Tene and Hallstatt Europe, and more recently a collection from La Tene Britain (*Salter and Ehrenreich 1984*), it would be impossible to draw any firm conclusions regarding advances in the technology of iron, without information on the type of artefact and the provenance of the find (type of site, cemetery, hillfort, etc). For example, use of the bowl furnace is hardly consistent with the quantity of iron finds (currency bars, etc) from pre-Roman sites. To ensure that such information is available a

comprehensive recording scheme has been suggested specifically for the interpretation of metallurgical remains.

We are now beginning to appreciate the range of these pre-Roman activities in Britain. Wakerley, Great Oakley, Broadfield, Brooklands, and others are recent additions to evidence of the level of the Iron Age industry. Evidence for the scale of production cannot be expected from the slag heaps because in many cases the bulk of early deposits have been removed at later periods for a variety of uses. Brooklands is a good example of an early production site, perhaps as early as the 5th century BC, with the remains of some 21 furnaces, but only 44kg of slag were recovered from the excavation. Vast quantities of slag were removed for ore in the blast furnace from the 17th century AD throughout the country, and this may have been the case here. while in the Weald, much of the early production would have been concealed by the later waste heaps. In recent years, excavation of Iron Age settlement and burial sites (Danebury, Wetwang Slack, etc) has provided an invaluable complement to the exclusively industrial sites, and in conjunction with the numerous hoards of currency bars, iron pokers, etc, the material from such sites is consistent with a significant industry by the 3rd century BC.

Sites with evidence for metallurgy fall into several categories. For instance, many of the Wealden sites appear to be exclusively industrial and must therefore have been established specifically to exploit the resources for export/trade. Larger sites, such as Danebury (Hants), importing large quantities of finished

artefacts of iron, bronze, stone, salt, etc., are end users and perhaps middlemen in the trade of these commodities (although both bronze and iron were also imported in a semi-finished state and worked (cast or forged) into finished products at the site). Others are settlements with a number of specialised crafts (e.g. Gussage, Glastonbury), producing goods primarily for trade, but obviously supplying the local community as well. In contrast, primarily agricultural settlements such as Odell (Beds.), while still primary producers, are probably only supplying the needs of the immediate community. While recognising that some sites will be difficult to categorise, such a classification of sites is a valuable dimension in reconstructing the influence and extent of the iron industry.

The impact of iron on late Bronze Age Britain is difficult to assess, and although there is a consequent decline in the use of bronze, it is evident that bronze continues to be used and extensively traded throughout the Iron Age. Bronze and iron are frequently associated and the smith is often skilled in the manipulation of both metals (e.g. Gussage All Saints, Bagendon, etc.). There is no evidence to support the contention that the arrival of iron resulted in the breakdown of trading networks.

Metallographic examination of iron objects from the Iron Age reveals that a similar level of technical knowledge to that of the Romano-British period was in existence, though perhaps not practised on such a grand scale. There are examples of deliberate selection of steel, ferrite and iron containing phosphorus for specific tasks, together with evidence of heat

treatment (quenching and tempering) and carburisation, although none of these is used extensively as the bulk of the metal is low carbon ferrite, or ferrite with a moderate phosphorus content (c.0.5%). The heterogeneous product of the early bloomery sufficed for the bulk of iron objects.

## Slag analysis and corrosion

Many analytical techniques were employed during this research – ICP, EPMA, XRF (energy and wave dispersive techniques) – and it was concluded that the microprobe was perhaps the most valuable technique for identification of the mineralogical composition and for bulk composition. While for the latter it has the drawback of being able to analyse only small areas (and is consequently open to subjective bias), it is able to investigate the heterogeneity (e.g. metal, sulphide inclusions, etc) and in particular avoid unrepresentative sampling (for example, corroded regions, unreacted material, etc). Microprobe area analyses and bulk analyses (XRF and ICP) gave comparable results and the technique was particularly useful in investigating and highlighting the problems of analysis and the influence of post-depositional conditions on slag analysis.

## Future directions of research

Although there have been numerous experimental investigations into ancient iron production, there is potential for further investigation: particularly experimentation with pure ores and bowl furnaces, and with some of the newly discovered types of furnaces (e.g. the large Laxton furnace) as they appear in the

archaeological record.

Of particular interest is the reconstruction of wider aspects of the industry, such as its organisation on a local and regional level. One of the major problems is the lack of complete excavations of industrial sites. Laxton, Northants., would have provided a considerable insight into the relationship between furnaces and other structures on site, but unfortunately too little time was available for its excavation. Perhaps the only means of circumventing this problem is to undertake a research excavation unhampered by the limitations of rescue work.

## Physical properties of slag and ore minerals

| Mineral name | Theoretical formula | mineral group | MW | SG | H | MP | CF | Oxides |
|---|---|---|---|---|---|---|---|---|
| alumina | $Al_2O_3$ | oxide | 102.0 | 3.8 | 9.0 | 2050 | 1.0 | $Al_2O_3$ |
| anorthite | $CaO.Al_2O_3.2SiO_2$ $CaAl_2Si_2O_8$ | feldspar | 278.3 | 2.8 | 6.5 | 1550 | 0.202 0.366 0.432 | $CaO$ $Al_2O_3$ $SiO_2$ |
| apatite | $CaF_2.3Ca_3(PO_4)_2$ | | 1000.9 | 3.2 | 5 | 1300d | 0.556 0.422 | $CaO$ $P_2O_5$ |
| calcia | $CaO$ | oxide | 56.1 | 3.1 | | 2570 | 1.0 | $CaO$ |
| fayalite | $Fe_2SiO_4$ | olivine | | | | 1205 | | $FeO$ $SiO_2$ |
| haematite | $Fe_2O_3$ | oxide | 159.6 | 4.9 | 6.5 | 1457 | 0.99 | $Fe_2O_3$ |
| kirschsteinite | $CaFeSiO_4$ | olivine | 188 | | | | | $CaO$ $FeO$ $SiO_2$ |
| leucite | $KAlSi_2O_6$ | feldspathoid | 218.3 | 2.5 | 6 | 1350 | 0.216 | $K_2O$ |
| limonite | $FeO(OH).nH_2O$ | oxide | 373.2 | 3.8 | 5.5 | 200d | 0.885 | $Fe_2O_3$ |
| magnetite | $Fe_3O_4$ | spinel | 231.4 | 5.2 | | 1538d | 1.035 | |
| marcasite | $FeS_2$ | marcasite | 120.0 | 4.9 | 6.5 | 510d | 0.665 | $Fe_2O_3$ |
| manganous oxide | $MnO$ | | 70.9 | 5.3 | | 1650 | | |
| pyrolusite | $MnO_2$ | | 86.9 | 4.9 | | 1080 | | |
| pyrite | $FeS_2$ | pyrite | 120.0 | 4.9 | 6.5 | 510d | 0.665 | $Fe_2O_3$ |
| orthoclase | $K_2O.Al_2O_3.6SiO_2$ | feldspar | 556.8 | 2.5 | 6 | 1200 | 0.169 0.183 0.648 | $K_2O$ $Al_2O_3$ $SiO_2$ |
| potash | $K_2O$ | | 94.2 | 2.3 | | 700 | | $K_2O$ |
| quartz | $SiO_2$ | | 60.1 | 2.7 | 7 | 1710 | | $SiO_2$ |
| siderite | $FeCO_3$ | carbonate | 115.8 | 3.8 | | 450d | 0.689 | $Fe_2O_3$ |
| wollastonite | $CaSiO_3$ | pyroxene | 116.2 | 2.8 | 5 | 1545 | 0.483 0.517 | $CaO$ $SiO_2$ |
| wustite | "FeO" | | 71.8 | 5.7 | | 1420 | 1.111 | |

# Appendix B

## ANALYTICAL TECHNIQUES

For bulk analysis three techniques were used: XRF (energy and wave dispersive) and ICP. Small area analyses were also obtained using the electron microprobe.

Degussa XRF (Philips-Edax combination with a molybdenum source and automatic sample change). The recipe used for preparation of the borate discs: 7gm $Na_2B_4O_7$, 1gm $NaNO_3$, 0.5gm $NaBO_2(OH)_2$ and 0.5gm of sample. This was then heated in a platinum crucible in an induction furnace for 10 minutes. The resulting liquid was poured onto a heated platinum disc and cooled, leaving a homogeneous glass disc which could then be submitted for analysis.

XRF-wave dispersive with automatic sampling and on-line PDP-11 computer control (Bedford College). Again using glass fusion beads: 0.8gm sample, 5.71gm of Na flux 10 mins shaker, 30min 900°C muffle furnace and then poured onto an aluminium disc and pressed. These were then cooled in a dessicator until loaded into the automatic sample holder.

## Dissolution techniques for ores and silicates

VAN LOON, J.C., and PARISSIS, C.M. 1969. 'Scheme of silicate analysis based on the lithium metaborate fusion followed by atomic absorption spectrophotometry'. *The Analyst* 94, No. 1125, 1057-1062.

> Describes the lithium metaborate-nitric acid dissolution technique and comments on other techniques such as hydrofluoric-perchloric digestion. Lists the interference levels for AA.

BOAR, P.L. and INGRAM, L.K., 1970. 'The comprehensive analysis of coal ash and silicate rocks by atomic absorption spectrophotometry by a fusion technique'. *The Analyst* 95, 124-130.

Standard AA technique of silicate analysis, with notes on the precision compared with that of conventional techniques.

THOMPSON, M. and WALSH, N., 1984. <u>A Handbook of ICP Spectrometry</u> Glasgow: Blackie and Sons.

A comprehensive handbook on all aspects of Inductively Coupled Plasma Emission Spectrometry.

## Electron Probe for Microanalysis (EPMA)

Cambridge 5 Electron Probe for Microanalysis with Links energy dispersive analyser and ZAF correction program. Wollastonite, pyroxene and cobalt standards were used. Analysis at 20kV.

## Inductively coupled plasma emission spectrophotometry (ICP)

A plasma is a gas or vapour hot enough to be partly ionised. In the Philips PV 8490 ICP an argon gas is used to form the plasma. The high temperatures, c.6000°C, increases the kinetic energy of particles sprayed into the plasma and results in dissociation of the sample into atoms, ions and electrons. It is the recombination of ions and electrons which emits a radiation of wave lengths characteristic of elements in the sample.

The sample for analysis must first be put into solution. For silicates this can cause a number of problems as many of the techniques, such as perchloric-hydrofluoric acid digestion, destroy the silica, while other techniques prevent analysis of alkalis. Fusions using lithium metaborate (or sodium borates and

carbonates) followed by nitric acid dissolution appear to circumvent this problem as the silica is not destroyed and lithium and boron are rarely analysed for in silicates. However, the high alkali concentration in these fusions results in interferences with other elements, and the best method of analysis is to use the fusion method to obtain silica, and the digestion technique for the other elements (N. Walsh (Kings College) pers. comm.).

Dissolution of slag and ore samples caused numerous problems, as the high iron content often resulted in a precipitate (ppt) forming in the solution. 1.5 or 2.0gm of flux, plus 0.5gm of sample were intimately mixed and heated to 900+ degrees in graphite — (high purity) or platinum — (5% Au to prevent wetting) crucibles. These were heated in a muffle furnace or, in the case of platinum, bunsen burners can be used. The resultant glass was then put in PTFE beakers and dissolved in dilute nitric acid. In many cases dissolution was incomplete where a black ppt formed or an orange ppt came out of solution. To overcome this problem several methods were tried: a) addition of extra silica; b) addition of ammonium metavanadate to reduce the $Fe_3O_4$ to the ferrous state; and c) boiling the residue in concentrated HCl. The solution was then diluted to 250ml, including 20ml of lanthanum nitrate, which is added as an internal standard. Standard solutions and blanks were prepared using the same methods. Two international rock standards, KC11 and KC13, were used together with an additional slag standard to cope with the high iron in the samples.

The solutions are then nebulised and sprayed into the plasma and the visible spectrum produced is then directed through a diffraction grating and analysed. In common with XRF, each element is characterised by emissions from electrons transiting from an outer electron shell to an inner one. However, here we are concerned with transitions (in the visible region of the spectrum) of the outer valence electrons, whereas in X-ray spectroscopy we are observing the transitions of the inner electrons (M or L to K, M to L ) . The observed intensity of the spectral line is proportional to the concentration of the element:

concn sample = Intensity sample/intensity std x concn std

The intensity is also affected by absorption or re-emission by neighbouring atoms. Spectral lines can be broadened, shifted, split by interactions with internal, magnetic and electrical fields or microfields due to neighbouring particles, (eg. the interference of Cu on the phosphorus line). It is therefore essential that the standards chosen are as close to the composition of the samples as possible. In this ways many errors introduced by composition differences can be avoided (reduced), corrections being carried out by an on-line computer.

Results are presented in percentages or intensities of spectral lines. Distilled water and blanks of the flux (borate) are analysed to assess the background noise. Standards are run at regular intervals to enable machine drift to be plotted and corrected. The final calculations include corrections for

spectral interference, instrument drift, variation in sample size and background noise. The advantage of ICP is its speed as it is able to process over 40 samples an hour and analyse for up to 50 elements simultaneously.

Overall the results are disappointing when compared with XRF. The flux, while enabling the analysis of silica, produces high concentrations of alkali which appear to introduce a number of interferences: certainly Fe K and Ca were not stable, while phosphorus could not be analysed in the presence of copper. As a consequence, ICP results presented in this thesis are from the hydrofluoric-perchloric digestion technique. This method produced results comparable to those using both wave- and energy-dispersive XRF, with the exception of iron, which was some 20% too low.

Appendix C

## Thermodynamics of the process (additional notes)

Reduction is essentially the removal of oxygen from its combination with metal to a combination with carbon. It is governed by local chemical and thermal environments, a point which should be stressed when considering the bloomery process as these vary significantly in small furnaces. Their large blast furnace counterparts also display considerable variation, but here the liquid phases enable faster diffusion [1], whereas the small size of many early bloomery furnaces and the solid state nature of the process results in a more heterogeneous product. The blast also facilitates mixing of the liquids. To some extent, this heterogeneity was overcome after the production of the bloom. Areas of differing quality were sectioned out or blended during shingling and other refining processes.

Variegation in chemical and thermal environments correlate with alterations in oxygen pressures of the furnace gases. These, together with differing assemblages of the mineral present, control the prevailing atmosphere and consequently reduction and partitioning of elements into the iron. In the blast furnace (BF) the entry of P, Mn, Si, and S into the iron is ultimately controlled by the conditions existing in the liquid slag at the bottom of the furnace. That is, interactions occurring as small drops of iron move through the slag bath to the liquid iron

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[1] This uniformity is because both the slag and the iron are in the liquid state and diffusion is much greater in fluids than in solids (Biswas 1962, 303).

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below, but beyond that the reaction at the slag-iron interface plays a small part (*Richardson et al. 1949*).

In the bloomery, the reactions at the slag interface will occur, not as the droplets of metal fall through the slag bath (for the metal is not in a liquid state), but in the higher levels of the furnace where iron particles have a slag coating. Some slag-metal interaction must also occur in the base of the furnace, where the slag is still liquating and dripping from the pasty iron at welding heat, although not ultimately a controlling factor as in the blast furnace.

At any temperature each oxide exerts a definite oxygen pressure, which is a measure of its tendency to dissociate with the evolution of oxygen, which increases logarithmically with temperature. Generally the higher the degree of oxidation represented by the oxide, the higher will be its dissociation pressure at any temperature (*White 1943, 621*):

$$Fe_2O_3 \; > \; Fe_3O_4 \; > \; FeO$$
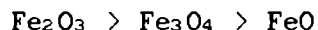
Equilibrium in any one part of the furnace is attained only when the dissociation pressure of the oxide is equal to the partial pressure of oxygen in the gaseous phase (oxygen potential of furnace gases). In the case of oxides of carbon this is dependent on the reversible equilibrium reaction:

$$2CO_2 \; = \; 2CO + O_2$$

for which the equilibrium constant (K) is:

$$K \; = \; \frac{(CO)^2 \, (O_2)}{(CO_2)^2}$$

The oxygen pressure of the system is directly dependent on the equilibrium ratio of $CO:CO_2$. Therefore, $CO:CO_2$ ratios are used as measures of equilibrium for the above reaction and as a guide to the oxygen potential of the furnace. The behaviour of minerals

in the reduction furnace to some extent can be predicted from the oxygen potential (Ellingham) diagrams, which relate $CO:CO_2$ ratio to a plot of oxygen potential against changes with temperature. For instance, from the free energies of formation for silicates, it is possible to predict that Mn-silicates are more stable than the oxides, and that the latter are much more difficult to reduce than FeO, i.e. the lower the line for the formation of an oxide lies on the diagram, the greater the stability of the oxide (i.e. the lower the partial pressure of oxygen at which it can be reduced to the metal). Hence a pure element is able to reduce the oxide of any other element whose free energy of formation (delta $^{o}G_f$) curve lies higher on the diagram (*Bodsworth 1963, 30*). Most of the reactions represented in the diagram have a small decrease in entropy and hence a positive slope, in contrast to the C-CO line, which represents a marked increase in entropy due to a change from one mole (of gas) in the reactants to two moles of gaseous product. As a result the slope is negative and for this reason it is of the greatest significance in extractive metallurgy, as it enables almost all Me-MeO lines to meet the C-CO line at high temperature where reduction by C or CO is possible. The carbon, by reacting with oxygen and carbon dioxide, is always attempting to lower the oxygen potential of the gases passing through the furnace, in contrast to the ores which, by their reaction with CO and the consequent formation of $CO_2$, are trying to raise the potential. It is therefore expected that the lowest possible oxygen potential would be given by the C-CO line corresponding to CO pressures recorded, and the highest

by those of the particular oxide system prevailing at the various

levels.

In any system containing an iron oxide dissociation will, in theory, occur when
the oxygen pressure [of the furnace] is lower than the dissociation pressure of
the oxide at the temperature within the system, and equilibrium will not be
attained until the oxide has dissociated to such an extent that the dissociation
pressure of the altered oxide is equal to the pressure in the system (White 1943,
622).

For example, at $650^\circ - 700^\circ C$, $CO_2$ reduction tries to raise the

percentage of CO to its equilibrium value, but, because of the

reaction $Fe_3O_4 + CO = 3FeO + CO_2$, the percentage of CO is

continuously being diminished while magnetite is present. This

continues until FeO is the only solid phase present. Above $700^\circ C$,

the Boudourd curve cuts the Fe-FeO line and then free metal is

produced (see fig. 1.5 page 29).

Oxides of Si, Mn, and Cr are very stable because their

dissociation pressure, even at high temperatures, is very small.

Oxidation is therefore difficult in contrast to Cu and Ni, whose

oxides have high dissociation pressures. From the Ellingham

diagram we can see that the curves of $Cr_2O_3$, MnO, $SiO_2$, $Al_2O_3$ all

lie below the CO and $CO_2$ curves. Therefore, with a knowledge of

dissociation pressure and its variation with temperature, it is

possible to predict a reaction under given conditions. Thus, the

reaction $FeO + CO = Fe + CO_2$ occurs only when the oxygen pressure

of the $CO/CO_2$ mixture (given temperature) is equal or less than

FeO. The early smelter was able to control the furnace gases by

observing the ignited flame, which would vary between blue

(reducing) and orange (oxidising) as it issued from the mouth of

the furnace. Conditions could then be adjusted by changing the

fuel to ore ratio. Apart from the primary reaction (Fe-oxides to

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Fe), changing partial pressures of oxygen also affect the equilibrium status of the other MeO–Me reactions seen on the diagram (see discussion of $Cr_2O_3$ and $MnO$ above), and therefore the potential reduction of impurities into the metal.

The presence of gangue minerals also markedly affects the equilibrium reactions calculated for pure minerals. For those elements which dissolve in or combine with the iron as reduced, the minimum temperatures of reduction may be much lower than the intersection temperatures, whereas, for those oxides dissolved into the slag or other states of combination when the reaction occurs, the minimum temperatures may be considerably increased owing to the lowering of chemical potentials. The presence of silica, which is a common gangue mineral, lowers the oxygen dissociation pressure of iron oxides, i.e. their reducibility is decreased in its presence (*Biswas 1962, 273*). MgO and $Al_2O_3$ cause a similar effect by forming solid solutions with FeO and consequently make reduction more difficult.

Thus, partitioning of elements between the metallic phase and the slag is not only dependent on the oxygen potential of the gaseous phase ($pO_2$), but also on the composition of the burden. The reduction of Mn is a good example of this. As in the free state, it will be reduced at 0.5atm CO c.1370°C, but, as Mn in Fe, it is theoretically possible at 1080°C. However, this is difficult to assess because of the secondary effects of C, Si, P on the dissolved Mn (*Richardson, 1949, 404*), and the diffusion of Mn into Fe can only proceed at a significant speed under conditions

where liquid iron is in contact with MnO during reduction at temperatures above 1200°C (*Richardson 1949, 405*). Similarly, if we look at P/Phosphate potentials, it is hardly possible to reduce tricalcium phosphate below 1360°C, but it can be reduced to iron phosphide even in the presence of lime around 1080°C. However, this is hardly possible until liquid iron can come into contact with the phosphate during the reduction process. Richardson (*et al. 1949*) concluded that the reduction of the compounds of Mn, Si, P and S can hardly occur at temperatures below 1200°C, but can proceed rapidly as soon as liquid iron becomes available as a reactant (cast iron is liquid c.1200°C). Also, the reduction of Mn and Si requires a gas virtually free from $CO_2$, and thus as soon as $CO_2$ is introduced in the system the reduction reaction stops. Therefore, reduction of MnO, $Cr_2O_3$, with CO gas is practically impossible unless solid C is present, when we have the occurrence of two simultaneous reactions: the initial reduction of the metal oxide by $CO_2$; and the interaction of the $CO_2$ with solid carbon to form new CO, and equilibrium between MO, M, and C occurs at temperatures where the lines intersect.

$$MO = CO = M$$
$$FeO = CO = Fe$$

e.g. $\qquad FeO + CO = Fe + CO_2 \quad c.670°C.$
$$CO_2 + C = 2CO$$
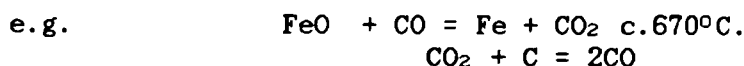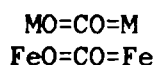
The formation of cementite can occur < 700°C:

$$Fe_3O_4 + 6CO = Fe + 5CO_2$$
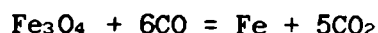
## Note on the use of Ellingham diagrams

The lower the free energy of formation of a compound (i.e. the greater the -delta $^oG$), the more stable the compound. The lower the position of an oxide on the diagram, the lower its oxygen pressure and the greater the affinity of the element concerned for oxygen. At any particular temperature, an element from any lower line is theoretically capable of displacing oxygen from any oxide of the line above it. The greater the vertical distance, the greater this tendency, but they cannot be be used to predict the rate of reaction. However, these figures are constructed under standard conditions which signify the tendency of the reaction to occur where all participating substances are at their unit activities, i.e. pure phases or standard solutions. If the solutions are unsaturated, and if there are forces of attraction and repulsion (as is always the case with complex silicate melts), the free energy is subjected to variations which are sometimes considerable.

## Slag composition

The composition and properties of a given slag for a certain process determines the quality of the desired metal, the rate of production, the performance and the efficiency of the process, the temperature obtained (*Rosenqvist 1974*).

Oxygen potential has been discussed with regard to reduction of the metal and to some extent partitioning of elements between slag and metal, but it equally influenced the quality of the slag. For instance, as there is no intersection of $Al_2O_3$ and $CaO$ with the C/CO line at bloomery temperatures, there will be no

significant reduction of these minerals, which, as a result, will enter the slag. There is obviously a delicate balance between oxygen pressure and composition, and it is in the slag that they play a significant role in influencing the partitioning of other elements, such as phosphorus, into metal or slag. As mentioned above, both these elements effect the reducibility of iron. In basic steel making, entire phosphorus content, and to a lesser extent the sulphur, is removed by the slag, which functions to hold these elements and compounds in a state of lower activity.

Theories of activities of slags divide into two main categories: ionic and molecular. A full discussion of the various slag theories can be found in Coudurier (*et al. 1978*) and elsewhere, as it is a complex subject and beyond the scope of this thesis. However, no single theory appears to explain all slag behaviour and experimental measurement appears to be the only reliable way of determining the characteristics of different slag compositions. Many theories, such as Masson's (*Coudurier 1978*), still employ the concept of basicity as a rough guide to behaviour and structure. For example, in a basic slag silica will mainly be present as $SiO_4^{(4-)}$ tetrahedra, while with greater degrees of polymerisation, as the slag tends towards greater acidity, the slag will contain the ions: $SiO_4^{(4-)}$, $Si_2O_7^{(6-)}$, $Si_3O_{10}^{(8-)}$.....$Si_nO_{3n+1}^{2(n+1)}$, all in equilibrium with each other.

Thus the behaviour of slags is complex and, while undoubtedly relevant to understanding the ancient processes, it is very

difficult to apply theories of slag behaviour, particularly to slags of compositions no longer of interest to modern industrial processes. And especially as very few ancient specimens even remotely reflect equilibrium conditions. This is an important point, as for example, carburisation of iron may occur owing to disequilibrium even in a basic slag. This is because diffusion of CO is greater into iron than into the slag phase.

## List of abbreviations

| | |
|---|---|
| *PPS* | Proceedings Prehistory Society |
| *JISI* | Journal of the Iron and Steel Institute |
| *JHMS* | Journal of the Historical Metallurgy Society |
| *BHMS* | Bulletin of the Historical Metallurgy Society |
| *SxAC* | Sussex Archaeological Collections |
| *SyAC* | Surrey Archaeological Collections |
| *PACT* | Journal of the European Study Group on Physical, Chemical and Mathematical Techniques Applied to Archaeology |
| *WIRG* | Wealden Iron Reasearch Group |
| *UISPP* | Symposiums of the 'Comité pour la Sidèrurgie Ancienne de l'Union Internationale Scientifique Pre et Protohistorique' |
| *CBA* | Council for British Archaeology |
| *BAR* | British Archaeological Reports |

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**Plate 1**

(a) The reduction process; charcoal (cellular structure) can be seen reducing iron out of the surrounding slag. From an experimental smelt Ol.4, using roasted ore from the site of Odell.


(b) Ol.4: metallic iron (white) in contact with slag comprising wustite (large light grey dendrites) and secondary dendrites in a glass matrix. On the lower left is a spherical inclusion of partially slagged and reduced ore. Without slagging, the iron has no means of agglomerating.

# PLATE 1



25KV       6571     10.0U CRYST

a



25KV       6569     10.0U CRYST
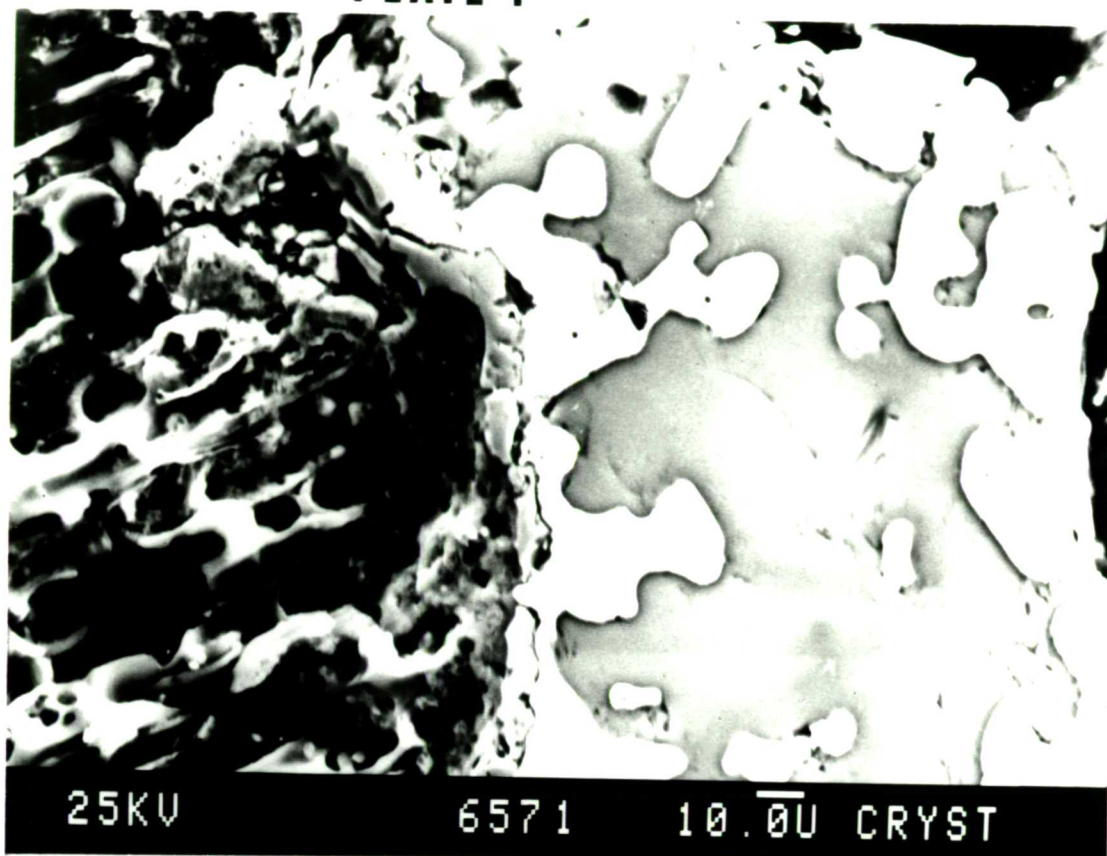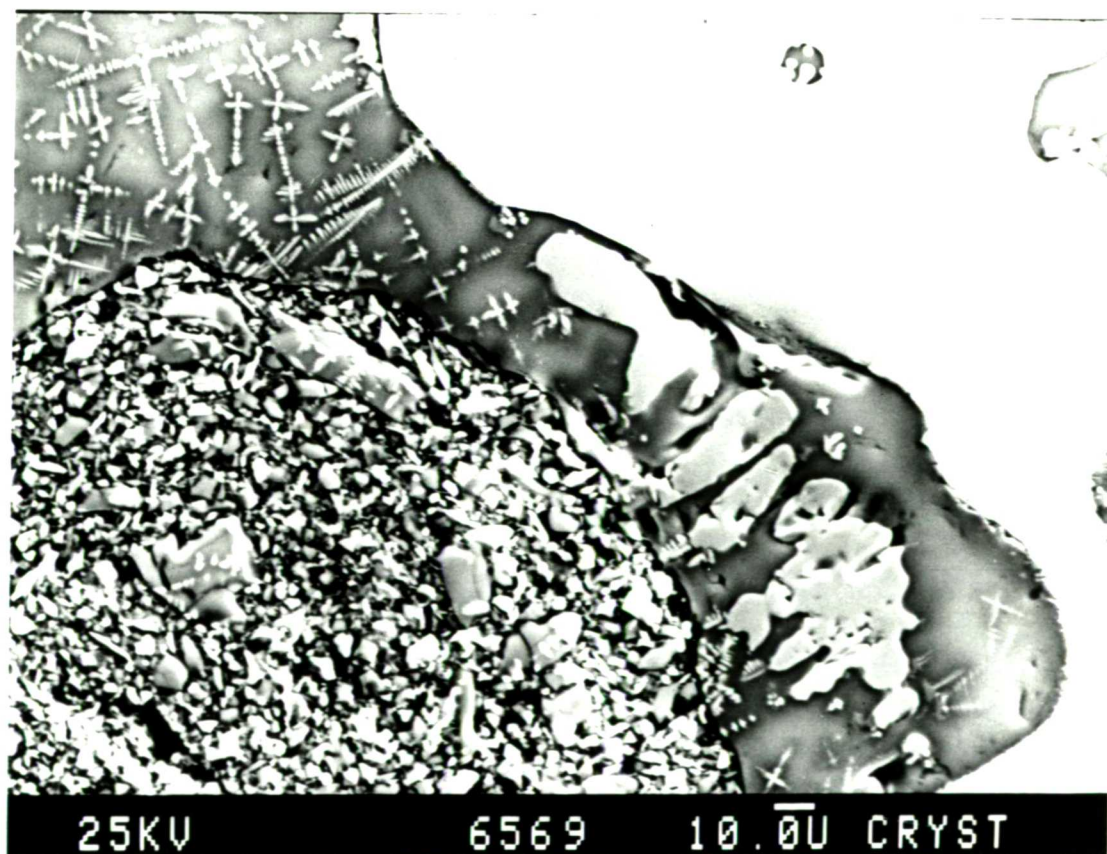
b

## Plate 2

(a)  Agglomeration  of the bloom with smaller particles
     moving towards the bulk of the metal.  Primary and
     secondary  wustite  is seen in a  massive  olivine
     matrix.


(b)  Enlarged  section  of  (a) indicating  that  small
     wustite  and  iron particles are collected  by  or
     attracted to larger particles during growth of the
     bloom.

# PLATE 2



25KV          6566          100.0U CRYST

a



25KV          6563          10.0U CRYST
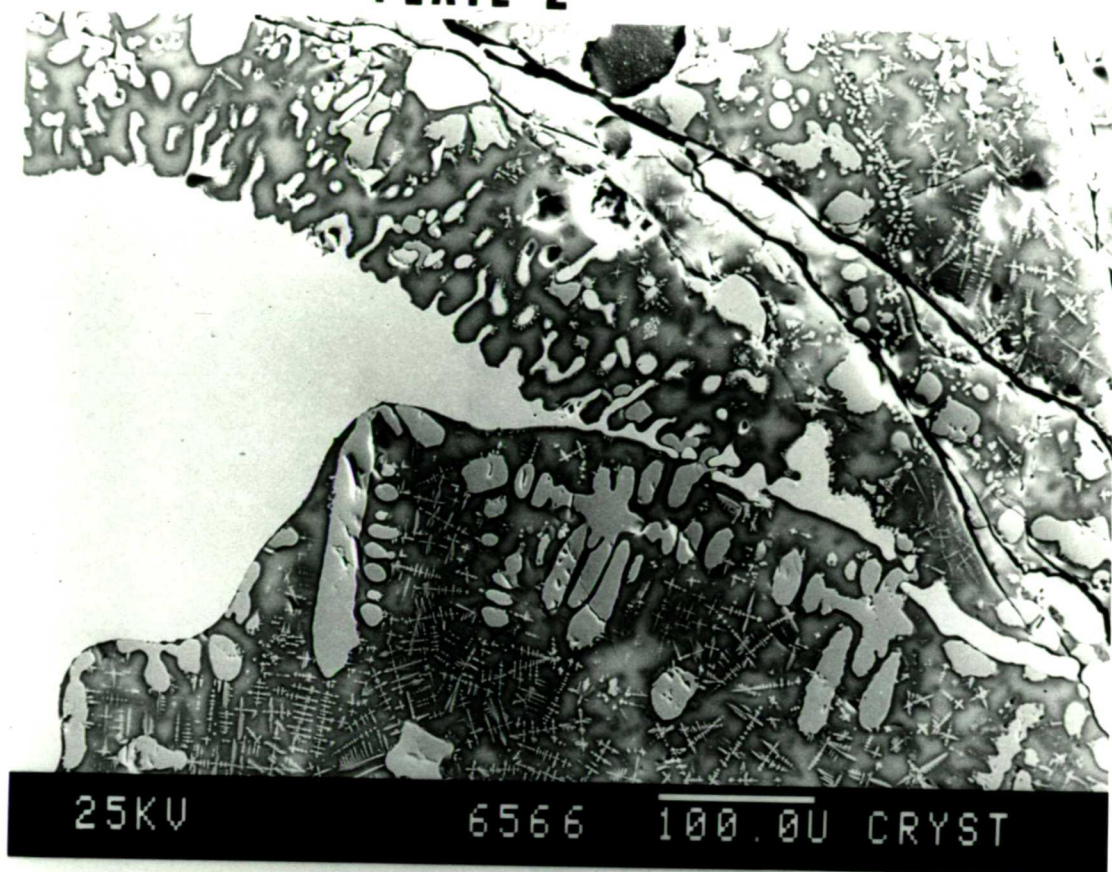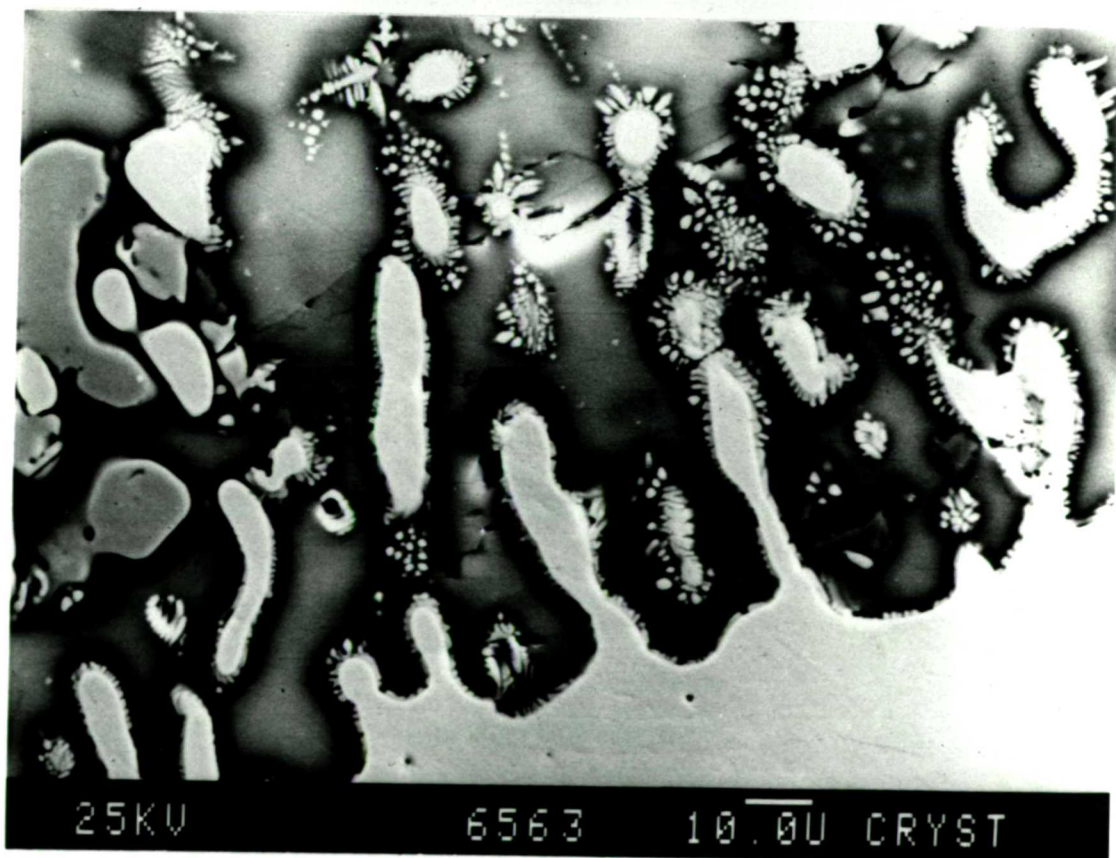
b

**Plate 3**

(a) 'White Horse' particles of iron bloom indicating their growth from wustite dendrites. These are intertwined with dendrites of wustite.


(b) Bloom in slag, with fine wustite adhering to the surface and primary and secondary dendrites of wustite in the slag structure.

# PLATE 3



25KV      6568    10.0U CRYST

a



25KV      6567    10.0U CRYST
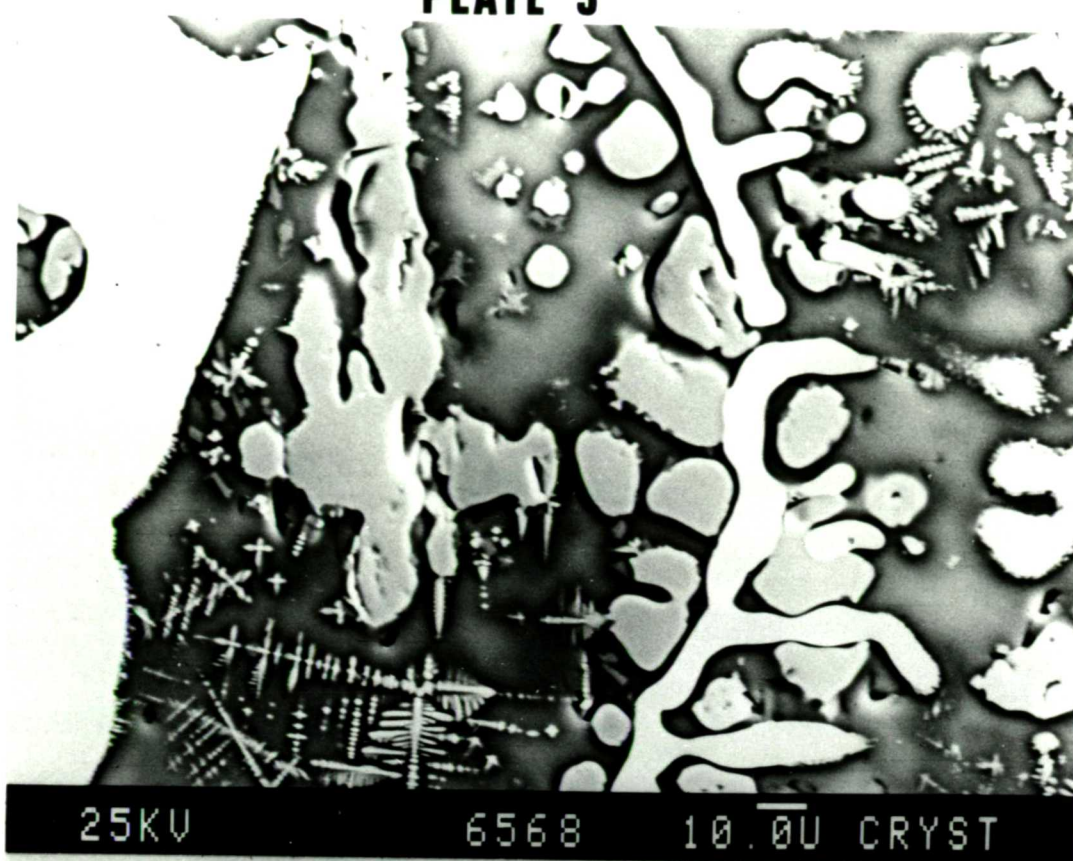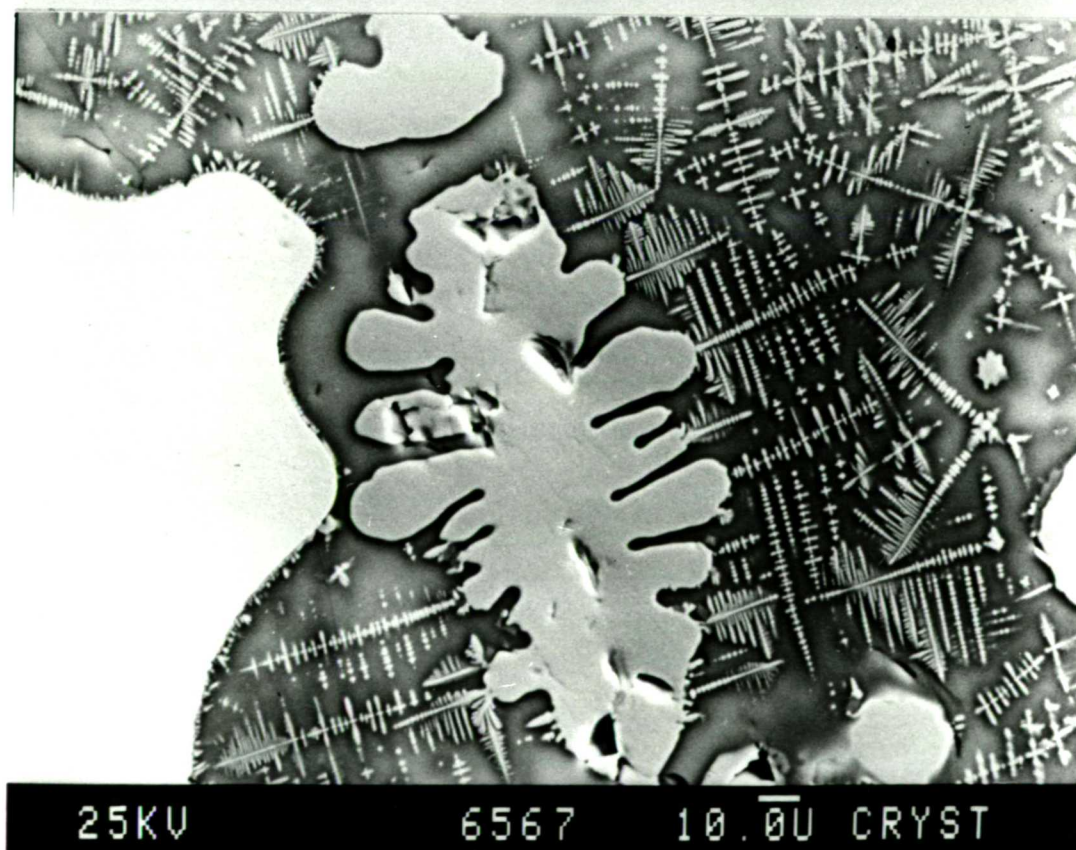
b

**Plate 4**

(a)   Odell experimental smelt O3. Furnace bottom with dense grey crystalline slag entapping charcoal at the base of the furnace. This structure is characteristic of many furnace bottoms deriving from smelting operations.


(b)   O4 (Odell smithing experiment). Frothy slag, a light and porous material formed in the forge from an interaction with some slag and fuel ash. This vesicular foam is commonly formed in the forge, but it is occasionally a product of smelting and has been recorded from glass manufacturing sites.

# PLATE 4



5 Cm

(a)



Cm
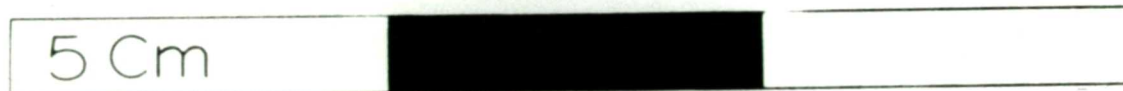
(b)

## Plate 5

Demonstrates the variability found in bloom from one smelt:

(a) Section of experimental bloom from West Hoathly ore. On the left is a eutectic composition of coarse pearlite with some surface decarburisation, while the region to the right has a structure of grey cast iron with graphite flakes in a matrix of pearlite and ferrite (50x).

(b) A region of the bloom with large graphite flakes and coarse eutectic pearlite. On the right is an island of pearlite and ferrite surrounded by a network of phosphide (400x).

(c) Smelt WH1 bloom showing a clear demarcation between the pearlite and ferrite resulting from decarburisation of the bloom in the tuyere zone of the furnace (400x).

(d) Regions of phosphide in matrix of ferrite and pearlite with graphite plates (200x).

(e) WH1 bloom forged. Low carbon content seen as pearlite at the grain boundaries. Widmanstatten structure indicative of rapid air cooling (100x).

(f) Another region of WH1 forged. A ferritic structure with equiaxed grains and small slag stringers. A large slag inclusion at the top of the microstructure is two phase, wustite and a glassy matrix (200x).

(g) WH1 forged. A region with a higher carbon content than (e) or (f) above and also a clearly defined Widmanstatten structure (200x).

(h) Area similar to (e) (400x).

# PLATE 5



(a)
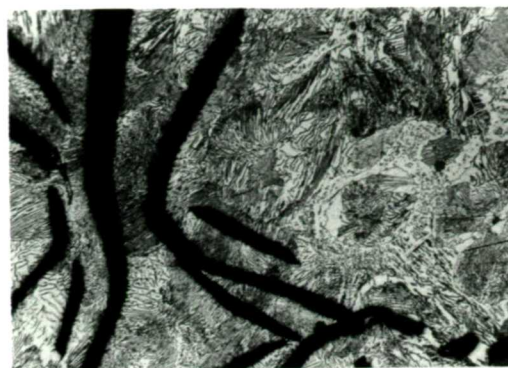
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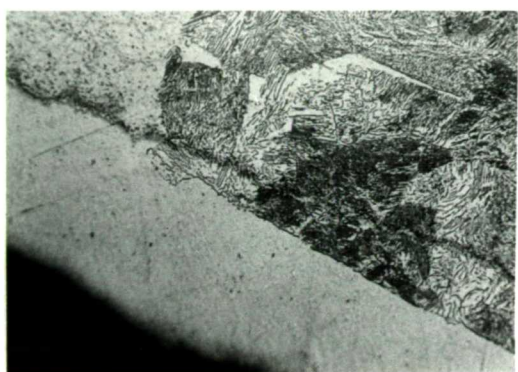
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(d)
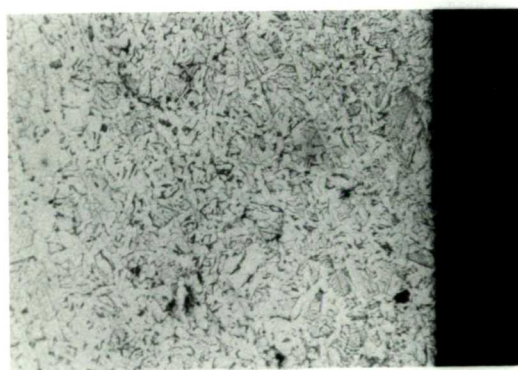
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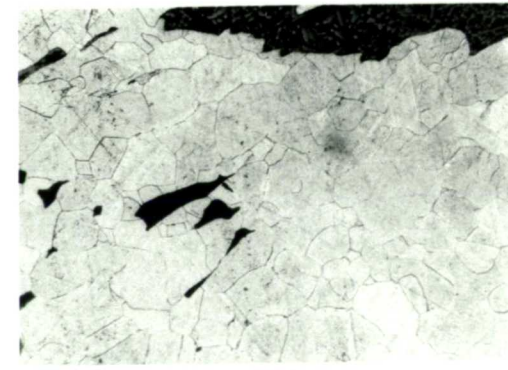
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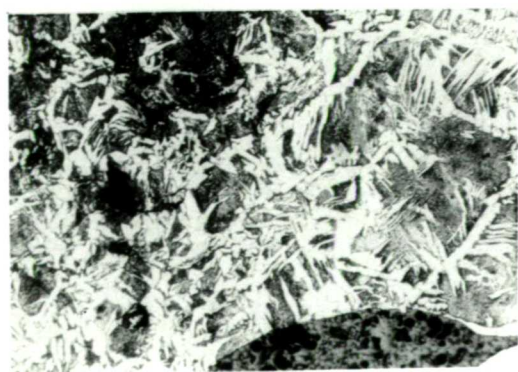
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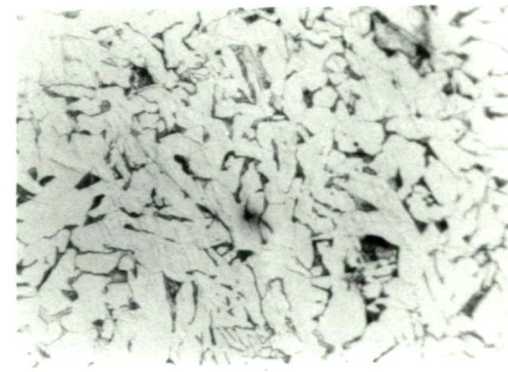
(h)

**Plate 6**

Impurities and inclusions in bloomery iron

(a) Similar to plate 5b; clearly shows the phosphide surrounded by coarse pealite and a graphite flake (400x).

(b) An elemental map for phosphorus in a section of WH1 bloom in a region similar to (a). The white represents concentrations of phosphorus (as phosphide) in the bloom (60 microns wide).

(c) Regions of high phosphorus in an object from the site of Odell (Fiii 62). There is a moderate level of phoshorus thoughout the metal with high concentrations in the slag inclusions. (80 microns)

(d) The light phase is metallic copper in the bloom of smelt WH1. 300ppm of Cu was analysed in the ore, but this was presumably localised in the ore (60x).

(e) Secondary electron image of the above copper inclusions (95 microns across).

(f) Electron probe X-ray map for copper in area (e) (95 microns).

(g) Experimental bloom (O.1) from Odell ore: slag inclusions in ferrite matrix (50x).

(h) O.1 slag inclusions indicating differences in mineralogical composition: the inclusion on the left having a composition of olivine (long lath-like crystals) and spinel in a glassy matrix in contrast to the inclusion to the right, which has a finer olivine phase with a considerable proportion of wustite (lustrous dendritic phase) (100x).

PLATE 6



(a)
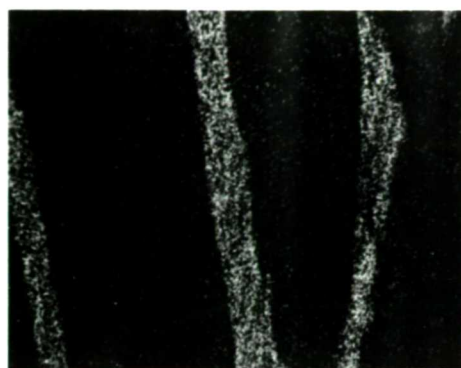
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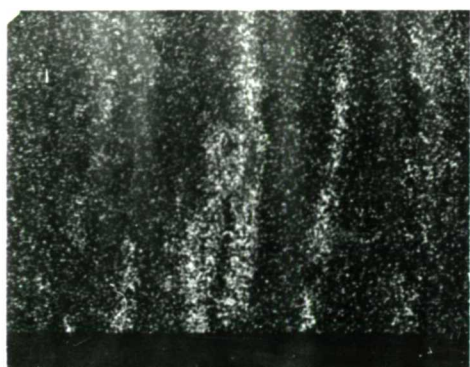
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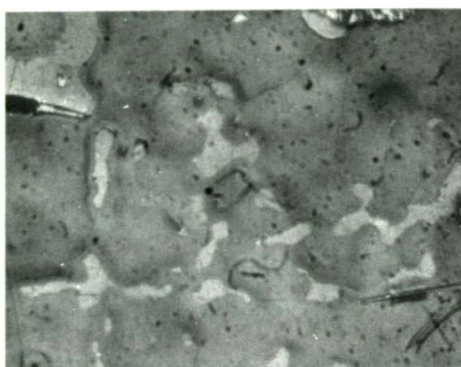
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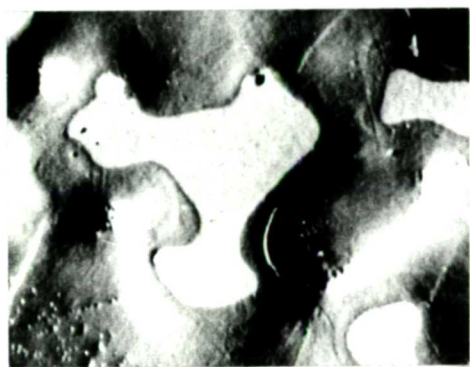
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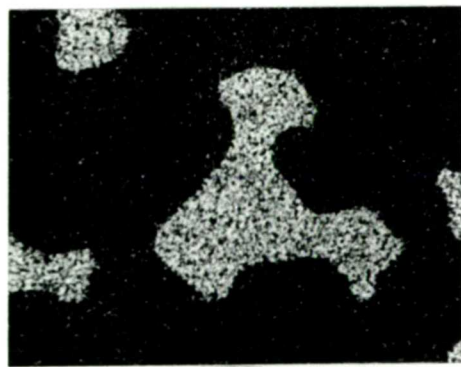
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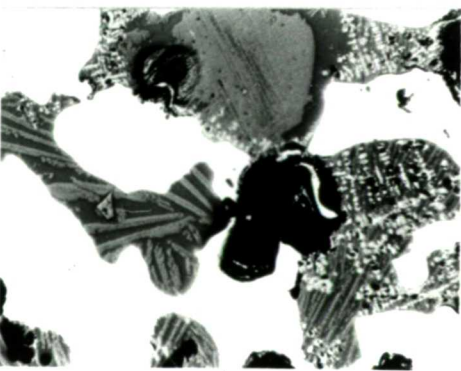
(h)

## Plate 7

**Sulphur and sulphides in iron**

(a) Bloom from smelting Bognor Regis (BR) pyrites nodules: ferrite with sulphide coating the grain boundaries (50x).

(b) Another area of the above bloom which shows variable sulphide content with regions almost free of sulphide (lower half) (50x).

(c) Probe electron image of the BR bloom (300 microns wide).

(d) X-ray element map for sulphur showing the concentration of sulphur at the grain boundaries (300 microns wide).

(e) Element map for iron indicating, as expected, the lower concentration of iron at the boundaries (300 microns wide).

(f) WM1: Sulphur map for a region of the bloom produced from marcasite nodules showing concentrations of sulphide in the slag inclusions, but very little in the metal (340 microns wide).

(g) WM1 different area of above: map for sulphur indicating small spheroidal sulphide inclusions in the metal, but with no sulphide coating the grain boundaries (340 microns wide).

(h) Irregular sulphide inclusion in the bloom from smelt SE1. These sulphide inclusions were numerous in a bloom smelted from a non-sulphidic ore and presumably derive from inclusions of sulphide or sulphates in the ore body (60 microns wide).

# PLATE 7
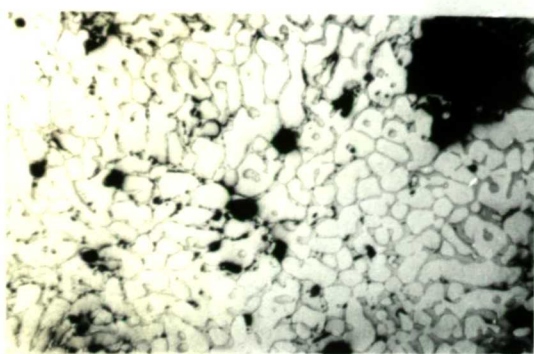

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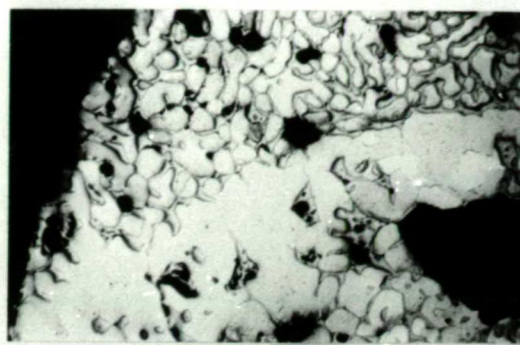
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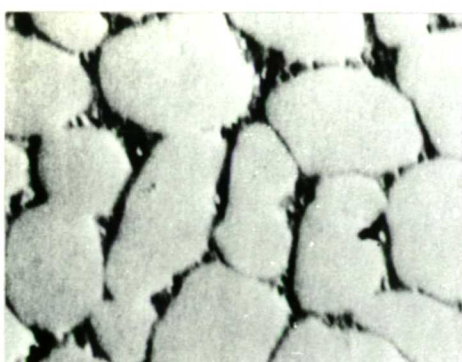
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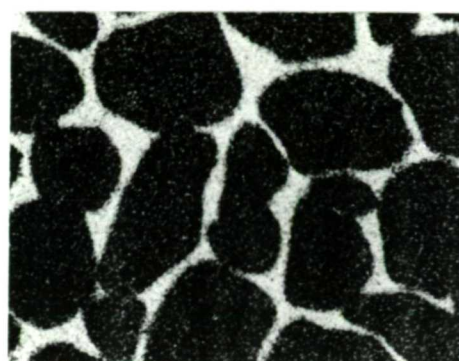
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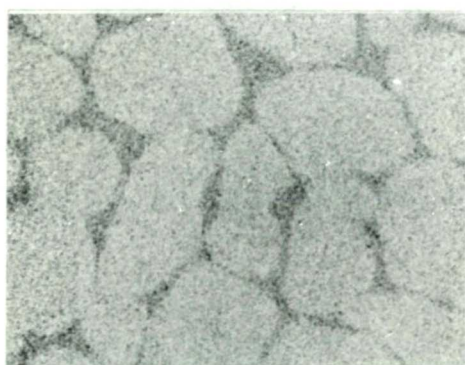
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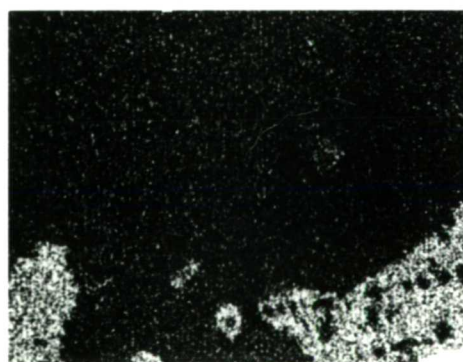
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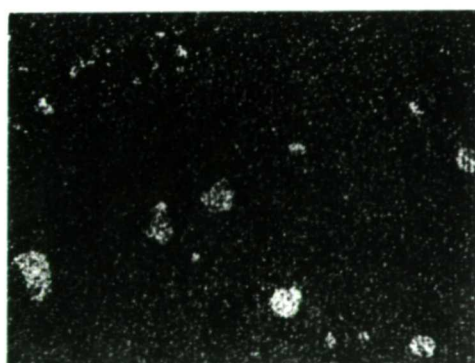
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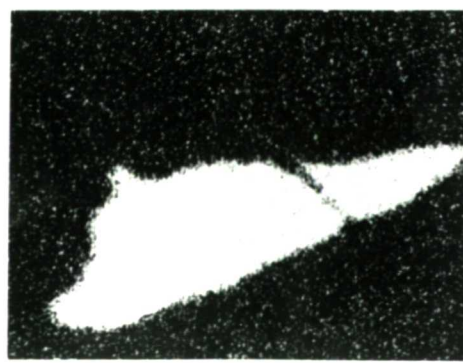
(h)

## Plate 8

(a)  Microstructure of bloom from smelting of sulphide nodules from Bognor Regis (BR): grains of ferrite with Fe-FeS euctectic coating the grain boundaries (100x).

(b)  BR iron as above showing the two phases in the sulphide matrix (400x).

(c)  Iron from smelting marcasite nodules: WM, unetched with c.1-2% spheroidal sulphide inclusions (100x).

(d)  WM1 etched structure of part of the above bloom with similar spheroidal sulphide inclusions and an area of coarse pearlite and cementite needles (plates) in a largely ferritic matrix (200x).

(e)  Another area of the WM1 again with many small sulphide inlclusions and cementite both as needles (plates) and at the grain boundaries (200x).

(f)  0.1, Odell, experimental bloom forged: microstructure indicates a clear division between areas of differing compositions: one essentially a fine pearlitic structure with c. 0.4-0.6% carbon, and an adjoining ferritic region with slag stringers (50x).

(g)  0.1 as above with two-phase slag stringers demarcating the regions of differing composition, presumably where the bloom has been welded during preliminary forging (400x).

(h)  Repeated hot forging of the above bloom has resulted in spheroidising of the pearlite (200x).

# PLATE 8
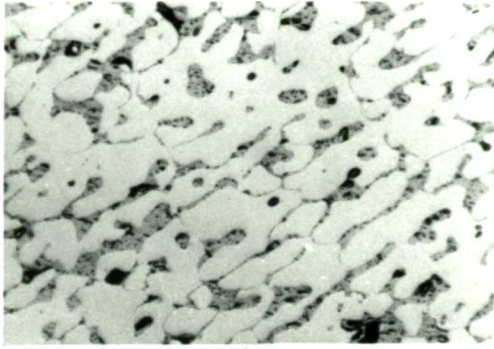


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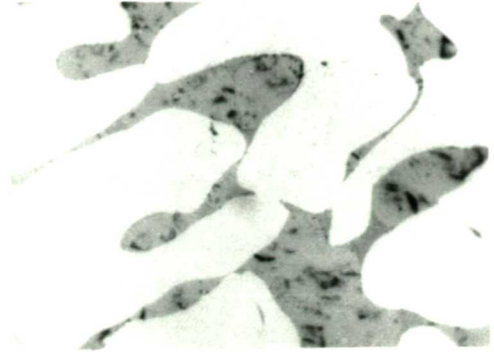
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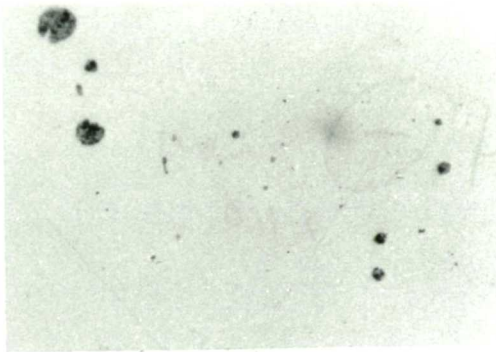
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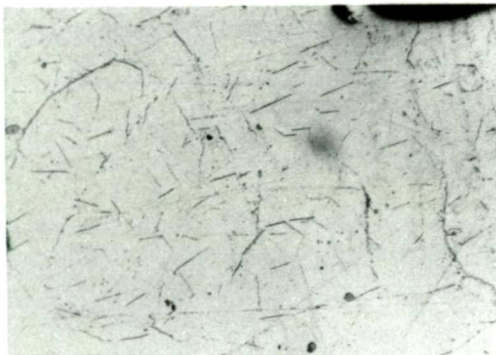
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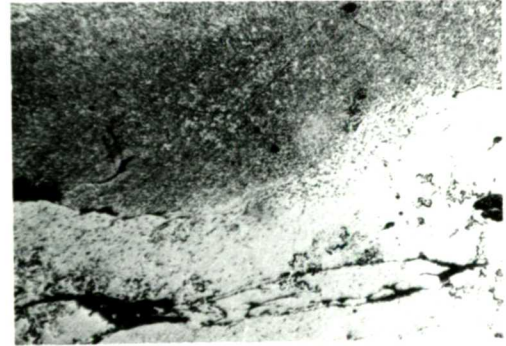
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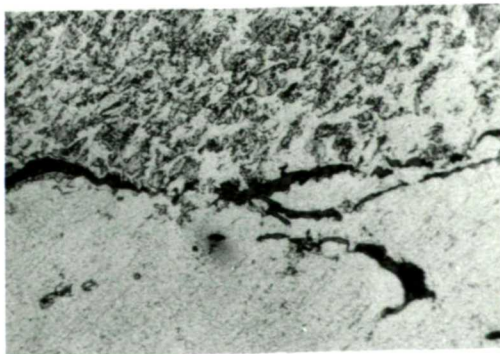
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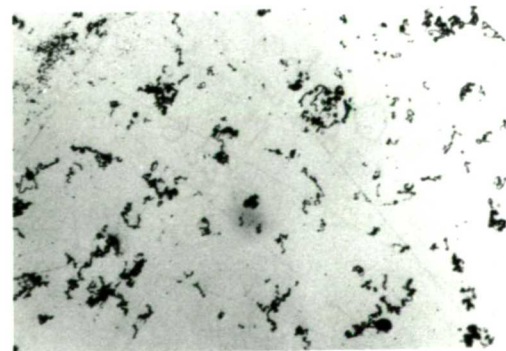
(h)

# Plate 9

(a) Slag section from WM1 smelt with bright metal droplets, duller sulphide inclusions, large light grey wustite dendrites with massive olivine (medium grey) in the background and fine matrix of a dark glassy phase between the olivine laths (200x).

(b) Section of slag from BR smelt with a lustrous sulphide phase and light grey calcium-rich olivine in a dark glassy matrix (200x).

(c) BR slag-matte interface: the lower half of the section is a two phase matte-iron composition, while the upper half is slag of similar composition to (b) (200x).

(d) Multi-phase spheroidal slag inclusion in BR bloom incorporates slag and sulphide phases (200x).

(e) BR slag inclusion: wustite light dendrites, medium grey olivine and small sulphide (matte) inclusions between fayalite laths (400x).

(f) Weybridge A. Section of slag from furnace bottom with dense, lustrous wustite dendrites overlaying a light grey fayalite matrix (100x).

(g) SE1 slag section revealing a small proportion of wustite (white) over a massive olivine phase (medium grey) and patches of a dark glassy phase with secondary wustite exsolving (100x)

# PLATE 9
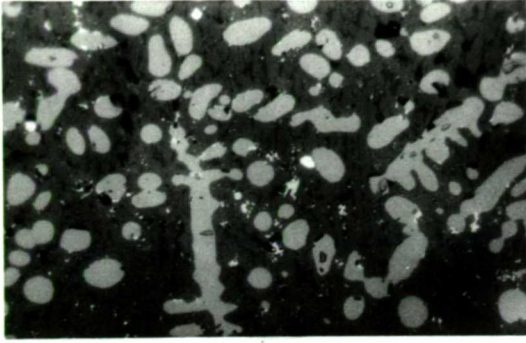


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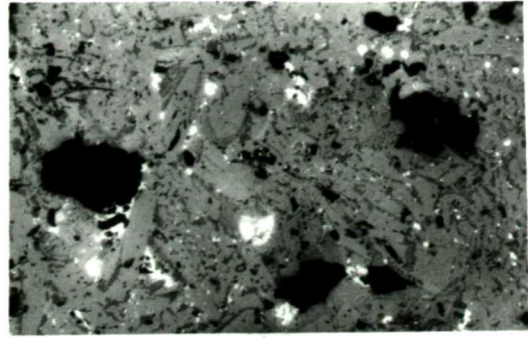
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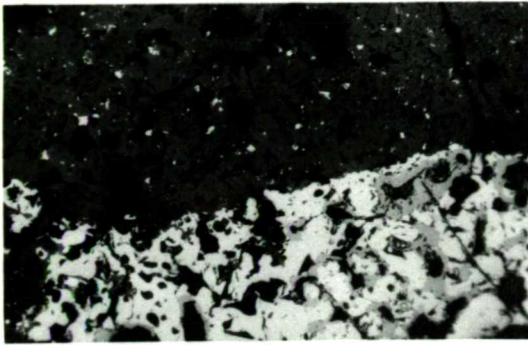
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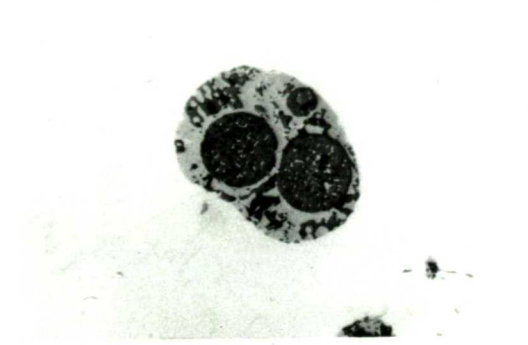
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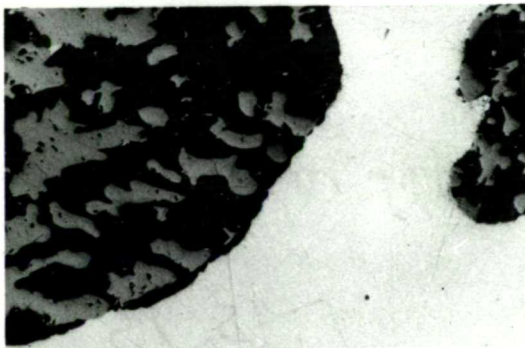
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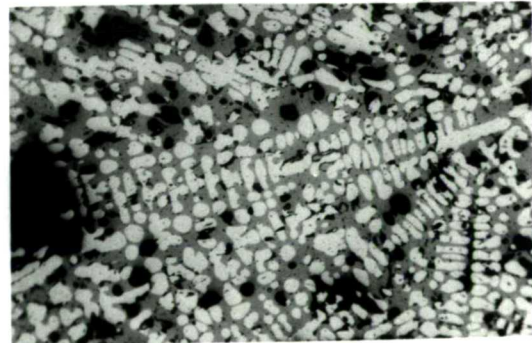
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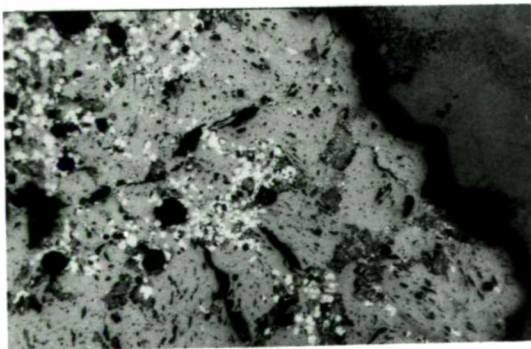
(g)

Plate 10

Slag phases

(a)  Odell Ol.1: euhedral spinels (medium grey), wustite and olivine in a glassy (dark grey) matrix (100x).

(b)  The same: wustite dendrites over a background of parallel olivine laths and a dark glassy matrix (100x).

(c)  WH1 smelt: large fayalite laths and secondary growth of fayalite in a dark glassy matrix. Secondary wustite dendrites (light) are seen crystallising on the smaller fayalite phase (400x).

(d)  WH1: large parallel fayalite laths in a glassy matrix (dark). Both secondary wustite and fayalite can be seen crystallising out of the glass phase. Skeletal formation characteristic of rapid cooling (400x).

(e)  Similar to above but with primary and secondary fayalite (400x).

(f)  WH2: primary and secondary fayalite in a 'spinefex' structure indicative of rapid cooling, often found in archaeological slags which all represent rapid cooling relative to geological processes (200x)

(g)  Ol.2 (Odell): a close examination of the glassy phase of many slags reveals that they are often microcrystalline as seen in this section. The growth of wustite dendrites is seen in a microcrystalline 'glassy' matrix (1000x).

(h)  Caldecotte: the density of wustite varies throughout the slag and will relate to where and at what stage the slag formed in the furnace. Wustite (light) is dense in the lower right of the section. Fayalite is massive with a glass matrix (200x).

PLATE 10
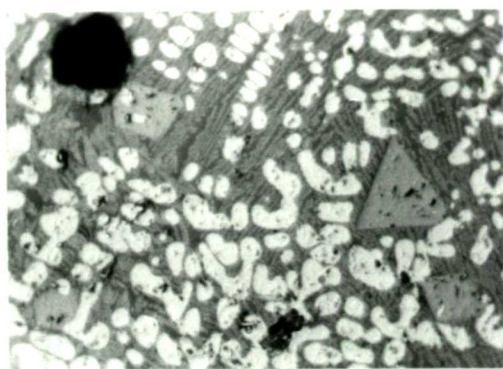


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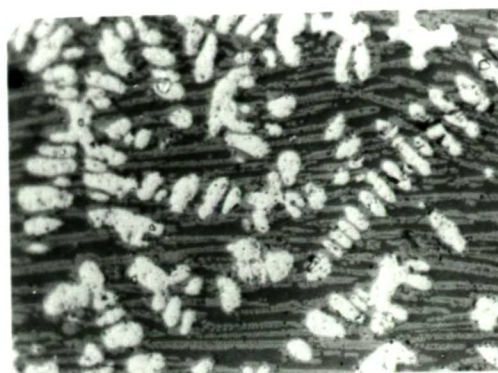
(b)
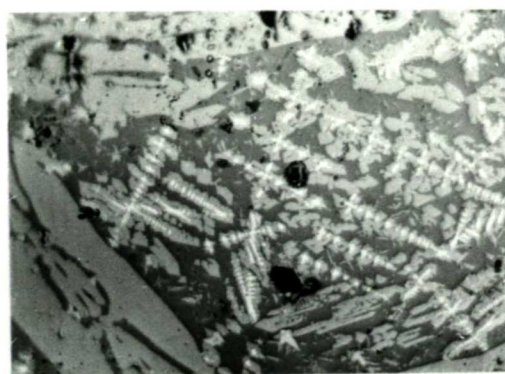
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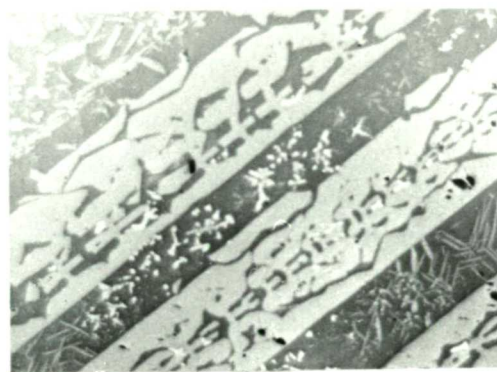
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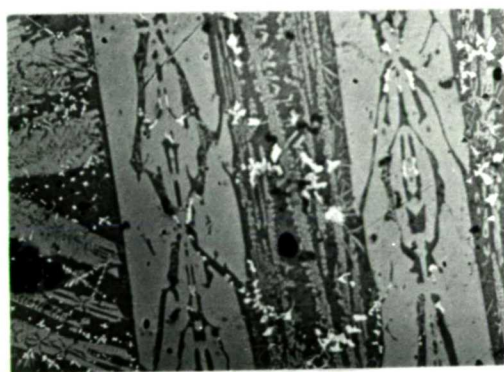
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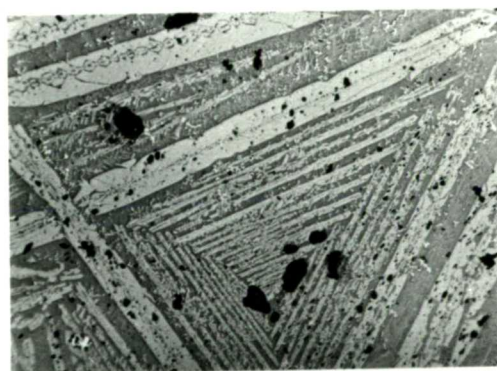
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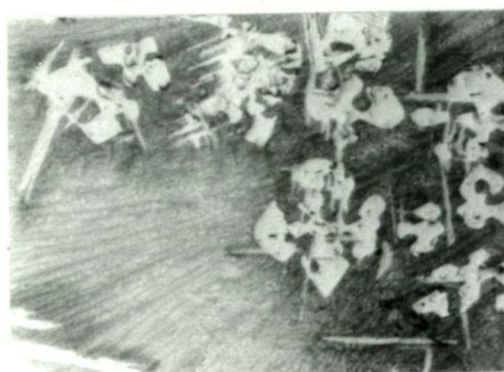
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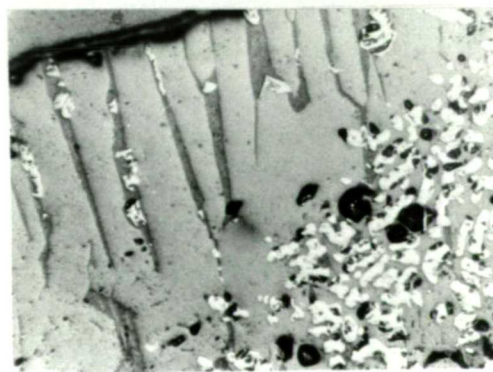
(h)

**Plate 11**

(a)   Garden  Hill:   slag  from  J5,  wustite  (white),
      massive  fayalite  (grey)  and  a  dark  glassy  phase
      with  an  exsolution  of  secondary  wustite.    A
      eutectic  structure  is  occasionally  seen  in  the
      glass  phase  with  potassium  and  calcium-rich
      constituents apparently immiscible (300x).


(b)   Odell experimental slag: a similar glassy phase to
      the above specimen but with very little wustite in
      the slag (400x).

# PLATE 11
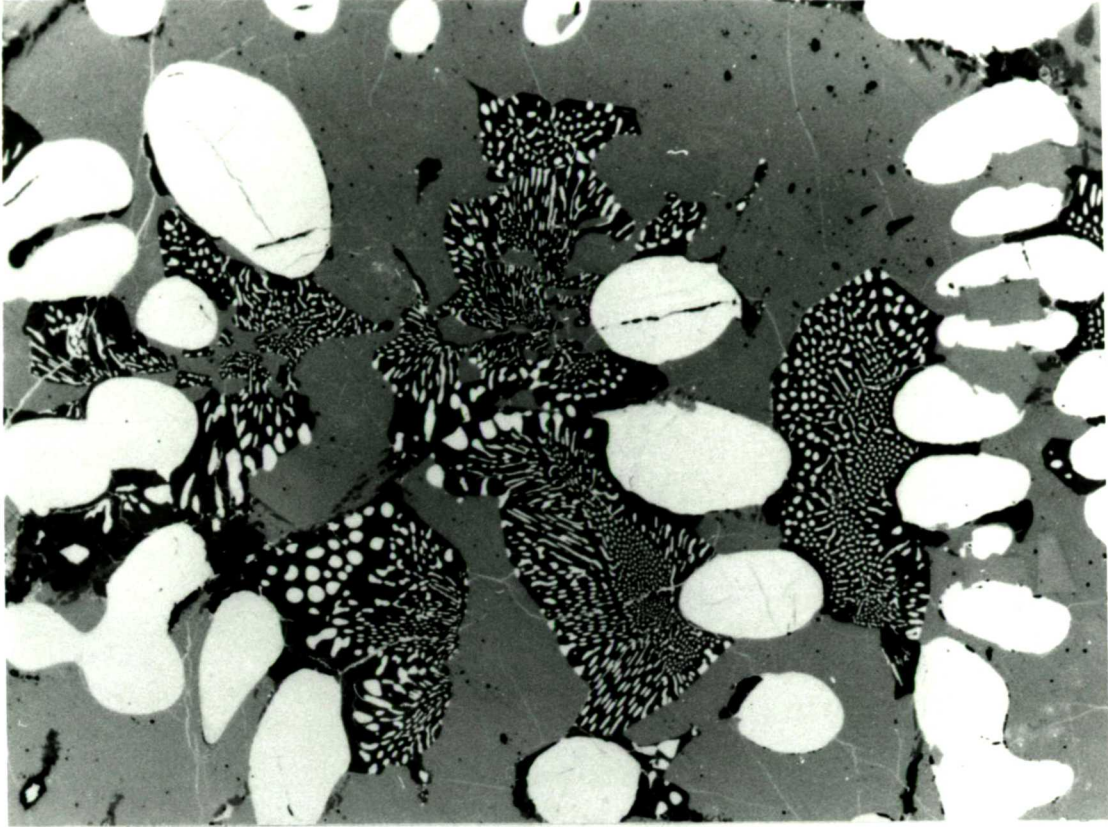


a
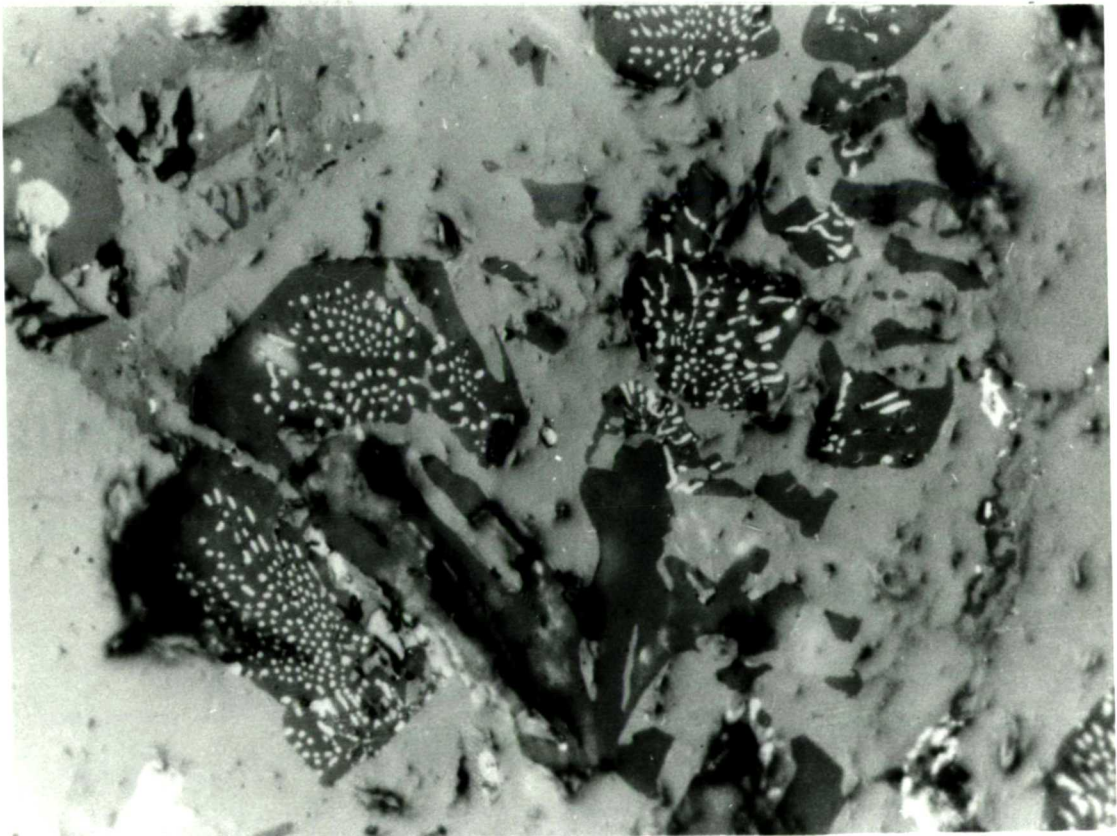


b

## Plate 12

(a) Broadfield: a chill surface is seen as a white line running through the centre of the section. The crystal structure coarsens as the distance from the surface increases. This results from oxidation and rapid cooling of the slag surface as it is tapped from the surface. The white line is thought to be largely magnetite. The bulk of the slag comprises olivine in a dark glassy matrix (50x).

(b) As above (200x).

(c) As above but away from the chill surface. Secondary wustite is crystallising along the planes of the olivine phase (200x).

(d) WM1: a slightly different chill surface detected in the slag from an experimental smelt, but on this occasion from a furnace slag and not tapped. Here the chill surface must result from the blast causing oxidation at the slag surface before it was covered by a fresh flow of slag. The lustrous phase is largely the spinel, magnetite with some wustite. In the background, fine laths of olivine in a glassy matrix can be observed (50x).

(e) WM1: The same chill surface, but with the iron oxide phase taking on the more characteristic rounded dendritic structure of wustite in the top right-hand corner. As the oxygen content of the wustite increases, the crystal habit is thought to become more angular (400x).

(f) SE1: general view with dense (lustrous) wustite dendrites overlaying an olivine phase in a fine glassy matrix. Small droplets of metal are also evident (100x).

(g) Towcester: general view of slag from a smithing forge with familiar wustite dendrites, olivine and glassy matrix. Two area of corrosion (light grey, amorphous) are apparent, one to the left of the metal droplet and the other in the lower right corner (100x).

(h) Towcester: as above, with a clearer view of the corroded area in the top left corner. Similar slag structures can be found in both smithing and smelting slag (200x).

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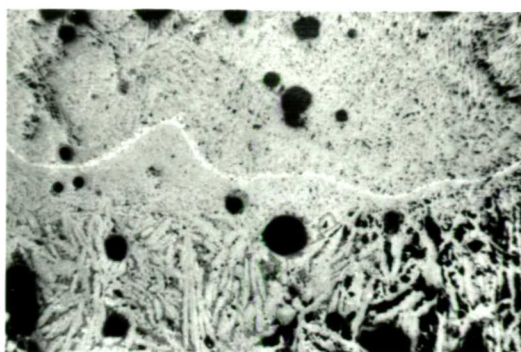
# PLATE 12



(a)
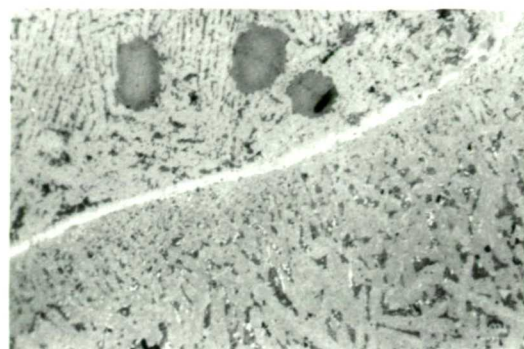
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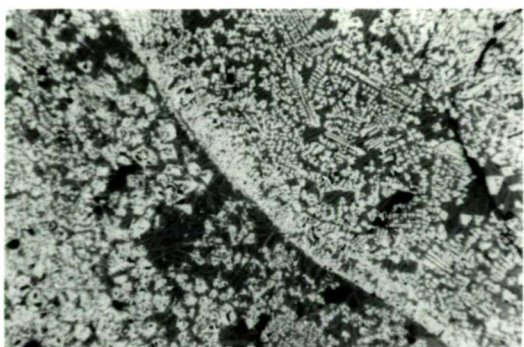
(d)

(e)
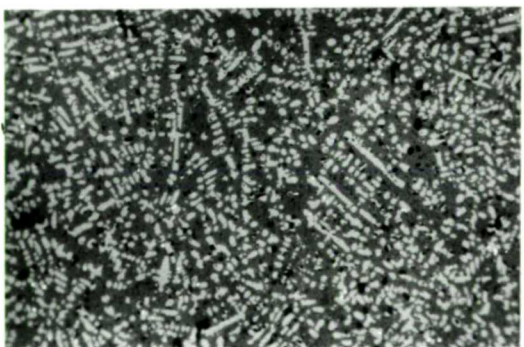
(f)

(g)
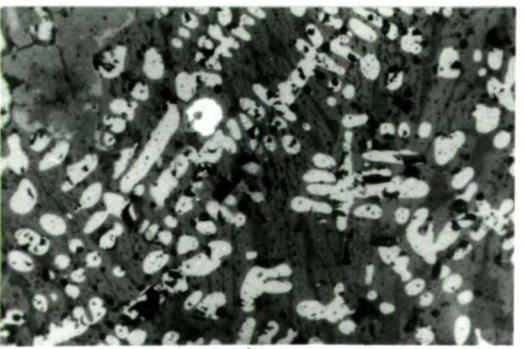
(h)

Plate 13

(a) Garden Hill: Sl-124, backscattered electron image, showing the bulk olivine with some wustite (light) and two small area of a glassy phase (dark) (60 microns wide).

(b) Sl-124: element map for silicon, dense in the glassy region at top of section (60 microns wide).

(c) Sl-124: iron, as expected, dense in the wustite and olivine phases, absent in the glassy phase (60 microns wide).

(d) Sl-124: calcium absent from the glassy phase and indicating two different levels of concentration in the olivine (60 microns wide).

(e) Sl-124: potassium concentrated in the glassy phase (60 microns wide).

(f) Sl-124: aluminium, with a similar distribution to potassium, with the exception of a high concentration in the lower right of the section. Here both aluminium and iron are concentrated and represent the spinel, hercynite (60 microns wide).

# PLATE 13
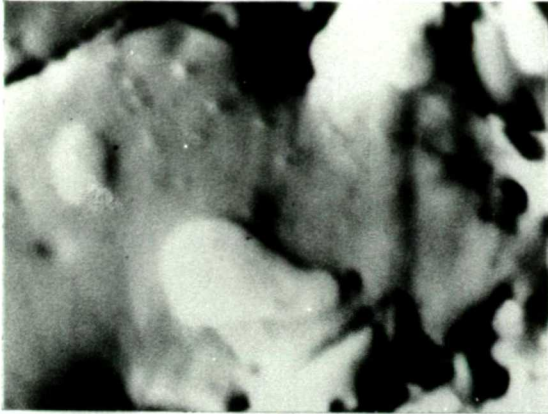


(a)
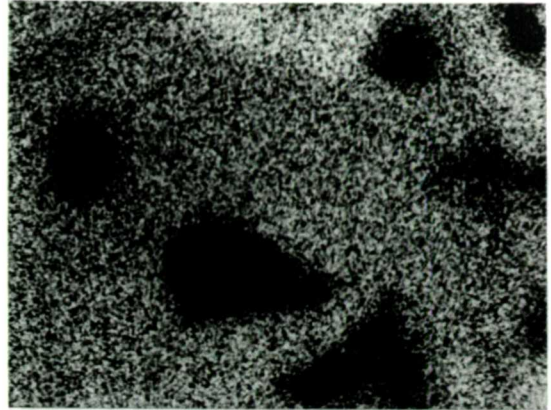
(b)
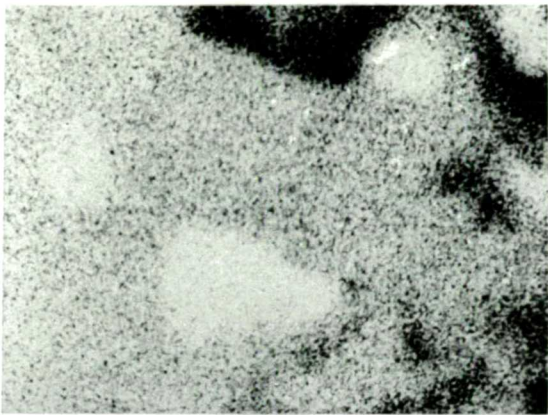
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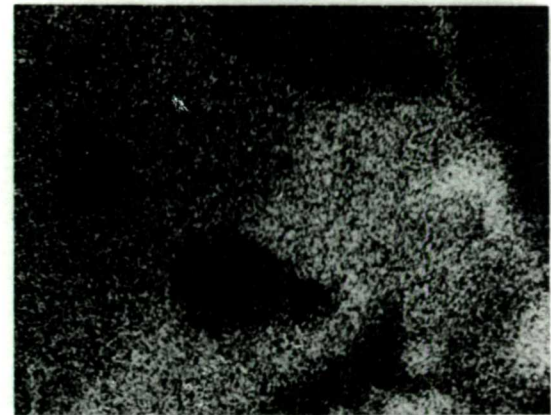
(d)

(e)
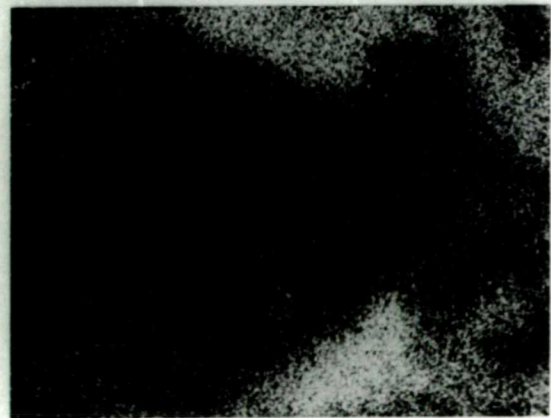
(f)

Plate 14

Analysis and element maps of slag phases from experiment O.4 smelting Odell ore.


(a) Odell experimental: O4, backscattered electron image. Wustite dendrites (white), olivine (medium grey, and glass (dark) (100 microns wide).

(b) O4: iron present in all phases but only minor amounts in the glass (100 microns wide).

(c) O4: silicon (100 microns wide).

(d) O4: calcium present in both glass and olivine (100 microns wide).

(e) O4: potassium (100 microns wide).

(f) O4: aluminium with an identical distribution to potassium (100 microns wide).


| | Olivine | Glass | Wustite | Spinels |
|---|---|---|---|---|
| $SiO_2$ | 26.5 | 36.0 | n.d | n.d |
| FeO | 66.1 | 21.0 | 96.8 | 47.7 |
| $Al_2O_3$ | n.d | 18.5 | 0.5 | 44.4 |
| CaO | 4.5 | 15.3 | 0.4 | n.d |
| $Na_2O$ | 0.0 | 0.8 | n.d | n.d |
| MgO | 2.9 | n.d | 0.5 | 2.5 |
| S | n.d | 0.2 | n.d | n.d |
| MnO | 1.1 | n.d | n.d | 0.7 |
| $K_2O$ | n.d | 5.8 | n.d | n.d |
| $TiO_2$ | n.d | 0.3 | 0.9 | 1.7 |
| $Cr_2O_3$ | | | | 1.4 |
| $V_2O_5$ | | | | 0.7 |

No hercynite was detected in the above section, but spinels of this composition were common in sample O1.4 and other Odell slags.

# PLATE 14
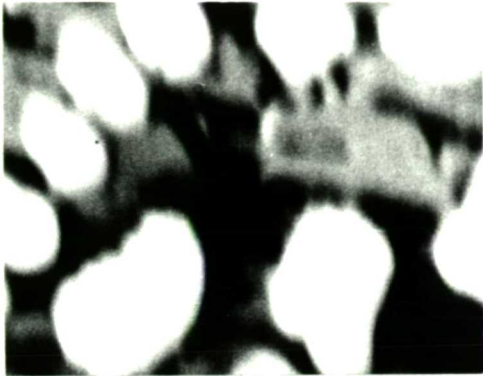


(a)
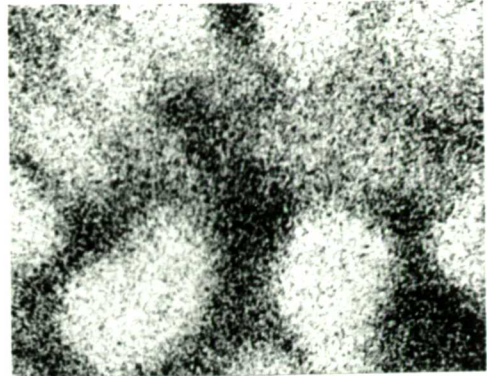
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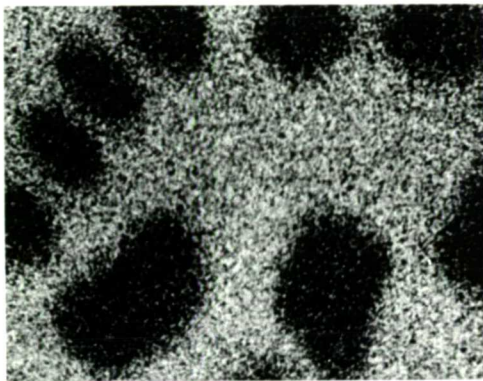
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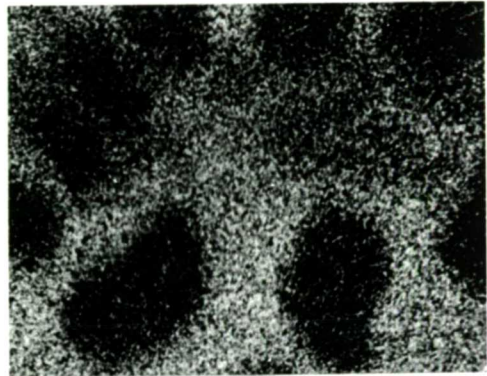
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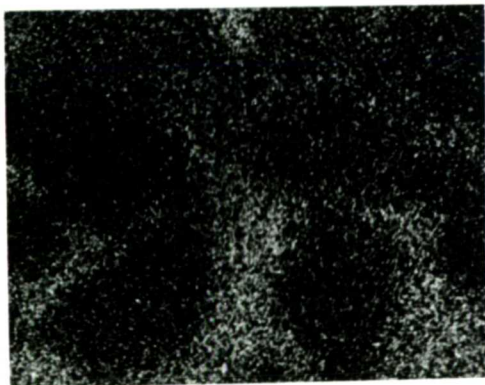
(e)
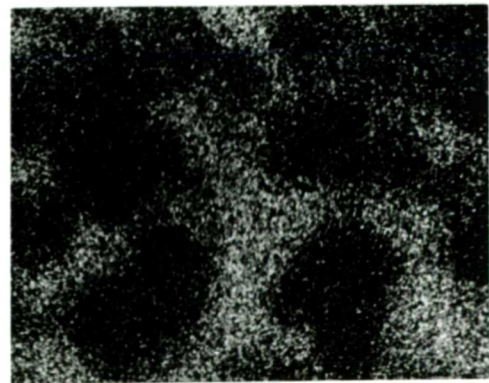
(f)

**Plate 15**

Partitioning of elements in slag phases

(a) Garden Hill: S1-495, backscattered electron image. Light phase is wustite, olivine (medium grey) and glassy phase (dark grey) (50 microns).

(b) S1-495: iron distribution indicating highest Fe concentration in wustite, with slightly less in the olivine and a minor amount in the glassy phase (50 microns).

(c) S1-495: silicon: absent from the wustite phase (50 microns).

(d) S1-495: calcium: primarily in the glass (50 microns).

(e) S1-495: aluminium (50 microns).

(f) S1-495: potassium (50 microns).

(g) Towcester: the right side of the section shows the beginning of slag corrosion with the glass phase being first to be leached (200x).

(h) Towcester: indicating extreme corrosion of the slag structure. The laminated surface to the left is redeposited iron oxides, mainly goethite, while the central area shows the olivine structure breaking down (200x).

PLATE 15



(a)
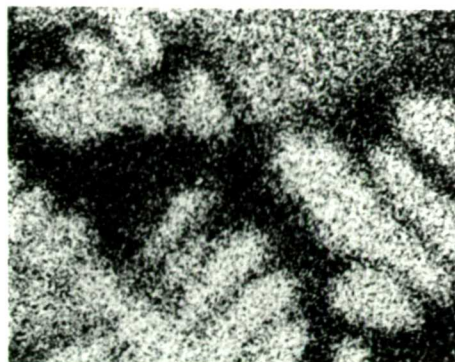


(b)
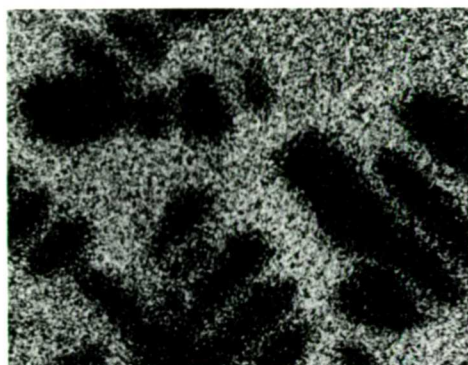


(c)
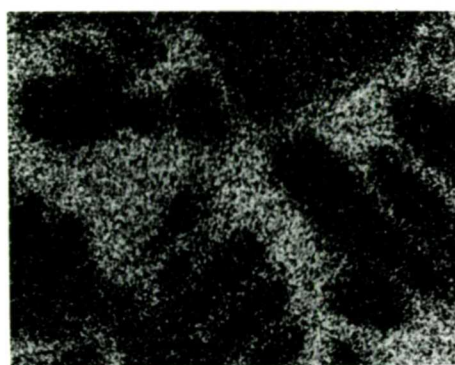


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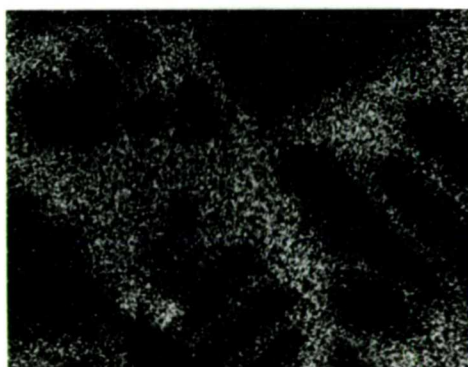


(e)
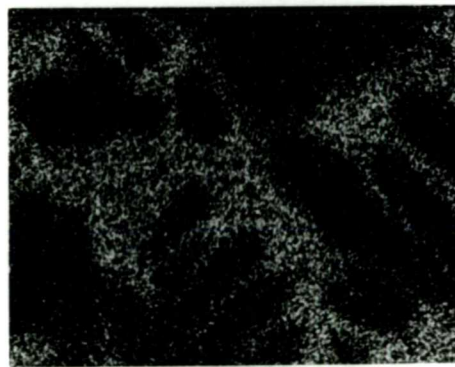


(f)
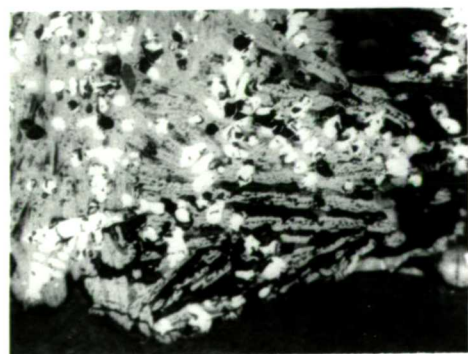


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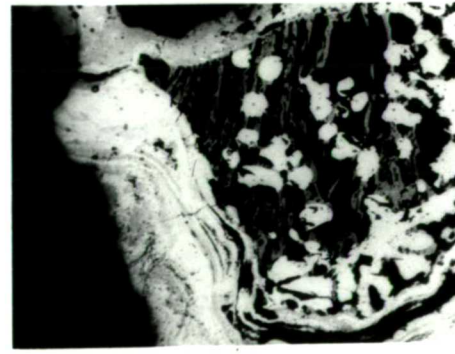


(h)

# Plate 16

## Slag Corrosion

(a) Garden Hill: S1-495, backscattered electron image with circular corroded region (rough) and the original slag structure of fine wustite dendrites and olivine with a small amount of glass (300 microns wide).

(b) S1-495: calcium, with noticeable depletion of calcium in the corroded area (300 microns wide).

(c) S1-495: iron, with vague outline of dendrites (300 microns wide).

(d) S1-495: silicon, evenly distributed but absence clearly defines wustite dendrites (300 microns wide).

(e) S1-495: potassium, with a similar distribution to calcium (300 microns wide).

(f) Garden Hill: S1-477, deep pitting in corroded area (100x).

(g) Brooklands A: the bulk consists of dense wustite dendrites in an olivine matrix, with a large area of dense corrosion (amorphous, light grey) representing either corroded metallic inclusion or iron mineral (100x).

(h) Garden Hill: S1-397, fine wustite dendrites, and fayalite in a glassy matrix, heavily corroded on the right of the section.

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# PLATE 16



(a)
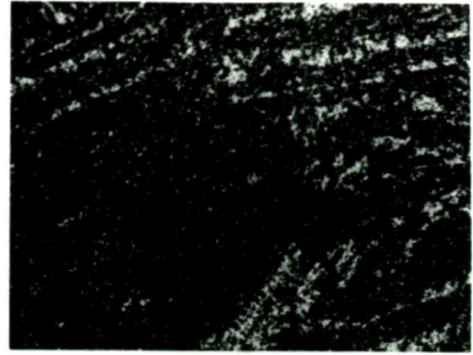
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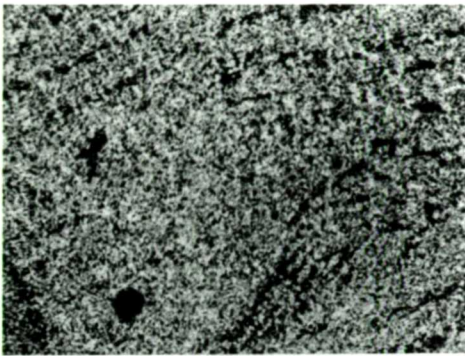
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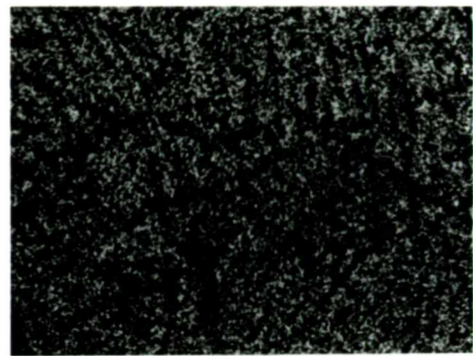
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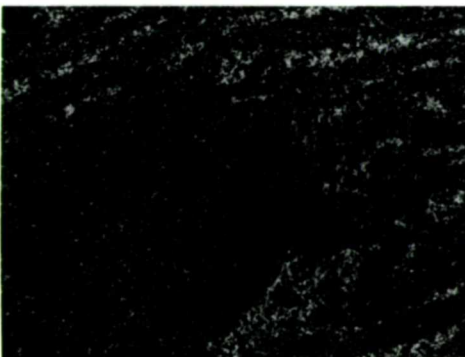
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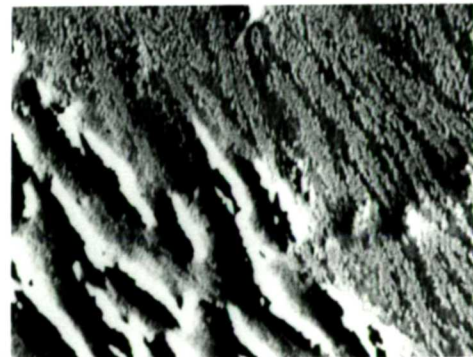
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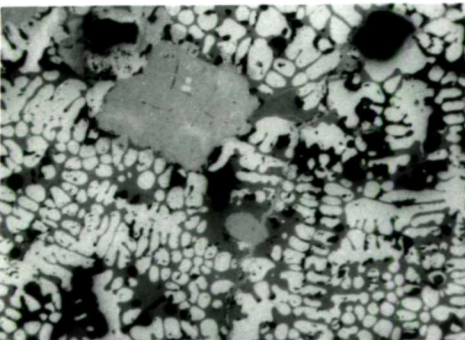
(g)
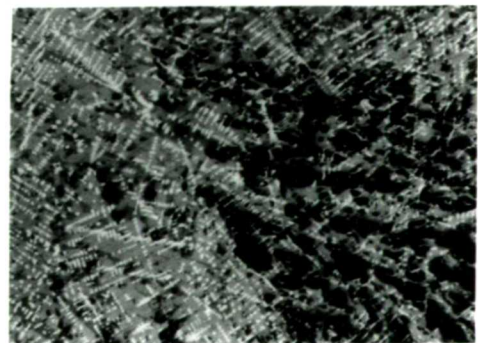
(h)

Plate 17

(a)  Odell:  Fi 30  even  fine-grained  structure  with
     approximately 0.4% carbon (50x)

(b)  Odell:  Fi 30, as above with some patches of dense
     pearlite (200x).

(c)  Odell: as above (400x).

(d)  Odell:  Fi 53,  a nail head with corroded surface.
     Fine-grained  and  heavily  worked with  slag  and
     corrosion  indicating  the  direction  of  working
     (50x).

(e)  Odell: Fi 53 as above, an uneven grained structure
     of ferrite and slag inclusions (200x).

(f)  Odell:  Fiii 37,  unidentified object with  uneven
     grain  structure,  corrosion and slag  inclusions.
     There  appear  to be several layers of  differing
     carbon  content  ranging  from  fine-grained  low-
     carbon  steel on the right of the section  to  the
     large  ferritic  grains  on  the  left.   Such  a
     combination  usually  suggests  the  presence  of
     phosphorus or piling (or both),  because  normally
     the  material  higher  in carbon would have a  lower
     critical  temperature;  thus  grain  growth  would
     occur  initially in this  region.  Alternatively,
     the  structure  relates  to  strips  of  varying
     composition welded together (100x).

(g)  Odell:  Fiii 37,  as above in ferritic region with
     cellular precipitation at the grain boundaries and
     two-phase slag inclusions (400x).

(h)  Odell:  Fiii 37,  In the higher-carbon region with
     small grain structure and a mixture of ferrite and
     pearlite in a Widmanstatten structure,  similar to
     the structure in the experimental bloom, plate 5h,
     (400x).

PLATE 17
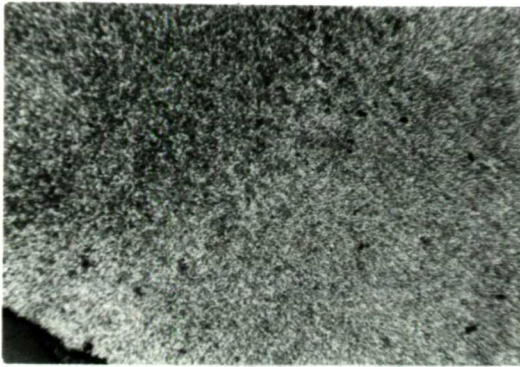


(a)
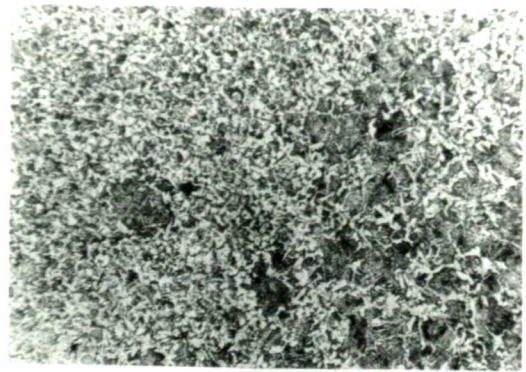


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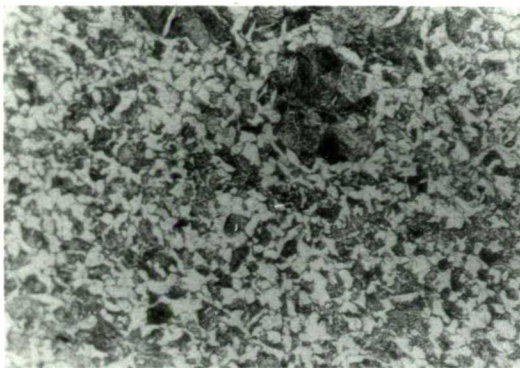


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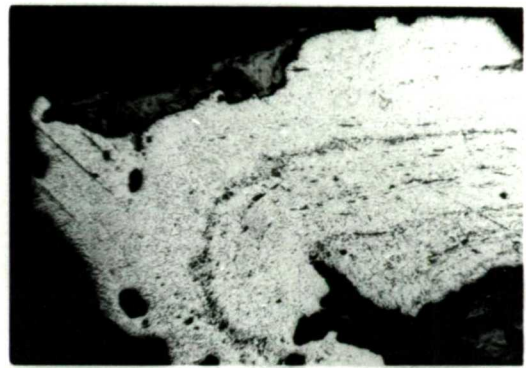


(d)
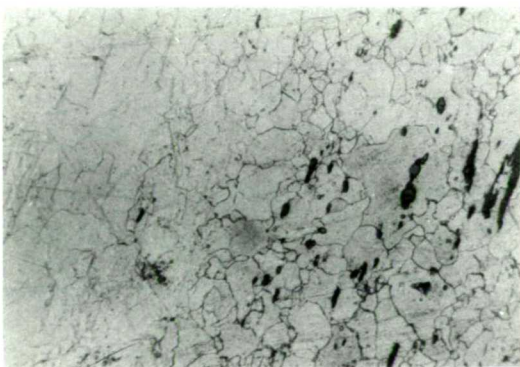


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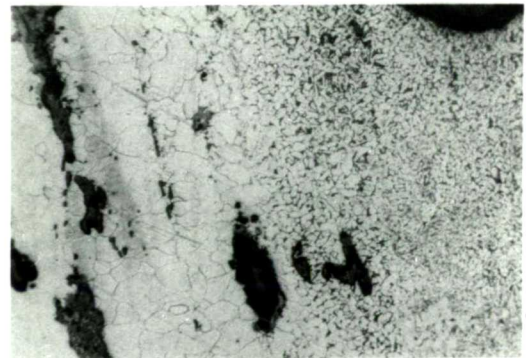


(f)
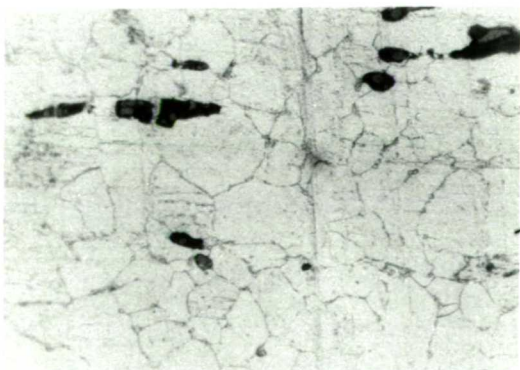


(g)
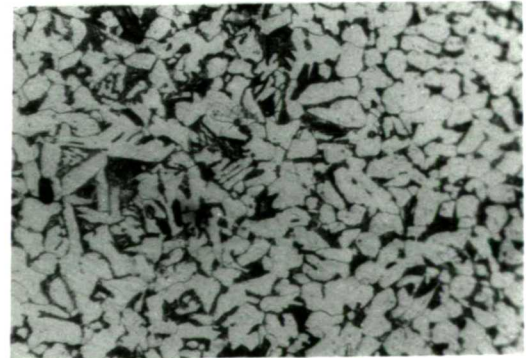


(h)

Plate 18

(a)   Odell,   Fiii   62:     a  heavily  corroded   low-carbon
      steel   with   a  fine-grained  structure  of   pearlite
      and ferrite (100x).

(b)   Odell,   Fiii  21:    end of bolt?   A  low-carbon steel
      with small equiaxed grains (200x).

(c)   Odell, Fiii 62: same as (a) (400x).

(d)   Odell,  Fi 57:  a  low-carbon steel with  uneven grain
      size  and at least four laminations demarcated  by
      slag and a concentration of pearlite, probably the
      result of piling (100x).

(e)   Experimental   slag  (Odell ore)  O1.1:   showing   the
      growth   of   the   bloom  in  a  slag   matrix.   Small
      droplets   of  iron  appear  to be  attracted  towards a
      larger    particle    (presumably    electromagnetic
      attraction?).   The   slag matrix   comprises   wustite
      (light),   spinels  (medium grey),  and olivine laths
      in a dark glassy matrix (100x).

(f)   The same:  with a globule of iron welding itself to
      a   larger   mass of iron in the slag   matrix.   The
      iron  is   ferritic with the exception of  a  small
      region of the globule which is a coarse  pearlite.
      Indicates   that carburisation has occurred in  the
      higher  levels of the furnace before agglomeration
      of the bloom (200x).

(g)   The same:   another example of bloom particles in a
      slag mass,   however,   on this occasion wustite and
      not  smaller  particles  of  iron  appear  to   be
      attracted  to and move towards the iron particles.
      The  slag has a pyroxene pq olivine composition  ?
      (100x).

# PLATE 18



(a)

(b)

(c)

(d)

(e)

(f)

(g)

Plate 19
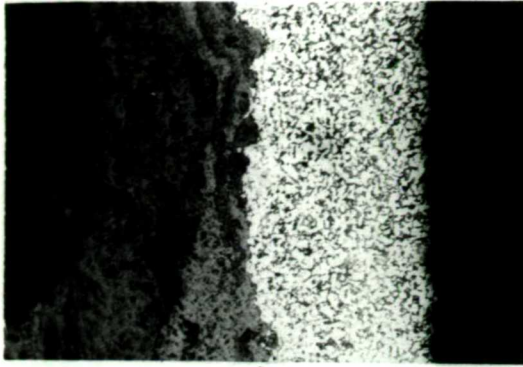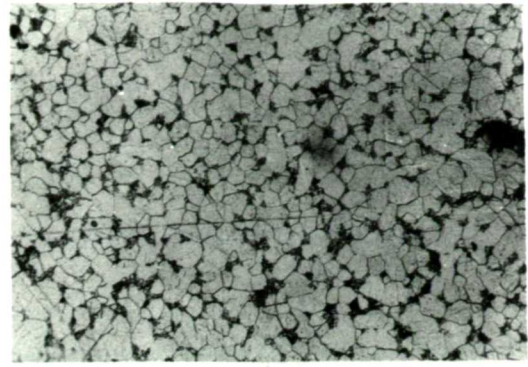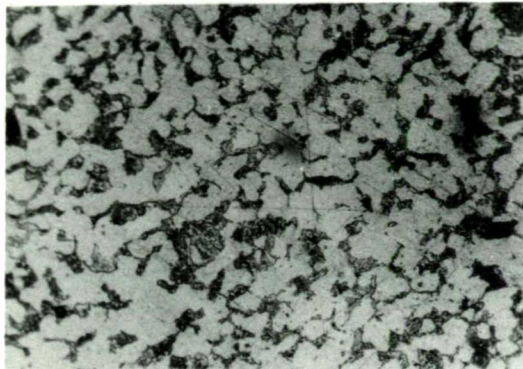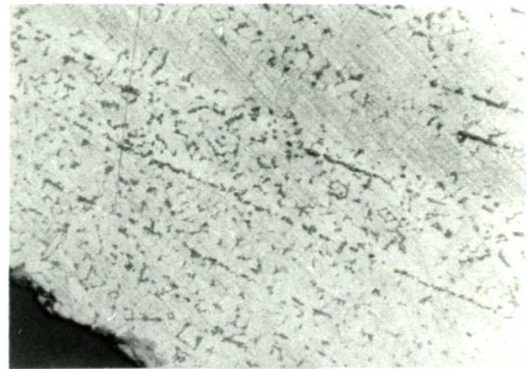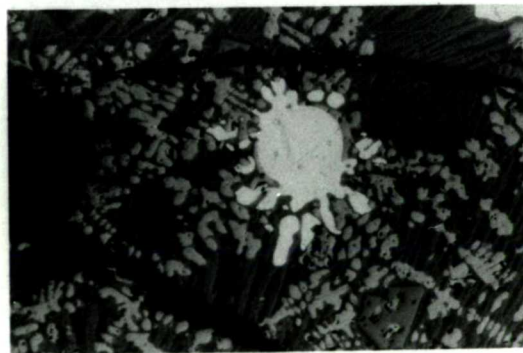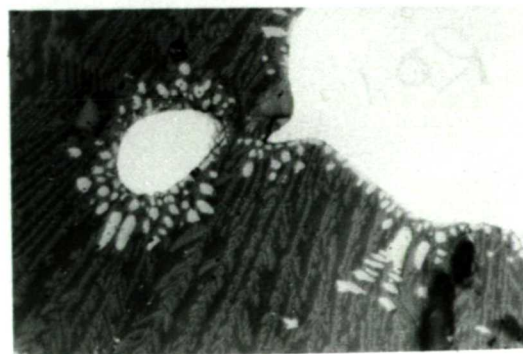
(a) Tapped slag: copper (left); iron (right) has a tapped appearance but was formed within a low shaft furnace.

(b) Tuyere (silimanite) with slag fused to under-surface (from experimental smelt).

(c) Small pieces of bloom from an experimental smelt using the roasted ore from Odell.

(d) Two small (c. 0.5kg) cakes of smithing slag from Bagendon (Gloucs.)

(e) Furnace bottom produced in a bowl hearth with the ore charged to the back of the furnace, with charcoal between the ore and tuyere (catalan method).

(f) Two cakes from Cow Down (see also 20c, left).

# PLATE 19



a

b

c

d

5 Cm
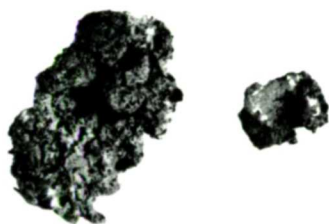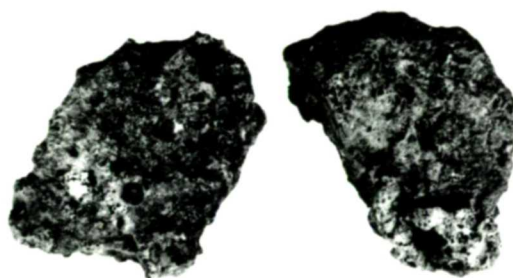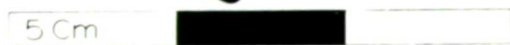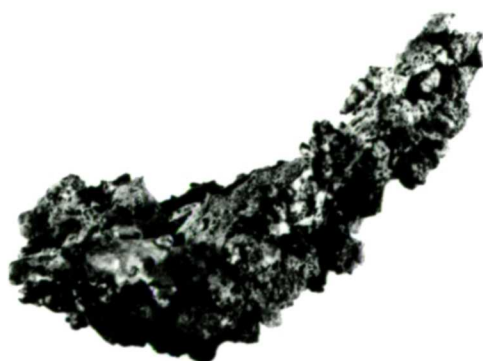
e
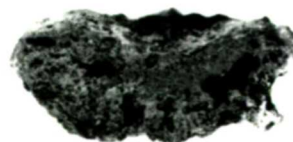
f

**Plate 20**

(a) Odell furnace bottom (F73). A plano-convex cake from a forge. Top left of the cake is very porous and low in iron, while the remainder is dense fayalitic slag.

(b) Footlands (Weybridge) is a large, dense and fairly homogeneous plano-convex cake of slag (c. 3kg). It is not clear whether this is from smithing or smelting (though most likely the former) and both smithing and smelting were carried out at the site.

(c) Two small plano-convex cakes from Cow Down (Hants), heterogeneous and very corroded with a high iron content (top view of the cake in 19f bottom).

(d) Similar cake from Gussage All Saints (top view). Evidence suggests smithing as definite smelting slags from the site are quite different in character.

(e) Towcester (Abbey Farm site) produced several plano-convex cakes of heavily corroded slag. These are fayalitic with dense wustite. The 'tails' are suggestive of small flows of slag tapped from a furnace, although such tails could form under the tuyere.

(f) A small cake of slag (top view) from a smithing experiment. Plano-convex in section, it also contains numerous charcoal inclusions.

# PLATE 20



a

b
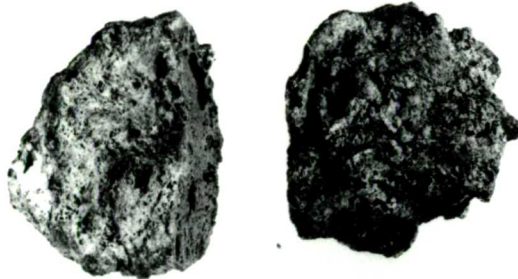
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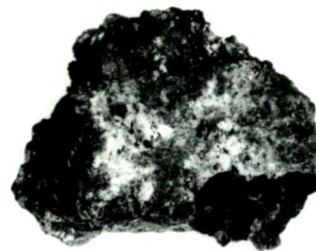
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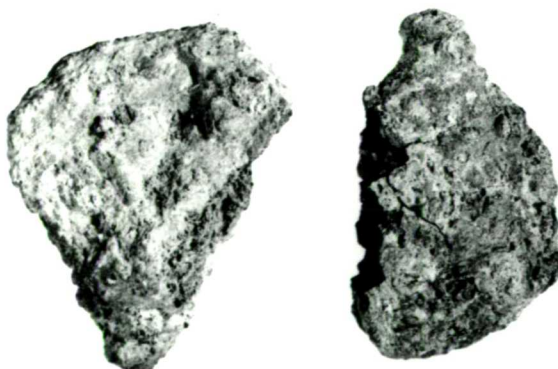
e

f

Plate 21

(a) Large furnace bottom from the site of Mucking.
Very fluid slag in the top half and a mixture of
large chunks of charcoal and intertwined slag at
the base.  Corroded remnants of iron skins around
the charcoal, produced by reduction of iron from
the slag as it coated the burning charcoal.  On
the lower left of the block and other parts of the
surface there are clear indications of reaction
with furnace lining.  It has been suggested that
this derives from a slag-pit furnace but its
characteristics appear consistent with a slag
forming in the furnace below the tuyere, but not
running into a tapping pit below the furnace.

(b) Furnace bottom from an experimental smelt
utilizing a low shaft furnace (ore from Seend,
Wiltshire).  The slag is dense (fayalitic with
very little wustite) and homogeneous.  The small
prills of metal seen in the base of the slag cake
are white cast iron with Vickers hardness c. 500.
On the top left of the cake, the slag is more
porous with some entrapped charcoal.  A small iron
bloom can be seen in section (low carbon c. 0.2%).
On the top right, the porosity is low and there is
an indentation caused by the blast from the
tuyere.

# PLATE 21



(a)

0    50    100    150    200    250 mm
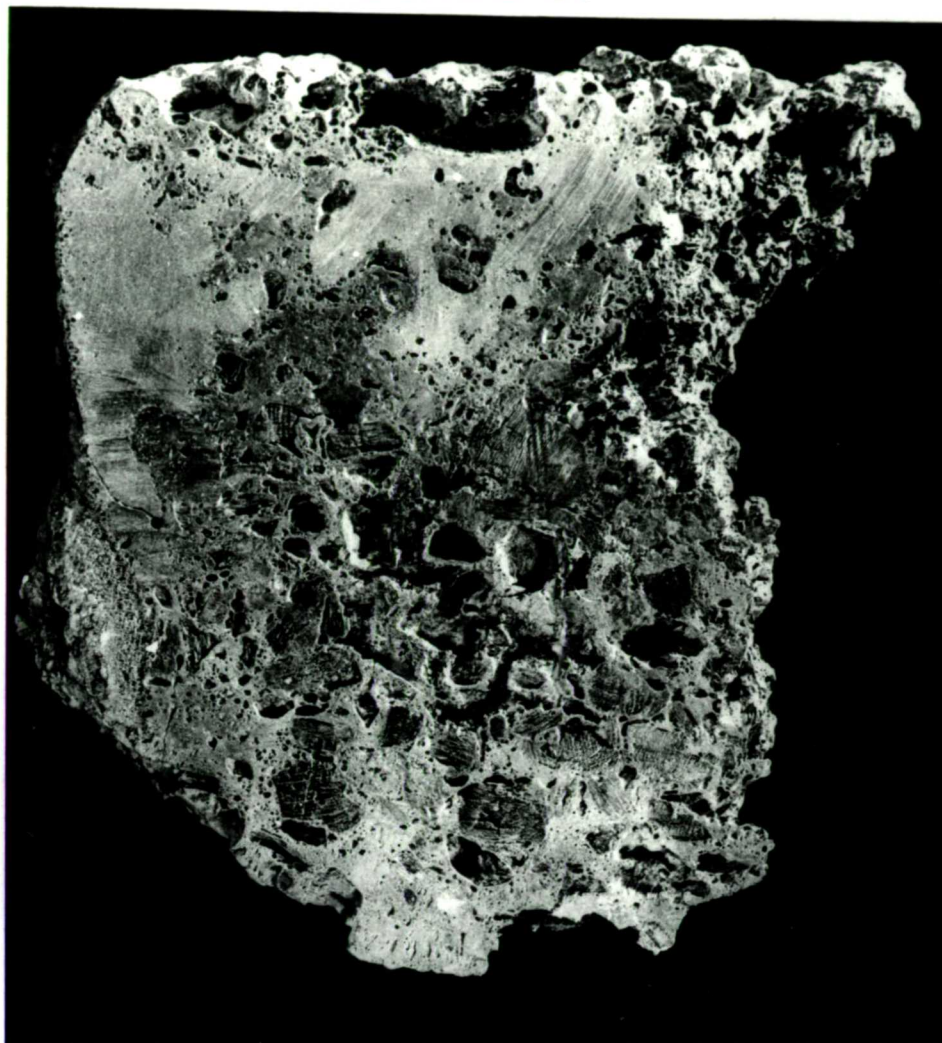
(b)

5Cm
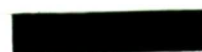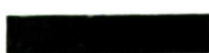
Plate 22

(a) Fiskerton 1981 (403). Section of an Iron Age hammer showing white segregation lines in a matrix of martensite and troostite (light etching). These probably relate to weld lines deriving from folding of the metal or joining two strips. The structure has been intentionally quenched (30x).

(b) The same: enlarged view of segregation line (200x).

(c) The same: troostite clearly seen in martensite (200x).

(d) Whitcombe hammer from the Whitcombe warrior grave with a suggested date of late Iron Age, displays a complex piled structure with segregation bands surrounded by martensite, and therefore a quenched structure (50x).

(e) A different region of (d) with troostite bands in a matrix of martensite (light etching) (100x).

(f) Enlarged section of (e) clearly revealing the quenched structure of bands of troostite in a martensitic matrix (200x).

(g) Fiskerton 1981 (332). A hammer with a complex microstructure. Piled bands of carburised iron together with some high in phosphorus. The hardness of the carburised bands is 247-308 VHN, while the low-carbon areas are in the same range. The hardness of the latter must be attributed to phosphorus levels. Closer examination of the carburised regions reveals some 'martensite' and other cooling structures. Hardness of the 'martensite' is low, c. 412/420 VHN, while the adjacent ferrite is 236. The structure suggests some quenching, but impurities such as phosphorus are probably responsible for the peculiar results (30x).

(h) The same: enlarged area of above with slag inclusions (100x).

Samples from Fiskerton and Whitcombe were kindly provided by V. Fells.
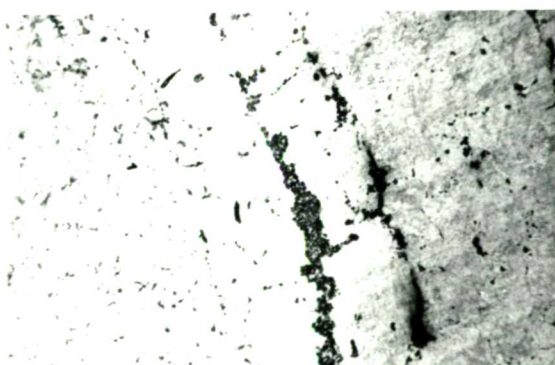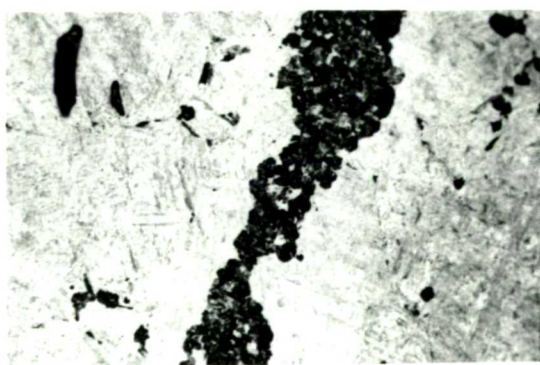
# PLATE 22
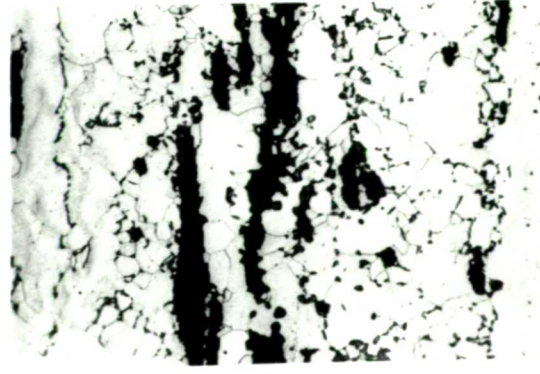


(a)
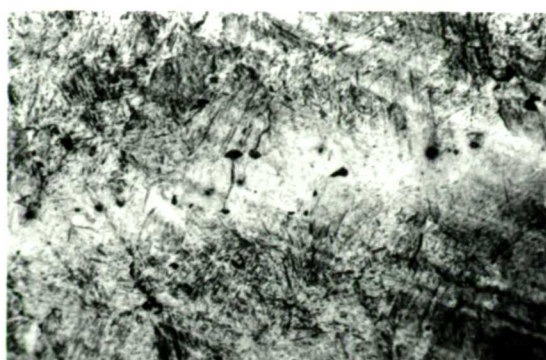
(b)
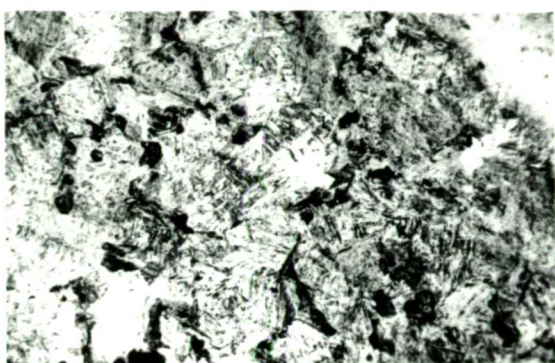
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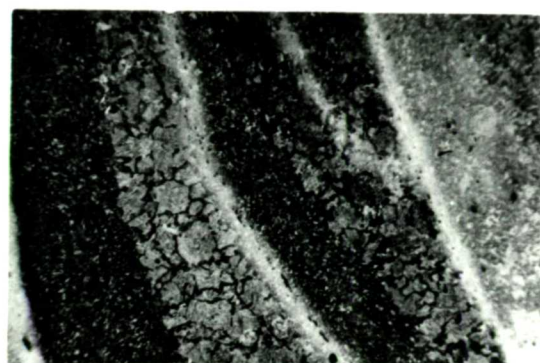
(d)

(e)

(f)

(g)

(h)

**Plate 23**

(a)   Late La Téne.   A massive furnace bottom from
      Eisenberg:   c.1m external diameter and 80cm  high,
      25cm  thick at the base with an internal  diameter
      45-50cm.   This furnace bottom consists of bloomery
      slag and some entrapped charcoal.   The latter was
      in   pieces   of  at  least  4  x  10cm   (surface
      examination only) (Speyer Museum)


(b)   *Spitzbarren  (Stumpfbarren)*.  One of several types
      of  these bars to be found in  the  Rhineland,  La
      Téne-Roman periods.   These weigh 3-5kg and date to
      the  second half of the last century  BC.   Others
      are more elongated (part of one showing on left of
      plate).   Two  are from Schmalenberg and one  from
      Ramstein  and  they  are  labelled  loom  weights
      (Speyer Museum).

# PLATE 23
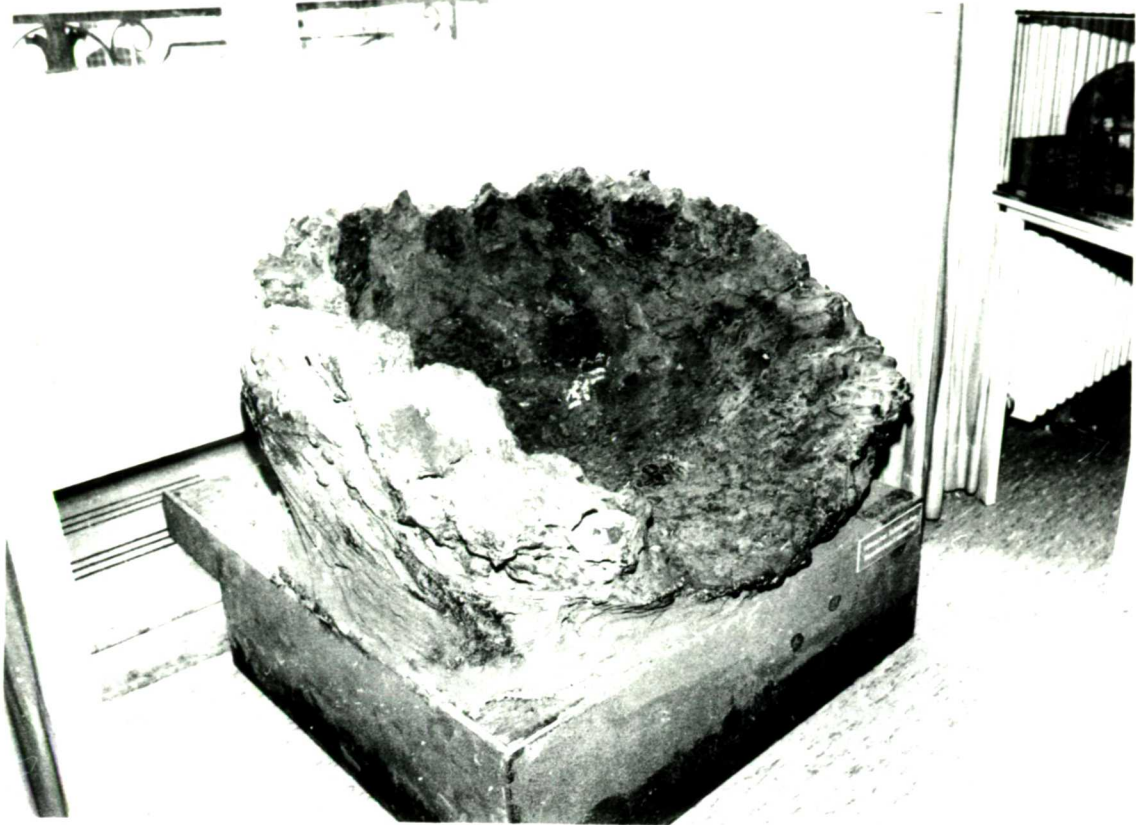


a



b

Plate 24

(a) Experimental low shaft furnace (non-tapping): 22cm internal diameter with a single tuyere inclined 45°, shaft 50cm high. This is encased in an asbestos/dexian frame which is filled with sand to reduce heat loss. The blast was supply by an electric pump and measured with a flow meter.

(b) A small experimental bowl-furnace: 30cm internal diameter 30cm deep, built of straw-tempered coils of refractory clay with one layer of refractory bricks to help contain the charge at the top.

(c) Garden Hill. The remains of a shaft smelting furnace, c.40cm internal diameter, with slag remaining in the tapping pit (lower part). Shows how little of the superstructure remains.

(d) Same furnace as above (feature 773), but in section. Concretion of slag in base of furnace and in tapping pit (right), with three layers of furnace lining presumably from rebuilding after a smelt.

(e) Hodges Wood (Crowborough). A stream had sectioned three furnaces (e, f and h) (Romano-British??); all c. 90cm in diameter. Viscous slag, some tapped, and other pieces from the furnace were found in the stream and in a deposit behind the furnace. Furnace F3 can be seen on the right of the section.

(f) Hodges Wood (F3) with a tree growing out of the furnace hearth. The tree was removed together with several large cakes of slag. Blocks of slag had been used to construct the walls of the furnace and near an adjoining pit overlaid a flat sandstone block which appeared to be positioned in the pit as an anvil. Residue of slag and hammerscale was found in the surface of the block. It is suggested that the bloom was extracted from the furnace onto this block and cut into smaller pieces and given preliminary forging.

(g) An enlarged view of furnace 2: see (e).

(h) A faint outline of furnace 1 (slightly larger than 2 and 3), but showing the same reduced to oxidised (blue-red) layers of the surrounding clay. Inside this larger structure was a considerable quantity of burnt ceramic and the remains of a shaft, 35cm internal diameter. This appears to have fallen into the furnace and possibly is, part of the superstructure of this large furnace 1.1m diameter.
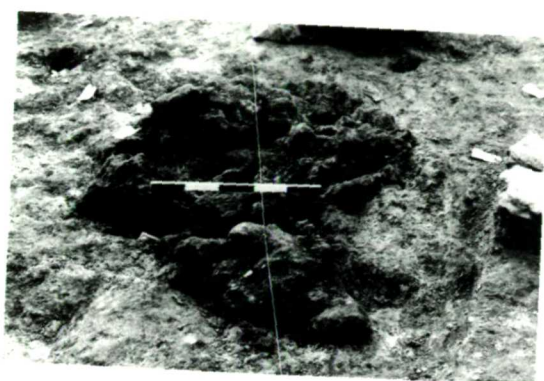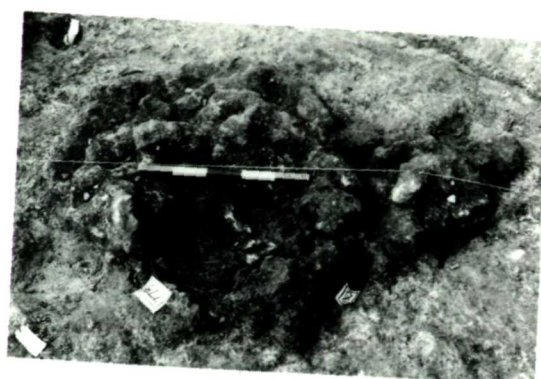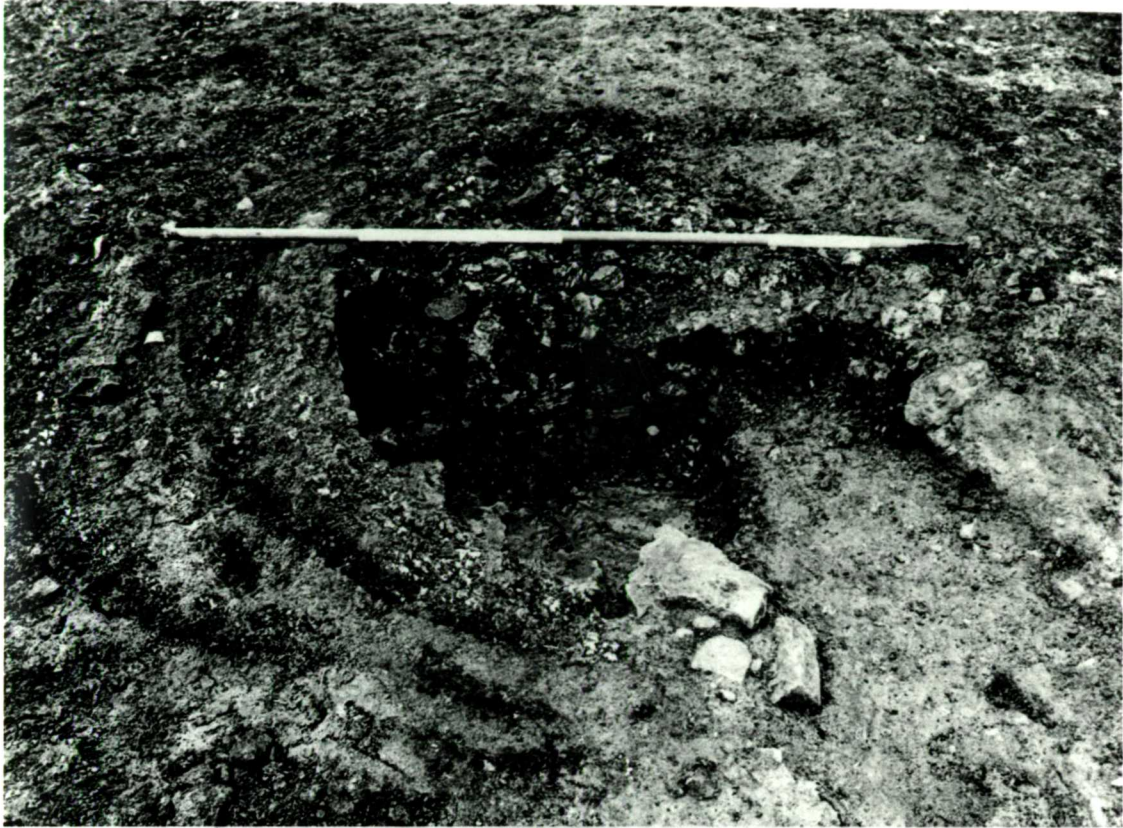
# PLATE 24



(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Plate 25

(a) Laxton Hall (Northants.). Remains of a large smelting furnace, c.1.2m internal diameter. The lower walls and hearth are heavily slagged and the structure of the slag is a typical bloomery product (olivine and wustite). The fill is largely burnt clay, probably from the original superstruture. Several rebuildings of the furnace walls can be clearly defined and are up to 40cm thick. To the left in (a) and at the top in (b) was a dense concentration of roasted ore fines and charcoal. Large quantities of charcoal were found on the site.

(b) Another view of (a) with the slagged base clearly seen.
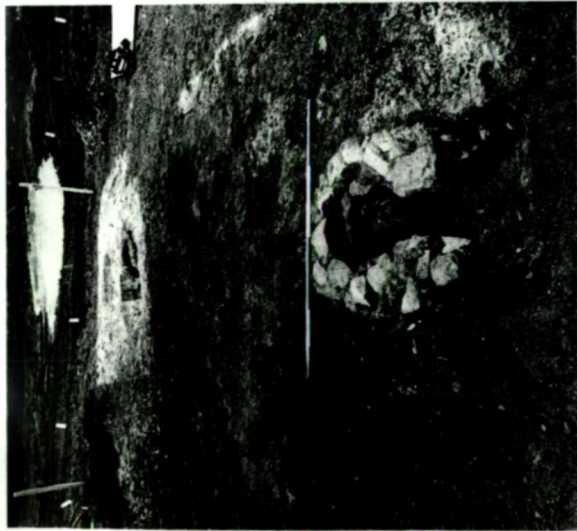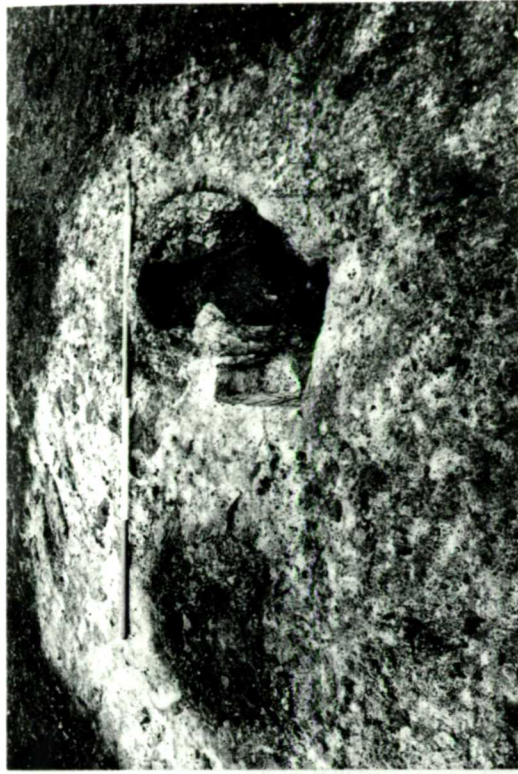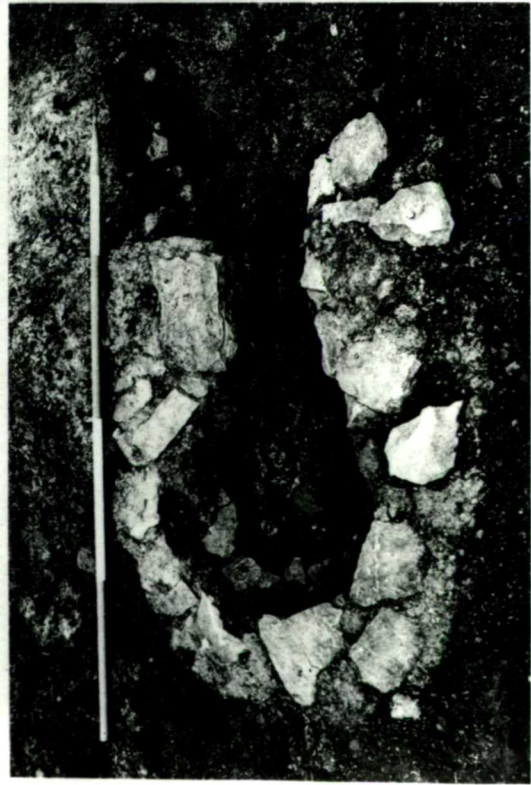
# PLATE 25



(a)



(b)

**Plate 26**

(a) Laxton Hall. Apart from the large-diameter furnaces (plate 25), this site had at least two further types both built into specially constructed clay banks (platforms). This plate shows the outline of the rectangular clay platform a stone-built furnace at the near end.

(b) The remains of two shaft furnaces, c.30cm internal diameter, are seen embedded into part of the clay bank. The one excavated appears to have a tapping pit under the clay.

(c) This low stone-lined hearth appears to have no superstructure and may be part of a forge.

(d) An enlarged view of the excavated shaft furnace, with evidence of three relinings. The surrounding clay has been reddened by the heat, suggesting that the clay was *in situ* and not used to fill in after the smelting operation.
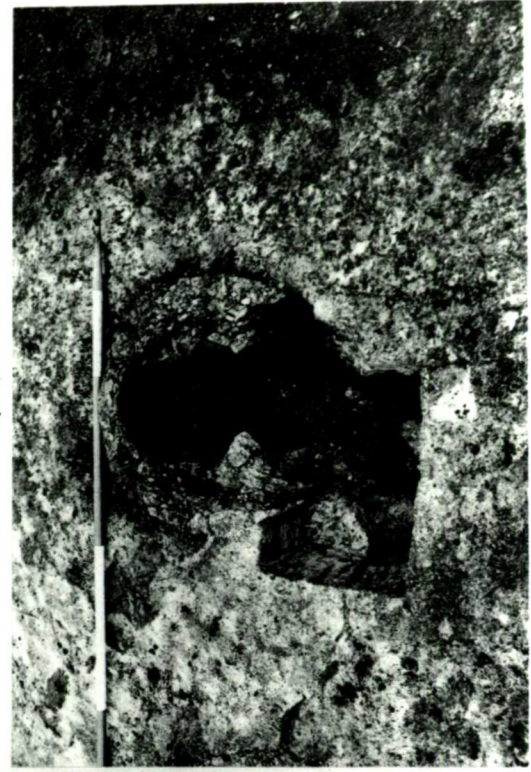
303

(a)

(b)

(c)

(d)

PLATE 26