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Cover illustration: Ironwork on the south door of St Mary's church at Meare, near Glastonbury in Somerset, NGR ST455416, photographed by George Parker. According to Nikolaus Pevsner's **South Somerset**, in **The Buildings of England** series, it could be early fourteenth century work, and the church was dedicated in 1323.

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An assessment of lead smelting processes and the use of XRF for the analysis of resulting slags

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Abstract

This paper examines, by means of a bibliographic search and experimentation, the development of the techniques employed in lead smelting, during ancient and historical periods. Using the Phillips EDAX 9500, at the University of Bradford, School of Archaeological Sciences, a series of 24 quantative analyses was made, and the results used in a discussion of likely modes of slag formation. These problems associated with the production of reference standard, for use with XRF, are identified, and solutions proposed.

Introduction

There is a growing interest, amongst archaeologists and industrial archaeologists, in the smelting of lead ores. A perusal of the various archaeological journals, however, soon reveals that great emphasis has been given to the study of the smelting of iron and copper ores, and the analysis of the resulting slags; whether from sites of great antiquity or more recent history. For the treatment of lead, however, this work is in a remarkably neglected state, with some descriptions of processes, and very little archaeological investigation of sites which might be used to test them.

It was the intention of this project to identify those problems which would have to be overcome before any large scale, controlled analysis of lead slags could be undertaken by means of the Energy Dispersive X-Ray Fluorescence System (Phillips EDAX 9500), available to the School of Archaeological Sciences, at the University of Bradford, and, also to compare the results obtained with those historically documented developments which were felt likely to be detectable in the slags. A glance at the gazetteer of sites, in the Appendix, will serve to illustrate the extent of any fieldwork, to be associated with such research, in Yorkshire alone.

A Historical Sketch of the Development of Lead Smelting in Britain

During the eighteenth and early nineteenth centuries, Britain's non-ferrous metal mining industry grew, in sympathy with her lead in other aspects of industrialisation and commerce, to dominate the World markets. By the later nineteenth century, however, the expansion of other, competitive, sources of ore, such as Spain, the United States and Austrialia, often with British capital and expertise, led to a rapid rise in imports. As a result of this, from the 1870's onwards, it became impossible to operate many of the mines economically, forcing the home industry into a catastrophic decline[1] and, whilst some richer mines did survive, by all realistic interpretation, it had become moribund by the end of the Great War.

That the Romans were quick to exploit the major sources of lead ore within Britain, is suggested by the number of "pigs" which have been found. Also, archaeological excavations on the Mendip, and at Carsington[2], in Derbyshire, have revealed smelting furnaces from that period. Because of the inscriptions on some of the pigs, there is a continuing debate about the nature of the Roman industry and its production of silver from the lead. That the Romans were aware of the technique of cupellation is without doubt, but the degree to which it was practised in Britain remains speculation. Some authors[3] have taken the variations of the inscription "Ex. Arg.", found on a number of the pigs, to mean that the silver was removed by a refining process. Others feel that the interpretation of the inscriptions should read "Without Silver". It was not, however, the purpose of this project to follow that particular argument, but it must be said that there is little evidence to suggest that, with perhaps two early seventeenth century exceptions[4], smelters from later periods regularly practised any form of de-silverisation in the Yorkshire and Derbyshire areas. Parts of Wales and the Northern Pennines were, however, large producers of silver, both by cupellation and by the more economical Pattinson Process[5], introduced in 1833.

As for the smelting of lead itself, there is much to suggest that the industry was very conservative in its methods and, unlike those for iron production, its furnaces never underwent a massive increase in scale. Even during the 1860s, arguably its most developed period, the average amount of metal produced by many of the reverberatory furnaces, or ore-hearths, was only in the tens of tons per week! Precise amounts are difficult to quantify because any one charge of ore would be recovered as: lead metal, lead fume and grey slag. The latter product required re-smelting, at a far higher temperature, in a slag-hearth, before the total yield of metal was obtained.

The early smelting sites, known as Bales or Boles, were wind blown furnaces and consisted of a ring of stones, about three or four feet in diameter[6]. They were normally positioned on the edge of a hill, facing the prevailing wind which, during 1774-75[7], in London came from the north-west and the south-west quarter for about 55% of the year, (Fig 1).

One early written record of a bole, is in the de Lacy Compotus[8], dated 1303-04, which refers to a lead mine at Baxenden in Rossendale, Lancashire:

	£	s.	d.
Carrying wood and ore to the bole		8	8.5
Expenses of burning the said ore	1	16	6
Making a pair of bellows anew for burning the said ore		7	8

From this, it is clear that bellows were in use for supplementing the natural draught, and careful excavation of such sites may prove that this was more frequent than hitherto thought.

A further example of monastic working is shewn on a set of maps[9] covering the lands of Marrick Priory, Swaledale, one of which is dated 1592. These indicate a line of four boles, running along Fremington Edge, Swaledale, with one set apart, and called the "Priores Bale". None of them appears to have been included in Barker's survey[10].

An even earlier date for their use is suggested by the discovery[11], in 1766, at a bole site on Cromford Moor, Derbyshire, of a pig of lead with an inscription said to place it in the reign of Hadrian (A.D. 117 - 138). The pig was reported as being "not very different from the pigs which are cast at present (1782); it consists of several horizontal layers of unequal thicknesses, and there is an irregular hole in it running from the top to near the middle of its substance; from these appearances it seems as if it had been formed by puring into a mould, at different times, several quantities of lead."

A survey of boles in Swaledale recognised some 35 sites, and recorded a C14 date of 1460± 10 A.D. for one on Calva Hill; regrettably, no such detailed survey has been undertaken in the Craven region, of Yorkshire, but, from place name evidence (Bale Hill, Tag Bale, Bale Bank etc. on the O.S. Sheets), it is perhaps not too unreasonable to infer a similar number.

During the sixteenth century, the Crown was actively encouraging the development of the nation's mining (and other industrial) potential and, to facilitate that objective, experienced miners were brought from the Augsburg district of Germany. A major monopoly[12] was granted to the Society for Mineral and Battery Works, by Queen Elizabeth, which gave it special mining and metal working privileges and, presumably stimulated by this activity, a number of innovations in furnace design appeared. Also, because monopolistic rights were a jealously guarded, litigation regarding infringements of patents gives some detail; from which, if one ignores the specific dates (which may have been produced to suit the case in question), one can see the nature of the processes then employed.

The first, of note, was that of William Humphrey (or Humfrey), of the Mineral and Battery Works, who erected his furnace at Beauchief[13], on the River Sheaf, in Derbyshire, near Sheffield, c1581. His mill had two furnaces, each with a pair of waterwheel-powered bellows, and was said to be smelting continuously, with a very small charge of wood and few workmen. Details of the hearth, and its mode of working, are vague, but it was made of stone and was 4 ft. high by 15" broad and 18" long. The brouse was stirred in the hearth by a gavelock, and the lead fell into a stone pan (sumpter pot). It was also reported that the hearth used less than half the fuel used by a bole, and that one furnace made three fodders of lead per week. Fumes were carried away by a single stack, less than ten feet high, which was set over the furnace.

By 1582, Humfrey had taken out an injunction against the miners of the Mendip for misappropriating his inventions, which resulted in a Commission, and the production of a certificate of depositions by various witnesses. We learn, from this [14], that once the ore had been dressed, *"After all this they melt the same ewer(ore) at a turne-harthe made without howse for gruff or great ewer only."* Also, because of improvements in dealing with finely crushed ore, *"they cannot melt their smetham or ewer, so gotten, by the syve at their turne-harthes aforesaid, but by an other harth called a slage harthe, much like the ould slag harth used in Darb(yshire) before Humfryes invention of his new harth."* And, from the same Commission, *"we find that the hearths that are now used at Mendip, for the smelting of lead ore and the like, have been there continually used to be turned about at the wind doth change and non others by the space of forty years and upwards ..... but before that time we find by examination that they were made first upon the ground and not to be turned and then as the wind did turn they were enforced to remove their bellows to other hearths ..... also we find that the firestone of every hearth (which commonly require replacement, as they burn away, within a week) are changed in their layout to suit the nature of the ore."* As for the turn-hearth, we must look to the writing of the Rev. Joseph Glanvil[15,16], Vicar of Frome, who writes *"Then they have a hearth about five feet high, set upon timber, to be turned as a windmill, to avoid the incovenience of smoke upon a shifting wind. The hearth contains half a bushel of ore and coal, with bellows on the top. The charcoal is put upon the hearth, where the ore is; laying white-coals (dried chopwood) upon the top. There is a sink (sump) upon the side of the hearth, into which the lead runs, that holds about an hundred and a half. Then it is cast into sand, and runs into those sowes (pigs) which they sell."*

In the State Papers, for the reign of Elizabeth, is to be found a sketch of yet another furnace from the period 1552-1578. This is ascribed to one Burchard Cranich, another German, who was in England by 1552, and was smelting lead at Duffield, in south-east Derbyshire. From that sketch, it appears that the furnace was similar to contemporary ones[17], which had masonry shafts, and were blown by waterwheel-powered bellows. Regrettably, previous writers on this period have concentrated upon Humphrey, and Cranich remains an enigmatic figure.

The next descriptions are interesting for their variance. The first[18], of a mill in Derbyshire: *"The furnace, which I saw near Worksworth, was very rude and simple, consisting only of some large rough stones, placed in such a manner as to form a square cavity, into which the ore and coals are thrown "stratum super stratum"; two great bellows continually blowing the fire, being moved alternately by water. I saw no other fuel used on this*

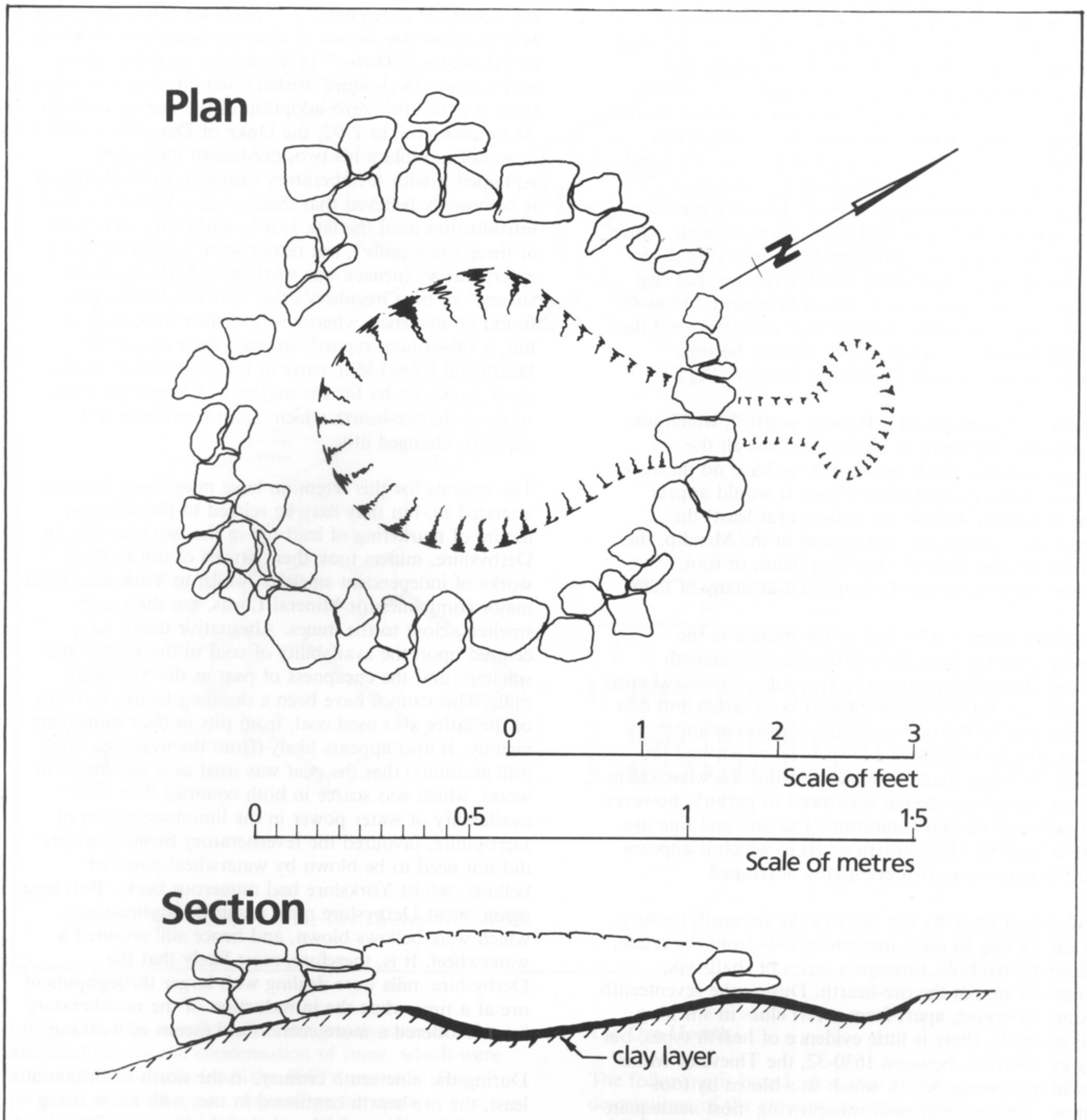

Figure 1 Bole, at Winterings, Nr. Gunnerside, Swaledale. Excavated in 1919 and reproduced with the permission of Arthur Raistrick.

occasion but dried sticks, which they call white coal. They generally throw in some spar along with the ore, which is thought by imbibing the sulphur to make it flux more easily. They frequently throw in also some cowke (or cinders of pit-coal) because they think it attracts the dross, and so makes an easier separation of it from the lead. When the ore is melted, it runs out at an opening in the bottom part of the front of the furnace, through a small channel made for that purpose, into a cylindrical vessel, out of which it is laded into the mould. The dross of the ore on smelting is called slag. This slag is afterwards smelted again with cowke only, and the lead obtained from it is called slag-lead."

The second account[19], dated 1735, is from "The draught of a smelting mill used by the Company of Mine Adventurers of England and others in Yorkshire". This, it has been argued[20], is the first account of what is actually recognisable as an ore-hearth; as it had a "work stone" — "the fore part of the hearth, onto which much of the partly melted ore and sticky slag could be drawn to be picked over and worked during the run of a smelting". The evolution of the ore-hearth is subject to some discussion, and Martyn's 1729 description does little to clarify matters. It may be that of a proto-ore hearth but this is at best a subjective appraisal from highly deficient data. Taking Raistrick's imperative, that an ore-hearth requires a work stone; then the Great Smelting Mill at Cwmsymlog Mine, Dyfed, in 1667, had "five hearths with: backs, cheeks, work stones, iron plates and other necessaries". Excavations[21 22], at two Yorkshire sites, have revealed the remains of two hearths which were from this period. The latter, at Buckden High Mill, can be positively dated to 1698 — 1713 and had a mixture of iron and gritstone parts (an iron furnace bottom and keeper "stone", plus a gritstone "pipe stone"). Both sites had one such ore-hearth, which was blown by bellows, and both black and grey slags were found, along with coal, which indicates that slag reduction was undertaken in the same hearth, but at far higher temperatures. Neither site had the horizontal flue, associated with later mills, which did not become common until the early nineteenth century, (Fig 2).

Although an example of a Roman hearth[24], which was excavated at Duffield, in Derbyshire, has all the appearances of a crude ore-hearth we have no means of knowing how representative it was. It would appear then, that boles were in use between (at least) the Roman occupation and, for certain in the Mendip, the mid-seventeenth century; and that hand, or foot, powered bellows would be employed at many of them.

It is presumably a reflection of the decline in the Mendip's stature that, even in the mid-seventeenth century, its smelters retained a two-fold process (whereas Humphrey's furnace accomplished both tasks) and that the majority of the ore was being smelted in an advanced type of bellows-blown bole, which had the facility for being made in various forms! To what extent this polymorphous design was owed to perjury, however, will probably remain conjecture. The slag and fine ore were treated in a slag-hearth — from which it appears that the true ore-hearth eventually developed.

In summary then, by the close of the sixteenth century, we are starting to see a metamorphosis from the crude, bellows-blown bole, through a series of shaft-type furnaces, towards the ore-hearth. During the seventeenth century, however, apart from a few clues in smelting mill accounts, there is little evidence of hearth types, but it is known that, between 1630-32, the Thieveley Mine[25] was using a stone hearth which was blown by foot-bellows. This arrangement was proving most inadequate and Roger Kenyon, the Steward, visited smelt mills in Derbyshire, and at Grassington, Yorkshire. Here the Earl of Cumberland had a mill with waterwheel-powered bellows near the river Wharfe. We know, from accounts[26], that this mill, too, was using stone furnace linings at this time; but by the 1700s had adopted iron hearths.

Another significant development in smelting methods, which occurred c1700, was the introduction of the reverberatory furnace to Flintshire and, by 1734, to Derbyshire[27]. As the eighteenth century progressed, an interesting bifurcation occurred between the methods employed by the Derbyshire and Yorkshire smelters. Until the middle of that century both counties had smelted in the ore-hearth but, by 1782, Watson was able to write *"It is not fifty years since the blast or hearth furnace was the only one in use for smelting lead ore in the County of Derbyshire."....."There are not at present, I believe, above one or two of these ore-hearths in the whole of the county of Derby."* In Yorkshire, however, where many of the Derbyshire smelters had direct involvement, there was not the same adoption of the new technology. At Grassington, in 1792, the Duke of Devonshire built a new mill to replace his two, ore-hearth mills, and equipped it with reverberatory furnaces. In Swaledale, it is commonly believed that there is no evidence for their introduction until the late 1850's, when they were tried at three smelt mills[28], but recent work[29] suggests that a reverberatory furnace was working in 1703. A recent survey[30] of the Greenhow area, near Pateley Bridge, found no evidence, whatsoever, of their introduction, but, a subsequent report[31] suggests their use, at the Heathfield (New) Mill, early in the present century. In short, however, by far the majority of Yorkshire mills retained the ore-hearth which, apart from increased capacity, changed little.

The reasons for this retention have never been properly attended to, but they may be related to the differing nature of marketing of lead ore in the two counties. In Derbyshire, miners took their parcels of ore to the works of independent smelters, whilst in Yorkshire, most major companies, or Mineral Lords, ran their own smelters, close to the mines. Alternative theses have centred upon the availability of coal to the Derbyshire smelters, and the cheapness of peat at the Yorkshire mills. This cannot have been a deciding factor, as many of the latter also used coal, from pits in their immediate vicinity. It also appears likely (from the available smelt mill accounts) that the peat was used as a substitute for wood, which was scarce in both counties. The non-availability of water power in the limestone region of Derbyshire, favoured the reverberatory furnace; which did not need to be blown by waterwheel-powered bellows, whilst Yorkshire had numerous becks. But, here again, most Derbyshire mills retained slag-hearths, which were bellows blown, and hence still required a waterwheel. It is, therefore, most likely that the Derbyshire mills were dealing with larger throughputs of ore at a time when the introduction of the reverberatory furnace offered a more economical means of working.

During the nineteenth century, in the north of Britain at least, the ore-hearth continued in use, with a few being retained into the early decades of this century. The major mills of the northern Pennines were fairly evenly split between the use of reverberatory and ore-hearth, whilst the mid-Pennines maintained the latter. Most of the mills during this period were fitted with a separate slag-hearth, which did not have a workstone as it ran at far higher temperatures (1100-1200°C), and did not produce pasty, grey slags. Its slags were tapped as a liquid phase, which floated upon a reservoir of molten lead in the sump, which cooled to form a black, glassy slag. This slag, greatly reduced in its lead content, was often worked yet again, by a process of "knocking-up", or crushing, to a fine matrix; from which lead-rich material could be separated by use of buddles and "dolly" tubs.

The higher temperatures employed in the slag-hearth also had the effect of volatilising more lead than did the

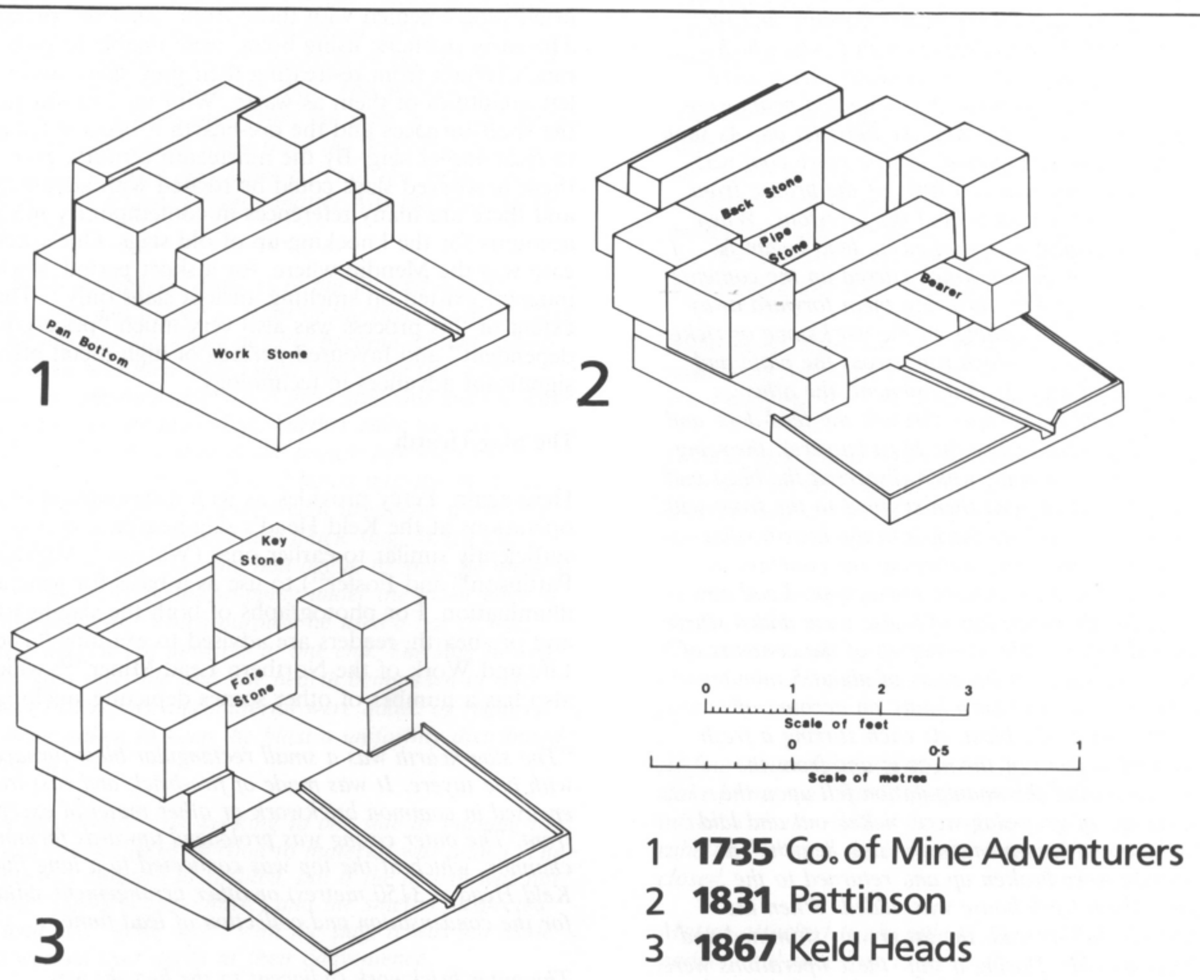

Figure 2. The evolution of the Ore Hearth 1735-1867.

ore-hearth. This is reflected in the greatly extended flues, and facilities for the condensation of fume, which were added to many mills from the 1840's onwards. The proposal of an adequate chronology for these developments would alone be a useful guide to the rate of their uptake, and supplement the available accounts[32],[33].

Description of the Smelting Techniques employed in the 18th & 19th Centuries

Fortunately, a number of descriptions of lead furnaces, have been left, which, in the case of the ore-hearth, date between 1735 and 1867. During that period, the ore-hearth underwent no significant change in its morphology, other than an increase in its overall size, and, in some cases, the provision of an inbuilt well to hold a larger quantity of the molten metal upon which the fire and charge floated. This latter innovation was felt to help prevent the tendency of the hearth to overheat, and to protect the furnace bottom from slag-attack.

The Ore-Hearth

The following is based upon one of the most complete descriptions of the smelting process, which was published in Percy's *"Metallurgy of Lead"*[34]. It details the operations, during an eight hour shift, at the Keld Head Lead Mining Company's smelting mill, near Leyburn, Yorkshire. The ore-hearth, here described, represents what was then (1867) an advanced type, and was part of a smelting complex, associated with a relatively prosperous mine, which was handling three to four hundred tons of ore per annum[35].

"The fuel used was a mixture of coal and peats; which were cut into prismatic pieces from 9" to 12" long by 2.5" square. The bouse (ore charged) used at this mill was not calcined (roasted) prior to smelting. The agglomerated masses of semi-reduced ore produced during smelting were known as brouse or browse.

The hearth was supposed to be in working order, and the bottom left nearly full of lead, after the last shift. A small *quantity of coal was laid on the hearth-bottom, and the remaining cavity of the hearth filled with peats, which were well walled up in front, while smaller pieces were thrown in without order behind. A few ignited peats were next placed before the nozzle, and the blast let on. As soon as all the peats were well ignited, a little more coal was added, and shortly afterwards a little of the brouse from the last shift was thrown on behind the forestone. When about half of the brouse was worked in, lead began to flow; and then one of the workmen stirred up the contents of the hearth with a poker, throwing them forward away from the blast, a portion falling on the workstone or ricket plate (ricket = a groove, which ran across the plate and carried the molten lead). At that moment, the other workman introduced his scraper through the feed-door and removed any slag from before the blast (tuyere), throwing in front of the nozzle a peat, which dispersed the blast and kept open the fire. Both men then stepped to the front with their brouse shovels. and put back into the hearth what had fallen on the workstone, setting up the contents so that the blast was well distributed throughout. Lead now flowed freely. Small quantitites of bouse were added where the fire seemed bottest. The stirring up of the contents of the hearth was repeated at intervals of about 5 minutes where the fire was seen to burn badly on account of imperfect diffusion of the blast. At each stirring a fresh peat was placed in front of the nozzle; and from the portions, which during this manipulation fell upon the workstone, lumps of grey-slag were picked out and laid aside for subsequent treatment in the slag hearth. The pieces of brouse were broken up and returned to the hearth, after which fresh bouse was added. When the sumpter pot was full of lead, the latter was skimmed and laded into pig-moulds. During a shift these operations were performed alternately by the two workmen. Thus, the man who used the poker, laded out the metal, whilst the other skimmed it; and the latter attended at the feed-door while the former used the poker.*

Towards the end of the shift, no more bouse was charged; but the contents of the hearth were afterwards worked up two or three times, after which the blast was stopped. All the brouse was taken out, thrown on one side, and separated from the intermingled grey slag. Lead was laded from the sumpter pot back into the hearth bottom, so as to fill it ready for the next shift."

From this account, it is apparent that the hearth needed continual attention to prevent its charge from congealing, and that this agitation, along with a peat used as a baffle, helped to disperse the blast throughout the charge and prevent localised "hot-spots". It is also apparent that the lead was sweated from the bouse at a temperature only just above its melting point, and that this produced grey-slags which were never liquified, and remained rich in lead (15-30%) and brouse. The former were taken to the slag-hearth and the latter were returned to the ore-hearth with the next charge of ore. Percy gives the results of a week's trial at the Keld Head ore-hearth, and concludes that the percentage of lead direct from the bouse was 74.44%. This is also supported by the mineral statistics[36] which indicate an average recovery of 72% of the ore's weight.

The treatment of slags was an important part of the economics of mining and smelting operations, as it was often supplemented with those from "ancient" processes. The early smelters, using boles, were unable to gain much benefit from re-treating their grey slags, and so left quantities of them as waste. With the introduction of the shaft-furnaces and the ore-hearth it became feasable to treat earlier slag. By the nineteenth century, even these re-worked slags could be treated with advantage and there are many references in contemporary mine accounts for the knocking-up of old slags. One special case was the Mendip where, for a short period, a whole industry existed on smelting ancient slags only[37]. The extent of this process was also very much "price/cost dependent" and favoured periods of high metal prices or significant advances in technology.

The Slag-Hearth

Here again, Percy provides us with a description of the operations at the Keld Head's slag-hearth, and it is sufficiently similar to earlier ones (Watson[38], Mulcaster[39], Pattinson[40] and Foster[41]) to use as a basis for general illumination. For photographs of both the slag-hearth and ore-hearth, readers are advised to examine "The Life and Work of the Northern Lead Miner"[42]; which also has a number of other scenes depicting smelting.

"The slag-hearth was a small rectangular blast-furnace with one tuyere. It was made of fire-brick and cast-iron encased in common brickwork or other material except in front. The outer casing was prolonged upwards forming a chimney, which at the top was connected to a long flue (at Keld Head = 3150 metres) or other arrangement suitable for the condensation and collection of lead fume.

The outer brickwork (adjacent to the hearth) was supported by cast-iron plates with suitable bracings of wrought iron (through which the tuyere passed – at the back). Above the hearth-front was an open space, arched at the top, and there was a similar, but smaller, space on the left.

The bed-plate was covered with a layer of hard-burnt and coarsely sifted coal ashes to within about 25mm below the nozzle of the tuyere, forming the ash-bottom, which was made to slope towards the lower edge of the fore-stone. The space in front of the ash-bottom, between the bearers, was plastered up with clay. This ash-bottom acted as a filter by means of which the molten slag and lead which, in the process of smelting, fell to the bottom of the hearth, were separated from each other, the slag running out over the ash-bottom through openings made in the clay-stopping under the lower edge of the forestone, whilst the lead percolated through the ash-bottom to the bed-plate and ran down into the lead-trough in front. The larger division of the lead-trough was filled with spongy cinders, which likewise acted the part of a filter, the slag flowing over the top into the slag pit, previously filled with water, whilst the lead ran through and found its way to the bottom, where it was laded out from the smaller division on the left.

The products of smelting in the slag-hearth were slag-lead and vitreous black-slag, which was thrown away. The fuel was coke and peat. The hearth was worked by two men, a smelter or charge man, who had charge of the hearth, and a labourer who supplied the material to be smelted, including fuel, and removed the slag-lead and black-slag *produced. A shift lasted about 8 hours, during 6 of which the blast was uninterruptedly continued, whilst about 2 hours were devoted to the preparation of the furnace and emptying it at the close of the shift. This preparation consisted of "stubbing out" from the sides of all the slaggy matter left adhering to them from the preceding shift, and "stemming up" with clay those parts of the furnace much burnt in. The detached slaggy matter was put aside to be re-smelted.*

In lighting the hearth, peats were put in, and a little burning coal was placed in front of the tuyere, and a blast then let on, and the whole quickly became ignited. About 1 cwt of coke was then added and, whilst the fire was burning up, the men sharpened their stubbing-tools to have them ready for the next shift. Further coke was then added, along with a little of the brouse left from the previous shift. At about 1.5 to 2 hours into the shift, the hearth should have been hot enough to receive a mixture of grey-slag, a little brouse and black slag. When the smelter judged that the slag had begun to melt, he made a hole in the centre of the stopping under the lower edge of the fore-stone; for which purpose he used a bar of iron pointed, and curved upwards at one end. The slag flowed out through this hole and, the hearth being then in full working order, fuel and material were added as required, care being taken to keep the blast a uniformly distributed as possible.

When the furnace was working to one side or burning too freely, less coke in proportion to material was added. The slag-pit was emptied as it filled, but if the hearth was not working regularly (smoothly?) and the smelter suspected that lead had "gone over" with the slag, it was put aside to be worked over again at their convenience.

Towards the end of the shift, no more material was charged, and the blast was kept on for about 20-30 minutes, after which it was shut off and the clay-stopping in front of the ash-bed was removed. Using a poker, the smelter then worked out the ashes and as much of the adherent slaggy matter (slag-hearth brouse) as practicable, on the bed-plate, for re-smelting during the next shift. A few bucketfuls of water were then thrown into the hearth in order to put out the fire and cool the interior preparatory for stubbing at the ensuring shift."

Again, we see the importance of keeping the blast flowing freely amongst the charge to attain far higher temperatures. But, this time, the smelter was producing, and tapping, both molten lead and liquid slag. As with the ore-hearth this hearth was representative of the best, and Percy suggests that it performed somewhat better than the earlier North of England slag-hearth (detailed by Pattinson) in that the former produced lead amounting to 22.5%, by weight, of its charge and the latter some 17.8% and that 8.89 cwts and 5 cwts of slag were smelted with 1 cwt of coke, respectively.

The Reverberatory Furnace

The reverberatory furnace appeared in a number of forms, but that which became known as the 'Flintshire Furnace" appears to have been most popular in northern Britain. The following observations, again by Percy, were made at a smelt mill near Holywell, Flintshire. The charge was 21 cwts (plus half a hundredweight for moisture). Two men were engaged, one on each side of the furnace which was in full working order and cooled down following the smelting of the previous charge.

"The charge was allowed to fall through the roof, from a hopper, and spread over the upper part of the bed. All the side doors, as well as the fire-door, were open to allow for calcination; which took about 1.5 hours. The two doors, one on each side, furthest from the fire, were then closed. The fire was well made up and the fire-door closed. Lead soon started to trickle from the charge.

About three hours into the shift, the charge was rabbled occasionally through each of the open doors nearest to the fire. Following this, the lead began to trickle quite freely.

At three and a half hours: all the doors were closed, the fire made up and the damper fully raised. Vigorous effervescence occurred, with a frizzling sound, and lead flowed freely from the charge.

At four hours ten minutes: all the doors on each side, also the fire-door, were opened, and the charge well rabbled. The door on each side near the flue was closed. The charge was wholly melted down into the well of the furnace.

At four hours fourteen minutes: a shovelful and a half of slaked lime was introduced on the tap-hole side and well mixed with the molten mass on the top of the lead by rabbling through the tap-hole door, which was afterwards closed.

Matter attached to the side of the bed was detached by the paddle, and raked up towards the fire-bridge by the man on the opposite side of the furnace. The flue door on each side was still kep closed, the fire-door remained open, and the damper fully up.

At four hours twenty minutes: a paddle was put in through the working side (the back) and used to detach as well as practicable from the sides of the bed the less fused and more adherent part of the charge; and the man on the opposite, or tap-hole, side (the front) at the same time used his rake for the like purpose. The matter so detached, as well as that thickened with lime on the surface of the lead in the well, was raked or "set-up" on the sloping part of the bed, near the fire bridge. After this "setting up" the door on each side near the fire, and the fire-door on each side near the fire and the fire-door were left open.

At four hours thirty eight minutes: the damper was raised, and the fire was well made up, and all the doors were closed.

At five hours fourteen minutes: on looking through the narrow tap-hole door vigorous effervescence, amounting to ebullition, was obvserved.

At five hours thirty two minutes: the fire-door and the two doors on each side nearest the fire were opened. The charge was well melted. Two shovelfuls of slaked lime were thrown in through the middle door on the tap-hole side, and well rabbled into the molten mass. The surface of the lead was cleared by pushing the thickened matter on its surface with the paddle from the tap-hole, as well as through the narrow door above the tap-hole.

At five hours thirty seven minutes: the tap-hole was opened, and after the lead had run into the pot, the thickened matter or "grey-slag" was raked out through the middle door and fell on an iron plate on the floor below. The damper was still up, and the furnace cooling preparatory to the next charge.

At five hours forty five minutes: another charge was let down and spread over the bed by the man on the working side, or side opposite the tap-hole. The damper was then lowered (it should have been lowered sooner, but the workmen find it cooler to keep it up a while. This is contrary to order. Slime-ore is carried away by the draught).

At five hours forty nine minutes: the lead tapped off in the pot was skimmed by perforated flat iron shovels. Coal slack and ignited coal from the furnace were thrown on top of the skimmed lead and well stirred in.

At five hours fifty two minutes: the coal slack etc., was skimmed off, and the skimmings put back into the furnace. Some lead sweated out and was tapped off in a few minutes afterwards. The tap-hole was stopped by throwing in a lump of thick lime-mortar through the tap-hole door and then ramming from the inside, which was easily done by a bent tool."

The addition of lime, briefly referred to by Percy, on the previous page, is given more prominance by others[43] — "In order to obtain the lead free from the slag which swims over it, the smelters usually throw in about a bushel of lime; not, as is usually supposed, in order to contribute towards the more perfect fusion of the ore, but to dry up the slag which floats upon the surface of the lead, and which might otherwise flow out along with it. The slag being thus thickened by an admixture of lime, is raked up towards the sides of the furnace, and the lead is left at the bottom. There is a hole in one of the sides of the furnace, which is properly stopped up during the smelting of the ore; when the slag is raked off, this hole is opened, and being situated lower than the lead in the furnace, the lead gushes through it into an iron pot placed contiguous to the side of the furnace".....from which it is ladled into moulds.

Watson[44] also informs us that *"In order to spare the lime and the expense of fuel attending the fluxing of the mixture of lime and slag, they have in some (reverberatory) furnaces lately contrived a hole, through which they suffer the main part of the liquid slag to run out, before they tap the furnace for the lead; upon the little remaining slag they throw a small portion of lime, and draw the mixture out of the furnace without smelting it. This kind of furnace they have nick-named a Maccaroni".* This reference to the tapping of liquid slag is especially interesting, as it dates from the late eighteenth century, but was obviously not a feature of the (particular?) reverberatory furnace described by Percy, about 80 years later. One explanation for this[45], is as follows."*.....as the bottom of the furnace declines, both from the fire-bridge to the flue, and from the labourer's to the foreman's or tapping side, it was found necessary to discontinue the slag tap, as it was so close to the lead tap."* As a result of this subsidence of the furnace floor, the smelters had found it necessary to dry up the liquid slag, by the addition of lime.

Fumes, Flues and Condensers

The debate regarding the use of long flues, and distant chimneys, received some stimulation from Watson[46] and appears to have been underway by the late 1770's. Prior to this, the chimneys had been directly above the furnaces! From his comments, it would appear that their value was a providential discovery, resulting from the need to build the chimney of Middleton Dale Mill, Derbyshire, on the side of a hill, to avoid contamination of some adjoining pastures by the lead fumes.

Despite Watson's enthusiasm, there is evidence[47] to suggest that the uptake of such a simple innovation was not rapid, and only reached the northern Pennine dales by about 1820, a date which also agrees with findings[48] at Grassington, Yorkshire. Even then[49], these chimneys were only "upwards of a hundred yards" long.

By the 1850's, these flues were being extended to much greater lengths, which are still readily evident, and it has been suggested[50], but not yet apparently tested, that this coincided with the introduction of the Spanish Slag-hearth. It is certain, however, that this was also a period in which engineers such as: Stagg[51], Stokoe[52] & Fallize[53] made advances in the efficiency of condenser design, and few major mills failed to incorporate such devices in their flue systems.

Selection, Preparation and Analysis

Sample Selection — Because of the limited nature of this work, there was no attempt to establish a rigid sampling rationale at sites, but, wherever possible, in order to obtain relatively homogenous specimens, only vitrified slags were selected. Because work[54] at the University of Newcastle upon Tyne had already concluded that macro-scopic examination would provide only subjective evidence of: whether a slag had been fluid or not, its rate of cooling and magnetic properties (though, in the latter case, this information was of doubtful value, as many slags contain non-magnetic compounds of iron), none was undertaken.

Preparation of Samples — Uniformity was achieved by means of pellets, which involved crushing about 2g of slag in a mortar and the careful weighing of 0.750g of the resulting powder. This was then mixed with 0.500g of cellulose, and subjected to a further crushing, in a ball-mill, before being made into a pellet by means of a 10 tons press.

XRF Analysis — This was performed on the Philips PV9500/80 Automated Energy Dispersive System which, after calibration by means of the auto-method, was run under identical conditions for all 24 analyses.

Peak identification soon indicated that only nine elements formed the principal constituents of the slags. These were the oxides of: aluminium, silicon, calcium, barium, iron, copper, zinc, lead, strontium. Because the slag was the product of the slag-hearth which, theoretically, had a reducing atmosphere, the lowest order of oxide ratio was employed. Subsequent cross-reference, using higher orders, showed only small differences. Whilst very small amounts of some other elements, especially sodium, magnesium and manganese were seen in some samples, they were ignored, as it was felt that their presence was fortuitous, probably deriving from the fuel, and has no significant, or intended, bearing on the smelting process. (The results are given in Table 1.)

(Table 1 **Provenance of Slags Analysed**

Name	**Mill Name**	**Grid. Ref.**	**Comments**
Slag1	Cockhill Mill	SE 115649	Very friable
Slag2	Providence Mill	SE 117651	Very friable
Slag3	Barbrook Cupola	SK 276739	
Slag4	Heathfield (New) Mill	SE 144664	
Slag5	Lumb Clough Mill	SE 008429	Black vitreous + vesicles.
Slag6	Harewood Cupola	SK 306684	
Slag7	Eagle Crag Bloomery(?)	NY 356138	
Slag8	Hogget Gill	NY 387109	
Slag9	Walloper Well (Bowland)	SD 713485	Black vitreous + tubular vesicles.
Slag10	Hipper Slag Mill	SK 310687	
Slag11	Hartley Mill	NY 849147	
Slag12	Buckden Out Moor Mill	SD 954781	
Slag13	Hoodstorth (Forest) Mill	SE 128604	
Slag14	Hebden Mill	SE 025641	
Slag15	Grovebeck Mill	SE 027970	
Slag16	Prosperous Mill	SE 117661	Very friable
Slag17	Prosperous Mill	SE 117661	Dark grey, fused many vesicles.
Slag18	Scotts Mill	SE 049974	
Slag19	Dukesfield Mill	NY 941580	
Slag20	Acton Mill	NY 980535	
Slag21	Acton Mill	NY 980535	
Slag22	Acton Mill	NY 980535	
Slag23	Moor Mill — Grassington	SE 025665	
Slag24	Cupola Mill — Grassington	SE 025663	

Results

Oxygen Ratio	Al_2O_3 **1.5**	SiO_2 **2**	CaO **1**	BaO **1**	FeO **1**	CuO **1**	ZnO **1**	PbO **1**	SrO **1**
Slag1	3.686	16.262	54.985	18.068	3.375	0.037	0.074	2.674	0.839
Slag2	3.916	17.910	27.412	28.689	5.877	0.520	10.630	4.491	1.025
Slag3	3.374	13.485	26.477	32.548	6.502	0.059	11.921	4.549	1.085
Slag4	3.492	17.877	63.727	11.625	2.325	0.036	0.000	0.605	0.314
Slag5	6.576	37.580	2.804	47.703	2.365	0.033	0.059	1.295	1.584
Slag6	15.074	77.444	1.312	0.629	5.338	0.021	0.000	0.181	0.000
Slag7	13.289	62.436	4.836	1.573	17.594	0.035	0.000	0.154	0.084
Slag8	5.513	29.856	5.850	5.926	41.762	0.051	0.000	10.728	0.316
Slag9	8.637	52.760	15.769	1.130	11.413	0.081	1.383	8.666	0.163
Slag10	5.074	36.751	20.743	24.760	3.504	0.037	0.621	7.906	0.904
Slag11	7.530	39.969	13.881	22.166	8.448	0.076	1.881	5.626	0.424
Slag12	11.131	50.888	3.907	19.191	9.141	0.030	0.776	4.756	0.151
Slag13	6.620	40.119	44.936	1.213	4.063	0.029	0.000	2.830	0.190
Slag14	6.379	29.943	36.133	23.051	2.832	0.135	0.524	0.306	0.678
Slag15	3.566	18.396	10.016	53.092	8.696	0.047	4.058	0.827	1.302
Slag16	6.693	27-912	11.639	39.505	5.209	0.050	3.651	4.057	1.283
Slag17	3.845	23.816	59.229	0.589	10.923	0.021	1.028	0.550	0.000
Slag18	7.111	35.651	22.293	21.515	4.899	0.034	1.651	3.547	3.299
Slag19	12.332	53.529	15.667	5.993	11.733	0.031	0.000	0.531	0.185
Slag20	7.582	53.219	13.985	0.543	10.170	0.036	9.255	5.210	0.000
Slag21	6.910	53.070	15.739	0.521	9.751	0.033	8.882	5.094	0.000
Slag22	5.203	40.505	25.391	0.607	8.946	0.046	13.561	5.684	0.057
Slag23	4.864	26.797	36.431	12.959	4.133	0.061	0.078	13.701	0.977
Slag24	3.663	16.051	33.647	37.960	5.941	0.469	1.439	0.126	0.704

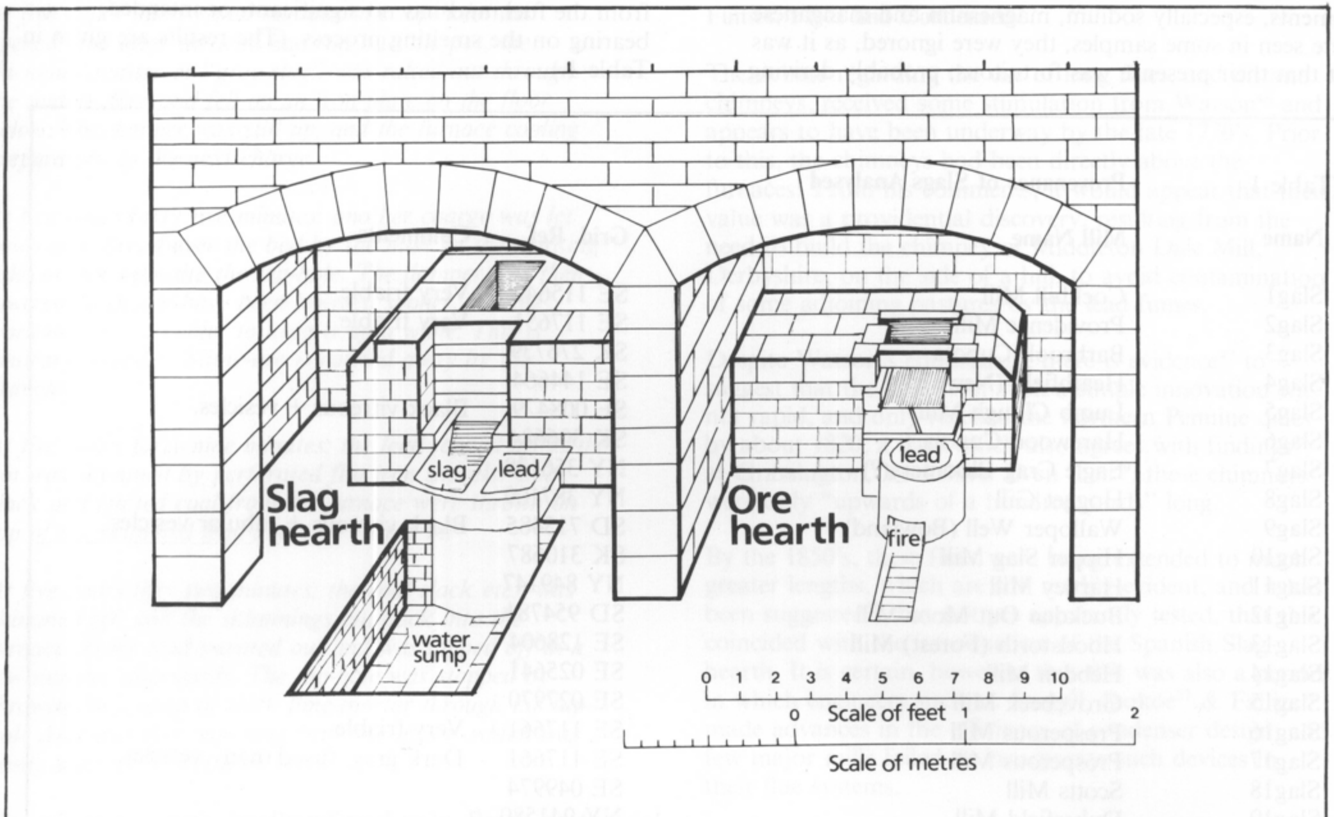

Figure 3 General layout of lead smelting hearths, reproduced from 'An account of the method of smelting lead ore and refining lead, practised in the mining districts of Northumberland, Cumberland and Durham, in the year 1831' by H. L. Pattinson.

In order to obtain some indication of the likely concentrations of these oxides, and allow the production of "standards", all 24 spectra were analysed by means of the "No Standards" package.

Preparation of standards — Using the values obtained from the No Standards Analysis, a standard was prepared for each of the four major groups of slags.

The oxides of each of the nine elements were weighed out, in proportions reflecting those in the analysis, to give a total weight of 0.750g. Lithium metaborate was used as a fluxing agent, at a ratio of 5:1 (flux:slag) and the kiln temperature set to 1050C.

In order to restrict the bead, and maintain its heat, moulds, made from 4mm long off-cuts from 12mm O.D. copper water-pipe, standing on a heavy section of pre-heated iron plate, was proposed. In order to obtain a more homogenous standard, it was decided to anneal the bead. To do this, the brass plate, carrying the filled mould was placed in a kiln, which was preheated to 750C. This temperature was maintained for 30 minutes, before turning the power off, and the kiln was left overnight, to cool slowly. This was found to remove much of the long, thin crystal structure.

Both sides of each of these four standards, were polished using metallurgical emery-paper pads. This was intended to remove any surface layer of contaminants from either the kiln or moulds. Finally, each standard was subjected to No Standards analysis, on each side and the results found to be close.

Calculation of Concentrations — Once satisfied that the standards were reliable, it was possible to proceed towards final quantitative analysis by means of the Lucas-Tooth Method. In cases when only a limited number of real standards are available, this method contains a facility for generating synthetic standards, based on those real standards which are to hand. The routine requires that, for each element to be analysed, target concentrations and ranges be input from the keyboard, and from these it assigns a high and low value to each element. These results were presented as a print-out of theoretical intensities and concentrations, of which the former were then adjusted to correspond with those X-ray intensities which were measured from the real standards.

At this point, the program for the Lucas-Tooth Method, which use either all real, or a mixture of real and synthetic standards merge, and the Delta-I Model was used. By this model, a graph of intensity versus concentration was given for each element. Also, it allowed adjustment for inter-element interference, which may have had an anomolous effect on actual intensities and concentrations. From this, and by reference to the real standards, a set of adjusted concentration values were obtained, for use with the adjusted intensities to give the final concentrations. The following were the allowances made for any such interference:

Element	Interfering Element
Al	Si
Si	Al
Ca	Al & Si
Ba	Si & Ca
Fe	None
Cu	None
Zn	None
Pb	Sr
Sr	Pb

The Use of Clustan — Further analysis of the results was achieved by running the data through the CLUSTAN2 package on the University's mainframe computer. The result of this exercise was the isolation of five principal groupings within the slags, according to their oxide concentrations, which were as follows:

Table 1A — Use of Clustan)

	Al_2O_3	SiO_2	CaO	BaO	FeO	Cu_2O	ZnO	PbO	SrO
Group 1	4.804	25.604	51.804	10.909	4.704	0.052	0.325	1.393	0.404
Group 2	5.392	35.604	21.780	12.570	8.241	0.139	10.840	5.001	0.433
Group 3	7.443	41.410	18.136	16.032	7.324	0.057	0.947	8.127	0.524
Group 4	5.987	29.885	11.688	40.454	5.292	0.041	2.355	2.432	1.867
Group 5	13.565	64.470	7.272	2.732	11.555	0.029	0.000	0.289	0.090

Obviously the sample size, being only 24, is too small to place much significance on these results, but any message that they may hold is likely to be coded.

Discussion

As yet, little attention has been paid to the use of fluxes, but, depending upon the nature of the brouse, the smelter probably used them from the earliest times. Percy's comment that, when the grey-slag is "stiff or short", the addition of iron slag will aid its free-running properties, is reinforced by Tylecote. There are earlier references[55] to its use in the smelting and refining of lead; but we have to turn to later writers[56] for an explanation. Here, it was the author's opinion that "in this operation, the iron having a stronger attraction for sulphur than lead, frees the lead from it, which by this means is reduced to its metallick form". The foregoing would appear to indicate that the smelters favoured the use of iron-oxides both for liquifying slags, and freeing lead from them.

The addition of spar (usually fluorspar) to the bouse was, "thought by imbibing the sulphur to make it flux more easily"[57]. Here, we have an alternative source of calcium to that added for stiffening slags.

Reference to various smelt mill accounts[58] indicates a rapid rate of furnace attrition. This was the combined result of slag-attack, and heat, on linings; which provided a likely source of the high silica values, and may also have enhanced the iron content. The clay used for packing the furnace linings would probably contribute some alumina.

Taking a selection of slags for discussion, Slags 1, 2 & 16 were of a particularly interesting type; being of a friable texture (grain size 1-3mm) and light grey in colour. Their mode of manufacture is enigmatic, but, because the matrix was sintered, rather than coalesced, it is unlikely that they were the product of a slag-hearth. It may be that they are lead fume (flue dust) which has been sintered in preparation for treatment in the slag-hearth. Whilst that process is known to have been necessary, to prevent rapid expulsion from slag and ore-hearths by the forced draught, the hypothesis remains pure conjecture.

Slag7, from Eagle Crag in Cumbria, was picked up at a site thought to have been a bloomery, but which may possibly have been a bole. Whilst the result is not conclusive, being proffered on the basis of a single analysis, it does appear that this slag is from an iron smelting site, having 17.6% iron and a very low (for such a crude smelter) 0.154% of lead. The resolution of this particular problem is, however, exasperated by the result from the neighbouring Hogget Gill smelter, Slag8, which has a far higher iron content (41.8%), but also has 10.7% of lead. This is a fairly early mill, said to date from the late seventeenth century, and would have fairly rudimentary ore dressing techniques available to it. There are, therefore, two alternatives, first, that the local lead ore either had a high iron content or, secondly, that it was being added as a flux. Analyses of the local ores may help to decide this matter.

The slags from Lumb Clough[59] and Buckden Out Moor[60] (5 and 12) are from mills which were excavated in the 1970s. Both had relatively early forms of the ore-hearth (see diagram of 1735 type) which were also used as slag-hearths, and Hoodstorth Mill, Slag13, is also known[61] to have been similarly equipped. Both Slags 5 & 12 have low calcium contents, suggesting that fluorspar/calcite flux was not used. The ore smelted at Lumb Clough Mill was from the same vein, but 100 years later, as at the Cononley Mine, Yorkshire, where James Ray Eddy[62], the Duke of Devonshire's Mineral Agent, wrote that "being mixed with heavy barytes and some iron-pyrites, the separation of the ore from the impurities was difficult, and its physical nature when prepared for the furnace made it most refractory in the smelting, very much more so than is usual in ores raised from mines in the same class of rocks (Namurian)." Eddy based this last comment on his experience at the Grassington Mines, which had also raised ore from the grits. Regrettably, a search at the site of Cononley Smelt Mill failed to produce any examples of its slag.

The analyses of Slags 23 and 24 are from the Grassington Moor Mill and the Cupola Mill, respectively. The former employed ore-hearths, and closed in 1793, whilst the latter was equipped with reverberatory furnaces[63]. In comparison with the results obtained from mills of similar, or greater age (ie 5, 12, 13), the lead content of Slag 23 may be slightly too high, but neither agrees with the 1836 analysis by Berthier, which was undertaken for Dufrénoy, showing 34.0% PbO, and of which Tylecote[64] feels, albeit tentatively, "that the high barytes content of Grassington ore was making separation difficult". It is also interesting that Dufrénoy ascribes the slag to being the product of an ore-hearth, as the smelting ledgers for this mill only record reverberatory furnaces. Judging from the high lead content, it must have been a very badly selected sample of grey-slag.

Alternatively, Slag 24, which had the lowest lead content (0.126%) of those examined, agrees closely with the comments[65], that "at Grassington, near Skipton in Yorkshire, with a similar (reverberatory) furnace worked at a slower heat, the operation taking from seven hours to seven hours and a half, instead of five (as in Flintshire), only 7.5 cwts of coal are consumed. But here the ores are less refractory, having the benefit of fluorspar as a flux, and are more exhausted of their metal, being smelted upon a less sloping hearth." As with Berthier's analysis, the barium content of this slag remains high.

As discussed in section 5, any detailed survey must answer the need for a far greater number of samples from each site. Examination of the results for Slags 20, 21 & 22, from Acton Mill, Northumberland, does, however, allow for some optimism as to the likely consistency. Here, the only sampling criteria used were that the three samples were each collected from distinct, but widely separate, locations on this large site, and that their physical characteristics were representative of the neighbouring slag. This optimism was reinforced when, in addition, the CLUSTAN-2 analysis assigned all three slags to the same group.

Superficially, at least, the results for the slags from Prosperous Mill, near Pateley Bridge, Yorkshire, run counter to the above. Slags 16 & 17 are, however, quite disparate. The former is very friable, and the latter dark grey, vitreous with many vesicles, which tends to reinforce the hypothesis, proposed earlier, that they are the product of quite different processes within the mill.

The far higher iron content of Slag 17 (100% higher than that of Slag 16) may, provisionally at least, be interpreted as evidence of the deliberate addition of iron, whilst the frequency of vesicles is indicative of a high rate of cooling, soon after tapping, which entrapped the gas content of the fluid. This phenomenon is supported by contemporary writers[66], who report that the slags were tapped into a bath of cold water, in order to break them up by means of the thermal shock. Indeed, such a sump was recognised in the excavation at Lumb Clough Mill, Yorkshire[67].

The opportunity to examine slags from three sites in Derbyshire was taken; these being: Barbrook Cupola, Harewood Cupola and Hipper Slag Mill; Slags 3, 6 & 10 respectively. The latter was also closely associated with a cupola (an alternative term for a reverberatory smelting mill). Slags 3 and 10 have calcium concentrations which are sufficiently high (26.5 and 20.7%) to conform with the addition of lime. On the other hand, Slag 6 has 1.3% calcium oxide, and is the lowest concentration recorded. This, combined with the low lead value, is a somewhat enigmatic result, and it may be that the sample, with its very high silica content, was contaminated with furnace lining material in the manner previously discussed.

Conclusion

There are many gaps in our knowledge of lead smelting, not least in that period between the Roman Conquest and 1700. Because of their location, on exposed hillsides, the remains of these early smelting sites are less likely to have suffered disturbance by subsequent activity, than the mines themselves, and it is on these smelting sites that archaeological examination must be focussed to gain some indication of the scale of mining operations in these period.

The value of XRF, when provided with an adequate number of man-made standards, for any analytical work associated with archaeological examination of lead smelting sites is undoubted. For, where the equipment is available to perform XRF analysis, it has the advantage of being both rapid and relatively inexpensive.

There appears to be little point in using XRF, or any other technique, for provenancing work, because of the known contamination from fuels, mixed ores and furnace linings. Also, the parochial nature of early lead smelting should render such work unnecessary.

Abbreviations

HMG	Historical Metallurgy Group
NS	New Series
NHSDN-T	Natural History Society of North Durham and Newcastle upon Tyne
NCMRS	Northern Cavern & Mine Research Society
NMRS	Northern Mine Research Society
PT - RSL	Philosophical Transactions — Royal Society of London
UDPS	University of Durham, Philosophical Society
YGPS	Yorkshire Geological & Polytechnic Society

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Appendix

Smelting Sites in Yorkshire & North East Lancashire ? = tentative site.

Smelting Sites in Nidderdale

Smelting site	Life-span	Grid Reference	Comments
Smelt Maria Dike ?		SE16 188619	
Lead Wath Wood ?		SE16 188163	
Lead House Ing ?		SE16 167643	(On 1854 O.S. Sheet.)
Baal Crag		SE16 163618	
Bale Bank		SE16 137653	
Smelthouses	Monastic	SE16 193643	
Eagle Hall Mill	- c1790?	SE16 153652	(Jeffrey's Map 1776.)
Heathfield New Mill	1855 - 1910	SE16 144664	
Heathfield Old Mill	c1814 - 1855	SE16 143663	
Cockhill Mill	1782 - c1882	SE16 115649	
Gillfield Mill	1783 - ?	SE16 115648	(On 1789 plan.)
Hoodstorth Mill	c1760 - 1789	SE16 128604	(Bolton MSS.)
Prosperous Mill	1785 - ?	SE16 117661	

Providence Mill	c1780 - ?	SE16	117651	
Merryfield Mill	c1796 - 1816	SE16	114663	

Smelting Sites in Wharfedale

Tag Bale	??	SE06	053668	
Hebden Mill	1858 - c1870	SE06	025641	(Bolton MSS.)
Hebden Old Mill	c1729	SITE UNKNOWN		(Bolton MSS.)
Grassington Low Mill	1603 - 1793	SE06	007633	(Bolton MSS.)
Grassington Old Moor Mill	c1650 - pre1700	SE06	025663	
Grassington Moor Mill	1754 - 1793	SE06	025663	(Bolton MSS.)
Grassington Cupola Mill	1793 - 1883	SE06	026663	(Bolton MSS.)
Kilnsey Mill	pre 1735 - 1827	SD96	973677	(Bolton MSS.)
Kettlewell Mill	c1650 - 1887	SD97	975728	(Rosstrick MSS)
Linton Mill ?	pre 1697	SITE UNKNOWN		
Starbotton Mill	c1849 - 1862	SD97	955750	(Bolton MSS.)
Birks (Buckden Low) Mill	c1704 - 1814	SD97	933769	(Bolton MSS.)
Buckden Out Moor (High) Mill	c1698 - 1709	SD97	954781	(Bolton MSS.)

Smelting Sites in South Craven and Rossendale

Cononley Mill	c1840 - 1871	SD94	983465	(Bolton MSS.)
Lumb Clough Mill	c1750 - ?	SE04	008429	
Malham Mill	c1815 - c1875	SD86	883661	
Rimington Mill	? - pre1850	SD84	815449	
Bale Hill	??	SD84	832440	
Baxendon Bole	1303 - ?	SITE UNKNOWN		
Thieveley Old Mill	1629 - 1629	SD82	874278	
Thieveley New Mill	1632 - 1634	SD82	881277	
Great Clough (Cupola) Mill	1754 - ?	SD82	806278	
Walloper Well Mill	1814 - c1830	SD74	712494	(Buccleuch MSS.)
Smelfthwaites ?	??	SD74	712494	
Sykes Mill	pre1800	SD65	638509	

Smelting Sites in Wensleydale

Bolton Bobscar Mill	c1663	SE	025939	
West Burton Mill	1670	SE	019854	
Preston Mill	1740	SE	079908	
Preston Mill	1740	SE	079908	
Keld Heads Mill	1845	SE	078910	
Cobscar Mill	1765	SE	059930	
Sargill Mill	1765	SD	897926	
Apedale Mill	1828	SE	031941	
Smelter Farm/Wood	pre 1774	SD	965823	Actual Site Unknown

Smelting Sites in Swaledale Area

Clints Old Mill	1589	NZ	088020
Clints New Mill	c1670	NZ	092028
Clints New Mill	c1670	NZ	092028
Clints New Mill	c1670	NZ	092028
Philip Lord Wharton's Low Mill	1669	NY	981001
Sir Thomas Wharton's Low Mill	1682	NY	981001
Philip L'd Wharton's High Mill	1670	NY	982002
Sir Thomas Wharton's High Mill	1670	NY	976004
Hartforth (Gilling) Mill	1669	NZ	160058
Waitwath Mill	1675	SE	180977
Ellerton Mill	1680	SE	069976
Applegarth Mill	1675	NZ	132009
Marrick Low Mill	1592	SE	089995
Marrick High Mill	1671	SE	089995
Slei Gill Mill	1628	NZ	019028
How (Grinton) Mill	1733	SE	049964

Moulds Old (or High) Mill	1674	NY	990018	
Moulds Low Mill (or Arkengarthdale)	1774	NY	992001	
Spout Gill (or Oxnop) Mill	1735	SD	931956	
Lownathwaite Mill	1784	NY	936007	
Grovebeck Mill	1769	SE	027970	
Scott's Mill	1774	SE	049974	
New Mill	1801	SE	033971	
Swinnergill Mill	1769	NY	912012	
Beldi Hill mill	1771	NY	909006	
Old Gang (or New) Mill	1770	NY	974005	
Summer Lodge Mill	1775	SD	965954	
Stainton Moor Mill	1786	SE	090952	
Octagon Mill	1803	NY	996036	
New Mill Langthwaite (or C.B. Mill)	1824	NY	997035	
Blakethwaite Mill	1820	NY	939029	
Surrender Mill	1839	NY	991001	
Keldside Mill	1839	NY	937018	
Cupola Mill	1839	NY	937018	
Cupola Mill	1854+	SE	043987	- Tyson = 1703?
Washton (Copper) Mill	1728	NZ	143055	
Middleton Tyas (Copper) Mill	1752	NZ	228060	
Hartley Mill		NY	80230815	
Augill Mill		NY	81651465	
Stainmore Mill		NY	849146	

Known Bole Sites in Swaledale — Barker & Tyson

Satron Side		SD	938968	
Harkerside — Blue Hill		SE	010975	
Harkerside — Shooting Box		SE	011973	
Grinton Smeltings		SE	047976	
Grinton Smeltings		SE	046977	
Beldi Hill — Muker		NY	902011	- probable
Beale Hill — Ivelet Side		SD	916989	
Kisdon Scar — Ivelet Side		SD	917986	
Kisdon Scar — Ivelet Side		SD	918985	
Windy Beale		NY	944008	
Winterings Edge		SD	949998	
Winterings High Scar		SD	948998	
Winterings High Scar		SD	954996	- five sites.
Potting Scar		SD	954992	
Winterings Gill		SD	956992	
Kinning		SD	958992	
Mount Pleasant		SD	957991	
Mount Pleasant		SD	956989	
Reeth Low Moor - Limekiln		NZ	000003	
Reeth Low Moor - Cleasby		NZ	004003	
Reeth Low Moor — Hill End		NZ	005004	
Reeth Low Moor - Calva Hill		NZ	009004	
Reeth Low Moor - Calva Hill		NZ	009002	
Reeth Low Moor - Calva Hill		NZ	013009	
Arkengarthdale - Windegg		NZ	007048	
Arkengarthdale - Windegg		NZ	008045	
Arkengarthdale - Windegg		NZ	009044	
Arkengarthdale - Langthwaite Scar		NZ	008033	
Arkengarthdale - Langthwaite Scar		NZ	009031	
Arkengarthdale - Langthwaite Scar		NZ	010029	
Arkengarthdale - Langthwaite Scar		NZ	008028	
Arkengarthdale - Tanner Rake Hush		NZ	013033	
Fremington Edge - Heggs Pasture		NZ	030018	
Fremington Edge - Heggs Pasture		NZ	031016	
Fremington West Hagg		NZ	058991	
Copper Rake Bales (4)	Working 1592	SE	056996	
Priories Bale	Working 1592	SE	063997	
Clouds Bole		NY	736993	

Some aspects of the origin of the blast furnace

Erik Tholander and Stig Blomgren

Abstract

Alternative suggestions of provenance about the origin of the blast furnace have been Germany and Sweden and bids for its date of birth vary from the 12th to the 16th century. Some confusion certainly is due to the presence in the same period of the high bloomery (Germ. Stückofen), also being a tall furnace capable of smelting coarse rock ore. Contemporary descriptions and characteristic criteria are lacking. Attempts based on various indications in archive material have not confirmed a very early appearance of the blast furnace. Other ways must be chosen to obtain objective grounds for the final judgement.

Recently, some interesting Swedish attempts have been made to use archaeological excavations of ancient furnace remains and microstructural examination of slag and iron as well as calculations based on chemical slag-analyses to establish the type of furnace being employed on three specific sites. Contradictory opinions are expressed in all of those cases, namly Harhyttan, Vinarhyttan and Lapphyttan.

One way to tackle this problem objectively is to define clear criteria as to the necessary requirements and design features for the two types of furnace.

Introduction

One problem of fundamental interest at every attempt of describing the historical development in modern iron metallurgy is the age and the origin of the blast furnace in the modern sense, i.e. the furnace producing entirely liquid pig iron which could be tapped at intervals without blowing down the furnace. Different bids have been offered at various time, as for the country and the period in which the origin could have appeared.

Difficulties are to some extent caused by the existance, for a long time in the Middle Ages and also later on, of the high bloomery (Germ. 'Stückofen') and variants thereof. This furnace type produced solid iron and, as a by-product, liquid pig iron. In contrast to the blast furnace, the high bloomery had to be blown down before it was possible to remove the iron produced. The lack of unity in classifying the respective types of furnace has been a problem to many observers. The occurrence of the cast iron on sites for iron-working also has been taken as a proof of the furnace being a blast furnace in the modern sense. A limited amount of cast iron could, however, as mentioned above, just as well emanate from a high bloomery.

In the following we will look at the literature in question and at first give examples of early production of cast iron and of early occurrences of blast furnaces. Then there will be a presentation of design features typical of the blast furnace and the high bloomery and, finally, a comparison of characteristic design features for the two furnace types will be made.

Examples on the medieval production of cast iron in high bloomeries

Firstly, it should on this occasion be mentioned that in China the production and the use of cast iron was known as early as in the 4th century B.C. How the furnaces producing that iron were designed and operated is, however, not very clear. Therefore, we will concentrate on the technology of the West.

In different European countries the producion of cast iron for foundry purposes did increase during the 14th and 15th centuries A.D. In Sweden, the earliest written indication on the casting of iron is made by St Birgitta in her Revelations[1] from about 1340 AD using the word 'giutara', i.e. 'the founders'. In England, some notes on the situation in Western Europe were made by Straker[2]: "...from quite early in the 15th century we have documentary evidence that iron founding and iron castings were known in Germany, France and Italy." He refers to some 15th century letters dealing with: "an ironfounder" (1415) in Strassbourg, a "plus gros canon de fer de fondue" at Dijon (1433) and "a cast-iron gun in a form of a lion at the Castle of Milan" (1460).

In Germany some examples are given by Gilles[3], of which one states that grey 'pigs' for resmelting were made in 1468 in the Siegerland and another that castings made directly from 'Plah' — or 'Floss' — furnaces were dated not later than 1468 AD. None of the above examples can with any certainty be connected with the blast furnace, because cast-iron was a normal by-product of the high bloomery. Gilles also remarked: "Since one had learned to cast the pig iron, the needs for cannon and other castings (stoves and stove-plates) did force forward an increased production."

Regarding the English term 'pig iron', we are of the opinion, that if it could be traced back to the Middle Ages, there seems to be every good reason to consider that this deprecatory term originated in the early period of iron-production in high bloomeries, when the non-malleable by-product was seen by the smelters as an undesired waste of good iron-ore.[3]a

Literature examples on early occurence of the blast furnace

The Latin poem by Nicholas Bourbon[4] is famous for its description of iron-making in France at the start of the 16th century. By Tylecote[5] it is described as *"the first* *description of any blast furnace".* Because in the translation by Straker[2], a distinction is made of *"the pure and the impure"* in a way indicating two kinds of iron, it seems possible that the furnace was a 'Flossofen', a high bloomery variant. Quoting Straker[2] (p.42) we read: *"...the founder...rules the molten iron...separates the pure from the impure...another worker aids (him)...to keep the furnace full...as the iron is withdrawn below. The iron that flows...cannot be called pure..."* Obviously, some "pure iron" was withdrawn in some way, not as a big solid but, perhaps, as several small lumps of wrought iron?

Certain it is, anyhow, that Bourbon describes the fining of pig iron to have been practised in France in 1517 for converting the "impure" product into "pure iron", i.e. malleable iron. To control the technique of fining the pig iron into real or 'pure' iron, was in fact, an inevitable economic condition for a successful introduction of the blast furnace producing entirely pig iron. At about the same time between 1510 and 1520, Peder Månsson[6] describes the procedure of fining pig iron in Bergslagen in Sweden. Also in this case, contradictory opinions on the type of furnace have been exposed. The present authors are in favour of the high bloomery[7], because of the two kinds of iron mentioned, the 'skärsten' (pig iron) and 'smelterne' (the masses).

According to Gilles[3], the refining of pig iron in Germany was practised in "Hammerhütten" from 1444 and onwards. The German reduction furnaces, at that time, Gilles called "Blas" - or "Plah" -hütten, i.e. a kind of 'Stücköfen'. After having stated (p.407) that a number of "Hochöfen" in the 15th century recorded by Otto Johannsen were not founded in a historically satisfactory way, Gilles[3] (p.412) concluded that the transition from "Flossofen zum Hochofen" in Germany must have taken place in the 16th century. In this paragraph, Gilles obviously regards the 'Flossofen' as a high bloomery.

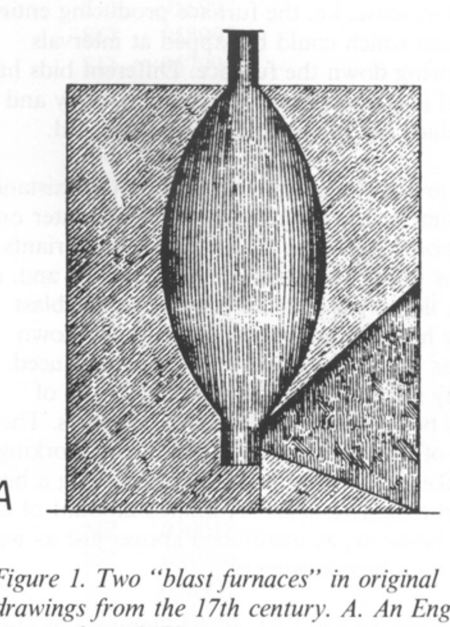
Remarkably, it seems, neither of the authors of the most famous books on 16th century metallurgy, Biringuccio[8] and Agricola[9], specify the blast furnace nor the fining of pig iron into wrought iron (but, instead, both authors describe the making of steel by "boiling" wrought iron in molten pig iron). As a consequence Gilles[3] (p.407) states that: *"Um 1600 treten die ersten hohen Giessöfen mit engem Gestell und offener Brust, die Holzkohlen-Hochöfen, in Urkunden auf."* He also states, that in France the name "haute fourneau" for blast furnace appears at first in the 18th century.

In Sweden the earliest signs of the fining of pig iron begin to occur in the middle of the 15th century with the records[10] of punishments for the mixing of "loppejärn" with 'osmunds' iron in the same barrel. The "loppejärn, apparently, was fined pig iron and the "osmund" iron was wrought iron from high bloomeries.[10]b A century later, that sort of regulation was revoked and still later in 1625, in a letter to the Prime Minister, Count Carl Bonde suggested that: *"all osmund-smiths should learn how to refine the pig iron into 'loprejärn'."* During the 16th century, King Gustaf I showed great interest in promoting the development of the Swedish iron industry. He was a private partner in the Osterby Iron Works, started in 1545, of which official records[11] have been preserved for the period 1551 - 1622. Very little pig iron was recorded there during the first three decades, indicating the single "masugn" to have been of the high bloomery type. Then, in 1580, about 12 tons of pig iron were recorded. In 1582 66 tons of cast-iron were produced. In 1583, three furnaces were recorded and, in all, 112 tons of pig and cast iron were produced, a figure which in 1584 grew to 207 tons. For the rest of the period, the production continued at a high level. The conclusion here must be, that in 1582-83 two new furnaces were built of a different type, which obviously was the blast furnace in the modern sense, producing liquid iron only. It is not possible to say here, that they were the first in the country, but it seems most probable that they were among the very earliest of the kind in Sweden.

"In Poland the blast furnace process appeared at the outset of the 17th century", as expressed by Miczulski[12]. There the Bishop of Cracow in 1610 gave priviledges to two Italians from Bergamo for the constructing and using of one blast furnace and three fineries at the river Bobrza in the region of Kielce in central Poland, a district with traditions in bloomery iron-production back to antiquity. Because of destroyed archives, Miczulski gives no original information on details, but he gives a few estimated figures with reference to another source about Italian furnaces in the 18th century, namely a shaft height of ca 7 m and a "working capacity of 300 - 600 kg".

Design features of importance in regard to furnace characteristics

Now we will have a look at some diagrams for the two types of furnace recognised and discuss some essential features, starting with the blast furnace. The illustrations are shown in the Figs: 1-5.



1A

Figure 1. Two "blast furnaces" in original drawings from the 17th century. A. An English picture from 1678[14].

The blast furnace, producing liquid pig iron "continuously", is from the 18th century very well documented as a tall shaft furnace with a narrow hearth. It is also known that its smelting capacity has grown tremendously because of successive changes in many respects, such as dimensions, shape, number of tuyeres, air supply, charging techniques and so on. The problem of interest here, however, is which design features were characteristic of one kind of furnace when it was new, and which had to stand competition from one or more types already well-established.

Because we do not have any detailed description of a blast furnace earlier than that in *'De Ferro'* by Emanuel Swedenborg[13], printed in Leipzig in 1734, and no earlier picture of the internal design than that published in London in 1678[14] and reproduced by Beck[15] and Odelstierna[16], we will have to use these to try and make a reconstruction of the probable design appearance of a blast furnace as close to its origin as possible. See Fig.s 1A and 2.

The measurements given by Swedenborg for some contemporary European furnaces are collected in Table 1. Furnaces of various age are represented, the earlier being characterised by square cross-sections and somewhat lower height than the newer ones. The lowest height-figures are 18 and 20 feet, observed in Liége and Harz.

In Swedenborg's survey, the oldest type of hearth was seen in Brescia and in Saxony, having bottom areas (by our calculation) of respectively 0.198 m^2 and 0.132 m^2, with corresponding two statements of interest here:

1 For 50 or 100 years ago, lower and square furnaces were used, as still is the case somewhere in Germany and here (Sweden). (Swed. transl. p.15).

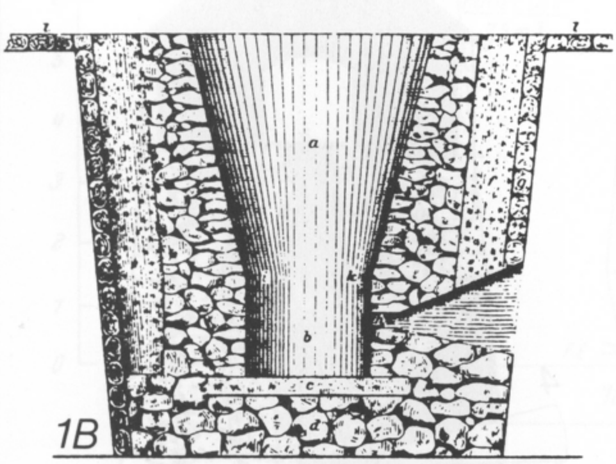


Figure 1: B. "Old Swedish Masugn" from 1673[16]. (The heights are approximately the same, 20ft.)

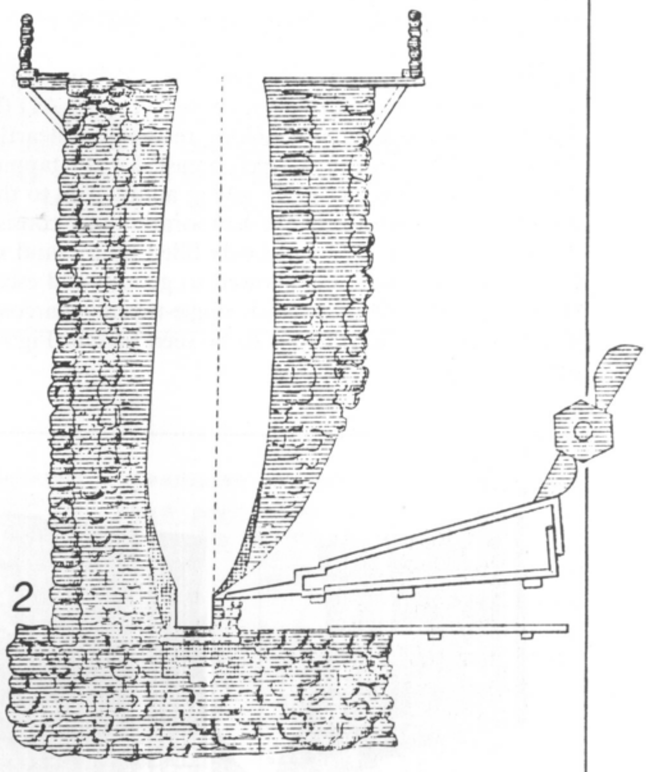


Figure 2: Swedish blast furnace, 1734. Drawing by E Swedenborg, in De Ferro, Table 1

2 The blast furnaces of the old days not in service any more, were less in size than "those today" and had hearths taking only two 'skeppund' or about 300 kg of pig iron (one third of the "modern"). (Swed. transl. p.23).

By considering this information from 1734 it seems probable, that the furnaces in Sachsen, Leíge and Brescia approach most near an original shape and size of the early blast furnace, namely:

Height: 18-20 feet (5.3m - 5.9m)
Top mouth: $2\frac{1}{2}$ x $2\frac{1}{2}$ feet (0.75m sqre)
Hearth size: $1\frac{1}{2}$ x 1 x 1 feet (0.04^3)
Bottom cross section: square

Swedenborg's hint of dating, 50 to 100 years ago, puts it to between 1685 and 1635 AD. The obvious character of estimation and an additional assumption here of at least a utlization time of 50 years for such a furnace, would put the early limit back to 1585 or even earlier. Remembering now the production records from Osterby Iron Works and the change there noted in the period 1580-1585, the coincidence with Swedenborg's information is striking. The erection of a group of two new furnaces seems to indicate the process development stage had been finished then. The real origin, or the very first workable unit, must have occured elsewhere at some place of which we today have no knowledge.

One feature which meets with most descriptions and pictures of early blast furnaces, i.e. before 1800 AD (but even later), is the square or oblong rectangular hearth combined with a so called 'open breast' for the tapping of iron and slag and, at need, giving admittance to the interior by the removal of the temporary block consisting of "tymp and dam", being loosely filled up by sand so that a little gas-flame was allowed to get out and escape. The "modern" type of Swedish single-tuyere, charcoal blast furnace around 1790, is to be seen here in Fig:s 3 and 4.

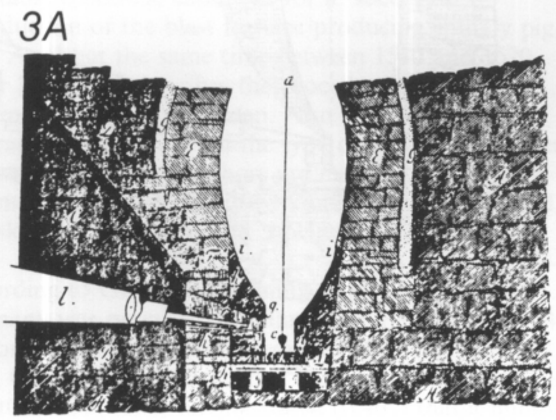


Figure 3:A. Vertical shaft section, lower part. Blast furn 1794. Drawing by J C Garney, Tab XIV.

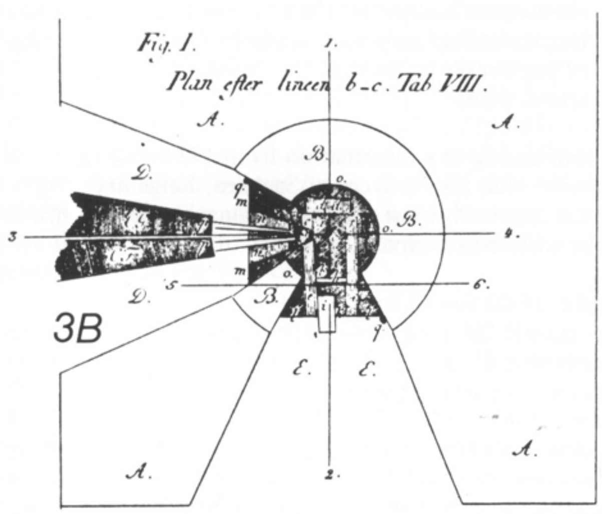


Figure 3:B. Horizontal cross section, above the hearth. 1794. Drawing by J C Garney, Tab XIV.

The high bloomery, if we now return to this type, which certainly originates from Austria in the 12th century, and is a water-driven, enlarged version of the antique bloomery used in the Roman Empire; it seems to be a type of furnace used for a long time and not only in Europe. In most countries it was abandoned in the second half of the 18th century, except for Finland, where it survived on a few places and in the 1880s was redesigned and modernised by Mr Husgafvel.[18] Thus the total utilization time will have been of the order of eight hundred years. The characteristic features were the wide hearth and the large front-wall opening for the extraction of the main, solid product, the "massa ferri".

In Sweden we have no contemporary documentation clearly usable for distinguishing the use of high bloomeries because of the uniform denomination 'masugn' for every tall furnace. The "Old Swedish Masugn" in Fig. 1 B shows, however, that this type of furnace without doubt belongs to the high bloomery type of furnace. And we have a somewhat mysterious description written in 1725 by P Saxholm and reprinted by Swedenborg[13] under the title: "Om svenskt osmundsjärn" and the substitle: "The older way of manufacturing such iron". Because of the history of Peder Månsson[6] two centuries earlier, we can class Saxholm's introduction as of dubious value when he tells of "bog ores and hand bellows". But in two respects Saxholm gives valuable information, namely on the "old furnace" having two openings: On the back wall a lesser opening near the ground for the inlet of the air-blast and on the front wall a bigger opening being carefully shut by well-fitting stones as long as the blowing lasted, whereafter the stones were removed and the iron-lump was extracted.

The value of the above information has already been commented on[7], but Swedenborg's lack of appreciation of the technical method may have had some unknown

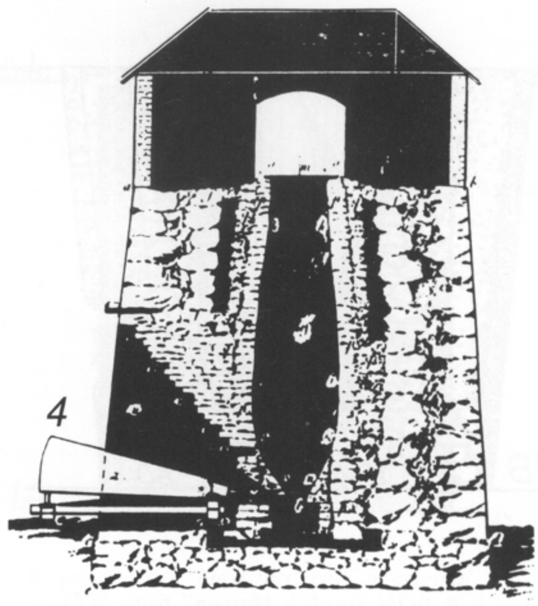


Figure 4. Swedish blast furnace, 1789. Drawing by Sven Rinman, Bergwerks Lex., Tab XXIV.

reason. Anyhow, a furnace equipped with two openings as mentioned by Saxholm-Swedenborg was excavated some years ago at Harhyttan by one of the authors[19].

From the diagram in Fig. 5 (after Gilles[3]) a lot of information can be gathered, which is useful here, as for example the following regarding furnace heights:
"Plah-hütten", similar to "Stücköfen", 13th cent.: height up to 3m
Stücköfen, 15th-16th cent., "flowering time": 3-4m
Stücköfen about 1700 AD: up to 4.6m
"Flossöfen" with a wide hearth 1750-1850: 5.8-6.2m

The shaft-profiles collected in Fig. 5 show clearly, that the furnaces of the types: Blas-, Blau-, Stuck-, and Floos-ofen' are relatively wide in the bottom-part, the hearth. There are seven examples of these types, here numbered from 1 to 7. The shape of the hearth cross-section may be square, elliptical or circular, but the width is not less than 0.7 m and may rise to 1.7 m. There also are three examples with narrow hearths, two of which seem more likely to be called "blast furnace' (Germ. 'Hohe Ofen', or 'Hochofen').

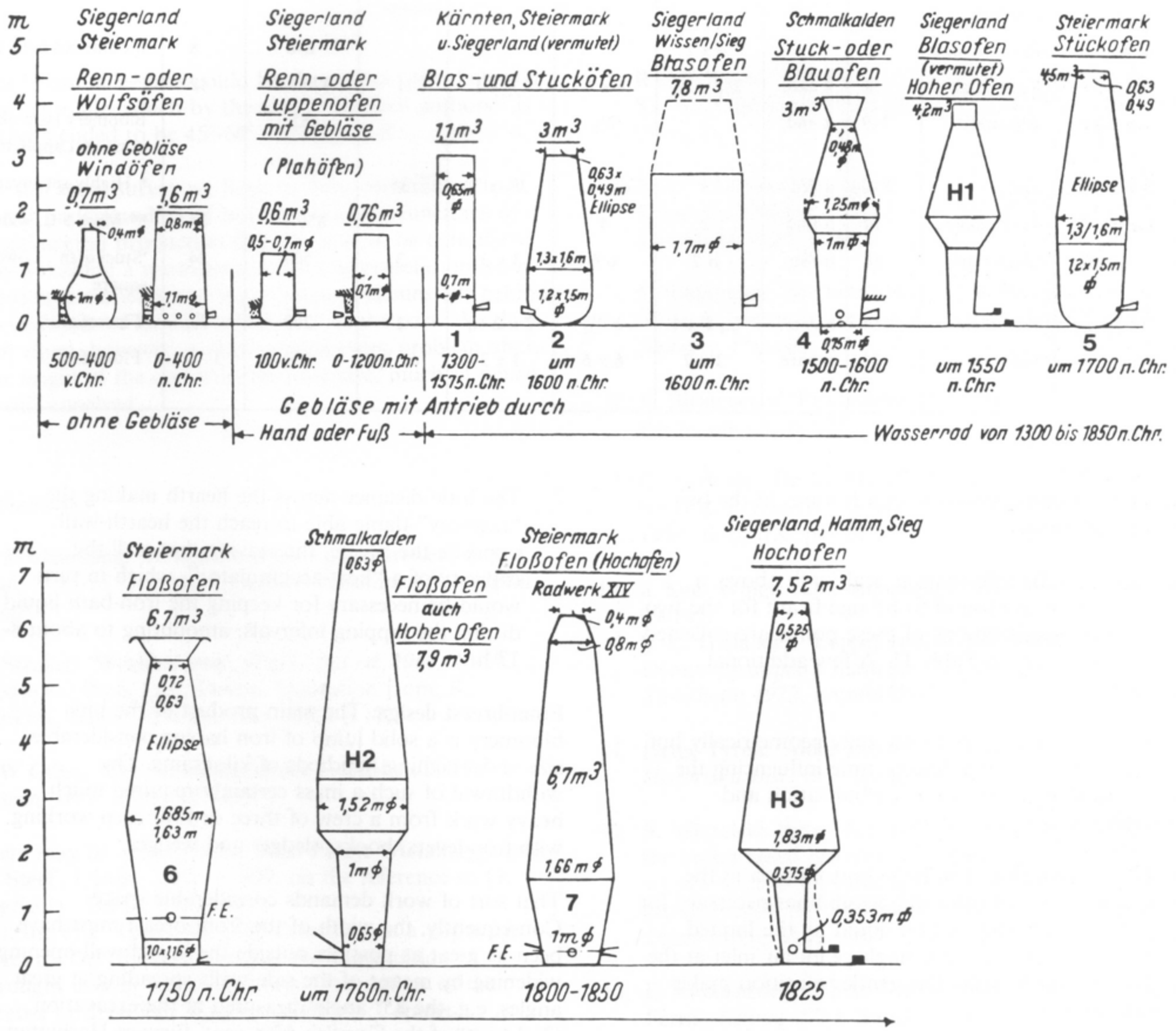


Figure 5. Profiles of German shaft furnaces until 1825 AD. After Gilles$_3$.

Additional numbers: 1 – 7: High bloomeries. H 1 – 3: Blast furnaces.

Table I Smelting furnaces for iron-making — with actual details in the 1730s.
After E. Swedenborg: *'De Ferro'*, Leipzig 1734. Page numbers in Swed. transl., Stockholm 1923.
Weights recalculated. Remarks by the authors.

Page No.	Country	Place or District	Height feet	Cross-profile profile	Mouth width feet	Shaft width max. feet	Hearth area sq. ft.	Hearth depth feet	Iron in hearth kg	Tapping intervals h	Remarks
155	Sweden	Roslagen	24-25	round	6-6¼	7½-8	3 x 1½	¾	1360-1530	8	
174	France	Grossouvre	27	square	2½	7½	3 x 1¼	1⅓			
179	Belgium	Liége	20	square	2 x 3	6-7			720	12	
180	Italy	Brescia	24	square	3 x 3		1½ x 1½				
186	England	Stourbridge	26	square	1¾		2 x 1½				Very wide boshes
		Gloucester (Sussex)	28	square	1½	8 x 8	4 x 1¼	¾ *			* Depth from tuyere
194	N. America	Pennsylvania	25		4 x ?				640	8	Bloomeries used too
207	Saxony	Rothendal	18	square	2½ x 2½	6 x 6	1½ x 1	1	420-510	12	
208	Bohemia	Altsattel	8-9	round		2½			85		Bloomery (size about same as Lapphyttan)
209	Germany	Harz	22-24	sq/rd	3	over 3	3½ x ?	3*			* Highly set tuyere
213	Austria	Vordernberg	14	round	2	4			850 **	24	** Mass 5 ft. wide
214	Germany	Steiermark	18	rd/sq	ø 2	ø 6	3 x 3	3	500	24	'Stuckofen'. Lower half square
217	Germany	Kärnthen	24	rd/sq	sq 1 x 1	ø 4½	2 x 2 sq	1	200	3⅓	'Flossofen'
219	Germany	Salzburg	24	square	2 x 2	6 x 6	3 x 3	ca ¾	120	3 - 3½	'Flossofen'

Comparison of characteristic design features at the two main types of furnace

In summing up the information dealt with above, a number of points are found to be significant for the two furnace types. Specifications of these points are collected in the survey shown in Table II. A few additional comments follows:

The height: This is important not only geometrically but, decisively, because of the descent time influencing the iron formed with respect to its carburisation and liquidisation.

Shaft/hearth transition: The large bottom-area in the high bloomery cannot offer the possibilities necessary for keeping a large amount of iron liquid by the limited heating-capacity evolved at a single-point air inlet at the periphery of a big hearth. The gentle transition makes that problem worse.

On the contrary, the funnel-shaped, sharp transition in the blast furnace limits the stack material supply into the hearth resulting in:

1 The main part of the metallic iron being kept back in the shaft until the carburisation has transformed it into the liquid state.

2 The little distance across the hearth making the "raceway"-flame able to reach the hearth-wall opposite the tuyere, thus giving that wall the capacity of a "heat-accumulator", which in turn would be necessary for keeping the iron-bath liquid during the tapping intervals, amounting to about 8-12 h.

Front-breast design: The main product of the high bloomery is a solid lump of iron having considerable size and weighing hundreds of kilograms. The withdrawal of such a mass certainly required much heavy work from a crew of three or four men working with iron-levers, hooks, sledges and wedges.

That sort of work demands considerable space. Consequently, the width of the front-breast must have been as great as possible outside the broad wall-opening, widening by means of the side-walls spreading at great angles, e.g. the 83° angle measured at the excavation (2nd turn) of the Swedish 17th cent. furnace Harhyttan.

At the blast furnace, however, the need for space in the front-breast was much less because of the need only for cleaning and preparing work usually made by one single man, as well as the tapping of iron and slag, which runs from the narrow opening in small streams along grooves suitably dug in the sand.

Table II Survey of design characteristics of the two types of reduction furnace, which dominated the European iron industry during the centuries before 1800 A.D.

Specification	High Bloomery (Stückhofen)	Blast Furnace
Total height, bottom to mouth, m	2.5 - 5 ('Flossöfen': 5.4 - 7.4 m)	5 to 10 m (17 - 33 feet)
Maximum width relation, shaft to hearth	2:1 or 1:1	4:1 or 3:1
Shaft cross section	square, elliptic, circular ('round')	Earliest: square; Later: round. Combinations occur.
Type of transition shaft/hearth	gently	sharp
Shape of hearth	mostly same as the shaft	square or oblong rectangular
Hearth width	more than 0.6 m	less than 0.6 m
Hearth front opening	wide; 0.7 m or more, closed during blowing period	narrow; equipped with 'dam & tymp' in 'open breast' arrangement giving a little space for the gas flame to escape
Air supply arrangement	various, in Sweden through a low opening in the back wall	by one tuyere perpendicular to the tapping direction, through a side-breast
Withdrawal of the iron	directly on the outside ground, eventually protected by a front-breast with side-walls spreading at a wide angle, 75° - 90°	running into ground-pits or moulds by passing a front-breast, the side-walls spreading at a moderate angle, 45° - 60°.

The breast side-walls could be closer and spreading at a smaller angle, which by the classic Swedish authors[17] is recommended to be 45°-60°. See Fig. 3 B.

By this short survey we hope to have contributed to a better understanding of how the working functions of a metallurgical production furnace have to be considered when making a reconstruction and interpretation from written documents and from furnace remains left behind as witnesses of an iron production in the past. We do not claim, however, to have solved every problem about the origin of the cast iron blast furnace, much of which is still unsolved.

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Primitive furnaces and the development of metallurgy

J E Rehder

Abstract

The traditional view of the development of metallurgy is that only limited temperatures were attainable in early charcoal furnaces, and that smelting ability progressed from lead to iron as furnace temperature capability improved. It is demonstrated here by present-day combustion technology and by reference to published test work that a simple charcoal furnace 30 cm in diameter with a single tuyere easily powered by one man can reach 1,600 C in temperature and smelt iron ore to molten cast iron. The production of bloomery iron actually requires a decrease in furnace temperature. The application of the combustion of charcoal to various furnaces and the quantitative analysis of a shaft furnace are reviewed and it is pointed out that early development of metallurgy must have been much more conditioned by the availability of ore deposits than by furnace capability.

Introduction

The traditional view of the development of metallurgy is that copper smelting preceded iron smelting because of the limited temperatures supposedly available in simple charcoal furnaces. It does not seem to be generally recognized that a simple charcoal furnace has the inherent capability of reaching temperatures in excess of 1,600 C, with the effort of less than one man on air supply. This removes furnace temperature capability as a major limiting factor in the development of metallurgy, and the traditional views of the course of development of the use of metals must be re-examined.

There are wide implications. For example, on the archeological evidence copper was smelted long before iron, but the opinion that this was because of its easier reducibility and lower melting point, is open to question. The wide distribution of copper, both native and as its colorful ores, seems to be a more practical reason for its earlier use. This leads to the suggestion that location and pace of development of metallurgy must have depended on the ores locally available and the skill with which smelted products could be made useful. Since the charcoal furnace was ubiquitous, development of metallurgy could have been at many independent points in geography and in time.

The primary issue is the temperature capability of charcoal fueled furnaces, and this will be demonstrated on the basis of current knowledge and experience in combustion technology and in heat transfer, and examples of test results will be given. Furnaces supplied with air through a grate perform quite differently from those using tuyeres, and the differences will be described.

A few of the implications of these facts will be outlined. Only charcoal is considered as fuel throughout.

Furnace Technology

An open wood or charcoal fire can reach 700 or 800 C, which can fire pottery to a good hardness or anneal copper but is of minor value in smelting metal oxides. The use of lump charcoal in an enclosure of stones or clay not only made a nearly smokeless and approachable fire, but increased internal temperature because of decreased heat loss by radiation and because of a more controlled air supply. This constituted the first true furnace and made possible the smelting of metal oxides.

Combustion Chemistry

A bowl of burning charcoal is a very simple thing. If the container is of sheet metal and an opening in the bottom allows a little air in, it is one of the garden barbeques that char acres of beef every summer. If however the container is lined with fireclay, the fuel bed is deeper, and the air supply is more vigorous, iron ore can be smelted to molten cast iron.

The reasons for this wide range of power are simply the manner in which lump fuel burns as a packed bed or enclosed mass, and the geometry and size of the container. To explore further we must go in some detail into the combustion of lump fuels in packed beds. This has been an extensively studied subject, since until fairly recently all industrial production of heat and energy has been by burning charcoal, coal, or coke. There are some consistent patterns in such combustion, summarized very well by Hiles and Mott (1).

Initial combustion is very rapid but incomplete to CO_2 with the production of a great deal of heat. It occurs within two to three fuel lump diameters, which with the usual sizes for charcoal is two to six cm. The flame temperature developed by initial combustion is readily calculated from the amount of CO_2 and the thermochemistry involved and is very high, about 1,920 C for the 10 to 12% CO_2 developed by charcoal. Heat is of course immediately lost to surroundings which decreases temperature rapidly, so that in small fuel beds with high heat loss only a tiny volume of very high temperature exists, surrounded by a steep temperature decline. It is enough however to melt a Pt-PtRh thermocouple bead at 1,800 C if in the right spot.

The initially developed CO_2 is then reduced to CO by the hot fuel through which it passes, at a rate that depends on the chemical reactivity of the charcoal, its surface area (inverse of lump size), and the gas velocity (time available). Gas temperature is decreased as CO_2 is reduced because the reaction is endothermic or heat absorbing, falling to about 1,600 C maximum when reduction is complete to CO. Charcoal varies somewhat in reactivity depending on the wood it was made from and how it was carbonized, and of course it can vary in lump size, but with a given charcoal fuel bed the length of the CO_2 - CO reduction zone is entirely controlled by the velocity of combustion air entry. It can therefore be varied considerably.

Heat and Temperature Development

The maximum temperature possible in combustion is determined by the thermochemistry, but the degree to which this is approached in a useful volume of fuel bed is determined by the ratio of the rate of heat input to the rate of heat loss.

The rate of heat input is determined by the rate of air supply, since the rate of combustion is a quantitative function of the rate of air supply. Because of its highly reactive nature, charcoal in normal lump sizes and bed thicknesses burns to nearly pure CO and N_2 gases, and then one cu m of air will consume nearly 0.20 kg of carbon and produce 540 kcal of heat. Air input rate is customarily defined as cu m per min per sq m of empty container cross-section, so one cu m per min per sq m of air creates or injects 540 kcal of heat per min per sq m.

Heat is lost in several directions. All containers lose heat from their surfaces, and since the ratio of surface area to volume is larger for smaller containers, furnaces less than about 15 to 20 cm inside diameter cannot reach as high a useful temperature as can larger furnaces at the same heat input or air rate. Other heat losses are to preheat fresh burden and to supply heats of reduction reaction of metal oxides, and considerable heat is lost to top gases particularly in short furnaces such as hearths and bowls. In summary to retain high temperature in useful working volume within a furnace, the rate of heat input (i.e. the air rate) must be relatively high, and the furnace must be reasonable large in size with preferably some height to recover top gas heat.

It should be noted that primitive furnaces were and still are operated on a batch basis, partly because of poor refractory wall life. Furnace walls absorb a great deal of heat to approach working temperature and this requires preheating for several hours to make possible sufficient bed temperature for successful smelting.

Two examples of direct measurement of temperatures in simple lump fueled furnaces blown at low air rates may be quoted. One is from an extensive series of tests with lump coke as fuel in a bowl furnace 35 cm diameter, in which a specific air rate of 10.0 cu m per sq m per min developed a maximum temperature of about 1,650 C and 21.0 cu m developed 1,750 C (1). The other was in a reconstruction of an early shaft furnace 30 cm diameter with a charcoal fuel bed 100 cm high. This was blown through a single tuyere 25 mm diameter with 300 liters of air per minute, i.e. at a specific air rate of 4.2 cu m per sq m per min. At tuyere level 1,600 C was measured and 10 cm higher 1,250 C, and the furnace readily smelted iron ore to molten cast iron (2).

The importance of furnace size and of specific air rate is major, and the development of fuel fired furnaces to the present day has been basically by increase in size and in the intensity of blowing. Modern blast furnaces are blown at 50 to 60 cu m per sq m per min, and in large furnaces measured maximum temperatures are close to calculated flame temperatures (3) (4).

Air Entry

Air can be introduced into a fuel bed either through a grate which supports the bed, or through one or more tuyeres which enter the bed from the side above a closed bottom. This constitutes a major functional division of furnace types because of the considerable difference in how the furnace can be used.

Furnaces with Work and Fuel Separate

If air enters a fuel bed through a grate the resistance to flow is small compared to that of the bed itself. Resistance in beds of charcoal is relatively low unless the bed is thick and the charcoal is very small sized, so natural draft can produce considerable air and heat flow rates which are nearly uniform across the bed. However if ore to be reduced or metal to be melted are mixed with the fuel, the resulting molten metal and slag will destroy the grate. This is a materials problem that has been solved commercially only in the last few years. Ore to be smelted or metal to be melted using a grate must be kept separate from the fuel in crucibles, and the operation can only be in batch fashion.

One or more crucibles embedded in charcoal at the right height above a grate can be heated with natural draft to very high temperature and this procedure was followed at least as early as the end of the fourth millenium B C at Abu Matar (5).

Since the charcoal on the grate is steadily burned away from under crucibles, they should be supported at a constant height above the grate by small clay stools to remain in the highest temperature zone of the fuel bed. Conical crucibles with very narrow bottoms were used in early Chinese furnaces (6) and in Europe, and these could very well have sat in special holes in the grate to provide the correct constant height for the crucible contents.

It is possible in such crucible furnaces to reduce metal oxides by mixing pulverized ore with enough fine charcoal to reduce it, and then heating the mixture in a closed crucible. At moderate temperature (depending on the metal involved) the oxide will be reduced to a loose metallic sponge; at a higher temperature to a coherent sponge; and at still higher temperature to a molten metal with a layer of slag floating on top. The famous Indian 'Wootz" steel containing 1.0 to 1.6% carbon requires a fusion temperature of 1,475 to 1,420 C, and can be made either by reduction and melting with excess carbon, or by melting bloomery iron with carbon.

The carbon necessary in such cases is much less than that necessary for burning to supply heat, so impurities in the carbon such as sulfur then matter much less, and coal can replace charcoal. The Chinese in Han times used ore plus coal mixed in elongated crucibles packed in rows with more coal between the crucibles. Air access was provided from below and the whole was enclosed in refractory walls. Combustion of the coal between the crucibles provided the heat, but the only sulfur reaching the metal was that in the much smaller amount of coal within the crucibles.

A two-chamber furnace, with fuel burned below a grate on which ware to be fired was stacked, was used as early as the 5th millenium B C at Khafaje (7). In a thoroughly preheated furnace the hot gas temperature could exceed 1,500 C and in order to avoid sagging or collapse of the grate, the operating temperature may have had to be controlled below the maximum possible by limiting the air supply.

Very high temperatures that would require special refractory clays for furnace construction, can be attained by carrying the fuel bed on a grate and then producing a secondary combustion of the CO above the fuel bed. The primary rate of combustion is controlled by the rate of air supply beneath the grate carrying the fuel, and the products of combustion with a fuel bed more than 15 to 20 cm thick will be CO and N_2 at a temperature of 1,500 C or more. If secondary air is then mixed with this gas the CO is burned to CO_2, creating a flame temperature of more than 1,800 C. This is more than most natural fireclays can stand but if such hot gas is drawn sideways over an adjacent hearth, a reverberatory furnace is created. This will not be pursued further here for lack of space.

Furnaces with Work and Fuel Mixed

If one or more tuyeres are used to introduce air through the furnace wall near the base of the fuel column, the materials problem of a grate is avoided and the hearth can hold molten metal or slag to be tapped, or a growing solid metal bloom. This does not interefere with air supply, and tuyeres if damaged are easily replaced. Fuel and work can be added as a mixture, which gives excellent heat transfer, and operation can be continuous.

This is by far the most commonly used furnace arrangement, but conditions across the bed are not uniform. A bed of broken solids such as a fuel bed has a strong diffusing effect on the passage of gas, and air introduced from the side of a fuel bed must have considerable velocity in order to gain penetration towards the centre. This is done by decreasing the diameter of the tuyere. The combustion sequence described above then becomes physically arranged as a cone expanding from the nose of the tuyere, the cone being also bent upwards by the effect of the container walls. The relatively high gas velocity shortens the time available for CO_2 reduction which is thus considerably extended in length, so that a long zone of high average temperature and oxidizing power is created. With a single tuyere there is a lop-sided effect until further diffusion takes place higher in the fuel bed. With two or more tuyeres there is a very desirable balanced flow towards the centre and wider lateral distribution.

The major disadvantage of the use of tuyeres is the considerable increase in resistance to air flow caused by their small diameter and necessary high air velocity. Standard orifice formulae show the increase in pressure drop to be inversely as the fourth power of the diameter, and in most charcoal furnaces the pressure drop in the tuyere is two to as much as 20 times that in the fuel bed. At larger air volumes the use of several tuyeres is necessary to keep power requirements reasonable.

As charcoal is consumed by combustion at and just above tuyere level it disappears as gas except for a small amount of ash, and the fuel column descends by gravity to take its place. There is therefore a steady downward movement of burden, and ore or metal mixed with the charcoal is carried down with it, through an upwardly flowing stream of reducing gas. This gas increases in temperature as tuyere level is approached, and metal oxides are reduced and metal and gangue are preheated.

As the reduced metal oxide, now hot metal particles and gangue, is lowered still farther it reaches the temperature level of its melting point. This will be higher above tuyere level for a metal like copper with a melting point of 1,083 C, than for iron with a melting point of 1,538 C. The resulting molten droplets trickle rapidly (a few seconds) down between lumps of fuel to collect on the hearth as a pool of molten metal covered with a layer of molten slag. With a peep-hole in a tuyere this action can be seen clearly. There is little oxidation of metal by the oxidizing gases at and just above tuyere level because of the very short passage time, but the droplets are increased appreciably in temperature by radiation from the very hot lumps of fuel.

If iron oxide is to be smelted, more energy is necessary for the reduction reaction than for example for copper oxide, and a larger zone of high temperature is necessary to melt the higher melting point iron. This is provided by using a moderately higher ratio of charcoal to oxide and by increasing the air supply rate, which increases the ratio of heat input to heat loss or absorption. The sequence of events is however the same as described above, and has been well established by extraction of samples and by examination of quenched furnaces. It may be noted that the temperatures and heat requirements for smelting manganese and nickel oxides are little more than those for iron oxide, and they will be reduced with iron if they are present in the ore.

However if iron oxide is charged to the furnace with lower charcoal to ore ratio and lower air rate, the average bed temperature is decreased and there is only a small volume with temperature above 1,500 C. Most of the iron reduced above tuyere cannot melt and must therefore pass through the oxidizing zone at tuyere level slowly, i.e. at the burden descent rate. The iron would largely re-oxidize if not protected by a slag formed from ore gangue and excess iron oxide, which becomes fluid at about 1,200 C. Most of the molten slag drips down through the charcoal in the hearth, and the particles of reduced iron are filtered out and consolidate to a mass or bloom just below tuyere level.

The rate of movement of burden and the residence time in a furnace depend directly on the air rate and are predictable from the properties of the particular charcoal used. It should be noted that the usual smelting ratios of charcoal to ore of 0.5 to 2.0 to 1 by weight, when converted to volumes are 9 or more to 1, so that charcoal movement essentially determines the movement of the whole burden. If a particular charcoal contains 70% fixed carbon and is of 200 kg. per cu m bulk density, then 1.0 cu m of air will gasify 0.29 kg of charcoal, which occupies 0.0015 cu m. If the specific air rate in the furnace is 7.0 cu m per sq m per min then the rate of descent of burden will be 0.01 m per min. In a bowl furnace with the top of the fuel bed 20 cm above tuyere level, fresh burden will then have 20 minutes to be preheated and reduced or melted; but if the furnace walls are high enough to contain a burden 100 cm deep then 100 minutes will be available for heat transfer and reactions. Such extended time increases heat transfer efficiency and temperature, and saves considerable fuel. If the ratio of charcoal to ore in a burden is doubled with no change in air rate, the rate of descent of burden and of production of heat are not changed but there is then half as much ore present per unit of fuel and so heat requirement is lower. This increases the ratio of heat input to heat loss, and furnace temperature increases while production rate decreases.

It is important to note that these metallurgical and combustion reactions are carried out in practice under far from equilibrium conditions, and one can be seriously misled by attempting to analyze what is happening, or what could happen, on the basis of equilibrium calculations. This is particularly true in small furnaces, since the most modern large blast furnace or cupola operates under far from equilibrium conditions (8) (9).

The Finery Hearth

The action of the finery hearth depends on non-equilibrium conditions. The bed of charcoal is relatively shallow so there is little preheating of metal put into it, and the air velocity from the tuyere is intentionally made high to give a long combustion and oxidizing zone. When one end of a bar cast iron (pig iron) is placed in the coals in the patch of the tuyere not far from its nose, the end of the bar is raised to its melting temperature in a short time by the very hot oxidizing gas. Some decarburization of the iron occurs during the melting, and increases while molten droplets with large surface area fall to the hearth. A molten slag high in iron oxide content covers the hearth and the droplets of iron falling through it are further decarburized. As the carbon content of the iron droplets is decreased their fusion temperature increases and the droplets become pasty. They are rabbled into balls which when of suitable size are removed from the hearth. Entrained slag is mostly squeezed out by forging which is done immediately on the ball to form it into rough bar iron. It may be noted that the final carbon content of the iron is approached from above and the course of reaction can be sensed from manipulation of droplets into balls, while in the bloomery process final carbon content is approached from below and the course of reaction cannot be followed. The final metal is essentially identical from both processes, and the slags differ only in a moderately higher silica content in bloomery slags from gangue in the ore.

Smelt versus Melt

The heat necessary to reduce a metal oxide to molten metal is much greater than that simply to melt the metal. For example molten copper from a high grade oxidized ore requires about 1,410 kcal per kg of copper, while simple melting of copper requires only about 180 kcal per kg. If the same furnace and air rate are used so that the heat losses and the heat developed are the same, the ratio of fuel required per kg of copper for smelting as compared with melting is 1,410 to 180, or 7.8 times as much to smelt as to melt. When the carbon necessary for reduction of the oxide in smelting is included, the ratio increases to 9.4 to 1.

This ratio increases farther if the ore is less pure because of the heat necessary to melt useless gangue to slag. Furthermore since the output of a furnace at constant air rate is inversely proportional to the fuel consumption, the size of furnace necessary to melt 10 kg of copper per hour is only about one ninth of that necessary to smelt copper at the same rate, and the air supply necessary is only one ninth as large.

There are therefore excellent reasons for smelting ore at the mine and then shipping the resulting ingot to where finished goods are required, where they are easily remelted to make castings, or become feed stock for a finery. This system was apparently set up and used early both in the Near East and in China and was likely more extensive than presently realized.

Since a small furnace will melt at a considerable rate it is easily made portable so that when a batch melt is ready the furnace can be detached from its air supply and carried with its hearth full of molten metal to a mold for pouring, with little loss of temperature and fluidity. Use of crucibles or ladles for transporting molten metal would be avoided wherever possible because of the high heat loss and resulting loss of fluidity.

Power Required

For natural draft no external power is required, but if a mixed fuel furnace is to work on natural draft the tuyeres must be numerous and of considerable diameter in order to decrease pressure drop, and penetration of air must be sacrificed.

If air pressure is created by some form of bellows, use of one or a few small diameter tuyeres can give good air penetration into the fuel bed. The power or effort required even on very inefficient bellows is small for a small furnace. For example a 30 cm diameter furnace 100 cm high blown with 0.3 cu m of air per minute through a single 20 mm diameter tuyere would smelt iron ore to cast iron at a rate of about 0.6 kg per hour, and the pressure drop through the bed would be about 0.32 mbar and through the tuyere about 2.3 mbar for a total of about 2.6 mbar. This would required 0.0013 kw and if a primitive skin bellows is assumed to be 15 percent efficient 0.009 kw must be put into working the bellows. This is about 9 percent of the sustained output of an average man. (10).

A comment should be made on the use of lung power or exhaled breath as a combustion air supply. It is not very effective since it not only contains less oxygen than ambient air, but carries water vapour and CO_2, both of which absorb heat during combustion. A typical analysis of exhaled breath is 13.7% 0_2, 5.3% $C0_2$, 6.2% H_20, and 74.6% N_2 (11), and the maximum flame temperature with charcoal fuel is only about 1,200 C.

Summary

In the foregoing exposition several points have been made about charcoal fueled furnaces and their inherent capabilities. Principal items are:

1 Temperatures above 1,600 C are readily developed in useful furnace volumes by combustion of charcoal with ambient air in simple enclosures.

2 Air supply rate is the basic controlling factor in furnace operation.

3 Iron ore can be reduced to molten cast iron in a simple mixed fuel furnace of moderate size and air supply rate. Oxides of manganese and of nickel are also reduced in such circumstances.

4 Solid state reduction of iron oxide (bloomery process) requires operation of a charcoal furnace at working temperatures well below those readily obtainable.

5 The finery process of decarburizing cast iron gives better control of final carbon content, i.e. steel properties, than does the bloomery process.

6 The final iron products of the bloomery and of the finery processes are essentially identical and there is no clear way of telling by which process an iron artifact was made.

7 Melting of metals can be performed in mixed fuel furnaces which are identical with smelting furnaces, but at rates 6 to 10 times faster and consuming proportionately less fuel.

Implications

A variety of probable consequences and further questions can be drawn from the conclusion that charcoal furnaces had high temperature capability from very early times. A few will be suggested.

Of basic interest is the ease with copper and iron metals can be melted. Because all metal, native or smelted, was more valuable than today it would be either in active use or immediately sold for remelting, and very little would be left as archeological evidence. In fact the scattered existing remains are very largely intentional leavings as grave goods or forgotten hoards, and this must seriously under-represent the amount of metal actually in use or circulation. There are certainly some traces of 5,000 year old iron and copper still circulating in Middle Eastern and Asian scrap yards.

Copper is very easily melted in a charcoal hearth and a native copper tool or knife inserted for annealing can easily disappear, to be found later as a small ingot in the bottom of the hearth. This would lead to intentionally melting several pieces to make a larger one, which is basic metallurgy. Copper oxide adhering to native copper from a local surface deposit would be automatically reduced when the copper was melted, to yield more metal in the hearth than was apparently added. This is a simple and natural origin of smelting.

The two step cast iron-finery procedure was possible very early, and it seems likely to have been used in more places and sooner than presently thought. There are direct references in early Greek writings for example that are usually explained away.

Since iron ore could be reduced to cast iron in any furnace capable of smelting copper, simply by adding a little less ore and blowing a little harder, it is a puzzle why more of it was apparently not done, and earlier. The Chinese quickly took advantage once they tried it, but why not a millennium earlier and why not others?

As pointed out, any nickel present with iron in an ore will be reduced with it. This means that presence of nickel in an iron object can imply positively meteoric origin only if the original Widmanstätten microstructure is present.

Conclusion

It is hoped that the above demonstration of the thermal and reduction powers inherent in a simple charcoal fuel bed will encourage review of some of the traditional ideas on the course and timing of the history of metallurgy. The fuel and the combustion technology are and have been universal, and it seems evident that the pace and direction of development have been controlled largely by the ores locally available, and therefore was in several locations and along different routes at different times.

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J E Rehder's background is that of a third generation family-owned iron foundry. After taking his degree at McGill in 1940 he became Chief Metallurgist to two Canadian foundries. Since 1963 he has been a consultant to the foundry industry in North America and Europe. He has published many papers, received several prizes and medals and been President of the Metallurgical Society of the Canadian Institute of Mining and Metallurgy.

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Metallography of brass in a 16th century astrolabe

Robert B Gordon

Summary

Metallographic examination of the brass in an astrolabe made in Nuremberg in 1537 shows it to be an alloy of copper and 19% zinc containing about 2% of iron, lead, and sulphur impurities. The outer ring of the astrolabe is a casting but the other parts were cut from hammered sheet that was fully annealed before use. The brass is of remarkably good quality except for surface defects in the sheet. The lead and sulphur impurities are present as inclusions visible in the microstructure. The lead particles are small and are uniformly dispersed. The sulphur is present in complex copper-zinc sulphides found in clusters or bands in the microstructure. These inclusions were probably formed during the cementation process by which the brass was made.

Introduction

The planispheric astrolabe, a combination of an analog computer for astronomical calculations and vertical circle for taking altitudes, was a popular instrument in the sixteenth century and astrolabes of various styles were constructed by a number of European instrument makers. I report here the results of an examination of the brass in an astrolabe made by George Hartman of Nuremberg in 1537. It is shown in Fig. 1 and appears to be identical to No. 262 in Gunther's catalog[1].

An astrolabe could be used to find the celestial coordinates of the principal stars, given the observer's location and the time, or -- and, according to North[2] this was its principal use – to find the time from the positions of stars or the sun if the observer's location were known. Astrolabes are usually marked with various calendars that were useful to astrologers, and have an alidade for taking the altitudes of celestial bodies or terrestrial objects and scales of the trigonometric ratios. Accurate construction was required to make an instrument which could be used to accomplish the tasks

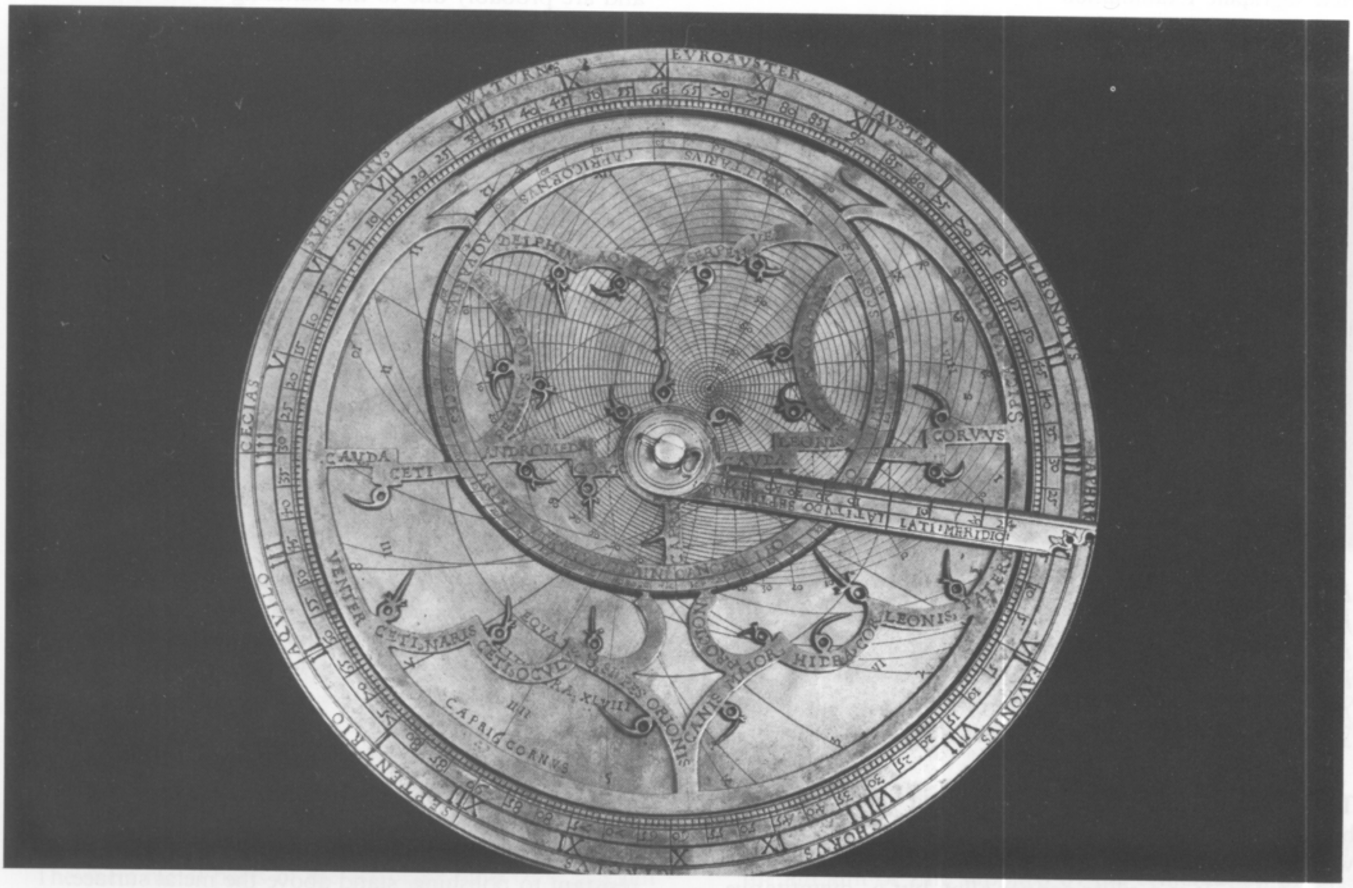

Figure 1. A brass astrolabe made by George Hartman of Nuremberg in 1537. The outer ring of the mother (the body of the instrument), the rete (carrying the eccentric circle and the star pointers), one of the tympans (visible under the rete), the rule, and the pin with its cotter are shown. A portion of the underside of the rule was polished for metallographic examination. The instrument is 160mm in diameter.

for which an astrolabe was intended and, because of the large number of complex scales engraved on it, much careful labour would have been expended in its manufacture. It is likely, then, that only metal of the best quality available would have been used by the makers of these instruments.

The Hartman astrolabe consists of twelve individual parts assembled on a disc 160 mm in diameter called the "mother"[3]. The mother consists of a brass plate that makes the back of the instrument. Three tympans, discs 1 mm thick by 135 mm in diameter and engraved with celestrial coordinates, and the rete, which carries the star pointers, fit inside the mother. The rete, the rule (attached over the rete) and the alidade (on the back) rotate on the central pin and are held in place by a cotter passed through a slot in the end of the pin.

The instrument was disassembled, the individual parts closely examined and their principal dimensions taken. An area on the back of the rule near the hole for the pin was polished by hand and etched for microscopic examination and a section of the mother was macroetched without previous polishing. Compositions were determined by an electron microprobe attached to a scanning electron microscope. The percentage of zinc in the brass was determined by reference to standard alloys but the analyses for other constituents was made by a standardless, semi-quantitative method.

Metallographic Examination

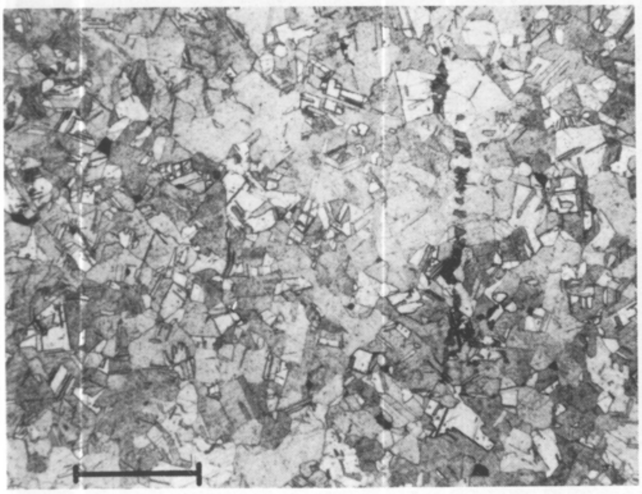

Figure 2. Micrograph of the brass in the rule. Etched with ferric chloride. Fine, recrystallized grains and two types of inclusions are visible in the structure. The small, isolated, dark inclusions are lead particles; the band of angular fragments is made up of particles of a complex Cu-Zn sulphide. Length of the scale bar is 0.1mm.

The slot in the end of the pin is plugged with a piece of brass soldered in place. The composition of the solder was investigated by placing the entire pin in the scanning microscope. It is a silver-copper alloy but a quantitative analysis was not done because only a thin layer of solder could be reached with the electron beam and signals from the solder and the brass beneath could not be separated. Light macroetching of a small area on the ring of the mother revealed grains with the cored structure usually found in cast brass. The grain size is about 1 mm. All of the other parts of the astrolabe except for the pin are made of brass sheet.

The average composition of the brass in the polished area of the back side of the rule is 19% Zn, 0.4% Fe, balance Cu. sulphur and lead were also detected but were not determined quantitatively. Scribed lines and tool marks visible on the rule suggest that it was cut out of a sheet of brass[4]. The uniform etching of the microstructure, which is illustrated in Fig. 2, shows that the composition gradients which would have been present in the original casting from which the brass sheet was made have been removed by annealing. Deformation markings are found in a narrow band surrounding the scribe marks. Their presence shows that the sheet has not been annealed after the rule was cut out and we may infer that the microstructure shown in Fig. 2 is that of the sheet as it came to the instrument maker. It is fully recrystallized and has an average grain size of 0.020 mm. Annealing the brass at a temperature of about 425° C after cold working would produce grains of this size[5]. The microhardness of the annealed brass measured with a load of 0.1 kg is 118. Deformation markings are present in a few grains located well away from the scribed lines; the density of these markings is equivalent to that which would be produced by a reduction of thickness of less than 5% and are probably due to the handling of the sheet in the instrument maker's shop.

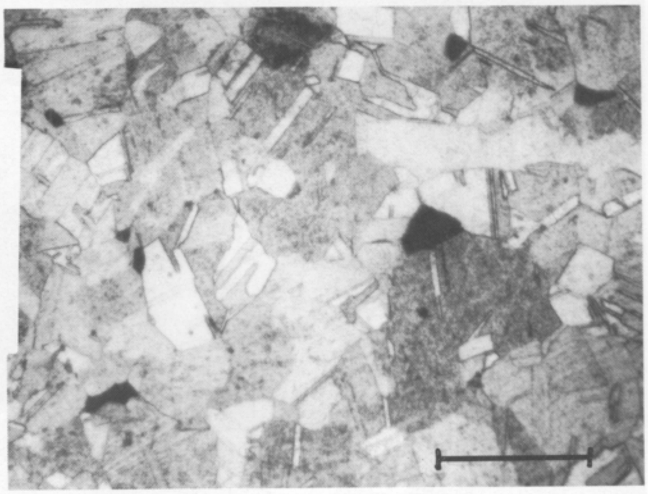

Figure 3. Micrograph showing the inclusions of lead in the brass grain boundaries. The dihedral angle at the junctions between the grain boundaries and the inclusions is about 90°. Length of the scale bar is 0.05mm.

Two types of inclusions are visible in Fig. 2 and are shown at higher magnification in Figs. 3 and 4. The first type, composed of strings of angular blocks which are resistant to polishing, stand above the metal surface. Inclusions of the second type are randomly distributed through the structure, are dark, and fall below the polished surface. Microprobe analysis shows that the dark inclusions are pure lead. They are found in the grain boundaries of the brass and are generally less than 0.01 mm in greatest dimension. During annealing of the brass the lead would have been liquid; the surface energy of the liquid has equilibrated with the grain boundary energy of the brass grains and the resultant dihedral angles, which may be seen in Fig. 3, are about 90°. This is large enough that the presence of the liquid lead would not embrittle the brass during hot working. A point count on micrographs shows that the lead content of the brass is less than 0.8 weight percent.

The inclusions which are resistant to polishing are generally smaller than 0.010mm and occur as angular blocks organized in clusters (as in Fig. 4) or strings (as in Fig. 2). The individual blocks can be seen at high magnification to contain two constituents, one red and one grey, but these constituents are too small to resolve optically and they lack sufficient contrast to be detected in the scanning electron microscope. Microprobe analyses of these inclusions shows that they are complex copper-zinc sulphides containing small amounts of Fe, Mn, P, and S. Point counts on micrographs show that the weight percent of sulphide present is 0.8.

Dimensions and Finish

All parts of the astrolabe except the ring of the mother and the pin have been cut out of sheet brass. The original surface finish of the sheet appears to have been retained in the interior of the instrument. It is smooth and uniform but is marred by occasional surface faults such as those on the back of the rete shown in Fig. 5. The sheet metal parts of the astrolabe have been laid out so that these defects are on inside surfaces and are not visible in the finished instrument. I infer from this that surface defects were sufficiently common in the brass available to the instrument maker that he could not afford to reject an entire sheet because of their presence.

The back plate of the mother and all three tympans are dished; the center of each is displacd by about 2mm relative to its edge across a radius of 70mm. It is likely that the sheet was not flat at the time work on it commenced. The thickness of the back plate was measured in 23 places; the measurements fall with about equal frequency between 0.89 and 1.04mm rather than in a normal distribution about the mean thickness. Thick and thin areas alternate over a length scale of about 50mm. Similar thickness variations are found in the three tympans.

Discussion

In 16th century Europe brass was made by the cementation process, which is described by Ercker[6]. Copper was heated in pots with calamine and charcoal powder. At a temperature of about 950°C zinc is reduced from the calamine by CO formed from the charcoal and diffused into the copper. A temperature above 900°C is needed in cementation both to reduce the calamine to zinc and to promote diffusion of zinc in copper. The purity of the resultant brass depends on the purity of the copper, calamine, and charcoal used. I infer that the copper used to make the brass found in the Hartman astrolabe contained copper sulphide inclusions. Since ZnS is more stable than Cu_2S at and below the temperature used for brass making[7], zinc diffusing into the copper is expected to concentrate preferentially in the copper sulphide inclusions. The composition of the resulting mixed sulphide depends on the amount of zinc supplied by the cementation process. Sulphide inclusions in bronze do not contain tin and are sufficiently ductile to flow while the metal is deformed by hot or cold working[8]. The Cu-Zn Sulphide inclusions

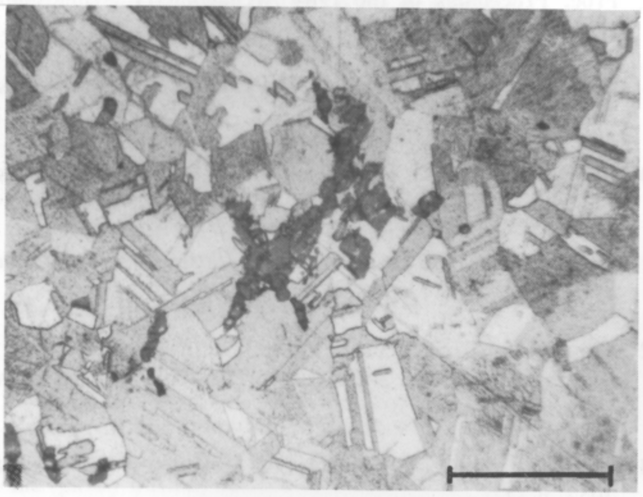

Figure 4. Micrograph showing the sulphide inclusions in the barss of the rule. The inclusions consist of two constituents, barely resolved at this magnification. The sulphide particles have been broken up by the deformation of the brass as it was hammered out into sheet. These inclusions occur in clusters, as in this example, or in strings, as in Fig. 2. Length of the scale bar is 0.05mm.

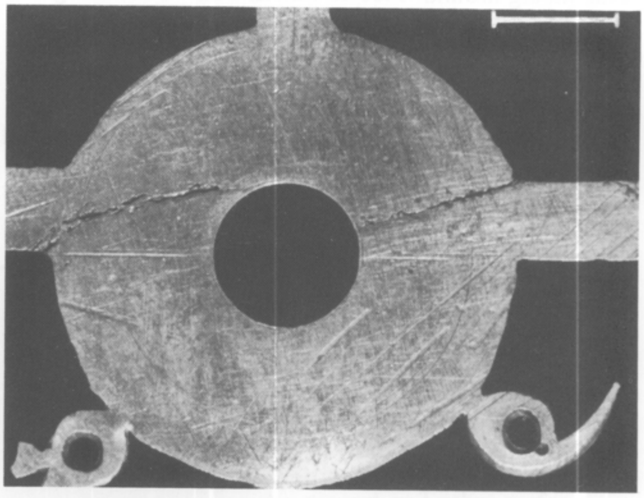

Figure 5. Photograph of the back of the rete showing surface defects in the brass sheet and traces of the scribe lines used to lay out the part before it was cut out. The parts of the astrolabe have been cut from the sheet so that all the defects are on inside surfaces and are not visible on the assembled instrument. Length of the scale bar is 5mm.

present in the brass studied here have been broken up during the working of the brass ingots into sheets and are, therefore, brittle at the temperature used for this purpose.

The brass casting practice used by the artificers who made the astrolabe was adequate to produce a sound casting for the ring for the mother but there were probably scabs or cold shuts on the surfaces of the ingots from which the sheet was prepared. These faults in the ingots caused the surface defects found in the sheets. It should be kept in mind that pouring ingots of the quality required for making brass sheet with a good surface finish remained a problem for brass makers up through the first part of the present century[9].

There is no direct evidence of the method by which the brass ingots produced by cementation were converted into the sheet used for the astrolabe, but some inferences can be drawn from the samples examined. The irregular variations of thickness found in the brass back of the mother and in the tympans suggests that the sheet used to make these parts was made by hammering rather than by rolling. This would have almost certainly have been done with the metal cold. (The cold working would be the cause of the fragmentation of the Cu-Zn Sulphide inclusions discussed above.) Frequent anneals would have been required and, as we have seen, the last of these was at a temperature appropriate to produce the fine-grained microstructure shown Fig.2. This inference is in accord with the limited documentary evidence available. Rolls are reported to have been used in Nuremberg around 1400 to flatten wire[10] but rolling mills are not illustrated or discussed by either Agricola[11] or Biringuccio[12]. The principal use of rolls in the 16th century metallurgy was in the preparation of strip for coining[13]. Rolls at least 140mm long, almost ten times the length needed to make strip for striking coins, would have been required to roll the sheet used for the astrolabe.

Substantial bearing blocks and, very likely, a source of mechanical power, would also have been needed. No evidence that rolls of this size were in use by 1537 has been brought forward yet.

Despite the presence of inclusions and surface defects, the brass used to make the astrolabe is of remarkably high quality; it is certainly a much more homogenous, uniform material than most ferrous products made at that time.

Acknowledgements

I thank Professor Asger Aaboe for permission to study the astrolabe and for an explanation of its use. I have benefited greatly from reading an unpublished manuscript on the history of rolling mills by Carolyn C. Cooper.

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Interpretation of some Romano-British smithing slag from Awre in Gloucestershire

J R L Allen

Introduction

Iron-making and/or iron-working residues occur at many archaeological sites of the Roman period in Britain. These residues tend to be described only cursorily, however, and to be reported essentially at the interpretative level. The recent development of slag typologies[1] has led to many improvements in description and interpretation, but these schemes are insufficiently detailed and related to an understanding of process to be easily applied at every or even many sites. The need remains for detailed description, particularly of morphology, and for a better understanding of primitive iron-making and iron-working processes.

Using a process-related typology, this paper briefly describes a range of microscopic smithing residues recovered from a Romano-British iron-making site at Awre, Gloucestershire. In addition to the geological implications of the find, the voluminous and well preserved metallurgical materials from here seem to offer novel insights into the character and significance of smithing residues, particularly when their detailed examination is linked to the results of simple experiments with a slag-like material.

Summary of the site

The village of Awre lies on the eastern side of the Forest of Dean coal and iron-ore field (Fig 1a, b), the iron-making site (British National Grid Reference SO 706 073) occurring on the right bank of the R Severn almost due S of the village (Fig 1c).

The stratigraphical context of the Romano-British material is complex (Fig. 1d). What is visible on the modern river cliff, currently experiencing vigorous erosion, appears to have been displaced into post-Roman estuarine mud deposits (Rumney Formation, Awre Formation)[2] from its original position just beneath the (partly buried) surface of a nearly level platform-like feature formed of the Main Terrace[3] (Pleistocene) gravels, which here erosively overlie the Lias (Jurassic). The pebbly sands (derived from the Main Terrace deposits) at the base of the Rumney Formation yield substantial quantities of both smelting and smithing slags, along with Romano-British pottery and other transposed cultural debris of this period, and some tonnes of further-reworked slag lies widely strewn over the present muddy beach.

The smithing slag was separated using a powerful magnet from a composite sample (7.2 kg dry mass) drawn from the basal bed of the Rumney Formation over a 15 m length of the river cliff NE of the gutter (Fig 1c). Inspection of the original sample under the binocular microscope showed that mainly fuel-ash slag remained behind. The magnetic separate (0.496 kg) consisted about one-third of fragments broken off larger masses of slag, together with some quartz sand. The remainder was strongly magnetic smithing slag, ranging from pieces 14 mm across down to a 'dust' of broken, paper-thin flakes mixed with tiny spherules. About two thousand representative fragments were picked out under the binocular microscope, cleaned ultrasonically, and further examined microscopically. Selected particles were studied under the SEM and by energy-dispersive analysis.

A Process-Related Slag Typology

Primitive iron-making[4] involves (1) the reduction of ore in a furnace to yield a raw bloom, namely, a spongy mass of metallic iron mixed chiefly with slag, followed by (2) the forging of the reheated raw bloom to express the contaminating slag, in order to obtain a purified bloom suitable for manufactures. We are here mainly concerned with the character of some of the slags — known as smithing slags — formed during the second stage. The standpoint taken is that the character of these slags depends on their (a) original composition, and (b) detailed thermal and mechanical history up to the moment of final freezing, as determined by the processes and circumstances that operated on them.

Consider the events likely to occur during the purification of a raw bloom by forging.

Although much slag drained from the bloom while in the smelting furnace, a significant amount, probably more than 10% of the total mass[5], will have been retained. The first few strokes of the hammer upon the raw bloom after its first reheat will therefore send an abundant spray of liquid slag droplets over the area around the anvil and hearth. Sufficiently small droplets, and those taking long enough atmospheric paths, will freeze before touching the ground and other surfaces, and so should assume a spheroidal form dictated chiefly by surface tension. More complex shapes might result where droplets had either acquired a spin, or proved unstable in flight because of their large mass. Droplets that fail to freeze in flight will in varying degrees either (a) mould to the shape of the surface on which they land, (b) alter in form due to impact, or (c) break up on landing to yield secondary spatter, which may then repeat either (a) or (b). The outcome — a uniformly thin flake, a bun-like mass, or a dimpled spheroid — will depend chiefly on the momentum and viscosity of the slag at impact. Meanwhile the bloom slowly cools as it is further worked. The slag now expelled from it will become increasingly viscous and rich in crystallized iron

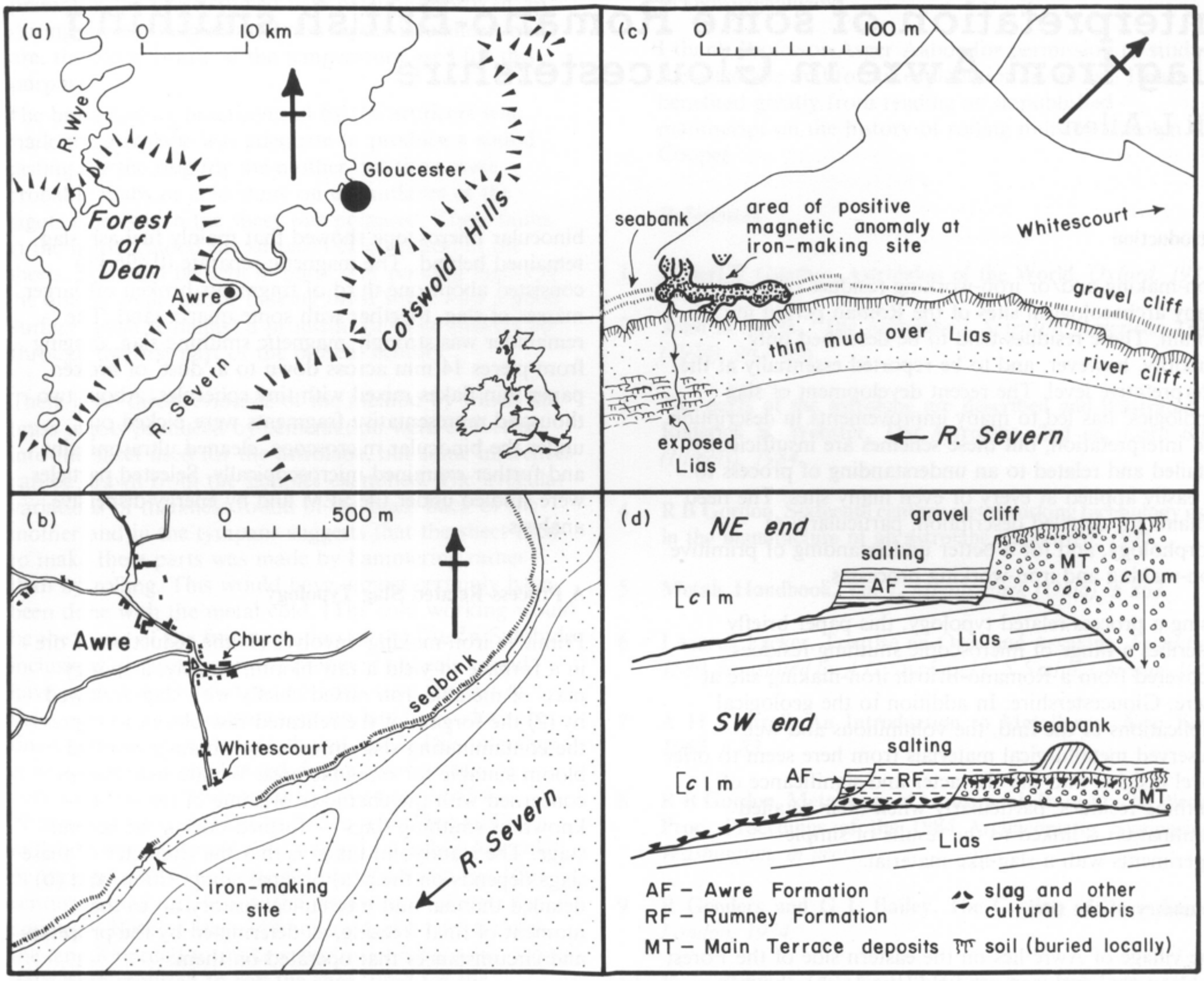

Figure 1

oxides. Irregular masses of crystal mush, rather than speroidal liquid drops, should prove the main micrscopic residue. Such fragments may finally freeze either during flight, or upon touching a surface.

By no means all the slag present in the bloom at its first reheat will be thus lost. Some slag may remain within the mass, to be expelled by hammering only after further reheats, while another quantity, either 'sweated' from the bloom or formed through oxidation, may adhere as local films and puddles to its worked exterior. Continued hammering as the bloom gradually cools to below the freezing point of the slag should dislodge these films in the shape of thin scales, one face of which will preserve the local form and, perhaps, the surface texture of the bloom. However, few of these scales will have had contact with the hammer.

What of the fate of liquid slag touched by the rapidly descending hammer? Some will chill against the much cooler hammer, and so be torn off or even violently extruded in a plastic state from between hammer and bloom. Such rapidly cooled and sheared films should carry, on one or both surfaces, delicate striae created by asperities present on, particularly, the face and edges of the hammer.

The above is a brief intuitive account of what probably happens during the purification by forging of a raw bloom. Three kinds of microscopic slag residue arise, in addition to any large masses, not considered further here, that may accumulate in the reheating hearth. Droplets forcibly expelled from the bloom constitute *spatter.* The name *bloom scale* is proposed for flakes of semisolid or solid slag dislodged from a cooling or cold bloom as the result of hammering. The term *contact scale* is proposed for slag that either froze partly or wholly in direct contact with a hammer that was executing a strike, or which was marked (sheared or cracked) by the descending hammer. All three kinds of residue are traditionally lumped under the name *hammer scale,* a term widely but perhaps loosely used[6].

The first reheat is used to illustrate the processes and circumstances that plausibly operate on slag during smithing, because it is then that most of the smelting slag in a raw bloom is lost. Further reheats permit the expulsion of progressively less slag, probably as increasingly small individual particles, and perhaps proportionately less as spatter. An increasing proportion of the residues will result from the oxidation of the iron on the anvil.

Descriptive Terms for Microscopic Residues

Particles with a *regular* overall shape approximate to a regular geometrical solid (e.g. sphere, ellipsoid), whereas *irregular* ones cannot be so matched. One or more of the surfaces defining a particle is described as *even* if it is of approximately uniform curvature overall, but as *uneven* if the curvature varies noticeably. The terms *smooth, crystalline, granular, vesicular, pitted, blistered* to *warty* and *striated* describe the local texture of a surface bounding a particle. A smooth surface reveals no smaller features when examined under the binocular microscope. A crystalline surface sparkles when lit, because of reflections from a multitude of tiny crystal faces. An increase in the size and degree of projection of the crystals leads to a granular texture. Typically, a vesicular surface shows crowded and partly interfering to spaced out sub-hemispherical cavities created by exsolved gas. A pitted surface reveals a series of shallow to deep pits of variable size, shape and smoothness of wall. Blistered surfaces display numerous smooth, rounded swellings, each underlain by a vesicle. In some instances a vesicle has burst, to leave a circular to oval pit or lipped crater on the surface as an accompaniment to the blisters or warts. A striated surface bears parallel markings, which may vary from delicate scratches to coarse grooves, and sharply detailed to obscure. The particle surfaces, in terms of reflectivity, range from *dull* to *mirror-bright,* and in colour from *dark brown* to *steel gray.*

An essential interpetative distinction is between categories of primary surface bounding a slag particle. The surface is termed *free* where there is evidence that it was exposed to the air when the slag froze. A *moulded* surface arose as the slag shaped itself and chilled against some object for example, the bloom, the anvil, the moving hammer, the smith's apron, or the surroundings of the anvil and hearth. Being relatively fragile, many of these microscopic particles also display broken surfaces.

Air-Chilled Spatter

These residues show no sign whatsoever of having frozen in contact with another object, and as individual particles present an outer surface of a single character, conistent with the free category. Compositionally, they are fayalitic, with silica contents similar to somewhat less than the associated smelting slags. Five kinds are distinguished.

Spheroidal air-chilled spatter, by far the commonest, takes the form of dark brown, leaden or steel gray, dull to bright, spherical to ellipsoidal grains from a few tens of microns up to 7.2 mm in greatest diameter (Fig 2). The surface is mostly smooth and satin-like but crystalline in a few instances. Some particles are solid, with a microvesicular interior, but most are hollow, with a microvesicular wall in some cases of an extreme thinness. The exteriors of some grains bear long, irregular cracks, sealed by liquid slag, as if a thin rigid crust had been fractured, either because of a vesicle growth or impact with another object. The wall of some grains is invaginated, suggesting inward collapse.

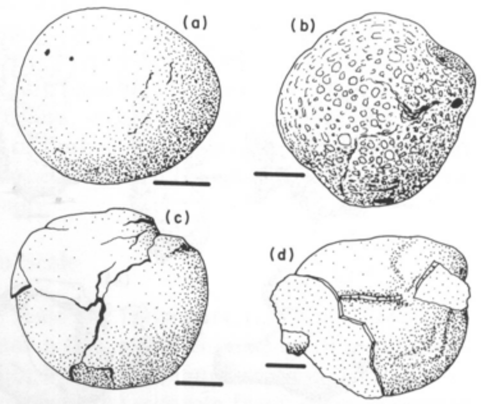

Figure 2 *All scale bars = 0.5mm*

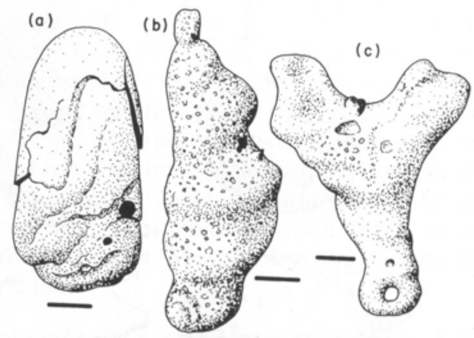

Figure 3

Projecting from or adhering to the surfaces of many particles are small, scale-like fragments of slag, perhaps all that remains of a protective crust that formed on the bloom after withdrawal from the hearth but before or during hammering.

The second kind of air-chilled spatter — smooth granules — is much less plentiful (Fig 3). The particles resemble spheroidal spatter in size, colour, reflectivity, and surface texture, but are markedly uneven and in form vary from potato-like, to sausage-like, to flat and either spindle-shaped, branched or irregular. Scale-like fragments of slag project from or adhere to some granules. Several grains reveal fractured crusts. Internally, the granules are microvesicular, but less commonly hollow than the spheroidal forms.

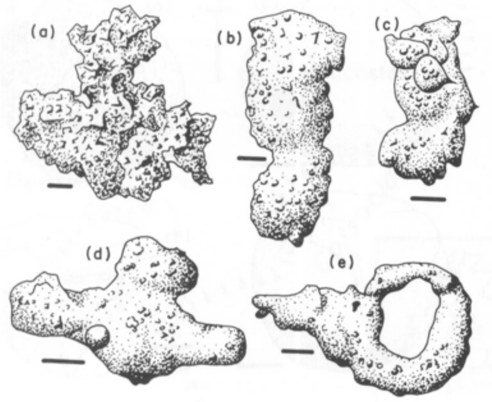

Figure 4

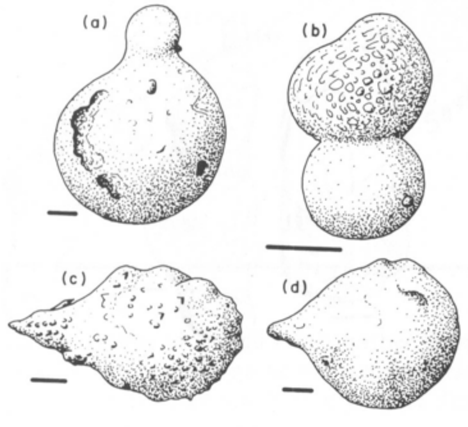

Figure 5

A third and also uncommon type of air-chilled spatter is aptly named rough granules (Fig 4). These closely resemble the spheroidal type, but differ in their finely to coarsely granular surface texture and uneven irregular form, which varies from equant to elongate, branched, and even ring-like, Rough granules are more dense than either spheroidal spatter or smooth granules. Microvesicles are rare and few particles are hollow.

Polyspheres (rare) consist of two or three equal to unequal spheroids forming a chain or cluster up to 6.8 mm long (Fig 5a, b). They otherwise resemble spheroidal spatter.

A very rare kind of spatter takes the form of pear-shaped grains up to 5.8 mm in axial length (Fig. 5c, d).

The particles are leaden to steel gray in colour, with an invariably smooth and dull to moderately bright surface. They appear to be chiefly hollow with a microvesicular wall.

Surface-Chilled Spatter

Notable in the strongly magnetic fraction from Awre are particles that resemble air-chilled spatter, yet combine a free with a moulded surface of much smaller to approximately equal extent, as well as showing features due to forceful impact. The residues are similar chemically to air-chilled spatter.

The clue to their identification and interpretation lies in certain delicate features developed locally along the boundary separating the free from the moulded part of the surface. These structures, ranging from single spikes to shapes resembling either an elephant's foot or a cat's paw with claws extended, are seen in their full relationship where the spatter stuck to the object(s) on which it fell (Fig 6). The spikes and claws are interpreted as frozen jets of slag that had begun to spread laterally

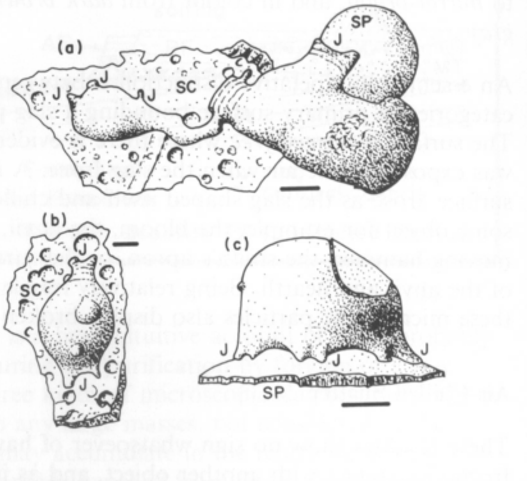

Figure 6

over the colder surface, under the impulse of the decelerating liquid droplet.

Three varieties of surface-chilled spatter — spheroidal, bun-like and biscuit-like — are recognized on the basis of particle shape and the texture of the free surface (Fig 7).

Spheroidal grains, closely resembling spheroidal air-chilled spatter, possess a relatively small moulded surface and a height similar to the breadth (Fig 8). Typically, the free surface is smooth, but crystalline and also sparsely granular textures are represented. The moulded surface in some cases is smooth and plane; it may otherwise either imperfectly mould striations or scattered pits. The contact angle (Fig 7a) is normally acute at the tips of spikes and claws but obtuse elsewhere along the

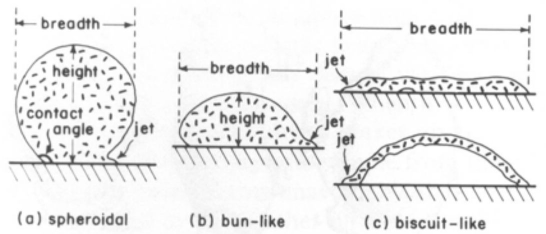

Figure 7

boundary between the moulded and free surfaces. It is common to see just two comparatively large, diametrically opposed spikes. The most frequent form of moulded surface is concave-outward, varying from a smooth and evenly curved depression to an irregular, rough-walled pit. Like spheroidal air-chilled spatter, these surface-chilled forms vary from solid to hollow and mocrovesicular. Some have cracked free surfaces and others display projecting or adhering slag scales.

Bun-like grains of surface-chilled spatter, reaching 14 mm in greatest diameter, have a height in the order of one-half of the breadth and a moulded surface that is not much less than the free surface in extent (Fig 9). They range in colour from dark brown with rusty flecks to leaden or steel gray, and in reflectivity from dull to fairly bright. The free surface varies widely in shape and surface texture, from smooth or crystalline and roughly hemispherical, to elongate and smooth or granular, to flat and branched and either smooth, granular or even blistered to warty. The moulded surface is equally variable and may entrap small objects from the substrate, particularly fragments of scale and tiny air-chilled spheroids. Surfaces that are flat are either smooth or imperfectly preserve either striae, scattered pits, or hemispherical vesicles; that the liquid slag commonly failed completely to fill these delicate recesses is shown by the occurrence of smooth convex-outward free faces locally on the spatter. Other moulded surfaces consist of either a single concave-outward pit, or are rough and highly irregular. Complex claws and spikes abound. Many hemispheroidal particles, however, display a pair of oppositely pointing spikes, as in the previous variety. A combination of obtuse and acute contact angles is again observed. Internally, bun-like grains are microvesicular, but only the more swollen forms are also hollow.

Biscuit-like grains of surface-chilled spatter have little thickness compared to breadth (Fig 10), but in surface features resemble bun-like particles. No complete grain exceeding 9 mm in greatest length was found; several originally much larger particles were unquestionably present as broken fragments. Plano-convex biscuit-like grains (Fig 7c) combine a smooth, crystalline, granular, or blistered free surface, with a moulded face preserving either striae, open vesicles, pits, or rough irregularities. On occasional particles, objects from the substrate — clusters of slag flakes and tiny spheroids, and even quartz sand — project from the moulded surface. The concavo-convex particles (Fig 7c) resemble the plano-convex type as regards the free surface, but almost invariably have shallow vesicles on the curved moulded face. Claws, spikes and frills occur along the natural edges of both sorts of particle. Acute contact angles are commonest. Broken biscuits are solid to microvesicular internally.

Bloom Scale

These scale-like fragments, many times wider than thick, combine a free with a moulded surface, but without evidence for forceful emplacement. This residue dominates in the separate from Awre, occurring as whole or broken particles that range from delicate, paper-thin flakes a millimetre or less across, to stout scales 12 mm long and 1-2 mm in greatest thickness. Typically, the scale is leaden to steel gray in colour, and moderately bright to mirror-bright. Compositionally, most grains are almost pure iron oxide (chiefly or wholly magnetite), with little silica. Three varieties are recognized.

Flat bloom scale, the dominant form, combines an essentially plane moulded surface with a free surface that is very slightly convex-outward, if not over the whole grain (smaller forms) then in a broad marginal zone (larger particles) Fig 11). The moulded surface ranges from irregularly rough to either shallowly pittied or vesicular. A smooth and satin-like, crystalline, granular, or blistered to warty texture characterizes the normally brighter free surface. On some grains either fragments of slag scale project from the free surface or tiny spheroids of spatter adhere to it. Most broken scales prove to be microvesicular.

Angled bloom scale is represented by particles 2-12 mm long that present on the moulded surface a straight edge where two essentially plane faces join approximately orthogonally (Fig 12). This corner is typically more curved on the moulded than the free surface, the slag tending to thin over the line of the edge. The scale is otherwise like the flat kind.

Striated bloom scale, the third variety, has a free surface similar in shape and texture to flat scale, but a moulded surface that bears one or (rarely) more sets of striations (Fig 13). The markings in each set are parallel to slightly divergent but never cross. On some flakes the striae start out in one direction before abruptly and all together veering off on a new tack. Rough moulded surfaces only preserve relatively deep and widely spaced striae. More delicate markings are seen on smoother surfaces. The smoothest and brightest moulded faces reveal striae varying from the faintest of scratches to coarese V-shaped to flat-bottomed grooves, in some cases overlapping in scale-like clusters.

Contact Scale

Residue attributed to this class either shows two moulded faces or, combining a free with a moulded surface, reveals upon the latter slightly divergent striae clearly related in pattern to the overall particle shape. The particles are solid to slightly microvesicular and compositionally like either spatter or bloom scale. Contact scale is comparatively rare at Awre.

The commonest sort combines a striated face like that found on some bloom scale (Fig 13) with a second moulded surface that is either plane and almost smooth, or (rarely) plane and vesicular. Typically, in the first case, the surface is crossed by short, irregular, incompletely joined cracks that cut the flake into unequal tesserae (Fig 14a, b). Across some fractures a small displacement and slight tilting with bending of the tesserae is apparent, but without the particle as a whole having list its integrity; the fragment therefore acquired its markings and fractures while incompletely congealed.

Striae decorate both moulded surfaces in a less common type of contact scale (Fig. 14c, d). The more complete grains vary in shape from approximately rectangular to roughly semicircular, and are wedge-like in cross section. Coinciding with the thick portion of the section is a ragged straight torn edge marked by partly detached masses of rough-textured slag. The opposite edge, where the two striated surfaces intersect, is sharp and blade-like though uneven. On most scales the two moulded surfaces are similar in brightness and their striae have a common orientation. Where the striae differ in trend, the less well-preserved set is found on the duller face.

The scarcest contact scale (eleven grains) takes the form of oval to semicircular scale-like particles up to 3 mm across, on which a free and a moulded surface are combined (Fig 14e, f). The invariably bright free surface is satin smooth, lacking even the tiniest irregularities. On the moulded face appear delicate striae that diverge for the most part obliquely toward the curved and delicately frilled feather edge of the scale. This combination of features is distinctive — the overall shape and the pattern of striae seem to record one and the same act — and unlike the way in which striae appear on bloom scale.

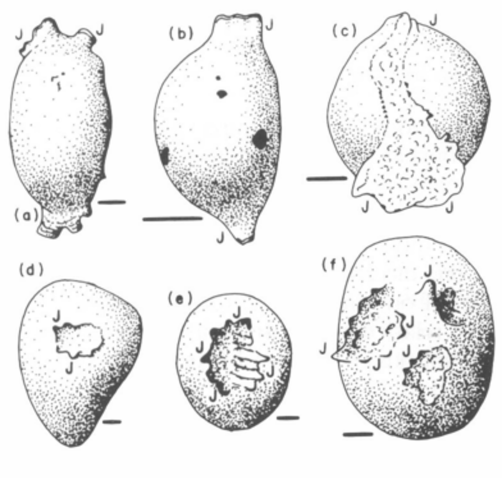

Figure 8

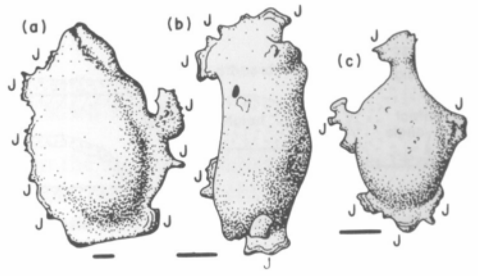

Figure 9

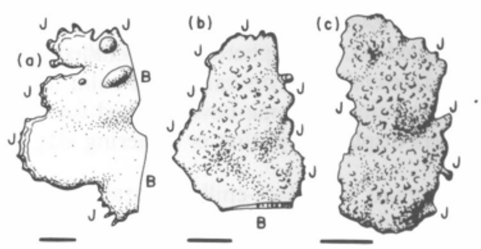

Figure 10

Discussion

The actual microscope residues transposed into the base

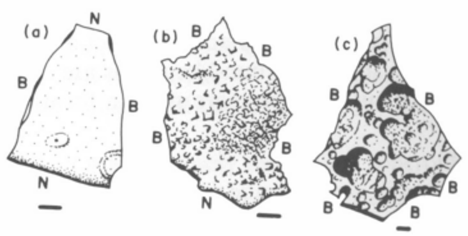

Figure 11

of the post-Roman Rumney Formation at Awre correspond well to the conceptual categories — air-chilled spatter, surface-chilled spatter, bloom scale, and contact scale — recognized in the above model for smithing residues (excluding possible hearth bottoms). Moreover, several morphologically distinct varieties can be distinguished within each category. When it is recalled that strongly magnetic debris makes up approximately 7% of the composite sample from the basal bed, the conclusion seems unavoidable that iron blooms were purified at Awre either on a substantial scale or over a long period. The extent of the magnetic anomaly (Fig 1c), and the visible presence of some tonnes of smelting and other slag washed over the modern beach, are sufficient proof that smelting, the prior operation, was also a major activity.

The model will be strengthened if residues like those from Awre can be produced experimentally under conditions bearing general comparison to primitive forging. Experiments were accordingly made using 60/40 solder, a material that resembles primitive slags in being a crystal mush over a range of temperatures just above the freezing point. However, solder is less viscous than slag close to this point, whereas its density is greater and there is no capacity to exsolve gas. Because of the much lower temperature of molten solder, effects in slags related to rapid radiative cooling cannot be reproduced.

Residues indistinguishable in morphology from many present at Awre resulted when drops and puddles of solder wetting a fixed hot steel plate were hammered (head pitted and burred) as the plate slowly cooled through the freezing point of the alloy.

Air-chilled spatter was represented by spheroidal grains and by smooth granules with either a smooth or cystalline surface texture. Many of the smooth granules were spindle-shaped, sausage-like or branched. Rough granules of irregular form with a fine to coarse granular surface texture were plentiful. Surface-chilled spatter was also abundant, and in the same three forms as at Awre. Most of the bun-like and biscuit-like grains showed claw-like projections and spikes (sharply pointed or bulbous) around their edges. Smooth, crystalline and granular textures were all recorded from the free faces. The moulded ones faithfully recorded the shape and texture of the surfaces on which the spatter fell.

Some solder froze against the hammer, the resulting scale either dropping off the head as it was subsequently raised, or remaining stuck, wholly or in part, to the hammer through a short sequence of blows. A variety of scale resulted. The largest particles showed either a striated (moulded) combined with a free surface, or two striated surfaces; many of these grains were cut by irregular, incompletely joined cracks, as observed from some contact scale at Awre (Fig 14a, b). Some flakes bore divergent striae related in pattern to the overall particle shape (see also Fig. 14e, f). A final close parallel is provided by numerous small wedge-shaped flakes of solder striated on each moulded surface (see also Fig. 14c, d).

Much of these residues can only be described as 'dust',

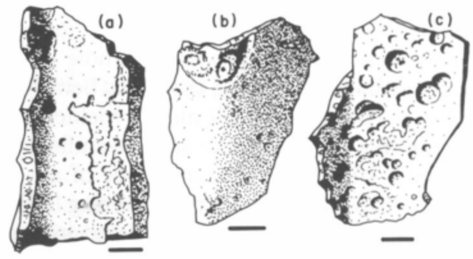

Figure 12

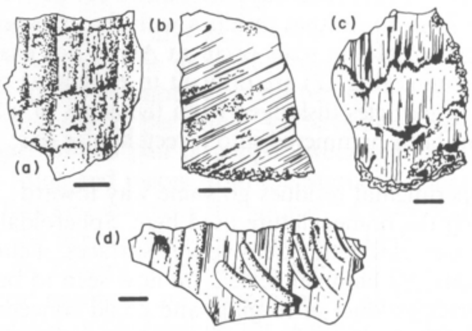

Figure 13

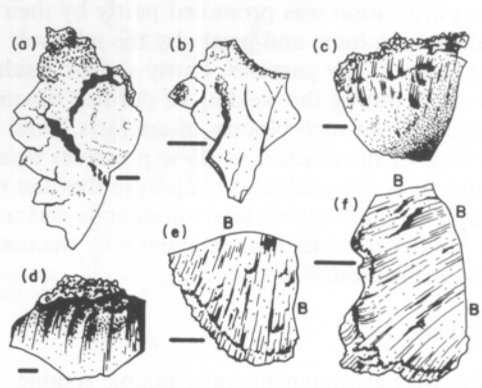

Figure 14

the spheroidal, spindle-shaped, sausage-like and branched forms of the air-chilled particles being just recognizable under the binocular microscope. Further experiments suggested that such dust is a residue derived only from high-momentum spatter. Solder just above its freezing point was poured through a bundle of fine twigs on to a cold surface at varying distances below (0.15 m, 0.5 m, 5.5 m). The shortest fall mainly yielded large grains of bun-like to biscuit-like surface-chilled spatter, but the longest afforded a predominance of air-chilled dust, partly because of secondary spattering. Surface-chilled and air-chilled particles were found in about equal measure after the intermediate fall.

Many of the forms and surface textures recorded from Awre were faithfully reproduced in these experiments, which therefore promote confidence in the model. Textures related to gas exsolution were not recreated, however, and nothing resembling bloom scale arose. Only a forging experiment with a freshly made bloom could hope to reproduce these features.

Although experimental support cannot yet be claimed, there is little doubt that residues with the expected properties of bloom scale occur at Awre. For example, angled grains (Fig 12) are difficult to explain as other than slag particles dislodged from the edges of a bloom that had been hammered into a rectangular bar.

The experimental residues go some way toward justifying the nomenclature used here. Spheroidal and similar particles with extensive free surfaces, included in the traditional hammer scale[7], are now seen to be only an indirect product of forging, and could conceivably arise in other ways, for experimental counterparts can be created simply by dripping molten solder on to a cooler surface. Flakes with either two striated faces, with a pattern of striae related to shape, or with microfractures, however, can be made experimentally only when molten solder is hammered. Contact scale would therefore seem to be the only sort of smithing slag of which it can be said that it was touched by a moving hammer.

The interpretation of the Awre residues in terms of bloom purification was promoted partly by their considerably volume and partly by the relatively large size of many of the particles. Partly similar residues could result during the welding of purified blooms and the forging from such blooms of artefacts. Until direct knowledge of the residues of these processes becomes available, it is reasonable to conjecture that the resulting scale will be considerably less voluminous and involve much smaller particles than is apparently the case with bloom purification.

Conclusions

1) The strongly magnetic, microscopic residue transposed at Awre (Gloucestershire) into a post-Roman deposit from an adjoining Romano-British site is smithing slag, recording the purification of blooms.

2) Four types of residue — air-chilled spatter, surface-chilled spatter, bloom scale, and contact scale — are distinguishable using morphological criteria.

3) Air-chilled spatter shows no sign of having frozen in contact with a solid surface, and is presumed to have solidifed while flying through the air. It represents liquid slag sprayed from a hammered bloom (or workpiece) and secondary spatter released as primary droplets splashed down.

4) Surface-chilled spatter solidified in contact with a rigid surface and after forceful impact with that surface. It too represents slag ejected from a hammered bloom (or workpiece) and secondary spatter released during splashing.

5) Bloom scale froze in contact with a solid surface, apparently the bloom itself. Many particles have a moulded surface that carried shear striae, and others preserve the form of the edges of rectangular bars. Evidence for forceful emplacement is lacking.

6) Contact scale is typified by either two striated faces or patterns of striae and microcracks, consistent only with final solidification in direct contact with a striking hammer.

7) Particles indistinguishable from the two forms of spatter arise when solder is dripped or splashed on to a cooler surface.

8) All recognized varieties of contact scale are reproduced when molten solder is hammered on a hot steel plate allowed slowly to cool through the freezing point of the alloy.

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The origin of the copper used for the Statue of Liberty

J P Franey, T E Graedel, D L Nash, Kay Lande Selmer and P R White

Abstract

Historical records make no mention of the source of the copper used in the construction of the Statue of liberty, although a local tradition suggests that the copper came from the French-owned Visnes Mine near Bergen, Norway. Records show that ore from this mine, refined in France and Belgium, was a significant source of European copper in the late nineteenth century. To investigate further the origin of the statue copper, we have analyzed samples of copper from the Visnes Mine and from the Statue of liberty by emission spectrography. A comparison of the presence and concentrations of metallic impurities show the two samples to be very similar, and a review of historical and geographical information on possible suppliers of the copper suggests that the Visnes mine is a very likely source. We conclude that it is highly probable that copper from the Visnes Mine was used for the Statue of Liberty.

I. Introduction

The Statue of Liberty ("Liberty Enlightening the World" by Frederick Auguste Bartholdi) in New York Harbour is sheathed in copper of average thickness 2 mm. The statue is 50m high and some 80 metric tons of copper was required for its fabrication (1). It is probable that few projects before or since the Statue's construction in 1876-1885 ever required as much copper. Nonetheless, no historical records have yet been found to indicate positively the source of the copper for the statue which was a gift from the French people.

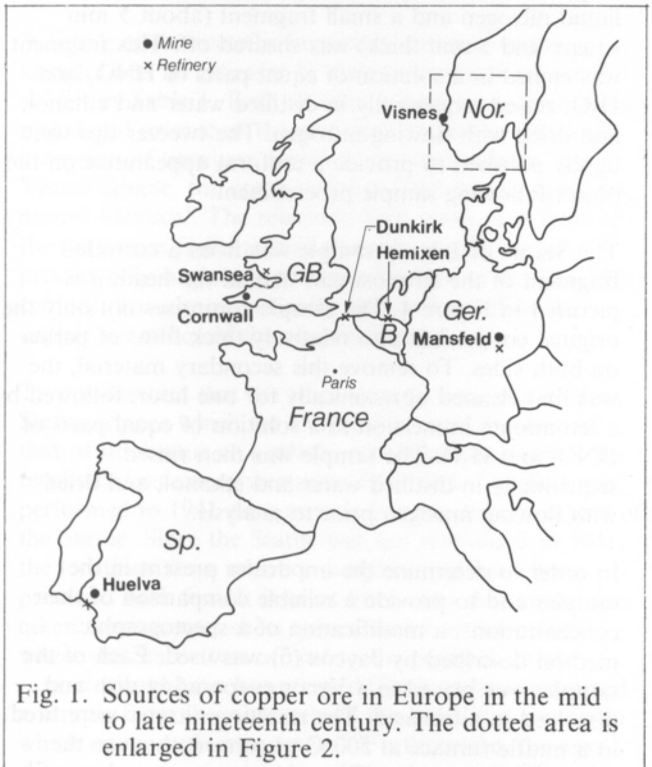

Fig. 1. Sources of copper ore in Europe in the mid to late nineteenth century. The dotted area is enlarged in Figure 2.

One of the mines which provided high-purity copper ore to the European metals industry in the late nineteenth century was the Visnes Mine in Norway. This mine was in operation throughout much of the latter half of the nineteenth century, and local Norwegian tradition has it that copper from the mine was used for the Statue of Liberty. In an attempt to obtain further information concerning the copper origin, we have analyzed samples of copper from a pair of copper tweezers found in the Visnes Mine and pieces from the Statue of Liberty. This paper lists and discusses the sources of European copper during the period when the statue was built, describes briefly the history of the Visnes Mine, presents the analytical results of our examinations, and discusses the implications of the findings for establishing the origin of the Statue copper.

II. Sources and Characteristics of Nineteenth Century European Copper

Copper has been mined in Europe for millenia, but a handful of deposits provided nearly all of the copper

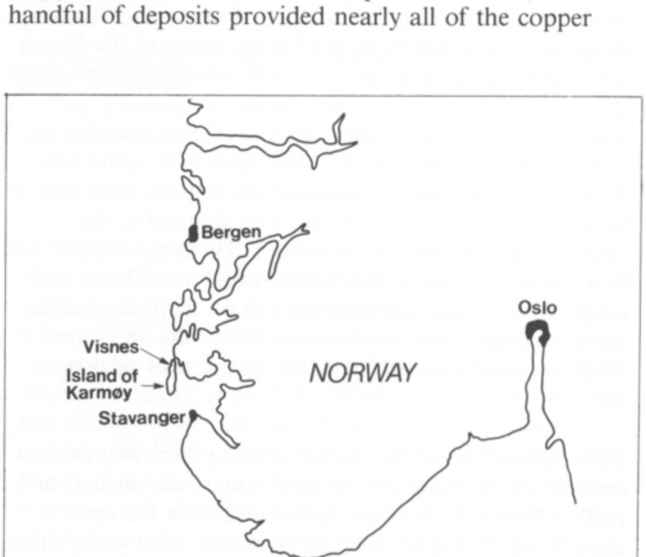

Fig. 2. The location of the Visnes Copper Mine near Bergen, Norway.

used in Europe in the nineteenth century. Their locations are shown in Figure 1. The English mines at Cornwall and Devon were the world's largest producers of copper ore during the first half of the nineteenth century (2). By the latter part of the nineteenth century, they had been supplanted by Montana and Arizona mines in North America and by the Rio Tinto mine in the Huelva Province of Spain in Europe (3). Copper ore was also derived from the Mansfeld mines in Germany and in a number of relatively small deposits in Norway. Negligible amounts of copper-bearing ore were mined in France.

From considerations of geography, one would anticipate that among the convenient sources of refined copper for a Paris sculptor would be Swansea, S. Wales, where the British ore was refined, Hamburg, Germany, where the German ore was refined, Huelva, Spain, a major source of copper for centuries, or ore mined in Norway and refined on the continent.

In the 1870s, one of the most active of the Norwegian copper mines was that at Visnes, a community situated on the island of Karmoy on the west coast (Figure 2). The copper at this site was discovered in 1865 and the mine constructed under the direction of Charles Defrances, a French mining engineer (4).

Defrances was employed by a mining company in Antwerp, Belgium. This company owned ore processing plants in France and Belgium and a refinery at Hemixen, Belgium (near Antwerp). The corporation formed to develop the Visnes ore body, Société des Mines et Usines de Cuivre de Visnes, used the same processing and refining facilities, but had its headquarters in Paris.

During the 1865-1890 period the Visnes ore, a high grade pyrite-complex copper ore with zinc, was shipped to sulfuric acid plants in Dunkirk, France and Antwerp, Belgium. The location of the Visnes mine on the North Sea made transportation of the ore relatively convenient.

The premium grade Visnes ore had had an average content of 3.5% copper, 3% zinc, and 44% sulfur (4). After it was roasted to manufacture sulfuric acid and to form the copper oxide, the ore was shipped to the copper leaching plant at Hemixen. There the copper was first put into solution (probably by dilute sulfuric acid leaching) and then precipitated out on iron to produce cement copper. The production during the 1870s and 1880s reached as much as 3,000 metric tons of copper per year (5).

Although details of the metallurgical processing are not certain, we presume the cement copper was melted and cast at Hemixen. It is not known whether the cast copper was rolled to sheet at Hemixen or at some other plant.

III. Preparation and analysis of Samples

The Visnes sample was a pair of copper tweezers found several decades ago deep in the Visnes Mine. These tweezers are part of the collection of the Visnes Kobberverkmuseum, Visnes, Norway, and were kindly loaned to us for these studies. We assume, though there is no firm evidence, that the tweezers, pictured in Figure 3, were made from Visnes copper ore. To obtain a sample for analysis, the tweezers were first cleaned in an ultrasonic wash utilizing hot water and "Micro" cleaning solution. (The latter is a commercial cleaning solution made by the International products Corporation, Trenton, NJ.) This initial cleaning removed the light corrosion layers on the tweezers and produced a "coppery"-coloured surface with minor etching grains. A microscopic examination revealed a hairline crack at the longer of the two tips. The tips were then dipped in liquid nitrogen and a small fragment (about 5 mm square and 3 mm thick) was sheared off. This fragment was etched in a solution of equal parts of HNO_3 and H_2O, rinsed sequentially in distilled water and ethanol, and dried with flowing nitrogen. The tweezer tips were lightly polished to provide a uniform appearance on the object following sample procurement.

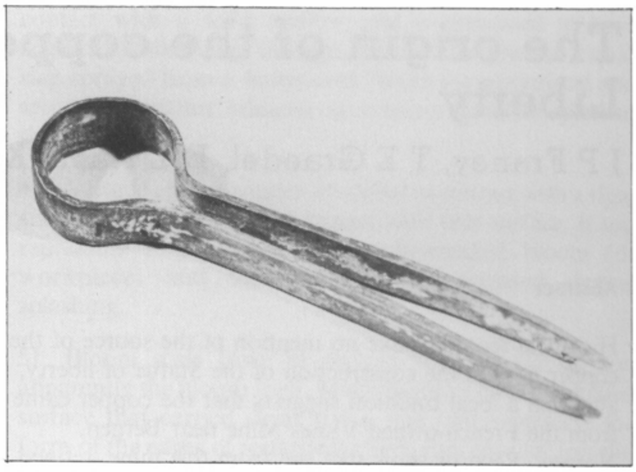

Fig. 3. The copper tweezers from the Visnes Mine. The tweezers are about 10 cm long. The sample which was analyzed was taken from one of the tips.

The Statue of Liberty sample was from a corroded fragment of the leftmost curl behind the head; it is pictured in Figure 4. The sample comprises not only the original copper but also relatively thick films of patina on both sides. To remove this secondary material, the was first cleaned ultrasonically for one hour, followed by a ten-minute immersion in a solution of equal parts of HNO_3 and H_2O. The sample was then rinsed sequentially in distilled water and ethanol, and dried with flowing nitrogen prior to analysis.

In order to determine the impurities present in the samples and to provide a reliable comparison of their concentrations, a modification of a spectographic method described by Jaycox (6) was used. Each of the samples was placed in a Vycor evaporating dish and dissolved in nitric acid. The resulting nitrates were fired in a muffle furnace at 500 C to convert them to the corresponding oxides. The oxides were ground to a fine

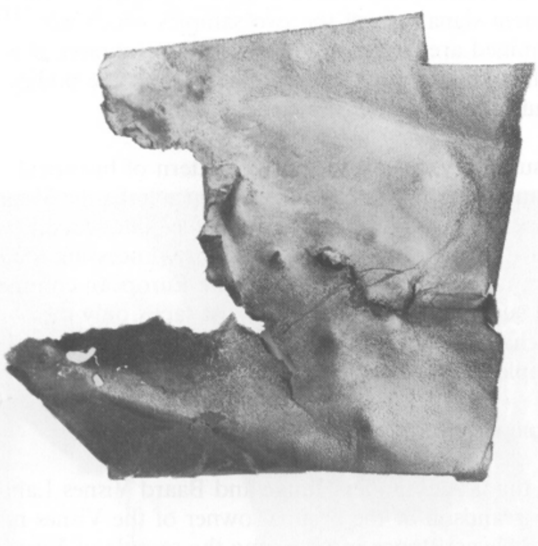

Fig. 4. The fragment (about 5 cm square) from the left curl of the Statue of Liberty, from which the sample which was analyzed was taken. The sample was from the upper right corner of the fragment, avoiding the severely corroded area in the left center.

powder, mixed with pure graphite, and loaded into graphite electrodes. A DC arc was used to excite the samples and the resulting spectra were recorded on spectrographic plates.

A listing of the metallic impurities detected in the samples and an estimate of their concentrations are shown in Table 1. Both samples we have analyzed show nickel and arsenic as the principal impurities. With the exception of titanium, which is detected only in the Visnes sample, the compositions of the two samples are almost identical. The relatively high levels of several of the impurities indicate that electrolytic refining, a process only beginning to come into use in the late 19th century, was almost certainly not used to refine the copper for either of the copper samples tested.

To demonstrate that the trace element signature of the Statue copper which we analyzed is representative of that of the Statue as a whole, we include in Table 1 the results of less extensive studies by others. The first was performed in 1941 on a sample fom an unknown part of the Statue. Since the Statue was not scaffolded in 1941, the locations from which a sample could have been procured were few. It is most likely that the sample was taken from copper sheet turned under at the point where the Statue was affixed to the pedestal. In any case, it would have been very difficult to have extracted a sample from the curls behind the head, the area from which our sample was derived. Furthermore, the area shows no signs of prior sample procurement. The second prior analysis cited in Table 1 was performed in 1984; in this case the sample is known to have come from the superfluous copper at the Statue-pedestal junction. The two analyses, though restricted, are quite consistent with our results for the important ore signature metals nickel, lead, antimony, and tin. The marked discrepancy is for silver, a metal known to vary widely in different segments of copper ore bodies. On the basis of this limited information, we conclude that the sample of the Statue which we have analyzed is reasonably representative of the copper used throughout the Statue.

Table 1. Elemental Analyses of the Copper Samples

Element	Tweezers	Statue Copper	1941 Analysis*	1984 Analysis‡
Cu	Major	Major	Major	Major
Ni	0.0X	0.0X		0.026
As	0.0X low	0.X low	0.02	
Bi	0.00X	0.0X low	0.003	
Pb	0.00X low	0.00X low	0.002	
Ag	0.000X high	0.000X high	0.012	0.020
Al	0.000X high	0.000X high		
Ca	0.00X low	0.000X		
Fe	0.00X low	0.000X		0.002
Mg	0.000X low	0.000X low		
Si	0.00X	0.000X high		0.007
Sb	0.000X low	0.000X high	0.006	
Sn	0.000X low	0.0000X high	0.001	
Ti	0.000X	ND		
Zn	ND	ND		

NOTE: Major = above 5% estimated. Minor = 1-5% estimated. 0.X, 0.0X, 0.00X, etc. = concentration of the elements to the nearest decimal place, e.g., 0.0X = 0.01-0.09% estimated. ND = not detected (under the spectrochemical procedure used, the detection limit for zinc is 50-100 ppm, or 0.005-0.01 on the scale used here).

* This analysis of copper from the Statue of Liberty is from Reference 9.
‡ This analysis of copper from the Statue of Liberty is from Reference 10.

In order to compare the elemental anlayses of Table 1 with those for copper from other sources, we present in Table 2 analyses of refined Swansea (S.Wales) copper from about 1850 and more modern anode copper and electrolytic tough pitch copper from the Anaconda Raritan refinery circa 1940. While the As and Ni from the anode copper are at similar levels to the Statue copper, the ETP copper, typical of later technology, shows much lower levels of these elements. Among the features that distinguish these analyses from those of Table 1 are the much higher concentrations of Pb, Fe, and Sb in the Swansea and anode samples and the much lower concentrations of Ni, As, and other elements in the ETP sample.

We cannot be sure that the tweezers were made from the same lot of ore as the Statue sample, and it is likely that the ore could vary somewhat in trace element composition at different locations in the mine. It is also possible that several lots of cement copper were smelted together, thus accounting for slight differences in composition. On balance, the metallurgical evidence argues strongly that the two samples of copper are from a common source.

Table 2. Elemental Analyses of Copper from Other Sources

Element	Swansea Cu‡	Anaconda+ Anode Cu	Anaconda+ ETP Cu
Cu	Major	Major	Major
Ni	*	0.05	0.0015
As	*	0.06	0.0015
Bi	*	0.003	*
Pb	*0.05*	*0.05*	*
Ag	*	0.1	0.001
Au	*	0.0014	0.00001
Fe	0.05	0.06	0.0025
O	0.04	0.10	0.02-0.05
Sn + Sb	0.04	*	*
Sb	*	0.02	0.0015
S	*	0.004	0.002
Se	*	0.048	*
Te	*	0.038	*

* Undetermined ‡ From reference 7 + From reference 8

IV. Discussion

Given the information presented above, we now come to the interpretation of it. Consider first the potential sources of copper. A sculptor contemplating an order for the very large amount of copper needed for the statue would be restricted to major supplies. The English ore was becoming less abundant in the early 1870s than it had previously been. Furthermore, it was rich in iron, tin, and antimony (Table 2), characteristics quite unlike either of the samples which we analyzed. A second potential source was Spain. The shipment of large amounts of Spanish copper to Paris would have been difficult and expensive, however. A third potential source is Germany. The Germans mines were not producing extensive copper in this period (7). Furthermore, the decisive defeat of France by Germany in the Franco-Prussian war of 1870-71 (in which Bartoldi served with the French Army) would have made purchases of German copper a few years later quite unlikely. We are unable to compare the trace element signature of the statue copper with Spanish or German copper of the period, since no analyses are known to us to have been performed and since we have as yet been unable to procure samples for analysis.

The fourth potential source was Norwegian copper. The copper was readily available in the required amounts from a French company with offices in Paris. Proximity is a very strong argument, as was probably a desire to utilize French-owned materials for a gift from the French people to the people of the United States. The metallurgical studies reported herein are capable of refuting a Norwegian source (which they do not), but not of conclusively establishing it. Nonetheless, the trace element signatures of the two samples which we examined are strikingly similar. In our opinion, it is unlikely that copper from quite different ore bodies would produce such similar results.

In summary, a very suggestive pattern of historical, circumstantial, and scientific evidence links the Visnes copper to Frederic Bartholdi's statue. The sequence of a Paris-based French copper company processing the ore from its mine in its smelter on the European continent and supplying it for Bartoldi's use lacks only the purchase order from Bartoldi or his supplier to make it complete.

Acknowledgements

We thank Aleksander Hauge and Baard Visnes Lande (the grandson of the original owner of the Visnes mine) for their assistance in obtaining the sample of Visnes copper, Blaine Cliver and John Robbins of the US National Park Service for making available the sample from the Statue of Liberty, and Hans Lund Anderson for information on the history of the Visnes Mine.

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Comments on the oldest known lead figurine

Wladimir W Krysko

Figure 1. Left, limestone figurine, and right, lead figurine, said to be from the Osiris Temple at Abydos, Upper Egypt, approx. 3800 BC.

Figure 2. Back of limestone figurine.

What has become known over the years as the oldest known representation of the human form in lead is an object of some curiosity (Fig 1, right).

The figurine is often referred to as having been found at Abydos in Upper Egypt[1,2,3,4], although one publication locates it at Abydos in the Dardenelles[5]. Its owners, the British Museum, say it was acquired by the Museum in 1899 as "part of a large miscellaneous collection of antiquities purchased from Egypt"[6]. It is not presently on exhibit, but at the time when it was on view and noted in the Guide Book, it was displayed in a case with acquisitions from the Osiris Temple at Abydos in Upper Egypt. This led many writers to refer to the figurine as coming from the Osiris Temple at Abydos and dating it therefore to 3800BC. The British Museum, however, will not commit itself to the statuette's origin.

The author had the pleasure of closely examining the figurine not long ago and found it a fascinating object. It is 5cm high and shows marked wear and tear, with the right arm completely missing. The whole figure is covered with a thin hard brownish layer of what is probably tetragonal lead oxide. Its style and size make it similar to the many carved limestone figures of the female form found during excavation of the Osiris Temple at Abydos (Fig 1, left, and Fig 2) though the artistry of this unique lead figure is considerably less refined. The head is disproportionately large, the facial features crudely worked, and in comparison to the limestone figures, the surface is quite rough.

Although the figure has never been subject to a detailed investigation, what can with certainty be said is that (1) the figure was carved and not cast, and (2) its composition is of remarkably pure lead, i.e. according to analysis conducted by the British Museum's laboratories, there are no noticeable impurities[7].

These two conclusions indicate the figurine is a genuine work of antiquity and could very well have come from the Osiris Temple at Abydos from 3800BC.

Even to an untrained eye it is obvious that the figurine was carved and not cast. Metals first extracted from ore were in the form of globules, lumps, or plano-convex ingots. Early extraction took place in furnaces and the solid metal was removed from the ash and slag only

Figure 3. Back of lead figurine, showing deep under-cutting of headpiece.

when the furnace had cooled[8],[9]. Only after the discovery of the fusibility of metals could shaped castings be produced. However, open mould casting could not have produced the intricasies of this small figure, and cire perdue casting was not known before 2500BC. The surface indentations and deep cuts on the upper left arm (Figs 3 and 4) are typical of those made by a carving tool. Also, the facial features are prominently incised and the chin is very deeply undercut. The headpiece (Fig 3) was made by a gouging out process with a sharp tool, as is that of the limestone figure in Fig 2.

If it is a fake, then the faker, carving a single figure, would have to have known at the time, say the late 19th century, that in pre-Dynastic Egypt casting of figures was unknown, and he would have had to select a lead of considerable purity, assuming most early lead was produced by reducing litharge from silver cupellation.

As to the nature of the statuette, one can surmise that it might have been a votive object from a temple. It could have represented a woman of another race or tribe than the limestone figures, which is suggested by the broadness of the face and prominence of the eyes and lips. This woman may have been of a higher caste because she is partially clothed while the limestone figures — of which there are many, while the lead figure is unique — are unclothed, a sign of slave status in

Figure 4. The carving technique shows up clearly in this enlargement of the lead figurine.

Ancient Egypt. Lead at the time had a similar value to gold and silver and the figure could have been made from this metal to imply a higher rank than one made of stone.

The appearance of the oldest figurine carved in lead, which is contemporary with the first known copper smelted articles from -Tepe Yahya[10], may give us an indication of the dawning of the representation of the human form in metal side by side with the continuation of ceramic and stone figures.

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Acknowledgement

I should like to thank Mr T H G James, Keeper of Egyptian Antiquities, The British Museum, London, for permission to inspect and photograph the figurine and for helpful information.

Work in progress

Aberdulais Falls, South Wales.

National Grid Reference: OS 772 995.

Aberdulais Falls lies within a natural sandstone gorge just above the confluence of the Neath and Dulais Rivers. The exposed rock in the cliff faces represent beds of the Upper Coal Measures or Pennant Sandstones which were laid down some 300 million years ago. Pennant Sandstone is hard and durable and was much favoured as a building material. All the structures at Aberdulais were built in Pennant. Glaciation during the Ice Age deepened the Neath Valley leaving the connecting valleys at a higher level, thus forming a series of "Hanging Valleys" which included the Dulais Valley. Gradual erosion by the Dulais River caused the formation of the narrow gorge and present waterfall at Aberdulais.

The Dulais Falls and Valley have been witness to a variety of industrial activities over a span of 300 years. The reason for the concentrated use of such a compact site is the abundant supply of water, the waterfall providing an ideal head of water to power a waterwheel. The Vale of Neath also provided access to raw materials, such as timber, coal and iron ore. An intricate system of canals and tramways provided an adequate transport system as the Vale of Neath developed as a highly industrialised area. All these factors have contributed to the attractive nature of Aberdulais Falls as an industrial site, through the centuries.

In 1584 documentary evidence shows that Ulrich Frosse, a German copper smelter, came from Cornwall and established a copper works in Neath, under the authority of the Mines Royal. It is probable that the exact location for the works was Aberdulais Falls, for in 1601 the "Lordshippe of Cadoxton" was described as extending "unto the Fall of the said Ryver Dylais into the great Ryver Neath called Aberdylais where the Copper Mylles are." The date of the abandonement of the works is uncertain.

In 1667 it was recorded by John Llewelyn that an iron forge was erected on his land near the falls. There is no evidence for the length of this iron working period.

In the 18th century a corn mill was built, the earliest known date for the mill is taken from a painting by J Lewis dated 1765 which was then engraved by J Bonnor and published in 1791.

Archaeological investigation of this period has produced two mill-stones and an external stepped wheelpit wall underlying the bastion.

The corn mill period is the best documented of all the phases at Aberdulais Falls, this is due to its popularity amongst artists of the day. These included Turner, Gastineau, Hornor and J G Wood who were all noted for their studies of South Wales. The development of The Welsh Landscape Movement led by artists such as Sandby, was an important aspect of the time and encouraged the production of many paintings, guide books and picturesque view albums. Thirtyfive separate studies of Aberdulais Falls and Mill are now known and there are many other views of the Vale of Neath. These include watercolours, drawings and prints produced by both amateurs and professionals.

All the works can aid the Archaeologist and Historian to interpret the corn mill period at Aberdulais Falls, but it must be taken into account that aestheticism often took precedence over topographical accuracy and photographic realism was unknown.

Aberdulais Falls was popular with artists for 60 years, one of the last original depictions of the mill and falls was a pen and ink drawing by Mary Ann Robins in 1819. A watercolour attributed to Ruskin must have been composed from other paintings after the mill was demolished and the site used again for iron working. The abrupt end to Aberdulais Falls' popularity coincides with the change from corn milling to iron working. Therefore the aspect of site which interested the artists was its picturesque setting combined with the falls, rather than its industrial use. An engraving by Tingle after Gastineau may have been produced after the second iron forge was established as it indicates the northern platform had been built. However the subject of the print is the "Cascade at Aberdulais, Vale of Neath" not the industry associated with the falls.

Archaeological evidence suggests that c1829 an iron works was established. A well stratigraphically defined deposit of compacted iron working debris lies below the bastion, a structure which was associated with the tinplate period. It is estimated that this period lasted no longer than 10 years and by 1830 was superseded by a tinplate works. The structures surviving on site represent a mixture of the final two industrial periods. The Aberdulais Tinplate Co worked from c1839 to c1890, in conjunction with the "Lower Works" which was situated on the River Neath. Present achaeological investigation and historical research aims to shed more light on the tinplate industry of Aberdulais and more generally of South Wales.

Peter Greenough (University College of Swansea) has done preliminary investigations on several samples of the slag deposits. Two deposits, dumped on to the river bed in a semi-molten state, were identified as slag from a dry puddling process. One of these samples, clearly associated with a river wall post dating the corn mill period, contained a fragment of unmelted grey pig iron, but both had quantities of sand which indicate the furnace lining for dry puddling.

A further deposit was found to be overlying a wheelpit wall associated with the corn mill period, and underlying one of the major structures of the tinplate period. It was a finely laminated deposit made up of hard, angular iron-rich particles of slag and scale, typically 2mm x 1mm, cemented together by rust (goethite) and mixed with wüstite and silica. This is consistent with the material being the residue of a forging or rolling process.

Archaeological evidence for this period is confined to these slag deposits and a waterwheel pit, although a mill pit later used for tinplate rolling may be contemporary. The waterwheel pit was reused during the tinplate period, and the construction of a further rolling mill may have obscured evidence for earlier forge hammers.

An interim report was published in *Industrial Archaeology Review*, 1985, Vol 8, No 2 by Richard Hayman and Charlotte Clough. For further information contact R Pool, the Project Manager, or S N H Thomas the Site Archaeologist, at The National Trust, Aberdulais Falls, Aberdulais, Neath, West Glamorgan, SA10 8EU.

Notes and news

Archaeometry, 1986

The 25th International Symposium on Archaeometry took place in Athens at the Democritos Research Centre during the week 19th-23rd May. The first two days were mainly occupied with matters of C-14 and Thermoluminescence dating but Wednesday was given over to archaeometallurgical matters. Due to the immense number of contributions much of the material was considered by two poster sessions. Amongst those of metallurgical interest were a consideration of the properties of phosphorus-containing iron wire by Martha Goodway, the hardness and toughness of copper-base alloys by Peter Northover, Southern Russian antimonial and arsenical copper alloys by Prof Selimchanov, the technique of melting bronze for Greek statue casting by Dr G Schneider and the provenance of North Indian "bronzes" (brasses) by C Reedy. Effie Photos had something to show on Mycenaean bronze melting and Catherine Mortimer on brasses used in early German and English scientific instruments.

One useful demonstration was on the TL dating of copper slags by G. Wagner of The Max Planck Institute at Heidelberg who found silicates such as fayalite useful TL emitters.

Naturally many of the papers related to Greece itself. One by Bassiakos related to iron mining and smelting remains near Neapolis in the SE Peleponese. Professor Conophagos gave a paper on the perfection of the cupellation technique used in the 5th-4th century at Laurion, and Joan Mishara talked about the extraordinary hydraulic lead-based mortar used to line the water cisterns on the washery sites. Miss Photos gave the results of work done on smelting beach sands from Thasos. Among the non-Greek papers was one by Justine Bayley on crucibles and moulds from Britain and another by Elizabeth Nosek of Cracow on the bloomery process in the Holy Cross Mountains of Poland and the high concentration of radioactive elements in the slag. Christiane Eluere gave a paper on joining processes during granulation and Emel Geskinli of Turkey spoke about the occurrence of high arsenical phases in copper-base alloys. Andreas Hauptmann of Bochum discussed the slag phases present in copper, iron and lead slags from Oman and Jordan and their relationship to the furnace regime.

A visit was paid to the washery site near Laurion which has been newly conserved by the Archaeological Service. This is the first industrial site to be so treated in Greece and it is hoped that there will be many more. Thurday was devoted to Theme Session, "The Transition from Late Neolithic to the Early Bronze Age in the Aegean", and naturally many of the papers given had a pronounced metallurgical content.

The proceedings will be published in due course and will make a very useful contribution to the history of metallurgy.

American Activities

The National Park Service is organizing a meeting on the restoration of the *U.S. Statue of Liberty* for September 22-24 in New York City. Further information can be obtained from the office of E. Blaine Cliver, National Park Service, Building 28 — Charlestown Navy Yard, Boston MA 02129, telephone 6-7-242-1977.

The Microbeam Analysis Society is meeting jointly with the Electron Microscopy Society of America to have another full-day session on *Micro Analysis of Art Objects* on August 10-15 in Albuquerque, organized by Dr. Robert Ogilvie of the Museum of Fine Arts, Boston, 465 Huntington Avenue, Boston MA 02115, telephone 617-267-9300, and Professor Michael Notis, Department of Metallurgy and Materials Science, Whitaker Laboratory 452, Lehigh University, Bethlehem PA 18015, telephone 215-861-4225.

SHOT, the *Society for the History of Technology*, will meet in Pittsburgh on October 23-26, jointly with the History of Science Society, the Philosopy of Science Association, and the Society for the Social Studies of Science. Proposals for papers or sessions should reach Professor W. Bernhard Carlson, Department of Social Sciences, Michigan Technological University, Houghton MI 49931 by May first.

The second archaeometallurgy conference in *China* has been set for October 21-26 this year. Announcements are expected shortly.

A proceedings volume, *Sculptural Monuments in an Outdoor Environment*, edited by Virginia Norton Naude (1985, ISBN 0-943836-04-2) has been published by the Pennsylvania Academy of the Fine Arts, Broad and Cherry Streets, Philadelphia PA 19102.

Professor Robert Gordon of Yale has been studying *puddling slag* from Funtley Forge, the site of Henry Cort's development of the puddling process in the early 1780's. Slag found at Roxbury Furnace in Connecticut appears to be identical.

At Harvard's University Museum Dr. John F. Merkel has been studying twenty pieces of *Roman jewellery* from Hesban in Jordan; four of these pieces are brass.

The Getty Conservation Institute is sponsoring a short course on metallography April 7-11 in Los Angeles. The instructor will be Dr. David Scott of the Institute of Archaeology of the University of London, and the course is one developed for the Institute's Conservation Summer School. The Conservation Analytical Laboratory of the Smithsonian offers this same course September 8-12. For information, call me at 202-287-3733 or write me at CAL MSC, Smithsonian Institution, Washington DC 20560.

Martha Goodway

Hungarian Research in Industrial Archaeology and Archaeometry

A conference was held at Vezprem in 1982 and its proceedings have now been issued (1984) and edited by Janos Gomori. This Volume II covers mining, brick and pottery kilns, geophysical prospecting and metallurgical aspects. These include the earliest cast iron-making furnaces in Hungary (1650-1750) by G. Heckenast, the earliest iron artifacts and their archaeological environment by Patek, the metallography of 8th cent BC iron by M.Kaldor, remains of a smithy in Gorsium by Z. Banki and iron slags from Hungary by Peter Kishazi. This volume shows that the development of archaeometry and Industrial Archaeology is following much the same lines as elsewhere in Europe.

This conference resulted in the publication of a Newsletter, *Industrial Archaeology and Archaemeometry News* with an English supplement produced on the eve of the Athens conference on Archaeometry.

There are now two working groups:- Industrial Archaeology and Archaeometry which work inside the History Group of the Veszprem Academic Committee of the Hungarian Academy of Sciences. The supplement to the newsletter deals with graphited pottery, Sarmatian jewellery, laser spectroscopy, iron mines and smelters of the Arpad period and the need to interest 10-16 year old schoolchildren in this work over the whole of Europe.

Further information can be obtained from Marta Jaro at the National Centre of Museums, H — 1476, Budapest — 100.

Radiocarbon Dating of Iron

New techniques have been developed which make it economically possible to carry out radiocarbon dating on iron artifacts with small amounts of carbon such as those made of wrought iron. Richard Cresswell of the Isotrace Laboratory at the University of Toronto, M5S 1A7 is anxious to cooperate with anyone who needs dates on such material. The cost would be about £150 per specimen.

Book reviews

The Great Laxey Wheel and Mine

Catherine Clark, Mark Horton, and Michael Stratton. *A survey of the Mining Remains at Laxey, Isle of Man. Research Paper No. 2, Institute of Industrial Archaeology, 1985, £3.75. ISBN 0948821000. 141pp; 55 illustrations.*

The Lady Isabella Waterwheel at Laxey is one of the best known British industrial monuments; it is less well known that it forms merely one component of what must (on the basis of this report) be among the most extensive and interesting metal mining sites in the country. It is therefore very pleasing to read that the Manx Government has decided to develop the site as a whole as an industrial archaeology museum, and has incorporated archaeological advice from the outset of what appears to be a well-designed programme.

The present report is the first fruit of this programme: it is the result of a two-week season of fieldwork and excavation in July 1985, and the authors must be congratulated on the amount that they achieved in this time, and the commendable speed and cheapness of their report. However it must be clearly stated that the report is in fact an interim report written for distribution to those involved, of which extra copies have been run off for publication: the uneven coverage of the site, very poor reproduction of photographs, and lack of proof-reading and general 'polish' are acceptable in a circulation-standard interim (especially as the price for rapid availability), but will jar with the reader who expects a more definitive report.

The report opens with an introductory chapter on the scope of the survey (which was limited to the surface remains, and concentrated on areas in Government ownership), a review of previous work, and an over-brief historical summary: the geology is not discussed. It continues with a gazetteer of surface remains (the bulk of the text), a description of the complex water supply, a brief description of what the authors refer to as 'service industries' (under which title they include important aspects of the working mine such as the washing floors, as well as contemporary tourist arrangements), and a detailed discussion of two items of machinery (a turbine of 1862, and the Man Engine and hydraulic engine of 1881). The report concludes with a review of the development of the mine, integrating the authors' field survey with previous work. There are no references in the text, although a bibliography is included.

This report is a valuable contribution to the literature on an important and complex site, but must be accepted as a hastily-prepared interim. It should be no substitute for a comprehensive site report at the end of the project, which will be awaited with great interest.

David Cranstone

Kodo-Zuroku; Illustrierte Abhandlung uber die Verhuttung des Kupfers

Translated and edited by Bruno Lewin, Andreas Hauptmann and Werner Kroker. *Deutsches Bergbau-Museum, Bochum, 1984, pp 119. 18 x 27 cm; Price 49 DM*

This is a German version of the collection of famous Japanese drawings recently made available with an English commentary by Professor Cyril S. Smith and published by the Burndy Library (see our review in the Journal, 1984, volume 18 (1), 52). In a way it is a pity that it has appeared only a year after Cyril Smith's version, but this goes to show what a valuable archive these drawings are and how experts in many countries are interpreting them.

This version contains a short history of copper extraction in Japan based on Kodo-Zuruko, followed by the illustrations from KZ in the form of coloured black and white wood block prints. This has a brief commentary. This is followed by a catalogue of the tools used in copper mining and smelting. Then follows an essay on copper extraction, with the Japanese text on the facing pages. Finally we have a discussion on this section based on Gowland and Agricola. Professor William Gowland, who went out to advise the Japanese Government on mining techniques in the 1880s was largely responsible for drawing attention to KZ and was the first to publish extensive abstracts.

The difference between this version and Cyril Smith's lies mainly in the greater emphasis in this version on mining and tools. All the original material is present in both books so that it will be more convenient for German readers who have little knowledge of English. But there is a good deal more colour in the prints in Cyril Smith's version and readers who have time will enjoy looking for the merits of the two versions.

One or both of these works should be read by any person who considers himself an archaeometallurgist.

R F Tylecote

5000 Jahre Giessen von Metallen

Heinz Wubbenhorst. *Giesserei Verlag GMBH, Dusseldorf, pp 208, A4 format.*

This is a foundryman's introduction to the history of his profession and is correctly subtitled "facts, dates illustrations on the development of foundry techniques".

It covers a vast range of subjects and places including Nigerian "bronzes" and South American gold. It covers a vast number of artifacts including clocks and stove plates and it contains brief histories of all the foundry techniques and melting furnaces up to the 20th century. It is well illustrated, mostly in black and white, but with some illustrations in colour.

For what it claims to be it is an excellent production and for those wanting quick illustrative material for a lecture on the subject it is a very handy reference book.

R F Tylecote

Kurao Kubota

Folkloric History of Iron
(In Japanese) 1986, ISBN4-639-00549-0

The purpose of this book is to shed light on the impact of iron on the ancient Japanese folkloric culture. It comprises four sections:

Section 1	Iron and Japanese classic literature
Section 11	Iron and Japanese religion
Section 111	Iron and life-styles of iron-masters in ancient times
Section 1V	Iron and iron products made by ancient production techniques

Section I
In Japan many literary works were written between AD 700 and AD 1000. They include "Kojiki" and "Nihon Shoki" which are considered the oldest literature ever written in Japan. This section comprises comments on the myths and legends about the iron and iron products referred to in these literary works and make reference to the iron and iron products recovered in various parts of Japan.

Section II
The strongest desire of the Japanese people for a life affluent with iron and iron products was sublimed to religion, and iron came to be regarded as deity in many parts of Japan. God of iron, god of fire, god of wind and the god who taught iron-making techniques, and many other gods were enshrined. This section deals with these gods and their origins with reference to "Jinjya Engi" and other literary works.

Section III
This section deals with life-styles of those who produced iron in ancient times, focussing on the localities where iron was produced and on reactions of the Japanese who actually used imported iron and with their praises and scorns towards imports. Many legends and old literature are referred to in this section.

Section IV
This section focusses on the ancient iron slag with its properties and usages in daily life. It also deals with the quality of iron used for making swords and compares it with the present-day forged iron. It also shows how the cast iron used for making tea pots and iron lanterns in ancient times differ from the cast iron we have today, with comments on "Tama-Hagane" and white pig iron used as materials for the ancient iron products.

Iron was first brought to Japan from Asian Continent between BC 300 and BC 400. The Japanese started with the forging of the imported iron to produce semis and later proceeded to smelting of iron ore. Between AD400 and AD 500 various iron products such as swords, armors, helmets, hoes, spades and knives were buried in large tombs. Later, in the AD 700's workers who came to Japan from the Asian Continent brought to Japan with them a smelting technology using high temperature and produced reduced iron (sponge iron) which led to foundry technology. The foundry technology came to be used for the production of Japanese swords, tea pots and iron lanterns in large quantities, further leading to the production of iron products with high artistic values such as "wabi" and "sabi" and other Oriental qualities. The author hopes that the book will shed light on how ancient iron-making techniques came to produce artistic iron crafts through many generations.

Author

Other Books Noted

W H Manning, *Catalogue of the Romano-British Iron Tools, fittings and Weapons in the British Museum. British Museum Publications, 1985, £45.00.*

D V Clarke, T C Cowie and A Roxon. *Symbols of Power at the Time of Stonehenge. National Museum of Antiquities, Edinburgh. The Catalogue of the Edinburgh Exhibition. HMSO, 1985, £15.00.*

Abstracts

GENERAL

A S M de Jesus: Authentication of gold products by nuclear methods. *Gold Bulletin, October 1985,* **18(4), 132-9.**

The falsification of valuable gold items is an ever-present threat to the authenticity of gold products in general. Concomitant with this, there is a continuous search for reliable, practical and cost-effective means of identifying such forgeries. The possible techniques are reviewed in this article, and work on promising methods in the author's laboratory described.

Author

P T Craddock: Three thousand years of copper alloys: From the Bronze Age to the Industrial Revolution. In: Applications of Science in Examination of Works of Art, *Eds. P A England and L van Zelst, Boston Museum of Fine Arts, 1985, 59-68 plus microfiche.*

Comprehensive survey of copper alloy analyses, potential and uses. Broad trends in alloy types through 3000 years world wide, based on 7000 analyses.

Author

J Ogden: Potentials and Problems in the Scientific Study of Ancient Gold Artefacts. In: Applications of Science of Works of Art, *Eds. P A England and L van Zelst, Boston Museum of Fine Arts, 1985, 72-5.*

A detailed study of the techniques used to make good jewellery, and of the ageing processes during burial. This study carried out with especial reference to determining the authenticity of supposed gold antiquities.

PTC

M L Wayman: Native Copper. Humanity's Introduction to Metallurgy. Part I. Occurrence, Formation and Prehistoric Mining, *CIM Bulletin (Canada) 1985, 78, No* **880**, *67-9.*

An historical review of the occurrence of copper in Canada.

M L Wayman: Native Copper. Humanity's Introduction to Metallurgy. Part II. Metallurgical Characteristics and Utilisation. *CIM Bulletin (Canada) 1985, 78, No* **880**, *75-7.*

This is the second part of an article, the first part of which appeared in CIM Bulletin 1985, 78, 67-9. This part deals with the composition of the native copper, its structure and the artifacts produced from it.

E G West: Aluminium — the first 100 years. Metals and Materials, *March 1986,* **2(3)**, *124-29.*

Briefly reviews the history of the metal from its discovery in 1854, and the patenting of the electrolytic extraction process in 1886. A brief, authoritative account is given of the development of aluminium alloys, and of welding and fabrication techniques. Applications of the metal and its alloys are outlined.

APG

R K Liu and D J Content: Ancient Jewellery Moulds. *Ornament, 1979,* **4(1)**, *30-39.*

The article is a discussion of the techniques of making metal, glass, faience, or terracotta jewellery from moulds, often one-part open moulds. The objects shown are mostly Byzantine, Egyptian and Roman.

AATA

BRITAIN

R Inman, D R Brown, R E Goddard and D A Spratt: Roxby Iron Age Settlement and the Iron Age in NE Yorkshire. *Proc. Prehist. Soc., 1985,* **51**, *181-213.*

Mainly immediate pre-Roman Iron Age but traces of R-B and 6th cent.Anglo-Saxon. Circular houses, at least one containing a smelting furnace, and the remains of smithing in another. Analyses of slag from this area were given in this journal for 1975, 9(1), 32-3 under the authorship of N Harbord and D A Spratt, but no figures are available for Roxby itself.

RFT

I Barnes: The analysis and recreation of bronzes and brass mould residues. *The Laboratories of the National Museum of Antiquities of Scotland, n.d.,* **2**, *40-6.*

Stone or pottery moulds which have been used for metal casting often exhibit dark stains or discolorations of a metallic nature. In the National Museum of Antiquities of Scotland, a survey was made of the moulds in the collection. Most of the moulds were clay moulds. Of the stone moulds, the early ones were found to be made from sandstone or granite, and the later ones from soapstone. The stains in early moulds were found to contain less zinc and more tin than those in later moulds. Experimental clay-mould castings of known composition bronzes and brasses were performed and the stains produced on the moulds studied. Although those experiments provided some information about the factors which influence the amount and type of metallic stains produced on mould surfaces, they demonstrated that it is not easy to work back from the composition of the stain to the composition of the cast alloy.

AATA

D W Crossley and H Kellenbenz: The English Iron Industry 1500-1650: the problem of new techniques. In: Schwerpunkte der Eisengewinnung und Eisenverarbeitung in Europa 1500-1650, *Boehlau Verlag, Wien, Austria, 1979, 17-34 (in English).*

Development of blast furnaces and production during the 16th and 17th centuries. See also AATA 21-1970 and 19-1220 for other discussions of English history of technology in the medieval and early modern periods.

AATA

I D MacLeod: A genuine sixteenth century forged coin. *Australian Institute for Maritime Archaeology, Bulletin, 1984,* **8(2)**, *1-9.*

Describes the identification, conservation and analyses of a forged coin, dated 1568, from the wreck of the Batavia (1629). Techniques used include scanning electron microscopy, x-ray diffraction analysis and wet chemical analysis. It concludes with a discussion on the possible mode of fabrication of the coin.

AATA

C Mortimer: Bronze Age gold analyses. *The Laboratories of the National Museum of Antiquities of Scotland, n.d.,* **2,** *62-7.*

Summarizes the X-ray fluorescence analyses carried out on 19 Bronze Age gold artifacts in connection with author's undergraduate dissertation at Bradford University. Most of the pieces had been studied by optical emission spectroscopy prior to these analyses. There were significant differences between the two sets of measurements (of percentages of silver, copper, and gold), so specific gravity measurements were used as a check.

AATA

J Tate: Silver analysis by x-ray fluorescence. *The Laboratories of the National Museum of Antiquities of Scotland, n.d.,* **2,** *24-33.*

Was used to analyze 14-century silver coins. Tate describes the spectrometer and its functioning, and discusses the shortcomings of the technique. He presents the results of 26 analyses, noting that compositional differences are small over the periods in which they were minted, and discusses the composition of a Pictish pennanular brooch — one of several Viking silver pieces studied after the coin project was temporarily put aside.

AATA

R M Erhenreich: Trade, Technology and the Ironworking Community in the Iron Age of Southern Britain. *BAR British Series 114, 1985, pp 228, A4.*

This work contains 10 pages giving the results of the analyses of 503 iron artefacts of differing types originating from different areas of S. Britain. The sites include innumerable hillforts, and the elements sought include Co, Ni, Cu, As, P, S, together with some indication of the slag, carbon content and the hardness. Full descriptions of the objects are given and some indication of where the analysis was taken, but there are few drawings and few micrographs. The currency bars tended to be higher in slag than the rest of the objects. High carbon steel was relatively rare (only 40 out of 329 had more than 0.5%). Phosphorus was generally below the 0.5% mark; only 31, 17 of which were currency bars, had more than 0.5%. The average hardness for low-P high carbon was 206/HV and for low carbon 148 HV. The average for the high-P was 181 HV. Adzes and ploughshares seem to have been consistently made from high-P iron.

Chisels seem to be the only tool consistently made from high carbon iron. It is probable that carburization was only known to a few blacksmiths or it was a matter of selection from the high-carbon parts of the blooms. Either way it was not common and the bulk of the iron used in this period rarely had a hardness exceeding 200 HV and the highest hardness recorded in the tables is 519 from a high-carbon blade from Danebury. Clearly steel was not widely used in this period nor was the hardening of it widely understood.

RFT

J Tate, I Barnes and A MacSween: Analysis of massive bronze armlets: *The Laboratories of the National Museum of Antiquities of Scotland, n.d.,* **2,** *89-94.*

There are 22 known examples of North Britain 1st-2nd century AD massive bronze armlets. Seven of them are in the National Museum of Antiquities of Scotland. The analyses carried out on these pieces were begun by Barnes as a student project. X-ray fluorescence spectroscopy was used to determine the percent composition of major elements. In this summary of the results obtained thus far, the authors note that no particular alloy composition appears to have been aimed for and that some armlets seem to have been cast directly, while others were worked and annealed.

AATA

N White and J Tate: Non-dispersive XRF analyses of Viking silver from Orkney. *The Laboratories of the National Museum of Antiquities of Scotland, n.d.,* **2,** *105-10.*

Silver arm-rings taken from two Viking hoards — a rather modest one from Burray and a much richer one from Skaill — were analysed by x-ray fluorescence spectroscopy. All of the arm-rings were made from alloys of silver, copper and zinc with traces of lead, gold and bismuth. The arm-rings from the Burray hoard were found to have a much lower silver content (often less than 55% silver) and higher lead content than those of the Skaill hoard (which were more than 75% silver).

AATA

EUROPE

E D Brose: Competitiveness and Obsolence in the German Charcoal Iron Industry. *Technology and Culture, July 1985,* **26(3),** *532-59.*

Until about 1850, approximately 75% of German iron production was converted into wrought iron bars for use by the many finishing establishments in the country. Most of the bar had to be versatile enough to allow easy conversion to a number of different shapes and sizes. The extra cost of converting high sulphur bar made from coke pig-iron outweighed the lower cost of the bar — typically 70% of bar from charcoal pig-iron. Gradual improvement in the quality of the bar made from coke pig-iron associated with increasing demand for applications for which high quality was less important (eg. rails) led to a rapid drop in the production of charcoal iron from 275,000 tons in the peak year 1855-56 to about 150,000 tons in 1861, and the blowing out of the last charcoal blast furnace in 1925.

APG

P T Craddock: The metallurgy and composition of Etruscan Bronze. *Studi Etrusci, 1986,* **52,** *211-71.*

Comprehensive survey of copper and its alloys in Etruria based on the analysis of over 700 items principally in the collections of the British Museum.

PTC

J M Doyen: Recent investigations into the archaeometallurgy of the Viroin valley (Belgium), *Amphora, 1984,* **36,** *9-24 (in French).*

Late La Tène iron nails, bloomery furnaces of the late 1st cent. BC to 2nd cent. AD.

CPSA

C Eluère: Clous d'incrustation en or des tumulus armoricains. Paléométallurgie de la France Atlantique; Age du Bronze (2), *ed. J Briard, Rennes, 1985 (in French).*

Decorative gold rivets from the hilts of daggers. Analyses show most to be natural gold but one has 2.7% Cu. Used in conjunction with copper-base rivets as a decorative feature only. The latter have corroded completely.

RFT

C Eluère: Attention aux pierres de touche! (touchstones). Bull. Soc Préhist. Francaise, *1985, Oct. No***7,** *203-5 (in French).*

Examples of French touchstones with analyses of deposits of gold alloys on them.

RFT

C Eluère: Goldwork of the Iron Age in 'Barbarian' Europe. *Gold Bulletin, Oct. 1985,* **18(4),** *144-55.*

Archaeological and technological evidence have made it possible to construct a picture of the art of gold working during the Iron Age in many places in Europe from which no locally written records exist. Influences from oriental and Mediterranean cultures are discussed.

Author

Y Finslo: Surprisingly professional iron production 2000 years ago, *Forskingsnytt, 1984,* **29(4),** *33-42 (in Norwegian).*

Discovery of bloomery furnaces near Trondheim.

CPSA

V D Gopak and A G Djacenko: Old Russian sword making technology in the Severski Donets basin. *Sov. Arch., 1984* **(4),** *252-55 (in Russian).*

Two swords were investigated from 10-11th cent. AD. The first had a hard steel envelope and the second was very mild heterogeneously carburised iron/steel.

CPSA

M F Gurin: Investigations of three-layered knives from the Black Sea of Russia. *Slovenska Arch. 1984,* **32(2),** *311-26 (in Russian).*

Central steel cores enriched in Mn and Ni. Welded with white lines. Probably imported.

CPSA

I L Kyslasov: The history of artistic ironworking in Southern Siberian inlays in iron. In: Srednevekovaya gorodsksya kultura Kazakstana i Sredney Azii. *Alma Ata 1983, 120-30 (in Russian).*

Cu, Ag, bronze and Au surface inlays in various iron artifacts have been found in Siberia as early as the 7th-3rd cent. BC.

CPSA

L Malnati: Early tombs at S Maria d'Anglona. In: M Castoldi and L Malnati, *Studi e ricerche archeologiche in Basilicata, Milana, 1984, 41-95 (in Italian).*

Weapons etc. made in iron as early as 8th cent. BC. Similarly, a little earlier in Calabria.

CPSA

J R Maréchal: An example of technical migration during the Hallstatt period. *109th Congress National des Societés Savantes, Dijon, 1984, Fasc. III, 35-42 (in French).*

Based on analysis of Ni-containing Polish and Swedish iron objects. Blames deposits of chloanthite in Slovakia and Silesia.

CPSA

J P Mohen: Les bronzes de l'age du Fer en France et dans les pays voisins. Pal. du bronze à l'age du fer; les age du fer dans la vallée de la Saone. *RAE Suppl. CNRS, 1985, 315-9.*

A short discussion on the use of bronze in the Iron Age.

RFT

W A Oddy and S La Niece: Byzantine gold jewellery. *Gold Bull., 1986,* **19(1),** *19-27.*

Roman tradition. Photos of coins and jewellery with details of composition. Jewellery dated by stylistic comparisons.

RFT

V S Patrushev and L S Rozanova: Iron technology of the Early Akhmylovo Burial ground. *Sov. Arch. 1986 (1), 184-97 (in Russian).*

This burial ground is the largest Ananino necropolis of the late 8th-6th centuries BC. It is part of the Western Volga variant of the Ananino culture. 50 of the best preserved artifacts were microscopically and metallographically examined. They comprised daggers, spearheads, shaft-hole and socketed axes and knives. The structures ranged from cold-worked ferrite to piled medium carbon steel. Whereas the mean hardness was around 200 HV, one blade was martensitic with a hardness of 400 HV and had therefore been quenched.

ECJT

V E Radziyevskaya and D V Gopak: A sword of Roman type from Kolomak, Kharkov. *Sov. Arch., 1984* **(3)**, *209-11 (in Russian).*

3rd-4th cent. AD, soft ferrite plus pearlite, low slag.

CPSA

B A Schramko, L A Solntsev and L D Fomin: Iron working in the Scythian steppes. *Sov. Arch., 1986* **(2)**, *156-69 (in Russian).*

20 metallographic analyses of iron objects from the 4th cent. BC site at Kamenskoe. Iron and steel were used and many of the edge tools were welded steel to iron. There were no signs of carburizing to give cutting edges and quench hardening was absent.

RFT

J Stankus: Metallographic analysis of iron objects from cemeteries in Lithunia. *Lietuvos archeologija (Vilnius), 1984,* **3**, *35-41 (in Lithunian).*

94 specimens from 4th-8th cent. AD. 25% welded iron to steel. Few heat-treated.

CPSA

J Tournaire: Un essai novateur; l'acierie de Buzancais (1807-1829). L'Indre et son passé, *Group d'histoire et d'archéologie de Buzancais, 1982,* **No 14**, *73-86 (in French).*

A finery forge and its legal difficulties in regard to water supply from the R. Indre. Illustrated with drawings from Jars and Diderot.

CPSA

J Ypey: Some Viking Age swords from the Netherlands. *Offa, 1984,* **41**, *213-22 (in German).*

Discussion on pattern-welded and ornamented medieval swords.

CPSA

Z Bánki: Vasolvaszto (?) kemence maradvanya Gorsiumban. (Ruins of an iron smelting furnace in Gorsium (?). *Iparrégészet, 1984,* **No 2**, *195-98 (in Hungarian).*

A circular furnace with a diameter of 1 metre was found in Gorsium in 1963, during the excavations of building III/A below the basilica maior. The furnace was built from stone; its foundations were made of a tegula-layer. The upper structure could have been made of sun-dried unburnt bricks set on the stone base. It is not certain whether the furnace was connected with iron smelting or with a smithy. The author supposes it to be a smithy furnace. The iron slags found here contain iron ore inclusions as shown by P Kishazi, and not quartz inclusions as from a smelting furnace.

AATA

M Bemmann: Faelschungen bronzezeitlicher Fundstuecke aus dem Rheinland und aus Polen. (Forgeries of Bronze Age finds from the Rhine-region and Poland). *Archaeologisches Korrespondenzblatt, 1983, 13,* **no 3**, *335-38 (in German)*

Forgeries of Bronze Age tools and weapons in museums in the German Democratic Republic have been known since 1936. More forgeries of this type have since been found in museums in northwestern Germany and Poland.

AATA

L O K Congdon: Water-casting concave-convex wax models for cire perdue bronze mirrors. *American Journal of Archaeology, 1985,* **89**, *511-15.*

The author considers the wax models for the lost wax casting of bronze caryatid mirrors of ancient Greece. Based on her experience with the extraction and purification of beeswax, she postulates the use of a 'water-casting' technique to form the wax models; a concave-convex disc of wax is formed by pouring molten wax onto heated water. The author's experiments are detailed and discussed. See also AATA 7-1615 for an earlier discussion of ancient Greek caryatid mirrors.

AATA

A G Elayi, P Damiani, P Collet, K Gruel, F Widemann, G Grenier and D Parisot: 14 MeV neutron activation analysis of Gaulish silver alloyed coins. *J Radioanalytical and Nuclear Chemistry, Articles, 1985, 90,* **No 1**, *113-22.*

Gaulish silver-copper-tin coins attributed to the Veneti of Western France from the first century BC were analysed by a method that avoided the need for closely similar standards. Tin content has only been estimated. Twenty-four coins, originally ascribed to six separate groups typologically, were analysed with the result that a subdivision of one typology was possible.

AATA

R De Marinis and L Nistri: Il ripostiglio della Malpensa. (The deposit of Malpensa). *In book: Restauri Archaeologici in Lombardia-Attivita della Soprintendeza - 1977-1981; Exhibition Catalog, Como, 1982, 21-28 (in Italian).*

Reports on the excavation of a metal craftsman's storeroom. The restoration of several bronze objects is summarized.

AATA

H Drescher: Untersuchungen und Versuche zum Blei- und Zinnguss in Formen aus Stein, Lehm, Holz, Geweih und Metall. Ein Beitrag zur mittelalterlichen Giesstechnik von Kleingerät. (Research and experiments on the casting of lead and tin molds of stone, clay, wood, antlers, and metal: a contribution to the casting of small objects in the Middle Ages). *Fruehmittelalterliche Studien, 1978,* **12,** *84-115 (in German).*

From excavated moulds and literary sources, evidence indicates that moulds of different materials have been used in the Middle Ages. Experiments with moulds of different materials have demonstrated various possibilities of practical use.

AATA

T Follett: Amber in goldworking, *Archaeology, 1985,* **38** *(2), 64-5.*

Beyond the more established usage of amber as a decorative material in Etruscan jewelry, researchers at the University Museum of the University of Pennsylvania have detected its residual presence in Etruscan granulated gold jewelry. Entrapped between the underside of the tiny gold spheres and the underlying gold sheets to which they are bound, it is thought to have been used as a flux in the manufacturing process of granulation. The amber was identified using Fourier transform infrared spectrometry (TRIR).

AATA

D Gaborit-Chopin: L'orfèvrerie cloisonnée à l'époque carolingienne. (Carolingian cloisonné goldsmithing). *Cahiers archeologiques, 1980-81,* **29,** *5-26 (in French).*

Examination of the metalwork associated with Charles the Bald's donation to the treasury of Saint Denis: the paten of Saint Denis (Louvre, Paris), the mounting of the so-called cup of the Ptolemies (destroyed), the escrain de Charlemagne (crest, Cabinet des Medailles, Bibliotheque Nationale, Paris), and the altar frontal of Saint Denis (destroyed). Attributes the metalwork to goldsmiths of Charles the Bald, perhaps a Saint Denis workshop. Argues that the technique of cloisonné goldwork continued to be employed in the middle and second half of the 9th century.

AATA

F Froelich: Chemical and mineralogical study of prehistoric and Middle Age iron slags of Bavaria. *Acta Albertina Ratisbonensia, 1984,* **42,** *33-57 (in German).*

Chemical analyses are given of five slags and determinations of nickel, chrome and manganese are presented in 109 slags which contain nickel 17-71 ppm, chromium 30-148 ppm, and manganese 0.04-4.47%. Fayalite and wustite are the predominant minerals in the slags, which also contain magnetite, goethite, cristobalite, tridymite and pure iron.

AATA

J Gomöri and A Wallner: Geofizikai mérések and szakonyi Arpád-kori vasolvasztó mühelyek feltárásánál. (Geophysical measurements at the excavation of the Arpad-period iron smelting furnaces in Szakony). *Iparrégészet, 1984* **(2),** *227-42 (in Hungarian).*

Near to the village of Szakony, fragments of a furnace were found. Later more furnaces and other findings confirmed that a common Arpad-period workshop had been discovered. The conclusions are discussed and illustrated in detail.

AATA

G Heckenast: Megjegyzések a legrégibb magyarországi nagyolvasztók tipológiához (1650-1750). (Some remarks concerning the earliest pig-iron blast-furnaces in Hungary (1650-1750)). *Iparrégészet, 1984* **No 2,** *173-77 (in Hungarian).*

Pig-iron producing blast-furnaces appear in the Hungarian sources in German language as 'Hochofen', in Latin as 'formax maior' and in Slovakian as 'masa'. There are no technical data, pictures or archaeological excavations prior to 1710. The earliest furnaces, according to the author, follow models from Silesia, Bohemia, etc. Some very unique models were developed.

AATA

I Hegyi: A magyar bányászat középkori kezdetei (a fémbányászat kora). (The beginnings of mining in Hungary in the Middle Ages. The period of mining non-ferrous metals). *Iparrégészet, 1984,* **No 2,** *61-72 (in Hungarian).*

Mining in the Carpathian Basin had been practiced long before the Hungarians settled there. The Hungarians, however, had rich experience in processing metals following the Eastern traditions learned in the Caucasus and Altai. Because of the lack of literature there are few historical data about medieval metal mining in Hungary. That is why the general archaeology, linguistics (toponomy) and comparative ethnography are very important disciplines for the historian of mining. The medieval period of mining methods was terminated by an explosion in the mine of Selmecbánya.

AATA

M Káldor and F Tranta: A mexocsáti "preszkita" temetoból származó (ie 8 század) vasanyagok fémtani vizsgálata. (Metallurgical study of iron objects found in Mezocsat pre-Scythian-period cemetery (8th century BC)). *Iparrégszet, 1984,* **2,** *187-93 (in Hungarian).*

Two iron objects from the Mezocsát cemetery were examined metallurgically and viewed by a scanning electron microscope. An energy dispersive spectrometer was also used in the analysis. The results are given.

AATA

P Kisházi: Néhány magyarországi régi vassalak ásványos vizsgálata. (A mineralogical examination of some of the ancient iron-slags from Hungary). *Iparrégészet, 1984,* **2,** *199-203 (in Hungarian).*

The examination of the composition of 16 ancient slag samples from different sites of Hungary proved 14 samples to be iron slags. The most frequent components were the fayalite, wüstite, leucite and monticellite. See also AATA 21-1032 and 22-2230.

AATA

L Köto and M Kis Varga: Ujabb eredmények a röntgenemissziós analizis régészeti alkamazásában. (New results in the archaeological applications of x-ray emission analysis). *Iparrégészet, 1984,* **2,** *273-88 (in Hungarian).*

Since the first Industrial Archaeology Conference in 1980, several Late Avar and Roman bronzes, and many prehistoric and 13th-14th century bronzes have been studied in the Research Institute of Atomic Nuclei of the Hungarian Academy of Sciences. The number of x-ray analyses, at present, amounts to nearly 1500. Increased sensitivity makes possible simultaneous measurement of seven chemical elements. The data measured are recorded and evaluated by computer. The results are described. The method will be extended for various artifacts and new elements.

AATA

J Makjanić, I Orlić and V Valković: Analiza Legura metodom spectroskopije fluorescentnih x-zraka. (Elemental analysis of alloys by x-ray emission spectroscopy). *Vjesnik Arheoloskog muzeja u Zagrebu, 1982,* **15,** *59-68 (Serbo-Croat w English summary).*

In order to identify provenance of archaeological artifacts, it is useful to identify their composition. X-ray emission spectroscopy enables fast and simultaneous analysis of all elements in the sample Z 15. Twenty-eight objects from the Archaeological Museum in Zagreb were analysed to illustrate the method. Mo-tube was used as an x-ray source for the sample excitation. Matrix effects correction by the method of fundamental parameters was employed. The analysis of 22 objects showed that copper was the main ingredient with concentrations ranging from 43.4% to 97.6%. Twenty-one out of 22 objects contain lead, tin and iron. Zinc was found in 12 objects. Small concentrations of some other elements were present in few samples (eg arsenic 0.2-3.8%, silver 0.4-1.8% and antimony 0.6-3.3%). Sorting of the objects can be done according to the percentage of the major elements and/or according to the existence of some minor elements (arsenic, silver, antimony, iron and in some cases zinc and lead). The latter could be more significant because these minor components usually indicate that the objects were manufactured when it was still impossible to extract them. X-ray emission spectroscopy as an analytical method gives important results in exploring the origin or age of archaeological objects.

AATA

M Matteini and C Manganelli del Fa: The Lion of Braunschweig. *Maltechnik-Restauror, 1983, 3, 175-86.*

Reports investigation of the original bronze alloy and patches on a 12th century bronze sculpture of a lion. A complete report of the analytical data is provided. The composition of the surface patinas and their origins are also discussed.

AATA

K Kozák: Arpád-kori mühelyek és egy középkori fütokemence az egri várban. (Arpád-period workshops and a medieval heating oven in Eger Castle). *Iparrégészet, 1984* **(2),** *205-16 (in Hungarian).*

New discoveries extended information on the 15th-16th century rib furnace found and first reported in 1980. An Arpád-period smithy and potters' workshop have been identified. Remnants of iron and metal smelting were found near the so-called Varkoch-gate.

AATA

J Piaskowski: Metaloznawcze Badania Starozytnych Przedmiotow Zelaznych z Masowa i Pulaw-Wlostowic. *(Metallographic investigations of the ancient iron objects from Masow and Pulawy-Wlostowice). Sprawozdania Archeologiczne, 1985,* **27,** *139-51 (in Polish, English summary).*

Three iron objects from Masow and 8 objects from Pulawy-Wlostowice, all derived from cremation cemeteries of the Przeworsk culture, were examined. The investigations included metallographic observations with the classification of the grain size and of the microhardness of structural elements as well as measurements of metal hardness by Vickers method. Chemical quantitative analysis was also applied.

The lock spring and knife from Masow, the shears, knives nos 1 and 2, the ring, the key, spearheads nos 1 and 2 and the spur from Pulawy-Wlostowice were made of iron with low phosphorus content (up to

0.21% P), with a varied, usual uneven carburization. They had characteristics of metal produced in the great metallurgical centre in the Holy Cross Mountains, situated nearby. Only the shears from Masow had a higher phosphorus content (0.27%).

Neither carburization of iron nor welding of iron and steel were observed. The materials in question come from cremation cemeteries and therefore it is impossible to state whether they were submitted to heat treatment. Only the knife from Masow and knife no 2 from Pulawy-Wlostowice (and the lock spring as well) were made of steel with carbon content high enough to ensure the effectiveness of such treatment.

Author

V E Melucco and M Marabelli: Nota sul programma di indagini al monumento equestre di Marco Aurelio. (Comments on the research program of the equestrian statue of Marcus Aurelius). *Book. Istituto Centrale del Restauro, Roma, 1982, 9pp (in Italian).*

A summary of the history, research and studies being conducted by the Istituto Centrale del Restauro on the equestrian statue of Marcus Aurelius.

AATA

E Pernicka and H G Bachmann: Archaeo-metallurgical studies on ancient silver extraction in Laurion. III. Behaviour of certain trace elements when cupelating lead. *Erzmetall, 1983,* **36** *(12) 592-97 (in German).*

The ancient cupellation of Laurion lead ores for the smelting of Greek silver coinage was studied by determining the lead isotope ratio in the coins and trace amounts of impurities from neutron activation and atomic absorption data. The low contents of bismuth and other impurities in the silver coins indicate that the ancient cupellation processes were carried out in 2 stages.

AATA

A Uzsoki: Aranymosási módszerek és aranykinyerő eljársok. (Methods of gold-washing and extraction). *Iparrégészet, 1984,* **2**, *73-81 (in Hungarian).*

Shows how ancient methods of gold washing have survived in modified forms. Basically five different methods can be identified:
1 using a stone plate or stone basin, as was the practice in ancient Nubia and Sudan;
2 gold washing in a wooden trough as the Celts did;
3 using a board plate as in ancient Egypt or in the medieval Rhine Valley;
4 gold washing with fleece in the ancient Colchis; and
5 gold washing on a washing board, or table, a method widely used along the Danube and Rhine.
The extraction of gold followed two chemical methods. Smelting has been described by Diodors. The medieval amalgamation method applied a treatment with mercury. The purity of the washed gold in Hungary was between 92-95%

AATA

H Born (ed): Archaologische Bronzen. *Antike Kunst, Moderne Technik. 1985, 196pp, hundreds of first-class colour photographs and other illustrations, in German, with English synopsis.*

Excellent series of papers on all scientific and technical aspects of ancient bronzes. Scientific examination, corrosion and conservation, especially well illustrated. Papers include:

H Born, K Ruthenberg: Archaeologist-Scientist-Conservator = one study group.
A Hauptmann, G Weisgerber: From copper to bronze: early mines and smelting works.
G Zimmer: The casting of bronze statues as described in classical literature.
K Goldman: Bronze casting techniques in prehistoric central Europe.
W A Oddy: The gilding of prehistoric and Classical bronzes.
H Born: Polychrome prehistoric and Classical bronzes.
H Born: Surface products on bronzes — information for museum visitors.
D Ulrich: The chemistry and mineralogy of the corrosion products on bronzes.
H Brink Madsen: Black spots on bronzes.
H Born: The use of radiography on archaeological bronzes.
J Goebbels et al: Advanced radiological techniques in the documentation of Classical bronzes.
W-D Heilmeyer: A recent analysis on the sculpture of a youth from Salamis in the Antikenmuseum, Berlin.
K von Woyski: the documentation of an archaeological bronze with the aid of graphics and coloured drawings.
M Jaro: Chemical and electrochemical methods in the conservation and restoration of bronze objects.
P Eichhorn: The recovery, restoration and conservation of bronze archaeological objects.
E Formigli: The restoration of a Greek bronze statue from the sea at Riace, Italy.
H Born: The reconstruction of distorted bronzes using cast copies.
H Weslfhal: Galvanoplastic copper replicas.
P Eichhorn: Bronze replicas — future frauds?
K Ruthenberg: The development of bronze analysis from the beginning up to the present day.

ASIA

E Galili, N Schmueli and M Artzy: Bronze Age ship's cargo of copper and tin. *Int J Naut Arch, 1986,* **15***(1), 25-37.*

One ox-hide copper ingot and several tin ingots were found in unstratified levels off the coast near Kfar Samir, 1.5 km S of Haifa. The tin ingots weighed from 2.2 to 4.18 kg and were more or less plano-convex in shape with the usual Cypro-Minoan or East Aegean inscriptions. The tin ingots contained as much as 277 Sb, 216 As, 880 Fe and 64 ppm Ag, as well as about 1 ppm Co. The Cu ingot contained 650 Fe and 900 Zn. 4 stone anchors were also found, but it is difficult to decide whether all this was a closed find or the remains of several ships.

RFT

A Le Bas, R Smith, N Kennon and N Barnard: Chinese vessels with Cu inlaid decor in Chou times. *Preprints of Second Australian Conference on Archaeometry. Canberra, Feb 1985 (ed N Barnard).*

Shows how copper inlay was positioned in the mould with chaplets and cast onto bronze vessel to give colour contrast as well as high relief.

RFT

N Barnard: Recent archaeometallurgical studies in Australia.

This contains a list of all preprints of papers at the above Conference. Details the ways in which the scientist can help the classicist and anthropologist, and the techniques that can be used.

RFT

A Hauptmann, G Weisgerber and E A Knauf: Archäometallurgische und bergbauarchäologische Untersuchungen im gebiet von Fenan, Wadi Arabeh (Jordan). *Der Anschnitt, 1985,* **37***(5-6), 163-95.*

Excavations on the other side of the Arabah from Timna. Covers the Chalcolithic (3100-2900 BC) to Roman. Shows slag heaps, grooved hammer stones, shafts and underground mine workings, with an iron chisel from the Roman period. Gives ore and slag analyses. High Mn slags were common but the presence of slag-contaminated clay bars show that an unusual type of furnace was in use in the Chalco/EB period which seems to have worked by induced draught with air being induced through a wall of vertical clay bars with slag issuing through the spaces between. Yet another peculiarity is an Iron Age furnace of the low shaft type in which the slag-tapping pit is covered with a clay roof about 0.5 m high. This could have served to slow down the rate of cooling of the slag to allow copper prills to liquate through it to ease their recovery.

RFT

H Limet: Documents concerning iron found at Mari. *Annales de Recherche Interdisciplinaire, 1984,* **3***, 191-96 (in French).*

Reference to 2nd millennium iron daggers and rings. Sees iron spreading to Mari from the west (East Med).

CPSA

J Merkel: Ore beneficiation during the Late Bronze/Early Iron Age at Timna, Israel. *MASCA Journal, 1985* **3***(5), 164-69.*

This paper summarises the practical and analytical results of some handsorting experiments carried out at that time. The results demonstrate how strongly the minor and trace element patterning of a smelting produce is influenced by the initial choice of ore grade actually charged into the smelting furnace.

Author

B Prakash and K Igaki: Ancient Iron making in the Bastar district. *Indian J Hist Science, 1984,* **19***(2), 172-85.*

Report on one of the last bloomeries in operation. Slag-pit shaft, 80 cm high, against wall of sunken floored workshop, forced draught, 1150 C, 5-6 hrs/smelt, yield 1 kg Fe from 15-20 kg ore.

CPSA

L P Stodulski, P Bass and M F Striegel: Analyses of bronze. In book: Beauty and Tranquility: the Eli Lilly Collection of Chinese Art, *by Y Mino and J Robinson, n.d, 356-66.*

Chinese bronze vessels from the Eli Lilly Collection were analysed with atomic emission spectrography and atomic absorption spectrometry. The vessels analysed, with the exception of one modern piece, were found to be leaded bronze with widely varying concentrations of lead in the alloy and trace amounts of zinc.

AATA

K V Subbaiah: Leaded rolls of the Satavahana period. *J Arch Chemistry, 1984,* **2***, 31-2.*

Lead rolls of the Satavahana period were found to be mainly lead (99.75%) with traces of copper, zinc, nickel and silver. Apart from their use in antiquity, the rolls demonstrate the capability of the culture to prepare high purity lead.

AATA

K V Subbaiah and S Rao: Chemical composition of copper coins belonging to the Barid Shahi, Nizam Shahi, Adil Shahi and Qutb Shahi dynasties. *J Arch Chemistry, 1984,* **2***, 7-30.*

One thousand coins belonging to four Muslim dynasties - Barid Shahi, Nizam Shahi, Adil Shahi and Qutb Shahi - were analyses for copper, lead, nickel, gold, silver, antimony, bismuth and cobalt. Copper is a major constituent in all of the coins. The trace element content of the coins varies from one dynasty to another, suggesting different sources for the raw material employed. The silver to gold ratios vary in the range of 0.05 to 7.98 in the case of the Barid Shahi dynasty and 0.11 to 13.94 in the case of the Qutb Shahi dynasty.

AATA

T C Seeliger, E Pernicka et al: Archäometallurgische Untersuchungen in Nord-und Ostanatolien. *Jahrbuch Rom-Germ. Zentralmuseums, 1985,* **32,** *597-659 (in German).*

A survey of early slags and minerals from N and W. Turkey. Many analyses of ores and slags, some from well-known sites, others from lesser known.

RFT

I R Selimkhanov: Arsenical Copper: Some results from Optical Emission Spectrochemical Studies. In: Applications of Science in Examination of Works of Art, Ed P A England and L Van Zelst, *Boston Museum of Fine Arts, 1985, 68-71.*

Analyses of bronzes from the Azerbaijan, SSR show many arsenical coppers dating from the fourth millennium BC.

PTC

P Zicheng, D Yangyao and L Changfu: Qian tongweisu bizhi fa zai kaogu yanjiu zhong de yingyong. (The use of lead isotope ratio methods in archaeology). *Kaogu (Archaeology), 1985,* **11,** *1032-1037 (in Chinese).*

DBW

C L Reedy: Metallurgy in Himalayan culture. *Journal of Asian Culture, 1983,* **7,** *72-95.*

Discusses all aspects of metallurgy in the Himalayan cultural area from Gupta times (ca 200-800 BC) up to the present, using textual sources, data from ethnography and archaeology, and information gleaned from the study of the objects themselves. Topics covered included the close relationship fo Buddhism and Hinduism in Tibet (most artists could produce images for either), the status, case and training of metalworkers, iconographic rules, location of foundries, the physical mobility of the craftsman, his patrons, mixture and casting rules, the question of remelting sacred images (a rare if not nonexistent practice), the relation of sacred and secular metallurgy, and ore sources.

Religious beliefs bear directly on the casting technology and present-day conservation treatment of the objects. In South India, statues were supposed to be solid casts, not hollow. The Sariputra text says "If a statue is made with a hollow body, there will be, as a consequence, strife and quarrelling and the loss of possessions...famine..and the king will be ousted". The text does not allow hollow bases, a construction seen on a number of Chola and later images.

Opening a statue to find what is inside (while it enables certain types of study, such as 14C) involves some ethical problems. It is a defilement to remove sacred contents under any circumstances, and they must be replaced during another sacred ceremony. (Abstractor's note: This article is a useful introduction to Himalayan customs, relation, and culture as they apply to metallurgy).

AATA

F N Tavadze, B G Amaglobeli and G V Inanishvili: Study of Damascus steel. Soobshch. Akad. Nauk. *Gruz SSR, 1984,* **115(3),** *589-92 (in Russian).*

Metallographic and electron microstructure studies of goods made from Damascus steel in 17th-18th centuries are described. The microstructure revealed characteristic corrugated patterns composed of ferrite and cementite. The chemical composition revealed it to be highly carbonaceous with extremely small amounts of impurities. The high carbon content of the steel increased its hardness, brittleness and abrasion resistance. The purity of the matrix (ferrite) enhanced its pliable properties, and the high amount of cementite affords high deformation properties to the metal. The nonhomogeneous distribution of carbon was retained following annealing at 800-900°C. Martensite is formed during hardening of the Damascus steel. The swords, following the forging process, were quenched at 700-800°C.

AATA

L Zycherman: Technical examination of two owl-shaped Tsun. *Ars Orientalis, 1982,* **13,** *59-91.*

Laboratory study of two owl-shaped bronze vessels to determine materials, method of manufacture and age. Detailed experiments on one revealed new information on Chinese casting techniques and on corrosion of malachite; the other proved to be a 20th-century copy.

AATA

A Zhimin: Some problems concerning China's early copper and bronze artifacts, tr. by J K Murray, Early China (Berkeley), 1982/3 *(publ. 1985),* **8,** *53-74. (The original Chinese article was published in Kaogu xuebao, 1981,* **3,** *269-84).*

Masterful review of the evidence concerning the earliest use of copper, bronze and brass in China.

DBW

H Mabuchi: Origin of copper in Asuka and Nara era of Japan: lead isotopic compositions of archaeological specimens. Kagaku, 1984, 39*(10) 721-2 (in Japanese).*

Provenance studies of bronze utensils used in the Yayoi and Kofun era were performed using lead isotope compositions. Lead and copper objects from Japan were also examined.

AATA

L Khalil: Metallurgical analyses of some weapons from Tell el Ajjul. *Levant, 1984,* **16,** *167-70.*

Quantitative atomic absorption analyses of seven weapons showed that two EB-MB daggers were composed of arsenical copper, as were one MBII dagger. A javelin was a tin bronze (6.8% tin), two arrowheads were copper, and a third arrowhead was arsenical copper.

AATA

Z Jinbao, Z Jianhua and Y Guoqing: Qingtong bing de fangzhi. (The prevention of bronze disease). *Zhongyuan wenwu (Cultural relics from Central Plains), 1985,* **1,** *86-8 (in Chinese).*

DBW

H Tangkun: Dianchi digi jijian gingtong gi de kexue fenxi. (Scientific investigation of some bronze artifacts from the lake Dianchi region, Yunnan, China). *Wenwu (Cultural relics), 1985,* **4,** *59-64.*

Chemical analysis and metallographic examination of seven artifacts ranging in date from the 5th to the 1st century BC. One sword shows signs of cold deformation, which is extremely unusual in Chinese bronze artifacts.

DBW

H Tangkum et al: Luoyang ganguo fuzhe gang de chubu yanjiu. (Preliminary investigation of a piece of steel adhering to a crucible found in Luoyang, Henan, China). *Ziran kexue shi yanjiu (Studies in the History of Natural Sciences), 1985,* **4(1),** *59-63.*

The crucible is one of eleven found in a 2nd or 1st century BC grave. All are cylindrical, height 35-36 cm. outside diameter 14-15 cm, wall thickness 2 cm. Its analysis: Fe 98.37, C 1.21, P 0.227, S 0.584, Si 0.117 and A1 0.383. (Total 101.208).

DBW

H Tangkun: Ningcheng zaoqi tong jing ji qi kexue fenxi. (Scientific examination of early bronze mirrors found in Ningcheng County, Liaoning). *Kogu (Archaeology), 1985,* **7,** *659-61.*

These mirrors are dated to about the 8th century BC, and are thus among the earliest found in China. The article includes chemical analysis and metallographic examination: all the mirrors investigated were cast, and no sign of forging was detected.

DBW

L Jinghua and C Shuncheng: Henan gudai tong yejin jishu. (Ancient copper metallurgy in Henan province, China). *Youse jinshu (Nonferrous metals), 1985,* **37(1),** *91-5.*

Brief review of copper smelting and casting techniques from ca. 2000 BC to ca. AD 200.

DBW

L Yifeng: Guangdong Dongshan you faxian yipi Nan Han qian qian. (Another find of lead coins of the Southern Han dynasty in Gongshan County, Guangdong, China). *Kaogu (Archaeology), 1985,* **6,** *567.*

10 kg of lead coins were found buried in a ceramic jar. A total of about a ton of lead coins, all cast in the period AD 917-925, have been found to date in the province of Guandong.

DBW

L Zhongjun and L Qingyuan: Zhongguo gudai de kuangzheng. (Mining policies in ancient China). *Youse jinshu (Nonferrous metals), 1985,* **37(2),** *50-4, 57.*

A historical review of Chinese state policies on mineral resources from the earliest times to AD 1912.

DBW

T Cailuan: Guangxi Beiliu Tongshiling Han-dai yetong yizhi de shijue. (Trial excavation of a Han-period (2nd cent. BC-2nd cent. AD) copper-smelting site at Tongshiling in Beiliu County, Guangxi, China), *Kaogu (Archaeology), 1985,* **5,** *403-10.*

Fourteen small shaft furnaces were excavated. The following analyses are given: Ore: Cu 2.85, Pb 1.159, Zn 1.92, Fe 3.72, Si 77.88, Copper ingot: Cu 96.64, Pb 0.142, As 0.23, Sb 0.685. Slag: Cu 0.65.

DBW

W Kunyi et al: Zhongguo gudai tong gu de zhizuo jishu. (The fabrication techniques of ancient Chinese bronze drums). *Ziran kexue shi yanjiu (Studies in the history of natural science), 1985,* **4(1),** *42-53.*

The bronze drums studied here were manufactured continually in south China from about the 8th cent. BC to the 19th cent. AD. A very detailed investigation based on a sample of 95 drums spread through this time-span, including investigation of moulding technique, chemical analysis and metallographic examination.

DBW

X Chuanxin et al: hunan Mayang Zhanguo shiqi gu tongkuang gingli jianbao. (A copper-mine site of the Warring States period (5th-3rd cent. Bc) in Mayang County, hunan, China), *Kaogu (Archaeology), 1985,* **2,** *113-24.*

Detailed description of the mine shafts, the mining techniques used and the tools found. Appendix on the metallographic examination and electron microprobe analysis of two cast-iron hammer-heads and two wrought-iron chisels (0.1-0.15% C).

DBW

Z Jingguo, L Zhongda and H Jueming: Guichi, Dong Zhou tong ding de fenxi yanjiu-Zhongguo shiyong liuhua kuang liantong de yige xiansuo. (Analytical study of a copper ingot of the Eastern Zhou period (8th-3rd cent. BC) found in Guichi County, Anhui, China). *Ziran kexue shi yanjiu (Studies in the history of natural science), 1985,* **43(2),** *168-71.*

The ingot has a startling chemical analysis: Cu 62.88, Fe 34.35, S 2.08, Ni 0.233, Pb 0.066, P 0.02. Metallographic examination and electron microprobe analysis show three phases: Cu 92.96, 14.53, 60.28; Fe 4.25, 82.81, 15.52; S 0.00, 0.00, 20.55.

DBW

Z Qingyun et al: Gongxian Tieshenggou Han-dai yethu yizhi zai tantao. (A re-investigation of the Han-period (2nd cent. BC-2nd cent. AD) ironworks at Tieshenggou in Gongxian County, Henan, China). *kaogu xuebao (Acta Archaeologica Sinica), 1985,* **2,** *157-83.*

This famous site was first excavated in 1958-59 and published in 1962. The new excavation corrects numerous errors in the original report.

DBW

Y Xiang: Chiren tong lian chulun. (Preliminary study of bronze sawtooth sickle-blades), *Kaogu (Archaeology), 1985,* **3,** *257-66.*

Cast-in grooves give these sickle-blades a self-sharpening sawtoothed edge. They are found in large numbers in the lower Changjiang valley in contexts ranging in date from the 8th to the 4th cent. BC. No metallurgical details are given.

DBW

AFRICA

H E Eckert: Bergbau, Verhuttung und Eisenschmieden bei den Senufu in Westafrica. *Der Anschnitt, 1986,* **38(2),** *70-80 (in German).*

Aware that native methods of iron extraction and the traditional craftsman's skills would soon be lost in the rapid changes sweeping across modern Africa, the Deutsches Bergbau Museum (German Mining Museum in Bochum) promoted in 1974 a study of the mining and smelting techniques of the Senufo in Koni (Ivory Coast). The resultant publication, which has been reissued many times, has already become a valuable historical document. A study made in Spring 1985 - i.e. a mere 11 years after the previous one - is now available. It has produced quite different results, which once again document the continuous transformation of African society.

It was possible to enlarge the report on this most recent trip, undertaken a year ago, by incorporating the findings of other research workers which have appeared in the meantime and also independant eye-witness accounts of the further working of ball-iron, that is of hammering. In the first report it had not been possible to cover the forging process. It is now already foreseeable that the skills connected with this process will, like so many other traditional African crafts, soon be forgotton.

It is a testimony to the accurate assessment of the situation that one year later the Musée national de la Côte d'Ivoire in Abidjan, inspired by the first essay in 'Anschnitt', arranged for the Koni melting furnace (described in the report) to be re-erected by native skilled workers in its galleries.

JD

AUSTRALASIA

Anon: Could this be Australasia's Oldest Cupola? *Foundry Trade Journal, Jan. 1986,* **160 (3319),** *5. Illustrated.*

Amongst the ruins of Chillagoe smelter, Northern Queensland, lies the shaft of a 24-inch diameter cupola, probably brought into the area in the 1890s.

APG

ABSTRACTS

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