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Cover Illustration: Elegant ironwork for a mundane structure. Railings enclosing a gents urinal adjoining Bristol Bridge, photographed by George Parker in November 1974. In June 1981 they were cleaned and re-painted and a year later, demolished by a wayward Bristol omnibus. Now just a memory

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Metallurgical investigations of cast irons from Les Forges du Saint-Maurice Ironworks, Quebec, Canada

Henry Unglik

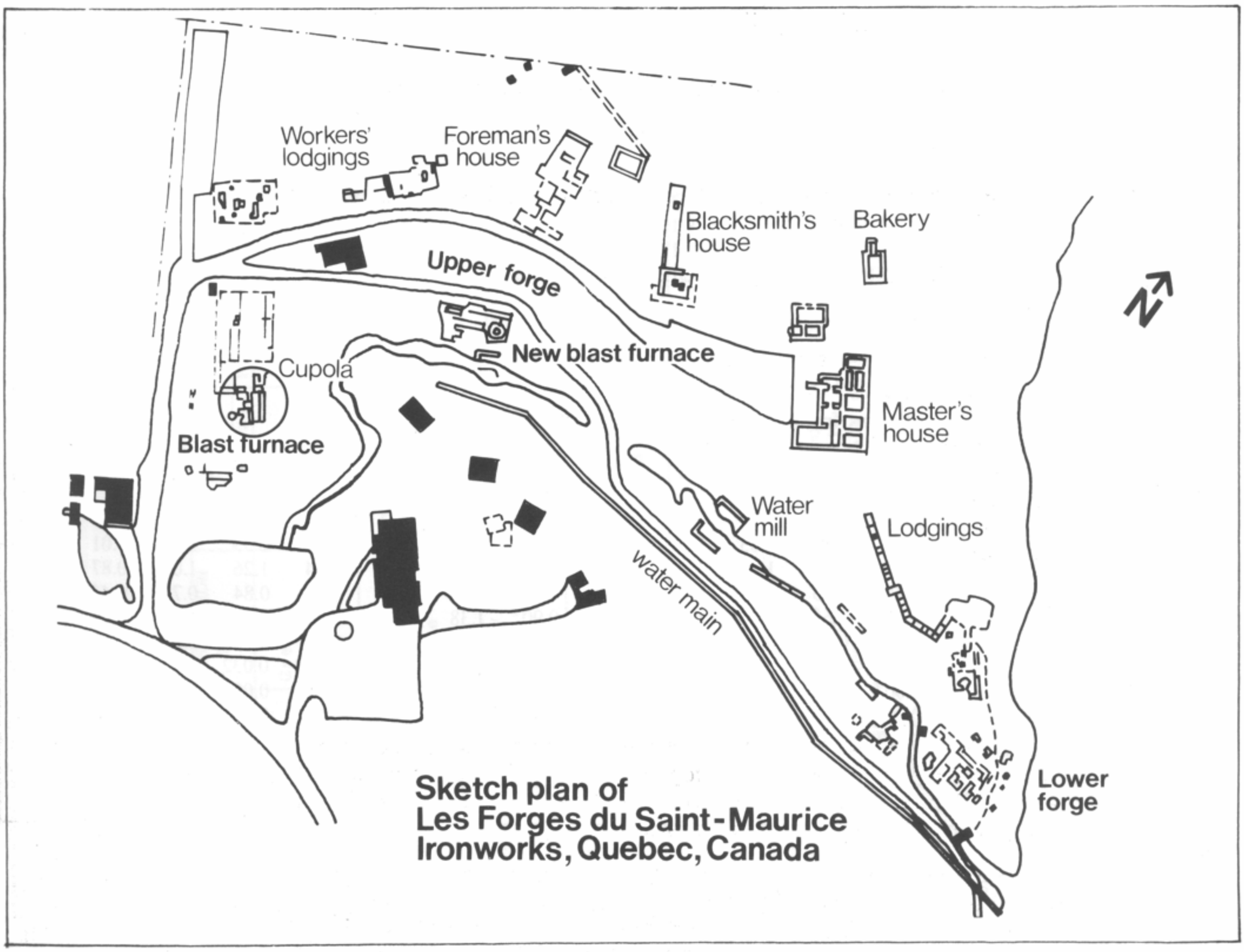
Abstract

This is an account of the metallurgical investigation carried out on twelve cast irons from les Forges du Saint-Maurice, Canada's first ironworks. The macrostructure, microstructure, hardness and chemical analysis of grey, mottled and white irons are presented together with a short history of the site. The results were used to characterize the material, its composition, structure, foundry and mechanical properties. The method of manufacture of the cast irons and the technological development of the ironworks is considered.

Historical

Twelve cast irons, recovered from Canada's first ironworks at Les Forges du Saint-Maurice, were subjected to metallurgical examination. This 18-19th century iron working site is situated near Trois-Rivières in the province of Quebec and has been thoroughly excavated by Parks Canada over the past ten years. The material was recovered from a domestic area with a relative chronology from four different occupational periods.

The ironworks were established in 1730 when King Louis XV granted a royal commission to a company headed by François de Francheville, a resident of New France. The construction of a blast furnace with a capacity for daily output of 2.5 tons of pig iron began in 1736. The smelting of bog-iron ore in the charcoal-fired blast furnace was carried out on a regular basis by 1738. In the same year the Master's House, the lower forge and the lodgings for the workers were built (see plan). Two finery hearths were erected in 1736 and two in



Sketch plan of Les Forges du Saint-Maurice Ironworks, Quebec, Canada

1739. Most iron was used in the form of castings. These were pots, large potash kettles, heating stoves, car wheels, plough shares, and such military equipment as cannons, mortars and cannon-balls. Wrought iron bars of various kinds were manufactured at the hammer forge. Some pig iron and bar iron went for export.

Les Forges du Saint-Maurice ironworks was closed down in 1883 due to exhaustion of local raw materials. Swank,[1] writing in 1892 about 'The First Iron Works in Canada', states: "at the time of its abandonment in 1883 the St Maurice furnace was the oldest active furnace on the American continent".

Results of Metallurgical Examination

Designation, size and chronology of the cast iron finds are given in Table 1.

Table 1 - Description of cast iron finds

Archaelogical period	Provenance No.	Sample No.	Find	Approx. Size cm	Thickness cm
I before 1760	25G7A40	C1	plate	23 x 16	1.5
	25G7E9	C2	sprue	7 x 8	1.5
	25G7E9	C3	scrap fragm.	6 x 4.5	0.6
II 1760-1800	25G7C15	C4	sprue	5.5 x 7	1.5
	25G7B47	C5	runner	18 x 6	1.2
	25G7E8	C6	sprue	5.5 x 5.5	3.0
III 1800-1850	25G7B30	C7	sprue	9 x 10	2.0
	25G7C8	C8	runner	17.5 x 3	1.5
	25G7F5	C9	sprue	8 x 11	2.0
IV 1850-1883	25G7B4	C10	plate	10 x 4.5	1.0
	25G7B23	C11	plate	12 x 10	0.8
	25G7B5	C12	plate	9 x 5	0.8

Table 2 - Analysis of cast irons from Les Forges du Saint-Marie

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Total carbon	3.45	3.91	3.91	3.95	4.18	4.51	4.21	3.81	3.77	3.79	3.71	3.88
Graphitic carbon	3.18	1.60	2.83	0.89	2.87	1.81	1.60	1.80	3.03	2.53	2.63	3.01
Combined carbon	0.27	2.31	1.08	3.06	1.31	2.70	2.61	2.01	0.74	1.26	1.08	0.87
Silicon	0.46	0.65	0.78	0.67	0.49	0.48	0.44	0.67	0.70	0.84	0.77	0.44
Manganese	0.46	0.65	0.94	0.13	1.42	0.90	1.38	1.46	0.91	0.12	0.11	1.00
Phosphorus	0.19	0.28	0.11	0.57	0.85	0.20	1.31	1.25	0.63	0.70	0.66	0.70
Sulphur	0.029	0.025	0.027	0.035	0.034	0.039	0.031	0.020	0.034	0.032	0.040	0.051
Chromium	0.003	0.03	0.005	0.007	0.006	0.007	0.007	0.005	0.006	0.004	0.004	0.005
Nickel	0.004	0.007	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.003	0.002	0.004
Copper	0.001	0.004	0.002	0.004	0.002	0.003	0.004	0.003	0.001	0.001	0.001	0.001
Titanium	0.02	0.03	—	0.02	0.03	0.02	0.02	0.03	0.06	0.03	0.02	0.02

The results of chemical analysis (Table 2) show that with few exceptions the carbon content is higher and the silicon content considerably lower than that usually found in modern cast iron. Phosphorus is often above the range of modern practice while sulphur is lower than would be found now. The generally high manganese content shows great variability, as does phosphorus but to a lesser extent. The remaining elements (Cr, Ni, Cu and Ti) are present only in trace amounts. The combined carbon content, which varies considerably from find to find, was used to categorize the material into grey, mottled and white iron groups (Fig 1).

The hardness of the artifacts in each respective group corresponds to the overall hardness of pearlitic grey iron, mottled iron and white iron (Fig 5).

The macrostructure of the grey cast irons is characterized by a dark surface with no visible defects and a light network of eutectic cells of phosphorus 2A). The mottled irons show the presence of shrinkage porosity and a shiny surface of massive cementite with numerous grey spots of graphite concentration (Fig 2B).

Table 3. Characterization of cast iron material from Les Forges du Saint-Maurice

PERIOD	SAMPLE NO.	CAST IRON TYPE	STRUCTURE		COMPOSITION (c)				FOUNDRY PROPERTIES				MECHANICAL PROPERTIES		
			Graphite(a)	Phases(b)	C total	C comb.	Mn	P	CE(d)	SC(e)	T°(f)	ΔV%(g)	HB(h)	TS(i)	CS(j)
I	C1	Grey	VII A/B 4	P+G+S+(C)	3.5	0.3	0.5	0.2	3.7	0.8	1215	+0.8	140	–	–
	C2	White	V	L+(P+G)	3.9	2.3	0.7	0.3	4.2	1.0	1150	-2.4	601	–	–
	C3	Grey	VII A/B 4	P+G+S+(C)	3.9	1.1	0.9	0.1	4.2	1.0	1150	+0.1	228	278	923
II	C4	White	V/VI	L+(P+G)	4.0	3.1	0.1	0.6	4.4	1.0	1120	-3.8	502	–	–
	C5	Mottled	VII B 4	P+C+G+S	4.2	1.3	1.4	0.9	4.6	1.1	1080	+0.1	251	–	–
	C6	White	None	L+(P+G)	4.5	2.7	0.9	0.2	4.7	1.1	1080	-2	590	–	–
III	C7	White	VII	P+C+G+S	4.2	2.6	1.4	1.3	4.8	1.1	1050	-2.4	464	–	–
	C8	Mottled	VII B 4	P+C+G+S	3.8	2.0	1.5	1.3	4.5	1.0	1100	-2	378	–	–
	C9	Grey	VII A/B 4	P+G+S	3.8	0.7	0.9	0.6	4.2	1.0	1140	+0.5	187	200	726
IV	C10	Grey	VII A/B 3	P+G+S	3.8	1.3	0.1	0.7	4.3	1.0	1130	-0.5	195	236	825
	C11	Grey	VII A/B 3	P+G+S	3.7	1.1	0.1	0.7	4.2	1.0	1140	-0.3	185	267	911
	C12	Grey	VII A/B 4	P+G+S	3.9	0.9	1.0	0.7	4.3	1.0	1130	+0.4	199	258	886

a) Graphite form, type and size according to the ASTM standard A 247.
b) P-pearlite, G-graphite, S-steadite, C-cementite, L-ledeburite; brackets denote a small amount of the microconstituent.
c) Composition range of the remaining elements is Si = 0.4 to 0.8%, S = 0.02 to 0.05%.
d) Carbon equivalent, CE = %C + 1/3 x (%Si + %P) — Walton[3]
e) Degree of saturation, SC = %C/[4.3 - 1/3 x (%Si + %P] — Walton[4]
f) Liquidus temperature (rounded to the nearest 10°C), T°C = 1669 - 124 x (%C + %P/2 + Si/4) — Humphreys[5]
g) Solidification shrinkage, ΔV, % = 2.0 (%C graph. - 2.80) — Hamaker et al.[6]
h) Brinell hardness HB 10/3000
i) Tensile strength in N/mm^2 (for uninoculated grey iron cast in simple shaped castings),
TS in psi = 10000 [b - 2 x (%C + %Si/3 + %P/4)]
b = 11.68 - 2.3 log (2 x plate thickness in inches) — Schneidewind and McElwee[7]
j) Compressive strength in N/mm^2, from TS vs. CS graph — Schneidewind and McElwee[8]

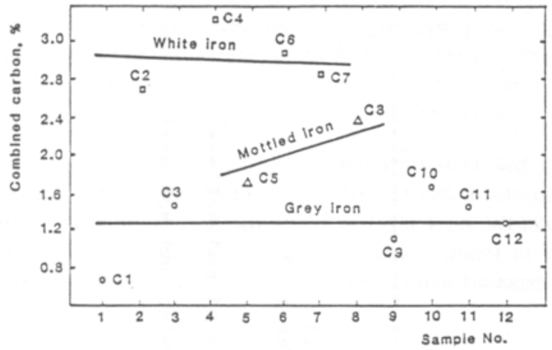


Figure 1. Groupings of cast irons according to their combined carbon content.

In the white irons the presence of casting defects, such as shrinkage cavities, interdendritic cracks or pores, is even more extensive than in the mottled irons; here the shiny surface of massive cementite contains only a few grey spots (Fig 2C).

The structure of the grey iron specimens is that of a hypoeutectic, phosphoric cast iron with flake graphite in pearlitic matrix (Fig 3A). Graphite occurs in the form of flakes of considerable length, random orientation and uniform distribution with some flakes in rosette groupings. The matrix of lamellar pearlite is relatively hard (385 HV50). The rather soft areas of spheroidized pearlite (204 HV50), occurring in plate C1, indicate that the plate was subjected to heating at uneaven temperatures. The ternary phosphide eutectic (963 HV50), with its characteristic lenslike shape, is another major constituent of the examined grey irons (Fig 3B). Furthermore, the presence of a surface chill zone was observed in plates C1, C3 and C12, as were some free cementite in plates C1 and C3, and a considerably amount of manganese sulphide inclusions in the structure of most grey irons.

The structure of most of the white irons is composed of ledeburite (913 HV50), and a small amount of graphite (Figs 4A and 4B). The irregular graphite pockets and aggregates show signs of deterioration and have an nonuniform distribution.

The structure of the mottled irons consists of graphite flakes, free cementite and a considerably amount of phosphide eutectic in a matrix of pearlite (Fig 4C). Graphite appears in the form of flakes characterized by rosette groupings and random orientation.

Characterization of Material

The average carbon equivalent value of CE = 4.4 and degree of saturation of SC = 1.0 show that the St Maurice cast irons have a eutectic or close to eutectic composition (Table 3); the only three strongly hypereutectic cast irons (SC>1) are C5, C6 and C7. The high carbon equivalent resulted in the formation of malformed and exploded graphite in the white irons.

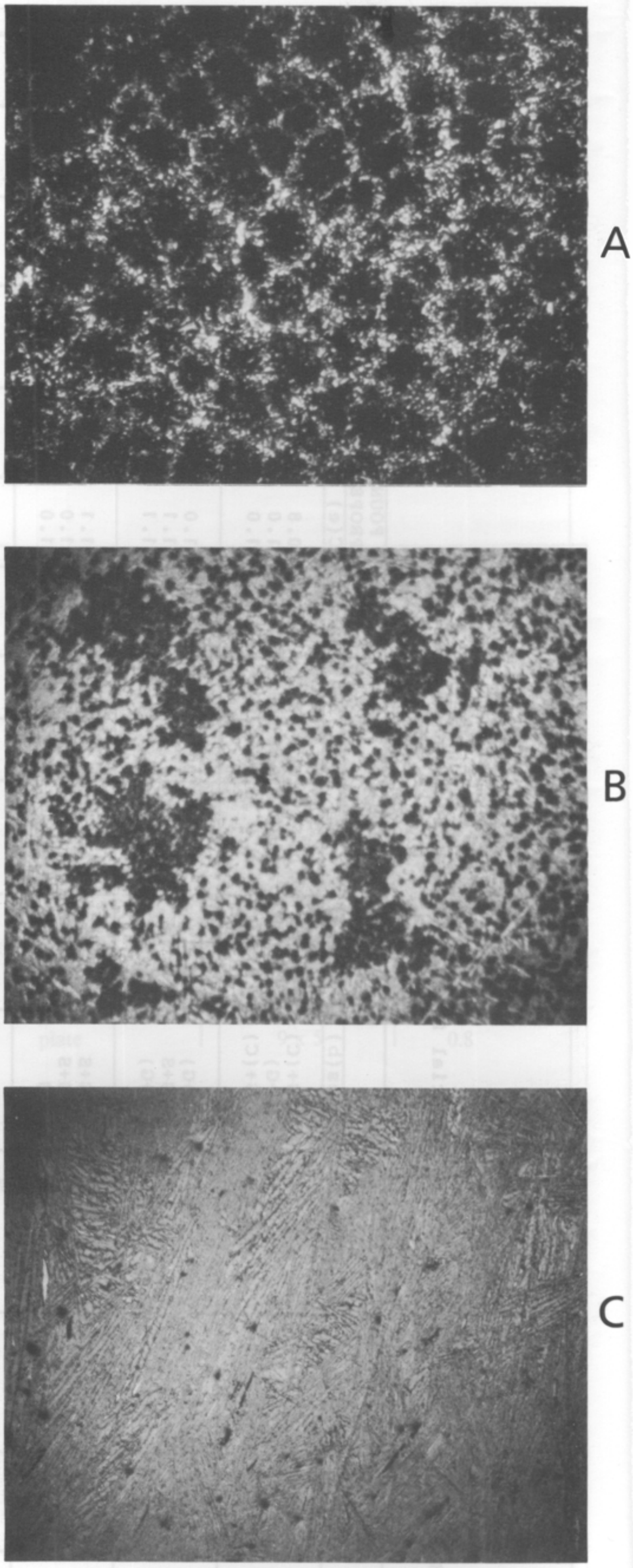


Figure 2. Microstructure of cast irons etched in Stead's reagent. A - grey iron, at x 1.5; B - mottled iron, at x 8; C - white iron, at x 8.

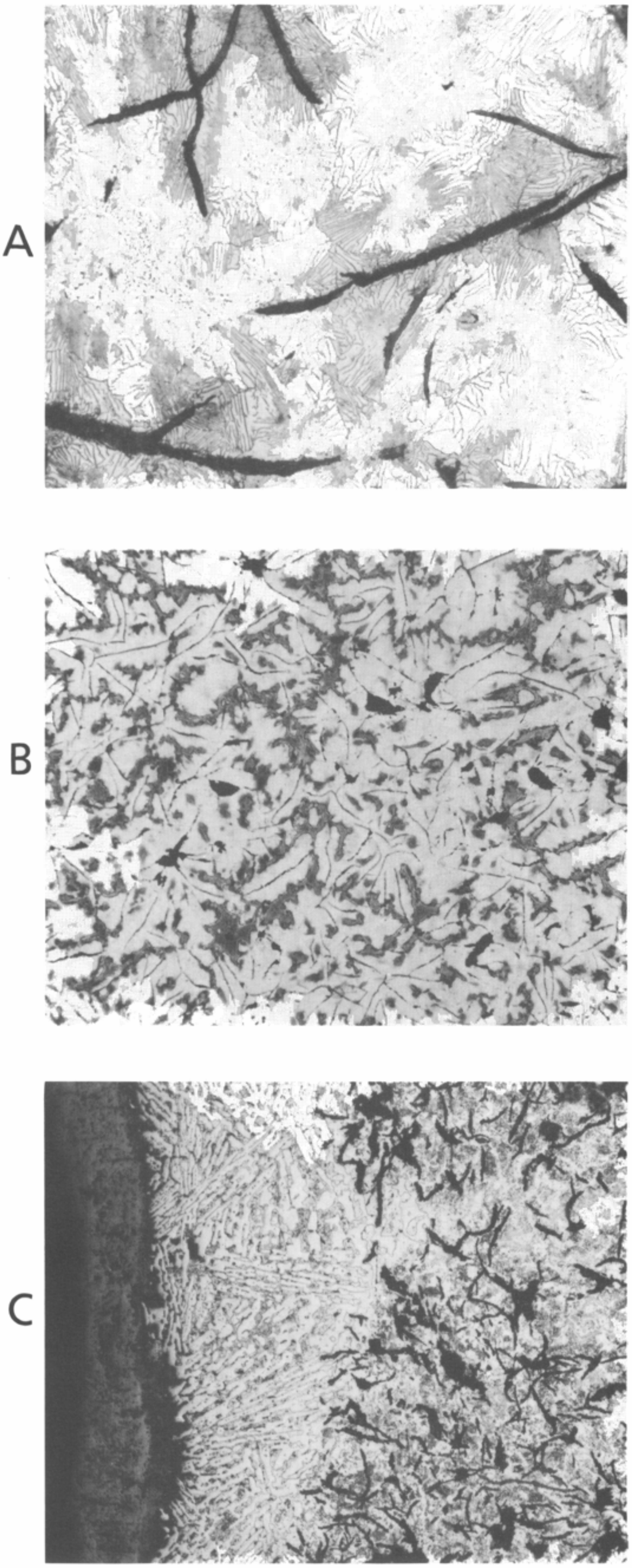


Figure 3. Microstructure of grey irons. A - 4% nital, x 500; B - Murakami's reagent x 100; C - 4% nital, x 100.

The extent of the graphitization tendency of silicon is limited here because of its low content and the counteracting effect of manganese. The manganese content is in most finds more than sufficient to balance the sulphur content. The higher than normal phosphorus appreciably increases the brittleness of the cast irons; it also hardens the material and improves its castability. The fine cellular structure, evident in these high-phosphorus grey irons, is conducive to greater tensile strength.[2] At the same time, phosphorus improves the heat resistance of the cast irons, i.e. resistance to growth, the retention of mechanical properties and resistance to scaling.

The properties of cast iron in Table 3, which have been directly correlated to its carbon equivalent, include the liquidus temperature, solidification shrinkage and tensile strength. The liquidus temperature of the cast irons from St Maurice ranges between 1050 and 1150°C. The readily graphitizible irons have little or virtually no solidifcation shrinkage (about 0.1% on average), whereas the white and mottled irons have considerable shrinkage (-2.1% on average). In fact, the presence of shrinkage cavities or porosity, which greatly weakens the metal, was observed mainly in the white and mottled iron finds. The tensile strength of the grey irons, estimated on the basis of composition, ranges from 200 to 278 N/mm^2, and the compressive strength from 726 to 923 N/mm^2.

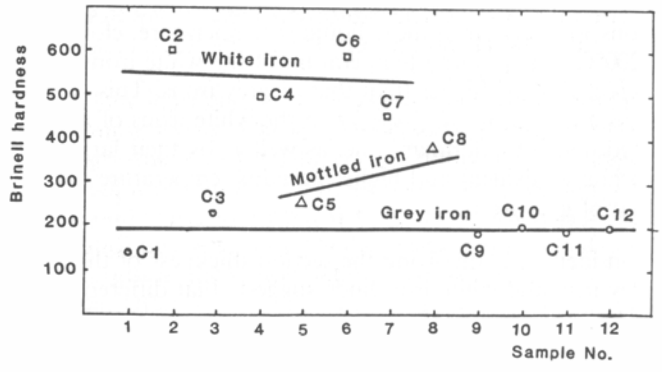


Fig. 5 groupings of cast irons according to Brinell Hardness.

Modern engineering specification ASTM A319-53 Class I recommends grey iron castings of a similar composition range as those from St Maurice for use at elevated temperatures. Applications of this material with thermal shock resistance are for firebox parts, grate bars, furnace parts, caustic pots and melting pots. For example, the plate C1, affected by high temperature, might have actually been used as a stove plate. The grey irons with a very hard and wear resistant chill surface, as in plates C1, C3 and C12, are well suited for manufacture of car wheels. The low phosphorus grey irons C1 and C3 are sufficiently tough in the cast condition to be used for hammers and anvils. The white irons, being more resistant to growth than the grey irons, could have been used, for instance, as plates in finery hearths.

Method of Manufacture

The low sulphur content suggests the use of charcoal as fuel for the reduction of the cast irons. The high phosphorus content indicates that iron ores rich in phosphorus were used in their manufacture. The very high carbon resulted from furnace conditions which secured plenty of carbon available for solution by the iron, while the low silicon content indicates a temperature ceiling in the smelting process. The lesser height and lower operating temperatures of the cold blast furnace, employing bog-iron ore containing little gangue, tended to give less absorption of silicon during smelting.

The cast irons have a composition not unlike that of other cold-blast charcoal-irons, and most of them represent a cold-short pig iron grade. It appears from the comparison with 18-19th century charcoal irons that those from St Maurice have a considerably higher carbon content, and generally higher manganese and phosphorus contents than that found in European or American cast irons. The amount of silicon is similar, and that of sulphur is commonly low. Since their carbon content equals or exceeds the upper limit of modern cast irons, the molten iron most likely was ladled from the open forehearth of the furnace and poured directly into prepared molds on the casthouse floor. The absence in the structure of graphite flakes which are promoted by undercooling (Types D and E),[9] the small size of the eutectic cells and the compact idiomorphic form of the manganese sulphide inclusions[10] are signs that the grey irons were cast from near liquidus temperature, close to 1200°C. The pouring temperature of the white irons is expected to be higher than that of grey irons. This is substantiated by the presence in the white irons of a predominant columnar zone, as well as by their larger carbon equivalent and higher liquidus temperature than that of grey irons.

Considerations involving the section thickness of the grey iron and white iron finds suggests that different techniques were used in casting these two groups of artifacts. The predominant presence of type A graphite flakes and the absence of undercooled graphite in pearlite matrix of the grey irons is a sign of moderate cooling as in a loam or sand mold. Also the presence of a fine cellular structure is indicative of a moderately rapid cooling rate, and of a small thickness of the mold walls. The white iron artifacts, on the other hand, probably were manufactured by casting the molten metal in a chilled mold, so that the cooling rate was high enough to produce white iron for the desired section size.

Conclusions

Comparison of the results of this study with the relative chronology of occupational layers shows that in the archaeological periods I or II there was a change in type of ore used for manufacture of cast irons from low to high phosphorus iron ores. The cast irons from period I have a variable structure, changing from one artifact to another. This might have been due to the lack of proper operational controls existing at that time in the manufacturing process.

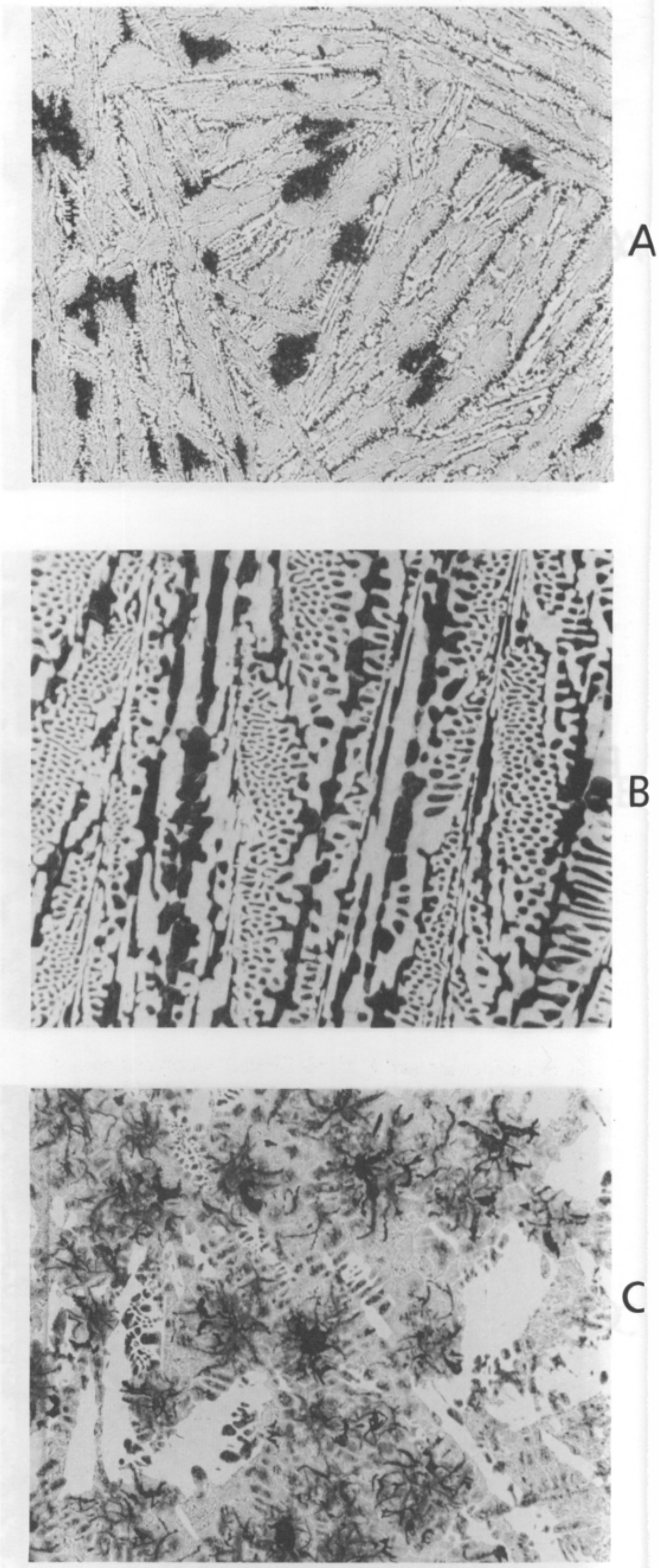


Figure 4. Microstructure of white and mottled irons, 4% nital. A - white iron, at x 100; B - white iron, at x 500; C - mottled iron, at x 100.

All the irons from periods II and III, except C9, are of white or mottled type, most of them with a very high total carbon content. During these two periods, a high proportion of fuel, charcoal rich in carbon, must have been used for smelting in the blast furnace. In transition between periods III and IV, there was a change in casting technology from a chilled mold to a sand mold. The last period (IV), distinguishes itself in phosphoric grey iron plates of uniform structure and composition.

A complete report detailing the results of the cast irons examination is available from Parks Canada.[11] The information obtained here can serve as a data base for further investigation of artifacts from Les Forges du Sain-Maurice; it should be broadened to include finished objects, slag, ore and furnace lining.

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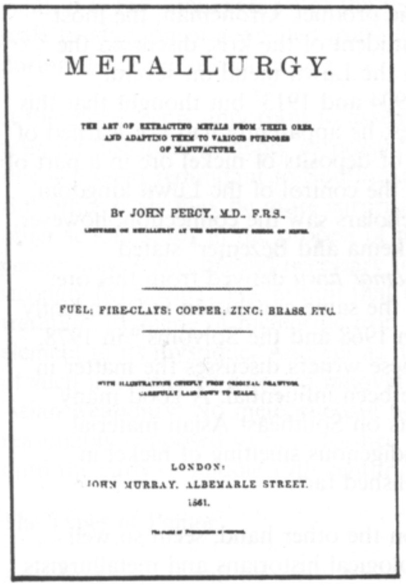
Biography

Henry Unglik completed Secondary School in 1959 in the city of Lodz, Poland, and in the same year entered the Technical University of Lodz. In 1965 he graduated from the Faculty of Mechanical Engineering, Department of Physical Metallurgy and Heat Treatment with a M Sc degree. For the next five years, holding a position of Senior Metallurgist he dealt with heat treatment processes, and as a Head of the Metallographic Laboratory conducted failure analysis, research and development work and quality control.

In 1971 he left Poland for Denmark and the following year immigrated to Canada. Upon completion of graduate studies at the University Toronto, Department of Metallurgy and Materials Science he received in 1975 his second masters degree (M Eng). From the end of 1975 until the present day he has been engaged as a metallurgist at the Conservation Division, Parks Canada, Ottawa.

Percy's METALLURGY

In 1861 John Percy, Lecturer in Metallurgy at the Government School of Mines, published the first book of his four volume series which has now become known as **Percy's Metallurgy'**. It was the first organised attempt in Great Britain to collect and set down in print, past and current thinking on metallurgical science rather than alchemy. It was a splendid start to a notable achievement and nowadays original copies of **Percy's Metallurgy** are rare indeed. In 1984 the Historical Metallurgy Society began to reprint the series and copies of Volume One, **Copper, Zinc, Fuels and Fire-Clays** are still obtainable from the Peak District Mining Museum, Matlock Bath, Derbyshire DE4 3PS price £22.00 post free.



METALLURGY.

THE ART OF EXTRACTING METALS FROM THEIR ORES,
AND ADAPTING THEM TO VARIOUS PURPOSES
OF MANUFACTURE.

BY JOHN PERCY, M.D., F.R.S.,

FUEL; FIRE-CLAYS; COPPER; ZINC; BRASS, ETC.

WITH ILLUSTRATIONS CHIEFLY FROM ORIGINAL DRAWINGS,
CAREFULLY LAID DOWN TO SCALE.

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1861.

Terrestrial and meteoritic nickel in the Indonesian Kris

Bennet Bronson

Abstract

Pamor, the etch-resistant metal traditionally used in the blades of Southeast Asian krises, appears to have been originally a smelted iron-nickel alloy. Small amounts of a meteoritic alloy were later used by kris makers, mainly in the 1840s-1860s. Modern alloys and pure nickel have also been used since about 1900. But most *pamor* came from the Indonesian island of Sulawesi, where there are large deposits of iron-nickel ores of a type that could be smelted in simple furnaces. The evidence, though incomplete, points to this as a probable case of the regular production of an iron-nickel alloy, on a modest but commercial scale, many decades and perhaps centuries before such alloys began to be made by Western steelmakers. It is one of the few such cases known.

Introduction

Piaskowski may have been the first modern archaeometallurgist to suggest that certain ancient European iron objects with a high nickel content might have been smelted from ore, not forged from meteorites[1]. Along the same lines, Hermelin, Tholander and Blomgren have argued in recent articles that an early nickeliferous axe from Sweden, partly because of its low phosphorus content, has a non-meteoritic origin[2].

The geological and technical issues involved in producing an early iron-nickel alloy are discussed by Blomgren[3]. He notes that the most common nickel ores, the arsenides and sulfides that usually occur mixed in a more or less intimate fashion with copper minerals, could not be added to an iron-making furnace without sophisticated preprocessing. A more likely candidate, he believes, would be garnierite, a nickel-magnesium silicate that has been mined in Silesia and several other parts of Europe[4]. Garnierite often occurs in intimate association with iron oxides, as in lateritic ores. These can in principle be smelted directly to an iron-nickel alloy in a simple bloomery.

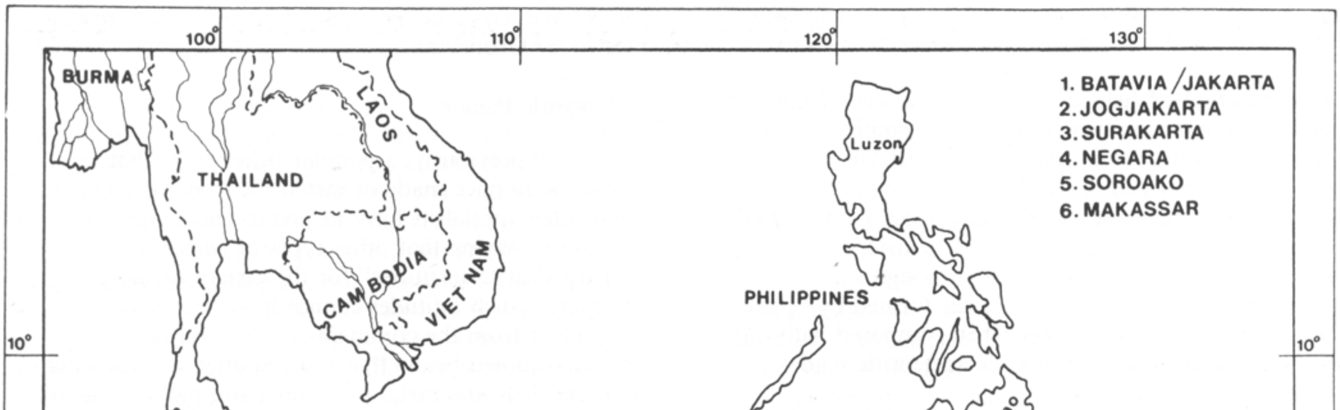
That nickeliferous laterites were formerly smelted in Mycenaean Greece has been suggested by Varoufakis[5], who has found nickel contents as high as 10.77% in iron rings dated to the 15th-13th centuries BC. He feels that this alloy is not meteoritic in origin, noting that he has managed to produce small amounts of a similar alloy by smelting local lateritic ore, presumably from deposits at Atalanti or in Euboea, in a small bowl furnace. Tylecote[6] comments that a number of these rings contained enough nickel to be rust-resistant and that the Polish and Swedish implements mentioned above would have had a substantially increased hardenability when quenched. In the former case, at least, it is difficult to believe that iron-nickel alloys were not used deliberately for the sake of their special properties.

In general, however, smelted iron-nickel alloys appear to have been very rare in antiquity. The cases cited by Piaskowski, Varoufakis and Blomgren are among the very few thus far identified among the many thousands of early iron objects that have been subjected to analysis. Thus it is of interest to point out that in Southeast Asia such alloys seem to have been quite common in a more recent but still solidly preindustrial context.

The alloys in question are a group of metals known during the late 19th century as *pamor luwu.* The context of manufacture is the eastern part of central Sulawesi (or Celebes) in Indonesia, an area which contains very large deposits of nickeliferous laterite. The inhabitants of that area, tribal peoples of the ToBada and eastern Toraja groups, are usually thought to have been relatively backward from an economic and technological standpoint. Yet the iron they made appears to have been traded over long distances and for several centuries to have formed a major component of weapons made in other parts of Southeast Asia. The most significant of these weapons was the straight- or wavy-bladed dagger known in most languages of the region as the "keris" and in English as the "creese" or "kris".

Many modern kris fanciers believe that most krises were formerly made of meteoritic iron. More academically oriented specialists, however, tend to be aware that a type of iron nickel alloy from Luwu in Sulawesi was once also used and that this may have been a smelted rather than meteoritic product. Groneman, the most influential Western student of the kris, discussed the presence of nickel in the Luwu metal on several occasions between 1904 and 1913[7] but thought that this came from meteorites; he apparently had not learned of the recent discovery of deposits of nickel ore in a part of Sulawesi once under the control of the Luwu kingdom. A number of later scholars saw the connection, however. As early as 1927, Alkema and Bezemer[8] stated unequivocally that *pamor luwu* derived from this ore. Others who reached the same conclusion independently include Marschall[9] in 1968 and the Solyoms[10] in 1978. Although none of these writers discusses the matter in any detail, they have been influential. A good many present-day specialists on Southeast Asian material culture regard the indigenous smelting of nickel in Sulawesi as an established fact.

This fact may not, on the other hand, seem so well established to technological historians and metallurgists



who work elsewhere in the world. These are likely to be sceptical because of the absence of detailed proof, because of the technical difficulties involved, and — most importantly — because the case is unique. If it is valid, it is the only example of the regular and large-scale production of a smelted iron-nickel alloy known during the preindustrial period.

It therefore seems important to assemble as much of the relevant historical evidence as possible. Some parts of this will seem redundant to Southeast Asia specialists. But other parts may be more surprising to them than to other scholars, for in the process of making a case for *pamor luwu* it has proved necessary to challenge a strongly held belief. The notion that the kris was traditionally made of meteoritic iron is a near-essential element in its mystique. And yet as it turns out the use of such iron may be a recent innovation in Southeast Asian weaponry. No meteorite can be shown or reasonably supposed to have formed part of any kris until the early or middle 19th century.

The Types of Pamor

As a first step, it will be useful to outline what is known about the heterogeneous group of metals known as *pamor.* All good Indonesian and Malaysian krises, and some Thai and Philippine krises as well, are made of two sorts of metal, iron or steel and *pamor* welded together in intricate patterns that are subsequently brought out on the surface of the blade through use of an etchant, often a mixture of arsenic sulfide and lime juice[11]. In Bali and sometimes in Madura, the etching process is stopped as soon as the two metals have developed differential colorations, giving a smooth grey-black surface embellished with silvery *pamor* lines. A more deeply etched surface is preferred in Java and most of the other major centers of kris manufacture. An old blade from those places eventually comes to resemble sand-blasted wood, with the *pamor* standing as much as a millimetre above the intricately etched-out surface of the iron.

The most desirable kind of *pamor* in the eyes of modern Javanese kris specialists is a metal derived from a meteorite that in the 18th century was found near the ancient temple site of Prambanan in central Java and later brought to the palace of the Susuhunan or Sultan of Surakarta[12]. By the time of Groneman's work in Java during the 1890s and 1900s, "pamor prambana" had become the standard by which all other types of *pamor* were measured.

Groneman himself helped to introduce a second kind of *pamor,* a pure Krupp nickel, to the kris smiths of the Jogjakarta court[13]. As in the case of a similar experiment performed in the 1970s by Solyom[14], the smiths seem to have had no trouble in using pure nickel as *pamor.* The krises made of it were considered by Javanese experts to be acceptable, although some may have felt that the very bright patterns formed by "pamor nekel" were almost too showy when compared with the delicate, muted patterns of the old meteoritic blades.

A third kind was just coming into use in Groneman's day: European iron nickel alloys obtained from such objects as bicycle frames and ship propellors. It seems likely that a good many 20th century blades have been made from this type of *pamor* even though few observed cases of its use have come into the literature. The kris analyzed by Frankel may, as he implies, have such an origin[15]. Of course, bicycle *pamor* cannot be very old. No commercial iron nickel alloys were produced in Europe before the publication of Riley's experiments in 1889[16]. Such metals would not have reached Southeast Asia until the middle or late 1890s.

The fourth kind is the miscellaneous class of scrap iron and steel that served for making cheap krises in most parts of Indonesia and Malaysia. At the instance of W W Skeat, a well known specialist in Malay culture, the metallurgist Rosenhain[17] analyzed several examples of finished blades and partially wrought *pamor* from Trengganu in Malaysia. The *pamor,* derived from Chinese agricultural tools, seemed to be an ordinary iron, leading Rosenhain to suggest that the patterned surfaces of these krises (and, he implies, of most or even all kirses) are due to the etching-out of defective welds between iron laminae and to the differential corrosion of steel and iron. Rosenhain did not test for the presence of nickel. Interestingly, neither he nor the usually well informed Skeat appear to have been aware of the use of meteoric iron as *pamor* in Java. Groneman confirms that seemingly ordinary irons could be used as *pamor* but adds that these had to be of a sort that would not be black after etching. He reports that two farm implements of this kind, bought in a Chinese shop and used as *pamor* by a Javanese smith, actually turned out to contain a little nickel[18]. A survey conducted by Jasper and Pirngadie in the late 1920s describes several semi-fraudulent methods for making ordinary iron and steel look like real pamor; the authors imply that some Javanese scrap iron did have a low nickel content[19].

It is a fifth kind that interests us most, the above-mentioned *pamor luwu.* Groneman's informants regarded this as a *pamor* of intermediate quality, less bright than *pamor prambanan* and pure nickel but better than ordinary iron as a kris ingredient. Five samples, identified as *pamor luwu* and obtained in a Sulawesi market, were sent to him. tests showed that these contained about 0.4 percent nickel[20]. Loeber, on the other hand, states that *pamor* luwu is richer in nickel content than Javanese meteoritic *pamor* and that it therefore produces whiter lines on weapon blades[21]. He may have seen a better grade of *pamor luwu* than that tested by Groneman.

Meteoritic Pamor

As noted previously, a popular belief exists that most krises were once made of meteoritic iron. Groneman and other specialists have helped to encourage this notion by saying that other types of *pamor* were regarded as "substitutes" for the meteoritic metal[22]. However, such attitudes cannot have been widespread. It is evident from the comments of the 19th century sources quoted below that most Southeast Asians did not get their kris metal from Java and had no idea of any connection between this and meteorites; the other types of *pamor* can hardly have been substitutes from their point of view. And even to the central Javanese, other *pamors* were substitutes only in the sense that the Prambanan material, though preferred, had always been exceedingly hard to obtain. No one except members of the Javanese royal families and persons with very good connections at the Surakarta or Jogjarkarta courts could hope to own a kris made from any other meteorite, nor none were available. Buchwald's catalogue of known iron meteorites lists only two from anywhere in Indonesia: a small one that recently fell near Rembang on the north coast of Java, and the one from Prambanan[23].

It is also relevant to note that meteoritic *pamor* had not been available to anyone for very long, whether or not they belonged to royal families. A common opinion is represented by Gardiner[24] and A H Hill[25], who assume that the earliest iron known in Southeast Asia came from meteorites and conclude that the earliest krises were therefore meteoritic. Neither the assumption nor the conclusion is tenable. No Iron Age site in Southeast Asia has yet produced an example of demonstrably meteoritic iron. And the historical sources make it quite clear that the Prambanan meteorite — which, to repeat, is the only iron meteorite known to have existed anywhere in the region before the 20th century — cannot have been utilized for making any kris until comparatively recent times.

We have two seemingly independent sources for the date when the Prambanan meteorite first became known to the Javanese. The first is a letter that Baumhauer quotes, sent to the Dutch Governor General in Batavia by the Susuhunan of Surakarta in 1865[26]. This says that the news of the fall of the meteor, described as a ray of light from the sky followed by a sound of thunder, first reached Surakarta during the reign of Pakubuwana III (1749-1788). Considering that Prambanan is only forty kilometers from Surakarta and that such a spectacular, omen-laden event would have had to be reported to the palace authorities with the utmost promptness, this would mean that the fall did not occur before 1749. The smaller of the two pieces of the meteorite was brought from Prambanan to the palace at Surakarta in 1784 and the larger piece in 1797. The first had disappeared by the time the letter was written, presumably through use by smiths. The second is the one that has survived to the present day[27]; during the reign of Pakubuwana VIII (1858-1861) it was briefly kept at the palace forge but was later moved to another, safer location.

The second source is Groneman, whose information came from informants at the Jogjakarta and Surakarta courts[28]. He gives the same dates for the transfer of the two pieces of the Prambanan meteorite to Surakarta but says that a friend, one Dr Verbeek, was told by a former Susuhunan that the fall occurred during the reign of Pakubuwana II (1725-1749) and that two or three other meteorites (which are not otherwise known) had fallen somewhere within the kingdom at separate times during the 19th century. Although Dr Verbeek's version of the story does not inspire confidence, it must still be given some weight. We may conclude conservatively that the first (and perhaps only) meteorite may have fallen as early as 1725 but that it probably fell in the 1760s, 1770s or early 1780s, and that it cannot have been used to make many blades until the first piece of it arrived in Surakarta in 1784.

However, even 1748 may be too early for the substantial use of meteoritic iron in weapons. It is noteworthy that Raffles, who was deeply interested in the kris and who during his tenure as the governor of Java in 1811-16 had unparalleled opportunities to find out about such matters, says nothing about meteoritic iron in his *History of Java* of 1817. He believed that all *pamor* was imported to Java from other islands, calling it "a white metal obtained from Biliton (Belitung) and Celebes (Sulawesi), which is worked up with the iron, in order to produce the damasked appearance of the blade."[29] Crawfurd, who was Resident at the Jogjakarta court under Raffles' administration, also fails to mention any connection between meteorites and krises either in his *History* of 1820 or his *Descriptive Dictionary* of 1856, stating flatly that Java produced no iron at all [30]. Both Raffles and Crawfurd would have been fascinated by any rumor that krises were being made from iron that had fallen from the sky. If court smiths had begun to forge parts of the Prambanan meteorite by 1815, it was still a closely guarded secret.

The earliest indication I have found that this secret, if such it was, had begun to leak out is a statement by Newbold in 1839 that the *pamor* used by Malay kris-makers came not only from Sulawesi but from Java[31]. This may just be a slip of the pen. On the other hand, Cyril Smith records that by 1844 De Luynes was already experimenting with kris blades and that he had shown that these contained nickel[32]. It is possible that both Newbold and De Luynes had heard rumors of the existence of an iron meteorite in Java.

By the mid-1860s Europeans knew the full story of the Prambanan meteorite and its connection with weapons of special quality. Baumhauer's article of 1866, which includes the above-quoted letter to the Governor-General from the Surakarta court, implies this. In 1867, an anonymous article in the *Natuurkundig Tijdschrift voor Nederlandsch-Indie* makes the connection explicit, giving an analysis of the iron and nickel content of the meteorite at Prambanan and calling it a "pamor-stone"[33].

Furthermore, by then the Javanese court officials seem not to have been at all secretive on the subject. The letter to the Governor General is quite free with information — indeed, it tells him rather more than he can have wanted to know. Conceivably this openness on the part of the Javanese was a new development in the 1869s, knowledge of the meteorite before then having been confined to the inner circles of the Surakarta and Jogjakarta courts. However, the possession of a blade made of meteoritic iron evidently conferred not just mystical power but social prestige, which would have militated against secrecy. We must therefore also entertain the idea that the meteorite was unknown to Raffles and Crawfurd simply because in their day, in the early 19th century, it was still unimportant. It may not have begun to be forged into krises and other weapons until the 1830s or 1840s.

This is of course only speculation. As the abundant historical material for 19th century Java has never been sifted for data on these matters, it is best to avoid drawing definite conclusions. But we may at least be certain of one thing. The custom of making krises of meteoritic iron is not demonstrably ancient. The mid-18th century forms an absolute limit before which no kris can contain iron from any known meteorite. The mid-19th century forms an evidential limit. We may believe if we wish that a few meteoritic blades were made before 1830, but we should recognize that there is no actual evidence for this. In the present state of knowledge, the notion that the meteoritic kris goes back to remote antiquity is no more than an appealing fiction.

Occurrence of Nickel in Premodern Krises

We should at this point consider the possibility that all nickel-containing krises except those made from meteorites might be very recent. Groneman's observations of kris making methods date to the early 1900s. His assumption that the silvery color and etch-resistance of pamor indicates that it contains nickel is plausible. But, with the exception of very fine court weapons known to have been made of meteoritic iron, he does not offer convincing proof that any other krises made prior to the early 1890s — that is, before the introduction of European iron-nickel alloys — actually do have a significant nickel content.

The few analyses of krises published since Groneman's time also do not prove this. As pointed out in the preceding section, Rosehain did not find nickel in the blade he analyzed, and the example described by Frankel could have been made during the 20th century. The same is true of the two blades investigated by Piaskowski[34] and Tylecote[35]. Neither kris is provable old. Moreover, even if both are old, they constitute a very small sample. One could perfectly well conclude from the published evidence that nickel-containing Sulawesi iron began to be used in krises at about the same time as European iron-nickel alloys and that before then the only krises with an appreciable nickel content were the scarce and valuable blades made from the Prambanan meteorite.

Current research being carried out by the author in collaboration with William Rostoker of the University of Illinois at Chicago makes this conclusion seem unlikely. By a fortunate coincidence, the Field Museum of Natural History has a relatively large number of krises that entered its collections in 1893. As these do not appear to have been new then and as nickel steel was not produced on a commercial scale in Europe until 1890, it seems safe to assume that any nickel in them derives from either meteoritic or locally smelted iron. Furthermore, none of the krises in question is elaborately decorated or of especially high quality in terms of pamor pattern or finish. It is an ordinary group of average medium-grade weapons of the kind that would have been owned by middle-ranking Indonesians and Malays.

Thus far, only preliminary semi-quantitative analyses have been performed on a sample of 131 krises, using one of Koslow's electrochemical spot tests.[36] The results of these tests, presented on Table 1, seem decisive. Of the 81 examples that entered the museum in 1893, 14 contain more than 1% nickel. This is far too many for meteoritic iron to be involved — there are not enough iron-nickel meteorites in existence for such a high percentage of ordinary krises, which numbered in the millions during the 19th century, to have been made of them. Most of the nickel involved has to have come from another source. The only plausible source before 1890 is a natural iron-nickel ore.

Table 1

Nickel in Krises, by Place of Origin and Accession Date

	Java-Madura		**Sumatra, Malaysia**	
Nickel	**1893**	**1900**	**1893**	**1900**
none, trace	59	13	5	18
1-4%	6	5	0	4
5%	5	3	0	0
	Bali		**Sulawesi**	
Nickel	**1893**	**1900**	**1893**	**1900**
none, trace	1	0	2	1
1-4%	2	3	1	1
5%	0		1	0

Table 1 shows that the average nickel content of Javanses-Madurese krises rises after 1900; presumably this is in part due to the use of imported European alloys. The table also seems to indicate that early nickel-containing krises were more common in Bali and Sulawesi, as well as in Java, than in Sumatra and the Malay Peninsula. However, here the sample size is too small to have statistical significance. Although it is tempting to conclude that the iron-nickel ores involved came from a source that was nearer to Java, Bali and Sulawesi than to the latter areas, the evidence presented in the table cannot prove this.

Two other results of these preliminary tests should be mentioned. First, there was a strong but unquantifiable association between nickel content and the presence of etchant-produce colour variations on the surface of blades. Marked variations in relief were present even in blades that had no appreciable nickel in them. Variations in color, however, seemed closely to reflect their nickel content. Blades with a noticeable dark-light patterning contained at least 1% of nickel; in those where the light parts of the pattern were actually silvery, the nickel content was closer to 5%.

Second, it appears that the cores of krises rarely contain nickel. Most such weapons are made with a central plate of steel that is larger than the other plates or iron or steel and of *pamor* welded on the top and bottom. This central plate forms the cutting edges of the weapon and therefore projects outward far enough for it to be possible to spot-test this without touching the other portions of the blade. In no case was an edge found to have enough nickel to appear as even a trace in the test employed. In cases where the original etched dark and silvery colors were preserved on the faces of the blade, the edges were nonetheless dark grey or black.

Smelted Pamor

It is apparent that before the mid-19th century the only "true" *pamor* known either to Europeans or to most Southeast Asians was a metal most or all of which came from Sulawesi. Raffles' comments on the subject have already been quoted; he thought that all *pamor* came from Sulawesi and Belitung. Writing in 1839, Newbold could correct Raffles with regard to the latter island:

> The bisi pamor or damask iron of which the blades are partly composed is brought from Celebes and Java. This is mixed with the iron of old hoops, nails, or a sort of iron brought from Billiton ...[37]

Substantially more information was available to Hendriks, a Dutch infantry captain who for intelligence purposes made a close study in 1840 of the indigenous arms industry at Negara in the kingdom of Banjermasin in southern Borneo.

> Pamor is a very white and easily worked iron that is brought to Banjermasin by Chinese and Buginese traders. According to information from the head of the Buginese in Banjermasin, it is a product of the Bugis kingdom in the island of Celebes and also from

> the island of Timor. The land of Raja-Paiyong, in Bugis, is obliged especially to deliver much *pamor* (in payment of tribute or taxes). It is obtained from the ore in the same way as the (low shaft furnace-smelted) Dusun iron mentioned above. Pamor is not worked by itself but is used in combination with ordinary smith's iron for the so-called damascening: a process whereby objects gain not only beauty but also cohesion and toughness.[38]

Clearly, Hendriks uses "pamor" to mean the same metal as that described by Raffles and Newbold. But his informants have first-hand data about where the metal comes from. Although he does not use the qualifier "luwu", he singles out the land of an unidentifiable chief who, he implies, was subordinate to a native Bugis kingdom, not to the Dutch colonial government. In 1840 this meant Luwu or one of the adjoining statelets at the head of the Gulf of Bone in central Sulawesi.

In 1853, St John, whose sources also had reasonably first-hand information, not only says that the inhabitants of Sulawesi used their own *pamor* in sword making but recognizes this as a metal of an unusual kind:

> From the steel prepared by the natives, mixed with a metal little known to Europeans, sword-blades beautifully damasceened, with keen edge and brilliant polish, are manufactured[39].

Grabowsky[40] in 1889 confirms Hendrik's statement that the *pamor* used at Negara came from Sulawesi. He does not mention Timor and gives no further specifics. The first authority explicitly to connect *pamor* with Luwu by name may have been the lexicographer Matthes, whose 1883 definition of the Bugis word "pamoro" is quoted by Adriani and Kruyt[41]. Matthes says that this metal derives from an ore, produces the beautiful "flames" in kris blades, and comes from Luwu.

Groneman indicates that the use of this kind of *pamor* was still quite widespread in the early 1900s. An informal survey at that time showed that *pamor luwu* was used by kris makers in nine centres on six different islands[42]. His report of analyses performed on samples of *pamor* obtained in Sulawesi in 1905 has already been mentioned. While to 0.4% nickel content of those particular samples seems insufficient to affect the performance of anything made from them, it does show that furnaces and ores existed in Sulawesi that could yield at least a low-nickel iron.

The ores in question are probably those discovered in about 1910 by a geological team led by Abendanon[43]. The nickel-bearing deposits consisted of extensive beds of laterite centred on the village of Soroako on Lake Matana in Sulawesi. These were definitley non-meteoritic, having derived from the weathering of an underlying nickeliferous serpentine. Initial analyses showed iron contents between 24.5 and 55.2 percent and nickel contents from 0.12 to 1.35 percent, the latter in the form of dispersed garnierite[44]. Further exploration later proved a substantial tonnage of ores with an average of 1.75 percent nickel[45]. Li states that the ore currently smelted in the plant of P T Inco Indonesia at Soroako comes from a saprolitic layer that averages 22% Fe and 2.2% Ni[46]. The overlying lateritic layer, with 45% Fe and 1.2% Ni, is not used at present in spite of its obvious potential as a source of iron.

It was almost certainly used as such in earlier times, however. The Lake Matana area is said by Kruyt[47] and Abendanon[48] to have been famous for its swords. Kruyt implies that the area was still producing these swords in 1900, noting that it was the last part of central Sulawesi to give up the export of objects made from locally smelted iron. Abendanon confirmed this in 1910 by finding a smelting furnace at Soroako itself that was still in operation [49]. The ironmakers, of either Bugis or tribal origin, employed simple bowl hearths equipped with four piston bellows to smelt a "bog ore". The hearth Abendanon illustrates is similar to other traditional furnaces in central Sulawesi reviewed by Marschall[50].

Unfortunately, Abendanon seems not to have secured a sample of this locally smelted iron, so we have no hard evidence that it contained nickel. We also have no evidence of nickel in any other iron object from the area, for none of these — of which there are a number in Western museums[51] — have ever been examined by a metallurgist. And yet the coincidence of nickel — bearing iron ores with an old and important ironmaking centre is surely significant. Since any bloomery, including the one seen by Abendanon, should be quite capable of extracting the nickel in such an ore, it would be surprising if some of the iron made in the vicinity of Soroako did not have an appreciable, if variable, nickel content.

All in all, the evidence for the nature of Sulawesi *pamor* during the 19th century is reasonably convincing. It was widely used. To most Southeast Asians it was the main and perhaps only type of true *pamor* — that is, a metal that could be pattern-welded with iron and that would remain "white" after etching. This fact and Groneman's one analysis suggest that at least some of it contained nickel. Data supplied by natives of Sulawesi to Hendriks and Matthes indicate that this nickel was smelted from an ore. And suitable ores exist, are of a type that could be smelted in simple furnaces, and are in a locality where many such furnaces are known to have been in operation. Although laboratory tests and smelting experiments would be needed to complete the proof, the data given here seem sufficient to establish this as a probable instance of the regular production of an iron-nickel alloy, on a modest but commercial scale.

Smelted Nickel in Earlier Periods

It is evident that Sulawesi *pamor* was already a well known product by the beginning of the 19th century. Tracing it further back in time is difficult, however. The main difficulty arises from the apparent fact that no source before Raffles either mentions *pamor* or connects a metal used in krises with Sulawesi. Yet there is a good deal of evidence that by 1800 central Sulawesi had long been an important regional centre of iron production. There is also evidence that by then a metal resembling *pamor* had already been in use among Southeast Asian weapon makers for several centuries.

References to iron exports from Sulawesi go back as far as the early 1500s. Weapons originating on or near that island are mentioned before 1520 by both Pires[52] and Barbosa[53]. An anonymous memorandum of 1603 preserved in the Dutch National Archives[54] emphasizes the profitability of exporting swords from Buton (Butung), which at the time controlled the west coast of central Sulawesi. In the early 18th century, van Dam's[55] and Valentyn's[56] encyclopedic summaries of the commerce of the Dutch East India Company list many iron-producing and weapons-exporting localities in the central part of the island. It was noted previously that the Soroako area was the only such locality in central Sulawesi to have survived the competition of cheap European iron down through the end of the 19th century. Other parts of Sulawesi may have continued to export weapons for even longer. As late as the 1920s, Winstedt can still write that in the judgement of the Malays, "the most esteemed weapons come from Celebes, and the most artistic workmanship will be found in the creeses of Java and Bali".[57]

The known history of unidentified Southeast Asian weapon alloys that respond to an arsenic sulfide treatment in the same way as the *pamor* of recent times may be even longer than that of Sulawesi iron. The earliest plausible reference to such an alloy occurs in Ma Huan's description of the knives carried by all Javanese men, written in 1433[58]. He says that these were made of steel and decorated with intricate "rabbit's-hair snowflake" patterns. The earliest unambiguous evidence comes from European museum collections, a number of which contain krises that were brought to Europe in the 17th and 18th centuries and that have blades made with recognizable *pamor.* L G Hill has described the three krises in the Tradescant Collection at the Ashmolean Museum[59]. Two of the three have good *pamor:* all certainly reached England before 1660. The Solyoms mention another, also with *pamor,* that entered the Worm Collection in Denmark before 1647[60].

The list of early blades with high-quality *pamor* would be greatly expanded if we could include heirloom weapons, of which many exist in museums and private collections and to which tradition often assigns a substantial antiquity. In most cases the relevant oral legends and written chronicles are less trustworthy when it comes to dates than are European museum records. But many such krises are unquestionably old. In spite of their deficient documentation, we can hardly doubt that a number of them go back to at least the early 18th and 17th centuries — that is, to a period when no *pamor* can have come from a known meteorite.

This early *pamor* cannot be directly linked with Sulawesi. No source before Raffles indicates that krises were made of metal from Sulawesi or that Sulawesi-manufactured weapons were made from an unusual kind of iron. However, we may perhaps infer that such a link existed if we accept three propositions: that metal that behaves like *pamor* contains nickel, that there was too much of this metal for it to be meteoritic, and that Sulawesi was the chief source of non-meteoritic nickel accessible to early Southeast Asian ironworkers.

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Denis Hayford: An early steel master

K C Barraclough and B G Awty

By the middle of the eighteenth century it was well established that the finest quality of steel produced was 'Double Shear', also known, after its first supplier, as 'Hayford Steel'.[1] According to Lewis this was

> "...common or blister steel, doubled and forged together but converted higher than usual because it loses in forging
> ...These steels are chiefly made near Newcastle".

Considering his importance in the steel industry, Denis (Dan) Hayford (Heyford) has remained a somewhat shadowy figure. He is known to have been connected with ironmaking operations in South Yorkshire and North Derbyshire and also in Cheshire and in Northumberland from the 1670s onwards. By 1693 he was supplying steel to the Lancashire market.[2] By the same date he was operating the so-called Duke of Norfolk's Ironworks, in partnership with John Fell and the account books have survived as the 'Staveley Ironworks Records'.[3] These also include ledger accounts of a 'Steel Trade' in which John Fell and Denis Hayford were the sole partners from 1699 to 1724; significantly one of the very first entries is the supply of 'steel for the Northern Trade'. From a small beginning, by the time Hayford died in 1727, this 'steel trade' was supplying some 60 to 70 tons of blister steel per annum.[4] After Hayford's death, his son, Millington Hayford, retained a three-eighths share in the steel operations, his widow selling out in 1744.

One of Hayford's well known customers for steel was the Hollow Sword Blade Company of Shotley Bridge in County Durham.[5] They appeared to prefer his steel to all other; in view of the proximity of the Crowley works at Winlaton, where steel was produced on a relatively large scale — certainly the North East was rapidly becoming the steelmaking centre of Britain at that time — this, on the face of it, was rather strange. By 1703 the Hollow Sword Blade Company was under contract to William Cotesworth[6] and one of the surviving manuscripts is a letter from Hayford, which is a complaint about non-payment, asking the swordmakers for a reply to be sent to him

> "at Roamley, per Bawtry post".

Here confusion has arisen, since Hughes, on the basis of this document, refers to Hayford having a forge at Roamley near Pontefract;[7] in point of fact, neither the presence of the forge nor the town of Pontefract appear to be mentioned in the document. Both Flinn and Schubert[8] have subsequently quoted Hughes and this has led to abortive attempts to locate Roamley, there being no such entry in the place name lists for Yorkshire or the adjoining County of Nottingham. Hopkinson, however, in referring to the Duke of Norfolk's Ironworks in 1700, includes Denis Hayford 'of Staveley' as one of the operating partners;[9] he also provides the interesting comment that Hayford was a descendant of that steward of Sir Francis Rockley who contrived the downfall of his master and subsequently took possession of the Rockley ironmaking activities.

The Staveley connection is quite clear from the so-called Staveley Ironworks records but is made more specific in the documents concerning a case in Chancery in 1717,[10] arising from a claim that the right of way to Hayford's steel mill was only

> "a horse or foot way and not for carts or wains".

In the preamble to his submission, Hayford describes himself as

> "of Roumbly in the County of Derby".

A search of the area around Staveley reveals both Romeley House and Romeley Hall on the six inch Ordnance Survey map of 1899, between Staveley and Clowne and both are only some three miles or so from the blast furnace at Staveley. The variations in spelling become even more confusing when reference is made to the earliest surviving large scale survey of Derbyshire[11] which shows Ramsley; Romeley first appears on an 1835 map[12] and persists thereafter. At the present time, Romeley Hall is a ruin but it has proved difficult to locate Romeley House; a search for evidence of the residence of Hayford at either the Hall or the House has so far proved abortive but is continuing.

If the Chancery records have only partially helped in the elucidation of the Romeley matter, they are of more substantial value in pointing out where the Hayford Steel for the Hollow Sword Blade Company originated, since Hayford clearly states that he

> "...for thirty years last hath been seized to him and his heirs of a certain steele mill or mill for the making or drawing of steele scituate upon the river Darwent in the County of Durham and standing on the north side of the river where formerly stood a corne mill and a fulling mill."

He goes on to report that the mill had been sold to him by Thomas Rutherford of Blackhall, the dam had been rebuilt about twenty years previously and about £1000 had been spent some five years previously in the rebuilding of the mill.

Steelmaking operations at Blackhall Mill, which is less than five miles from Shotley Bridge, could therefore have started before the end of the seventeenth century and this would have pre-dated those under Crowley at Winlaton Mill. A Swedish observer visited the site in 1719[13] and found a steelworks owned by a Mr. Dan Hayford the steelmaker being William Bertram. William (or Wilhelm) Bertram appears to have been a key figure in the operations; a steelmaker from the area around Remscheid in Germany, he was reputed to have been shipwrecked and stranded on the Durham coast in 1693. Angerstein[14] suggests that he first took charge of steelmaking operations at Newcastle and provides a sketch showing a cementation furnace on the north bank of the Tyne; Bertram then moved to Blackhall Mill and it is to be noted that the dimensions of the two cementation furnaces at Newcastle and Blackhall Mill as quoted by Angerstein are identical. It was Bertram who pioneered the forging down of blister steel in faggots or bundles to produce what was first known as 'German Steel' — presumably since it was remarkably similar to the imported product, just possibly, since Bertram himself was a German — but was subsequently referred to as 'Newcastle Steel'. It is reported that this came in five grades in ascending order of hardness and fineness: 'Single Shear', 'Double Shear', 'Double Spur', 'Double Spur and Single Star' and 'Double Spur and Double Star';[15] the comment is also made that it was very difficult to provide 'sufficiently converted' blister steel to provide the 'Spur' grades except in small quantities for special applications. Angerstein is also quite definite in his statement that Bertram's son was in sole charge of Blackhall Mill in 1753 and that his trade mark was a pair of crossed shear blades. It is no real surprise, therefore, that it was a smith trained at Blackhall Mill, one Thomas Eltringham, who introduced the practice of manufacture of Shear Steel to Sheffield when he went to work for Thomas Boulsover in 1767, an event which was to be of extreme importance in the growth of the Sheffield steel trade.[16]

Angerstein left a sketch of the Blackhall Mill site which shows a built-up abutment on the river bank which can still be recognised. The furnace has now long since gone, having been demolished in 1916 to make way for a school. An old postcard, however, shows the furnace to have been very similar in construction to that at Derwentcote, about a mile and a half upstream from Blackhall Mill and now the sole survival from the eighteenth century when this area of the North East was the centre of British steelmaking.

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British firebricks in North America

Karl Gurcke with notes by Arthur Dunn

When the cities of the Pacific Northwest were founded the local firebrick industry was rather late in developing because of the lack of deposits of good, or even adequate, fireclays. This coupled with the extremely low priced imported products restricted possible competition from local sources.[1]

The primary source for the region's firebrick was from the main exporting country, Great Britain, and this trade continued to exist from about the 1850s unto the beginning of World War I. By that time, and assisted by the fact that transport was simply not available, the local industry had established itself. It is fortunate for those who are interested in industrial archaeology, and the history of technology, that not only the British, but also the local companies clearly branded their own bricks.

Firebricks are made today in many sizes and shapes, but nearly all of those early firebricks were of a size that was referred to as a "9 inch straight", just slightly larger than the "common" brick used in building construction. As the temperatures necessary for industrial processes increased the higher heat resistance of the firebrick over that of the common brick made it a necessity for some of the more advancing manufacturing processes.

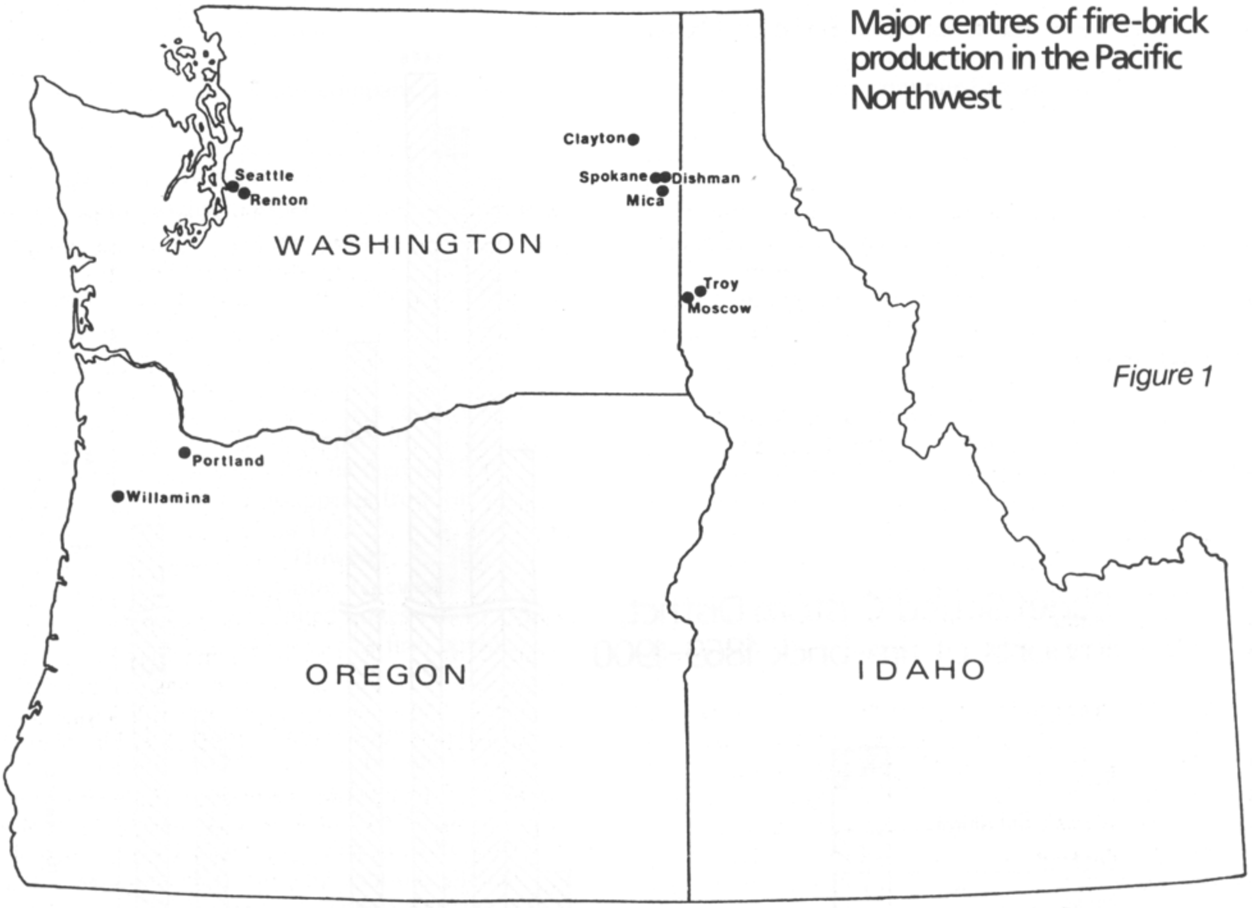
Industries such as the Roche Harbour Lime Kiln on San Juan Island, Washington (ca. 1882-1956), the Landore Copper Smelter (ca. 1893-1916) near McCall, Idaho, and the Oregon Iron Company's blast furnace (ca. 1865-1894) near Lake Oswego, Oregon, were large users of firebrick.

Firebricks of British origin have also been found at the H F McCormick sawmill (ca. 1908-1930), and the Warendale cannery (ca. 1876-1930) along the Columbia River near Portland, Oregon. Firebricks were also used around the fireboxes of stationary boilers and in the construction of kilns that were used to burn firebrick, where formerly common brick was often used, such as in the case of the kiln in Troy, Idaho, Firebricks were so plentiful that they were even used in the construction of home fireplaces (and even in the construction of houses and hotels in Canada) since they were readily available in quantity as a result of the British Law which did not tax any brick that was exported.[2]

Because of the scarcity of raw materials firebrick manufacturing occurs only in certain areas of the Northwest such as at Moscow and Troy in North Idaho, the region around Spokane in Washington State, and Portland and Willamina in Oregon (Fig. 1). The Idaho Fire Brick Company was established in Troy, Idaho in 1914 and is still operating under the management of the A P Green Company. The Moscow Fire Brick & Clay Products Company of Moscow, Idaho, was founded in 1916 and destroyed by fire in 1945. The Washington Brick, Lime & Manufacturing Company was making bricks by 1889, and was one of the largest in the Northwest with factories at Clayton, Dishman, and Spokane. The American Fire Brick Company broke ground for their new factory at Mica, Washington, in 1902 and is still in business, but is now known as Interpace. In Seattle, the Denny-Renton Clay and Coal Company began making firebricks in 1892, and their Taylor factory was in operation by 1893. The Renton works was started in 1901. In Portland, the Western Clay Manufacturing Company was making brick from 1897 to 1912, and the Monarch Fire Brick Company from 1916 to 1928. The Willamina Clay Products Company in Willamina, Oregon, was making firebrick from the 1930's onwards (Polk 1890:10; Spokesman-Review 1902:5,1916:7;Wilcox1935:20-21;Idahoian1961:76).

Because of the need for firebricks in industries operating prior to the 1890's, other sources outside the Pacific Northwest had to be found. The nearest centres of production were either in British Columbia, California, or Colorado. The Clayburn Company was established at Clayburn, British Columbia in 1905, the first in the province (Adams 1979:23). Firebrick was also made in California by the Gladding-McBean & Company as early as 1875, while the Denver Fire Clay Company of Colorado was in operation by 1880 (Greaves Walker 1941:215). However, these early industries were at a disadvantage because of the low prices imported firebrick would fetch. For example, in the 1850's English firebricks were selling for $50-$60 per thousand wholesale in the San Francisco market (Prices Current & Shipping List 1852:2) and $80 per thousand in the Portland market (Portland Commercial 1853:3). By the late 1860's, however, the price had dropped to between $40-$55 per thousand (Commercial Herald & Market Review 1867:2) and by the 1870's, when the local industry was just getting started the price had dropped even further to $25-$35 per thousand. In newspaper accounts of the time it was noted that this "price...will not cover the cost of importation" (Commercial Herald & Market Review 1876:1).

During the 19th and early 20th centuries, thousands if not millions of firebricks were being imported into the Northwest of the United States from such diverse countries as Belgium and Japan. The dominant source, however, was Great Britain. The existance of this trade is well documented in newspaper accounts and advertisements but the most important source of information is to be found in the United States Customs



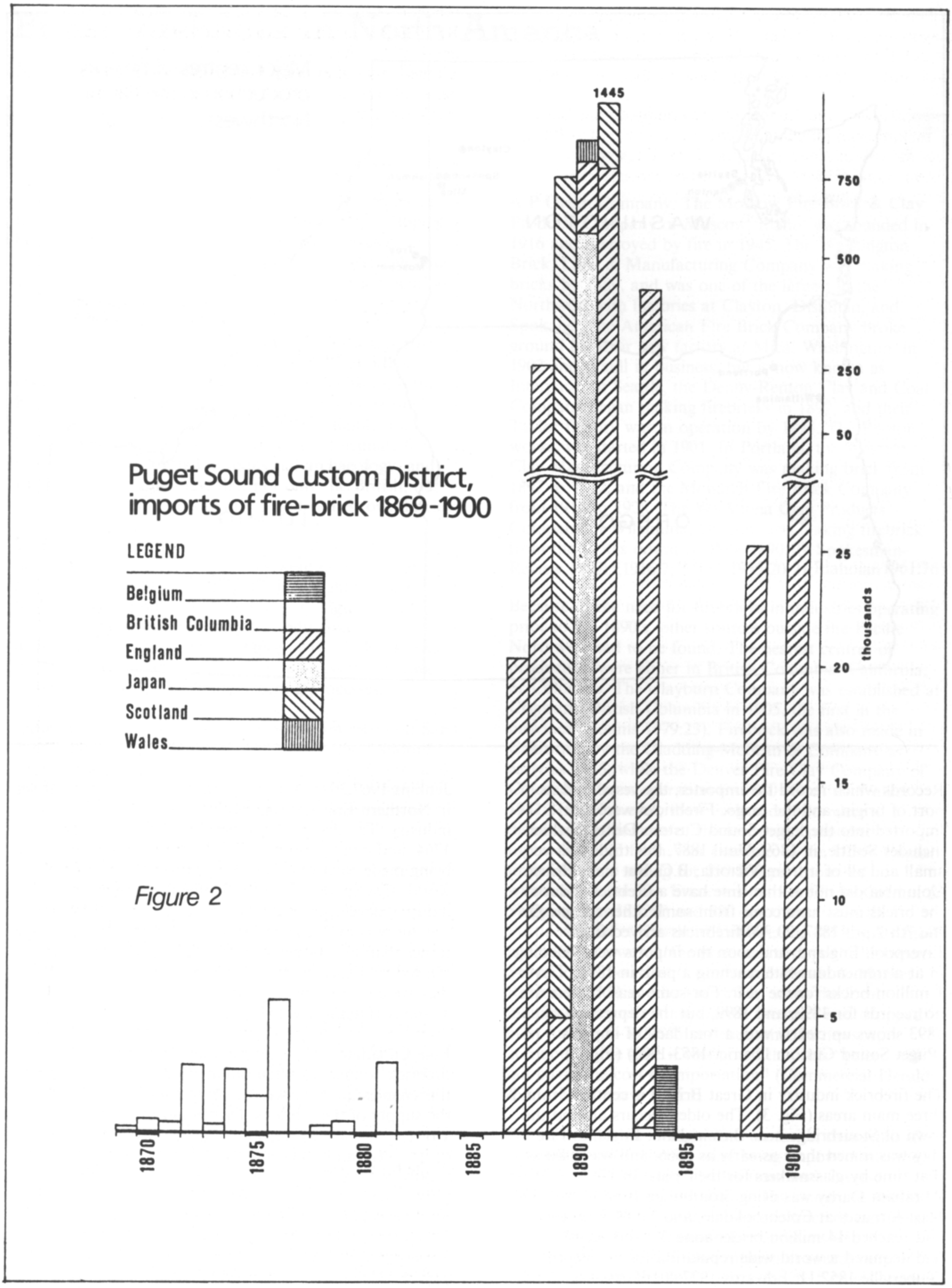
Major centres of fire-brick production in the Pacific Northwest

Figure 1

Records which record the importer, the vessel and its port of origin, and the cargo. Firebricks were first imported into the Puget Sound Custom District, which includes Seattle, in 1869. Until 1887, this trade was very small and all of it from Victoria, B.C. But since British Columbia did not at that time have a firebrick industry the bricks must have come from some other source. On the 7th April 1887, 20,300 firebricks arrived from Liverpool, England, and soon the imports were flooding in at a tremendous rate reaching a peak in 1891 of over 1 million bricks for the year. For some reason there are no records for 1892, and 1899, but the depression of 1893 shows up clearly with a total lack of imports (Puget Sound Custom District 1853-1900) (Fig. 2).

The firebrick industry in Great Britain is centred around three main areas (Fig. 3). The oldest occurs around the town of Stourbridge near Birmingham, England. Fire clay was mined there as early as 1566, and was used at that time by glassmakers for their pots. In 1718 Abraham Darby was using Stourbridge firebricks in his blast furnaces at Colebrookdale, and by 1852 production had reached 14 million bricks annually and Stourbridge had acquired a world wide reputation for excellence (Tuberville 1852:11; Edwards 1927:401; Greenslade and Jenkins 1967:269). A second centre along the Tyne River in Northern England was also preceeded by the glass industry. The first firebrick was made there around 1764, and one hundred years later 80 million bricks were being made each year and shipped to all parts of the world (Cowen 1864:208). In Scotland the firebrick industry developed much later (around the 1820's) and was more closely aligned with the iron and steel industry rather than that of glassmaking. It began in the region centred on Glasgow but rose rapidly that by the 1870's they were also producing some 80 million bricks annually (Dunnachie 1877:8).

Like Canadian and American manufacturers, British firebrick companies often branded their products, and this enables one to trace the companies involved with the supply of these bricks. One brand in particular, Cowen, was singled out in newspaper accounts because of its consistantly higher prices. For example, "the supply of English Fire (Brick) is excessive, (and) low prices rule.(but) Cowan's (firebricks are selling) at $55 per thousand (while) ordinary quality are obtainable at $40 (per thousand)" (Commercial Herald & Market Review 1867:2) The Cowen Brand was also registered with the United States Patent Office on the 26th of



Puget Sound Custom District, imports of fire-brick 1869-1900

Figure 2

September 1893, by Joseph Cowen & Company, Blaydon-on-Tyne, England. They were one of the few English firms to do so and claimed to have used the mark since 1823 (United States Patent Office, No. 23,653).

Joseph Cowen, the founder of this company, was born in 1800, he had purchased a coal mine at Blaydon Burn, near the city of Newcastle upon Tyne, England (Anonymous 1895:42, 1975:24). Since deposits of fireclays are always found in association with coal seams (3), and the needs for firebrick was increasing, the production of firebrick at that site soon followed. Joseph Cowen was later knighted and elected a Member of Parliament for Newcastle, and died in 1874. His son, Joseph Cowen, junior, was born in 1829, and took over active management of the company on his father's death. He also took over his father's seat in Parliament but retired from politics in 1886. Apparently he left no one interested in the business when he died in 1900, because the company's name disappears from the local directory after 1904 (Anonymous 1975:25; F W Manders 1981: personal communication). However, Priestman Collieries Limited, also of Newcastle, renewed the COWEN trademark with the United States Patent Office on the 26th of September 1943, and this firm continued in business until 1946.

Other British firebrick brands found in the pacific Northwest include BENSON, which is the mark of William Benson & Son, Newcastle upon Tyne, England, operating from at least 1873-1937. BONNYBRIDGE, manufactured by the Bonnybridge Silica & Fire Clay Company of Bonnybridge, Scotland with dates from 1874 to 1971. CALDER, made by Robert Fleming & Company of Coatbridge, Scotland, was in business some time before 1890, and merged with Bonnybridge in 1936. CARR, maunufactured by John Carr & Sons, of North Shields (a town at the mouth of the River Tyne in northern England) was in operation by 1844, and disappeared from English commercial directories after 1908. GARTCOSH, this company was established in 1867, but merged with others in 1882 to form The Glenboig Union Clay Company with its head office in Glasgow, Scotland. GLENBOIG was another brand of brick produced by this company and was manufactured after 1836. During the 1930s this form boasted that it was "the largest of its kind in Europe" (The Glenboig Union Fire Clay Company 1930:10). PATENT/R BROWN & SON/PAISLEY was manufactured by Robert Brown & Son, of Paisley, Scotland. This company was established around 1836, became a private limited firm in 1902, and was taken over by Associated Clay Industries in 1934 (R J Malden 1981: personal communication).

RUFFORD/STOURBRIDGE bricks were made by Francis T Rufford, Hungary Hill, Stourbridge, England. This firm was producing firebricks by 1800 and supplied the Hudson's Bay Company's Columbia Department for the outfit of 1852 (Ross 1979 (I):162). Some 15 years later this company was still selling firebricks to the H.B.C. as shown in a receipt made out to the Oregon Iron Works for 1200 "Rufford's best Fire Bricks" (Oregon Historical Society MSS. 870, Reel 1, Frame 60). By 1936 Rufford had ceased production but their goodwill had been purchased by E J & J Pearson Limited, also of Stourbridge (Ralph Heeley 1981: personal communication). However, the Rufford Firebrick Company continued to appear in English commercial directories until 1963. SNOWBALL a brick manufactured by George H Snowball of Swalwell, County Durham, England, a small town on the right bank of the River Tyne a little up stream from Newcastle was in business from 1854 until shortly after 1935. Their particular brand is interesting because bricks are found which have several different lettering styles. Finally, T CARR manufactured by Thomas Carr & Son, Newcastle upon Tyne, was established in 1827 and last mentioned in English commercial directories in 1918 (4).


Major centres of fire-brick production in Great Britain

Figure 3

Until the 1900's British firebricks were mostly made by hand (Clews 1935:438). The process is essentially a simple one but which required a definite skill to produce a quality product. The brick maker was provided with a lump of clay by an assistant which he raised over his head and threw it with as much strength as he could muster down into the mould. After forcing the clay into all the four corners of the mould, the brickmaker would strike off the excess clay with a wire or other device, and the mould with its clay insert was passed to an assistant who would, where necessary, imprint the manufacturers name and then remove it from the mould and place the formed brick on a wooden frame. Each frame when filled would be placed in the open air to dry. This process leaves certain marks on the struck surface. However, because firebricks require accurate dimensions, extra care was taken to produce a smooth and finished appearance. For example, the moulder, or his assistant, could rub the struck surface a number of times to eliminate these lines (Anonymous 1891:25). Sand or water were the two main elements used to lubricate the mould and allow the green bricks to slip free. Most of the firebricks from the Newcastle and Glasgow regions are water struck which is indicated by tiny ripples on the surface of the brick. On the other hand, all of the Stourbridge firebricks so far examined are sand struck. (5).

Summarising this subject we can say the firebricks were imported in large numbers from many different countries, but the major source was Great Britain. This trade existed from the early 1850's until at least World War I, by which time local companies were established. The brands that are shown on the bricks are an important source of information which is worthy of further study.

Notes by A D Dunn

Good fireclay deposits are very few in North America, and even then the quality of the clays for the manufacture of firebrick did not, in general, compare with the clays available in the vicinity of Stourbridge in England. The only possible exception to this was possibly those clays that were obtained in the vicinity of Perth Amboy, New Jersey, these clays were so much in demand as the need to better locally produced firebrick grew, and transportation by rail became easier, were shipped to all parts of North America and used, either 'as received' or alternatively mixed with local (inferior) clays to produce the quality of brick required. This practice was also prevelent in England during the middle of the last century, particularly in Scotland, where clays were imported from the Stourbridge area, and also from the Continent, and intermixed to form a reasonable quality of firebrick.

Enormous numbers of firebricks were shipped into Eastern Canada from Great Britain in the years after about 1840, as ballast for the ships employed in bringing timber from Canada for English needs. Many of these bricks were used for non-industrial purposes, and there are many reports that houses in Eastern Quebec, Lower Canada at that time, were built of firebrick. It is also reported that the old Newfoundland Hotel in St Johns, and the Chateau Frontanac in Quebec City are constructed with British firebricks.

Fireclays are the result of the action of humic acids upon layers of kaolin that lie under the strata of coal under formation. The action of the acids leach away some of the components in the clays deposited as a result of earlier tidal depositions which results in the clays becoming refractory.

4 The manufacturers of firebrick listed in the context of this article may not include the names of all the British suppliers who shipped firebricks to North America. Quite a number of bricks, or portions thereof, have been found whose manufacturers are unknown, almost all have been of the "9 inch straight" form. Around 1860 bricks specially formed for used in the blast furnaces seem to have been imported, but only few of these have been found.

5 The process of manufacture of firebricks in North America does not seem to be quite the same as that used in the Stourbridge area.

British firebricks known to be imported into the Pacific Northwest

1) Mark: BENSON
Manufacturer: William Benson & Son
Location: Newcastle upon Tyne, England
Dates: (ca. 1873-1937)
Remarks:
Provenance: Roche Harbor Lime Kiln, Washington

2) Mark: BONNYBRIDGE
Manufacturer: Bonnybridge Silica & Fire Clay Co.
Location: Bonnybridge, Stirlingshire, Scotland
Dates: (ca. 1874-1971)
Remarks:
Provenance: Roche Harbor Lime Kiln, Washington

3) Mark: CALDER
Manufacturer: Robert Fleming & Co., Calder Fire Clay
Location: Works Coatbridge, Scotland
Dates: (ca. 1890-1937)
Remarks: Merged with Bonnybridge during 1936
Provenance: Landore Copper Smelter, Idaho

4) Mark: CARDOWAN
Manufacturer: Heathfield & Cardowan Fire Clay Works
Location: Heathfield and Cardowan, Scotland
Dates: (ca. 1852-1970)
Remarks: In newspaper accounts only
Provenance:

5) Mark: CARR
Manufacturer: John Carr & Sons
Location: Low Lights, North Shields, England
Dates: (ca. 1844-1908)
Remarks: Noted Puget Sound Custom District records
Provenance: Roche Harbor Lime Kiln, Washington

6) Mark: COWEN
Manufacturer: Joseph Cowen & Co.
Location: Blaydon-on-Tyne, England
Dates: (ca. 1823-1904, take over from firm to 1946)
Remarks: Taken over by Priestman Collieries, Ltd.
Noted in newspaper accounts and the
Puget Sound Custom District records.
Also, brand registered with U.S.
Patent Office on 26 September 1893.
Provenance: San Juan Island, Washington and other
locations in the Northwest.

7) Mark: FOSTER
Manufacturer: Henry Foster & Co.
Location: Newcastle upon Tyne, England
Dates: (ca. 1890-1963)
Remarks:
Provenance: Roche Harbor Lime Kiln, Washington

8) Mark: GARNKIRK/PATENT
Manufacturer: Garnkirk Fire Clay Co.
Location: Garnkirk, Scotland
Dates: (ca. 1843-1901)
Remarks:
Provenance: San Francisco, California

9) Mark: GARTCOSH
Manufacturer: The Glenboig Union Fire Clay Co.
Location: Head Office: Glasgow, Scotland
Dates: (ca. 1867-1965)
Remarks: Original company formed in 1863 and merged with the Glenboig Union Fire Clay Co. in 1882.
Provenance: Found near Ridgefield, Washington.

10) Mark: GARTCRAIG
Manufacturer: Gartcraig Fire Clay Co.
Location: Head Office: Glasgow, Scotland
Dates: (ca. 1874-1967)
Remarks:
Provenance: Roche Harbor Lime Kiln and Marcus Island, Washington.

11) Mark: GLENBOIG
Manufacturer: The Glenboig Union Fire Clay Co.
Location: Head Office: Glasgow, Scotland
Dates: (ca. 1882-1965)
Remarks: Original company formed in 1836, works in Cumbernauld, Gartcosh, and Glenboig.
Provenance: Roche Harbor Lime Kiln, Washington.

12) Mark: HICKMAN & CO./STOURBRIDGE
Manufacturer: Hickman & Co.
Location: Stourbridge, England
Dates: (ca. 1786-1974)
Remarks: There is also a Henry Thomas Hickman listed in Kelly's Directories for Stourbridge.
Provenance: Oregon Iron Company and Warrendale Cannery, Oregon Fort Walla Walla dump, Washington.

13) Mark: M. T. & CO.
Manufacturer: Marshall Thomas & Co.
Location: Loxley, Sheffield, England
Dates: (ca. 1901-1963)
Remarks: Noted in a California directory for 1902.
Provenance: Mendocino, California

14) Mark: PATENT/R. BROWN & SON/PAISLEY
Manufacturer: Robert Brown & Son Ltd., Ferguslie Fire
Location: Clay Works Paisley, Renfrewshire, Scotland
Dates: (ca. 1836-1938)
Remarks: Taken over by Associated Clay Industries Ltd., in 1934.
Provenance: Roche Harbor Lime Kiln, Washington, Warrendale Cannery and H. F. McCormick Sawmill, Oregon.

15) Mark: RAVENS/W. B. I. & CO.
Manufacturer: (unknown)
Remarks: From a shipwreck off the Oregon coast near Manzanita.

16) Mark: ROBSON
Manufacturer: Robert and/or William Robson
Location: Newcastle upon Tyne, England
Dates: (ca. 1863-1908)
Remarks: William noted in earlier accounts, Robert found in later accounts.
Provenance: Roche Harbor Lime Kiln, Washington

17) Mark: RUFFORD/STOURBRIDGE
Manufacturer: Francis T. Rufford
Location: Hungary Hill, Stourbridge, England
Dates: (ca. 1800-1963)
Remarks: Later known as Rufford & Co.
Provenance: English Camp, Washington

18) Mark: STARWORKS/J D/GLENBOIG
Manufacturer: The Glenboig Union Fire Clay Co.
Location: Head Office: Glasgow, Scotland
Dates: (ca. 1872-1965)
Remarks: Began as a separate company in 1872 and merged with The Glenboig Union Fire Clay Company in 1882. The "J D" stands for James Dunnachie, the owner.
Provenance: Roche Harbor Lime Kiln, Washington

19) Mark: SNOWBALL
Manufacturer: George H. Snowball, Derwenthaugh Fire
Location: Brick Works Swalwell, County Durham,
Dates: (ca. 1854-1935) England
Remarks: Later known as Snowball Bros. ca. 1913.
Provenance: San Juan Island, Washington, H. F. McCormick Sawmill, Oregon

20) Mark: T CARR
Manufacturer: Thomas Carr & Son
Location: Newcastle upon Tyne, England
Dates: (ca. 1827-1918)
Remarks: Established in 1827 and taken over by Walter Scott Ltd. in 1893.
Provenance: Roche Harbor Lime Kiln, Washington, and the Landore Copper Smelter, Idaho.

21) Mark: WALBOTTLE
Manufacturer: Walbottle Coal & Fire Brick Co.
Location: Newcastle upon Tyne, England
Dates: (ca. 1825-1908)
Remarks: All bricks recovered from wreck were broken.
Provenance: From shipwreck off the Oregon coast near Manzanita.

Note: Dates for the British firebrick companies mentioned above provided in part by correspondence with the individuals listed in the acknowledgments and in part by Kelly's Directories Limited 1901-1980 **Directory of Merchants, Manufacturers, and Shippers and Guide to the Export and Import, Shipping, and Manufacturing Industries of the World.** *London: Kelly's Directories Limited, s. publishers.*

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An examination of Roman iron working residues from Loughor, West Glamorgan, Wales

A P Greenough

Abstract

Slagged material found dispersed through the earth which had slumped from a Roman rampart at the site of the fort at Loughor was identified as the residue from a forge used for welding iron though the hypothesis that it derived from a bloomery cannot be entirely rejected. Fragments of wood as well as charcoal were embedded in some of the specimens examined.

Introduction

During recent excavations by the Glamorgan-Gwent Archaeological Trust at the site of the fort at Loughor, some iron-working residues were found dispersed through the material (generally earth) which had slumped from the rear of a Roman rampart. Three samples were chosen for examination. All were non-ferromagnetic.

Experimental

Sample 1, weight 550g. was a piece of slagged material adhering to a lump of refractory (Figs. 1 and 2). A rough semi-circular hole resembling part of a tuyere hole can be seen. Here and there embedded amongst the slagged material were small pieces of charcoal. From a distance of about 3cm. round the tuyere nozzle the well glazed slag material was dark blue. Elsewhere the slagged material was generally brown. An experienced blacksmith identified the sample as a typical lump of rubbish adhering to a piece of refractory lining round the tuyere of a blacksmith's hearth which had been used to heat iron for forge welding[1].

Samples 2 and 3, weight 300g. and 250g. respectively (Figure 3) consisted of granules of charcoal held together by an iron slag which had been liquid or semi-liquid when it formed round the charcoal. On closer examination, some of the lumps of "charcoal" proved to be granules of wood. There was no sign of continuity between the granules as would be expected if the wood had derived from the roots of a tree growing through the lump.

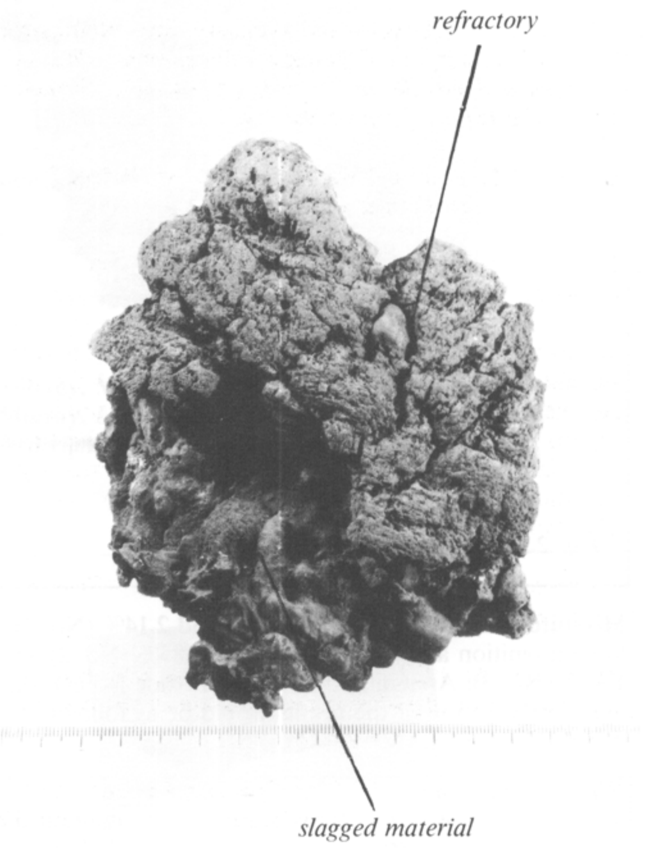

Fig. 1 Sample 1 rear view (one division on scale is 1mm).

These two samples were analysed by Mr Gulland of British Steel Corporation Welsh Laboratory. In each case a random sample was homogenized by ball milling, fused with lithium borate and the residue examined by inductively coupled plasma (ICP) analysis with the following results (weight %):

	Fe	Si	Al	Ca	Mg	Cu	Mn	Ni
Sample 2	49.0	8.25	1.55	1.00	0.16	0.05	0.05	0.05
Sample 3	62.2	4.62	0.76	0.37	0.15	0.07	0.05	0.05

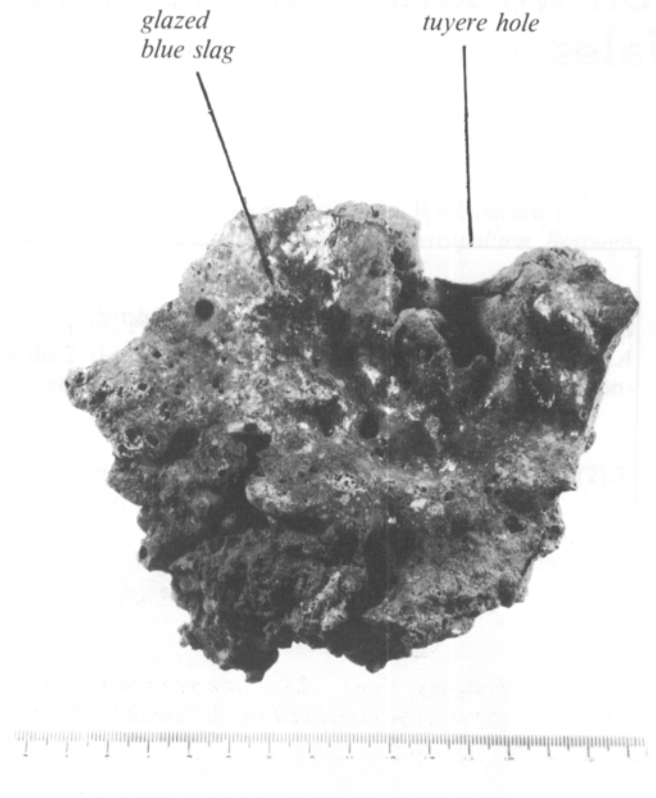

Fig. 2 Sample 1 front view.

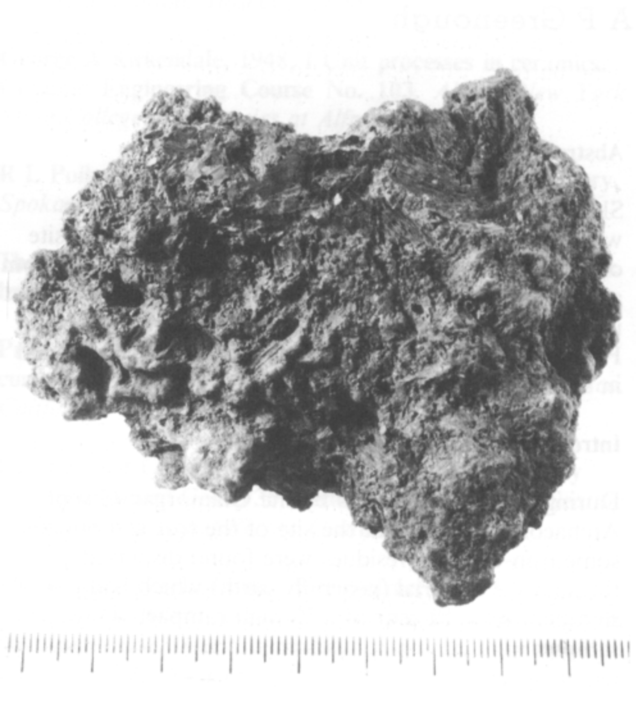

Fig. 3 Sample 3

One division on scale is 1mm.
Most of the fibrous material visible is wood, not charcoal.

Moisture content was 3.68% (No. 2) and 2.14% (No. 3); loss on ignition at 1000°C in air was 11.85% (No. 2) and 1.85% (No. 3). Assuming that the iron oxide is FeO, the usual presentation of the results would be as follows (weight %):

	Moisture	Ignition Loss	FeO	SiO_2	Al_2O_3	CaO	MgO	CuO	MnO	NiO
Sample 2	3.68	11.85	63	17.4	3	1.2	0.25	trace	trace	trace
Sample 3	2.14	1.85	80	10	1.5	0.5	0.25	trace	trace	trace

giving totals of 100% (for sample 2) and 97% (for sample 3).

Stereoscan electron microscopy showed that the charcoal (or wood) was from a hardwood, as expected for metallurgical charcoal.

Reflection microscopy confirmed that some of the ferrous material in 3 had been molten.

Discussion

As the melting point of compositions in this range is at least 1070°C, the lumps were clearly produced in a high temperature operation, and are unlikely to be the result of an accidental fire. It is more difficult to decide whether the residues were the byproduct of iron-making in a bloomery, or the rubbish from a blacksmith's hearth. Roman-era bloomery slags have been discussed by Morton and Wingrove[2]. The Loughor slag is similar in microstructure, and the analysis fits in well with the analysis of Corbridge slag and Sirzi (Turkey) slag. There appears to be no published discussion about the analysis and constitution of blacksmith's slags. However, when a blacksmith heats iron in a fire, particularly prior to welding, he will use sand to protect the iron from oxidation, and to act as a flux[1],[3]. This would produce a slag of composition and microstructure similar to that reported here. Other evidence must be used to decide on the possible origin of the samples:

1. In a bloomery, a shaft furnace is used. The tuyere or tuyeres will be set in a circular wall of appreciable height. In a blacksmith's fire the tuyere is set in the middle of a small block and the fire is open apart from this. Sample 1 strongly suggests the latter.

2. In a bloomery, there is extensive fusion so that the iron particles can agglomerate to form a lump (bloom) while the slag is allowed to flow out of the bottom of the furnace. There would normally be little charcoal trapped in the slag. With the localised heat in a blacksmith's hearth, fusion occurs only in a small area. The slag quickly flows to cooler regions and freezes giving much more porous and friable lumps in which considerable amounts of charcoal are trapped. Our samples 2 and 3 strongly suggests the latter.

3. X-ray diffraction of loose material from sample 3 shows that quartzite and fayalite were present. Quartzite is more likely to be found in the residue from the blacksmith's hearth than the residue from a bloomery.

4. Iron production on any scale would produce large quantities of slag — the weight of slag being at least equal to the weight of iron produced. Only a small amount (about 100kg) of slag has been recovered at Loughor from several cubic metres of earth material. Roman bloomery slags were often used for roadmaking purposes, although little slag has been found in actual road surfaces at Loughor, the majority of the slag was recovered from a position which showed that it had been used as a road make-up and substructure. However, slags from the blacksmith's hearth may well have been uses for roadmaking.

On balance, therefore, the evidence indicates that the samples were waste from a blacksmith's forge which had been used for welding.

The wood may have derived from kindling used to light the fire, or perhaps imperfectly charred wood left behind at the sides or bottom of the charcoal burner's stack.

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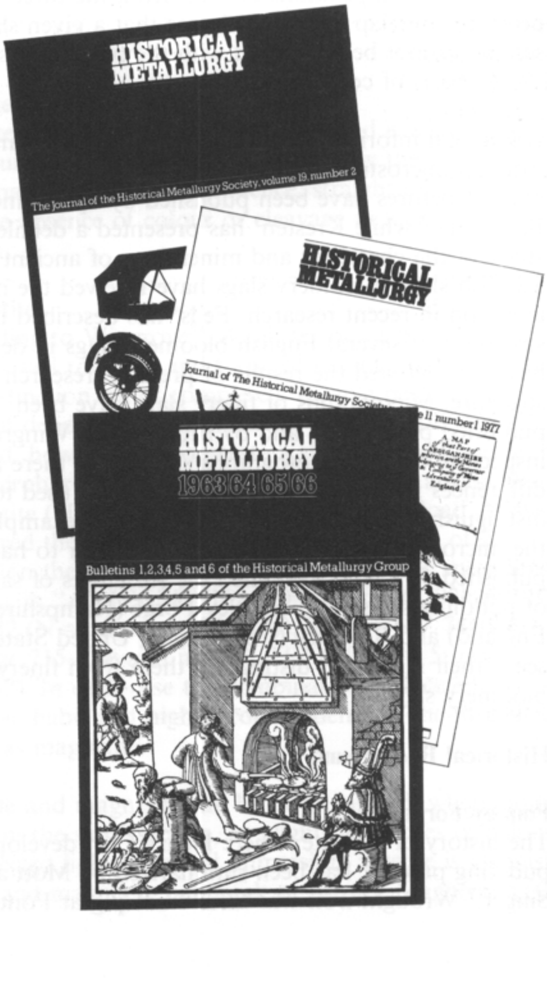

Microstructures of puddling slags from Fontley, England and Roxbury, Connecticut, USA

David Killick and Robert B Gordon

Summary

Samples of slags from the site of Henry's Cort's original iron puddling furnace at Fontley Forge, Hampshire, and a puddled steel works at Roxbury, Connecticut, have very similar compositions that are in agreement with what is known of the operation of puddling furnaces. Fayalite is the dominant constituent and is accompanied by varying proportions of magnetite, silica in the form of tridymite or cristobalite, iron sulphide, and a groundmass composed of complex intergrowths of magnetite, fayalite and glass. Wüstite and metallic iron are absent and the content of Na_2O, K_2O, CaO, and $A1_2O_3$ is very low. These characteristics distinguish the slags studied from bloomery and finery slags and, if found in other examples, may be diagnostic of puddling slag.

In the three principal methods of making wrought iron - bloom smelting, fining, and puddling - solid iron is formed in a liquid slag that approximates the composition of fayalite (2FeO SiO_2). Chemical analyses of the bulk compositions of slags from the three processes overlap to such a degree that a given slag sample cannot be associated with the process it is from on the basis of composition alone.

Additional information about a slag can be obtained from its microstructure. Compilations of slag microstructures have been published by Sperl[1] and by Bachmann[2] while Kresten[3] has presented a detailed study of the chemistry and mineralogy of ancient Swedish slags. Bloomery slags have received the most attention in recent research. Fells[4] has described the structures of several English bloomery slags in detail and has also reviewed the results of previous research on slag structure. Micrographs of finery slags have been published by Bedwin[5] and by Morton and Wingrove[6]; inspection of their photographs shows that there are no differences in microstructure that could be used to distinguish finery from bloomery slag. No examples of the microstructure of puddling slags appear to have been published. We have examined the structures of samples of puddling slags from Fontley Forge (Hampshire, England) and Roxbury (Connecticut, United States) to see if their structures distinguish them from finery and bloomery slags.

Historical Background

Fontley Forge.

The history of this site, where Henry Cort developed the puddling process, has been summarized by Mott and Singer.[7] Wrought iron was fined from pig at Fontley from the early 17th century until after 1775, when Henry Cort took over the management of the works. After about 1750 operators of charcoal forges in England faced diminished profits because the price of charcoal began to rise rapidly while the price of bar iron was held down by abundant, inexpensive imported iron.[8] Entrepreneurs in the iron trade began to search for new, less expensive methods of converting pig into bar iron. Since the price of raw materials was the major part of the cost of finished iron, attention was focussed on ways of eliminating the use of charcoal. The potting and stamping process, which used a coal-fired reverberatory furnace and clay pots for the final refining stage, accounted for about half of the production of bar iron in Britain by 1780.[9] Cort's puddling process, which he had operating at Fontley by 1784, eliminated the need for pots in the reverberatory furnace. No samples of the iron he made have been located for laboratory study, but extensive tests done on it at several Royal Navy dockyards in 1784-6 showed that it was a product of good quality.[10] Cort made puddled iron at Fontley until his bankruptcy in 1789 and production was continued by others thereafter. The subsequent history of Fontley Forge is obscure but John Bartholomew, a puddler who worked with Cort, is thought to have purchased the forge in about 1813. By 1840 the works were in decay.

No controlled excavations have been carried out at the site of Fontley Forge and archaeological reports on Fontley by Freeman[11] and Riley[12] are primarily concerned with the water power system used there. It does not seem possible to make a reliable estimate of the amount of iron puddled at Fontley but there is little doubt that it was sufficient to have produced much of the slag now present about the site. However, slag samples from Fontley cannot be positively associated with Cort's process until a careful excavation is made. The samples analyzed were collected at the ground surface in the Fall of 1983 at the approximate location of Cort's puddling furnace.

The process used by Henry Cort is now called "dry puddling" and was supplanted by the faster and more efficient wet puddling process after about 1818.[13] In dry puddling the oxidizing agent is air and a sand bottom is used on the hearth of a coal-fired reverberatory furnace. The metal that is oxidized during the process reacts with the sand to form a fayalite slag. Because the resulting attack on the furnace bottom is rapid, it is necessary to avoid accumulation of slag by draining it from the surface as it forms.[14] White cast iron or refined pig is required for starting material, the loss of iron is large, the process is slow, and removal of phosphorus by the slag is ineffective in dry puddling.[15] However, the metal on the hearth is protected from sulfur in the furnace gases by the slag and the flow of air through the hole in the side of the furnace used by the puddler to work his charge.[16]

There is no description of the construction of the furnace used by Cort but references can be drawn from changes made by Crawshay in the puddling furnace he built at Cyfartha according to Cort's specification. He replaced the clay ceiling and, for the bottom made of common earth, substituted sea sand.[17] It is likely that Cort would have obtained the sand for his furnace bottoms form the closest available source. Fontley Forge is sited on alluvium and the closest adjacent geological formation is the Reading Beds. However, the closest likely source of silicia-rich sand would be the Plateau Gravel, which appears within 0.3 mile to the west and 0.4 mile to the north of the works.[18] The gravel in area is described as sandy, ocherous, and partly stratified, containing masses of sand. A number of sand and gravel pits have been opened in this formation near Fontley.[19] Beds of London clay were worked for bricks near Fontley but the bricks made were of indifferent quality.[20] It appears that Cort could have obtained high quality refractories and furnace bottoms only at the cost of considerable expense for haulage.

We have found no published analyses of slag from dry puddling, but expect it to be a tap slag having a composition near that of fayalite with relatively few impurities.

Mine Hill

The second set of samples is from the site of the American Silver Steel Company at Mine Hill in Roxbury, Connecticut. This was the first integrated steel works in America and the manufacture of puddled steel from locally-mined siderite ore was carried on here in 1867-68, after which steel production ceased although the blast furnace continued in operation until 1872. The site remained undisturbed after the closure of the works and slag samples collected at the site can be positively identified with the process used. Samples of the pig iron, wrought iron, and puddled steel made at Mine Hill were placed in the Metallurgical Museum of Yale College in 1868[21] and a "Pudling Book" giving the names of the puddlers and their production survives. The remains of the steel mill were located during an archaeological investigation of the blast furnace which supplied the pig for steel making.[22]

A thorough study of the history and technology of steel puddling has been made by Barraclough.[23] Steel puddling was used in the mid-19th century, primarily in France and Germany, for large scale production of steel until it was supplanted by the open hearth process. Its principal advantage over the Bessemer process was that phosphorus could be removed. The procedure and equipment used were generally similar to those for puddling iron but the puddler attempted to stop the oxidation of carbon before the metal was completely decarburized. This was difficult to attain since the puddler had only limited control over the process and few means of estimating the progress of the refining reactions. More manganese than was usual in iron puddling slags was used in steel puddling to slow the oxidation of carbon and afford the puddler more time to adjust the composition of his product.

The puddlers at the American Silver Steel Company succeeded in making steel of good quality but the cost of operating the works proved to be too high for the company to compete with the output of steel works which were then beginning to use the Bessemer process and were located in more favorable geographic settings. Railway transportation did not reach Mine Hill until after the steel works closed and only locally-produced mineral and fuel resources could be used in the furnaces. Two factors contributing to the high costs at Mine Hill were the hard rock mining methods required to obtain the siderite ore and the use of charcoal fuel for the blast furnace and wood for the puddling furnace.

Descriptions of the Samples

Polished sections of the samples of slag were prepared for study by reflected light microscopy. The volume percentages of the various constituents were estimated by a 300-point count on the specimen as seen at 400x magnification. We also examined thin sections and obtained semiquantitative analyses of phase compositions with an electron microprobe attached to a scanning electron microscope. (The microprobe data were reduced by a standardless "ZAF" computation scheme. The lower limit of detection is about 0.1%.)

Constituents Present

Fayalite

Fayalite is the most abundant phase and can be distinguished from other iron silicates by the combination of high birefrinfence, straight extinction and the absence of colour or cleavage as seen in thin section.

Magnetite

According to Wingrove[24], dendrites of wustite are usually well rounded and those of magnetite faceted, but this distinction is not completely reliable because the form of dendrites is influenced by the rate of cooling. She did, however, demonstrate a significant difference in the microhardness of pure wustite (HV 506) and pure magnetite (HV 639) measured at a 25 gram load. We measured the Vickers microhardness at a load of 25 grams on the larger iron oxide crystals in our specimens, finding, in "A" HV 741 (N = 10; range 706-792); in "B" HV 782 (N = 10; range 724-824); in "D" HV 744 (N = 5; range 715-824; and in "G", HV 680 (N = 5; range 641-742). In each case the combination of faceted rhombic habit and high hardness identifies the measured phase as magnetite.

Wustite and magnetite can be distinguished, where both occur in the same section, by slight differences of colour in reflected light under oil immersion; wustite is greenish white and magnetite pale pink or brown. Maghemite (α

Fe_2O_3) is present in sample "G" as an alteration product of magnetite; it can be distinguished from the latter by its greater reflectivity and pale blue tint, and from haematite by the lack of red internal reflections or strong anisotropy.

Silica
Silica is present in the specimens studied in the form of its three polymorphs stable at atmospheric pressure, quartz, tridymite, and cristobalite. Examination in thin section or by X-ray diffraction is needed to distinguish these. All have low birefringence, but it is higher in quartz than in tridymite and cristobalite, where it can only be detected with the aid of the quarter-wave plate. Cristobalite and tridymite have moderate negative relief. One feature which distinguishes them is the wedge-shaped twins of tridymite and the interpenetrant twins of cristobalite.

Iron sulphide
Small circular or elliptical, cream-coloured dots of an iron sulphide, usually 1 to 5 microns in size but as large as 30 microns, are present between the fayalite crystals in these slags. Under oil immersion at 900x they are not noticeably pleochroic but are anisotropic from red-brown to grey as seen under crossed polars. Semiquantitative analysis of some of the larger dots gave a composition around 69% Fe and 31% S. We have not found a close match between the observed optical properties and those of any of the common iron sulphide minerals. Some of the sulphide particles contain a purple-grey, isotropic constituent, which is probably MnS.

Anorthite
The plagioclase feldspar anorthite ($CaAl_2Si_2O_8$) is present as laths which may be recognized in thin section by their very low relief, multiple twinning parallel to the axis of elongation and inclined extinction. They give a biaxial negative interference figures of high 2V and show first order yellow as their maximum interference colour in a section of standard thickness.

Hercynite
The spinel hercynite ($FeAl_2O_4$) is present in one sample as euhedral rhombs, opaque in thin section. In polished section, they have very low reflectance, a purple tint in blue light, and are isotropic.

Fontley Forge

Sample "A"

The hand specimen, shown in Fig 1, has a ropy appearance; each strand of slag is a separate flow 4 to 5mm in diameter, firmly welded to its neighbors. The structure suggests that the block was formed by a slow, steady exudation of molten slag from the furnace. The surfaces are dark grey and glossy. Fracture surfaces are hackly and show an irridescent play of colours. The boundaries of individual flows are clearly visible without magnification on cut surfaces and very slender grey laths up to 2mm in length can be seen in the core of each flow. The average bulk composition is 63% FeO, 36% SiO_2 and approximately 0.5% each of Al_2O_3 and S.

Figure 1. Hand specimen of sample "A" from Fontley Forge showing ropy structure.

The dominant phase is fayalite, present as slender laths with triangular or irregular ends. In some areas, parallel stacks of laths have evidently grown by elongation until impeded by other, parallel stacks, giving rise to striking geometric patterns like those of a log jam on a river. The boundaries between adjacent flows are marked by a continuous, bright, 2 to 3 microns wide ribbon of magnetite. Rhombs of magnetite, up to 0.1mm across the diagonals, are abundant near the flow boundaries and are unevenly dispersed within the core of the flows, where they occur in the interstices between laths of fayalite. The interstitial spaces between fayalite laths also contain bright, circular, cream-coloured dots of an iron sulphide less than 10 microns in diameter. Small, dark, rounded masses of tridymite and cristobalite are abundant in the groundmass, and have been incorporated into the margins of some fayalite laths (Fig. 2). Examples examined with the microprobe appear to be largely composed of silica with variable but minor iron content, but electron beam overlap onto adjacent phases prevented us from obtaining a reliable analysis. The oval inclusions in this slag, each about 1 x 0.5mm, are full of tiny rectangular colourless laths with very low birefringence. They are tentatively identified plagioclase feldspar from their similarity to the laths observed in sample "C".

Above 500x in reflected light the groundmass is resolved into a complex intergrowth of three phases (Fig. 2). The brightest phase is magnetic. The medium grey phase appears, from its reflectivity and chemical composition, to be fayalite. We were unable to determine whether the dark, continuous constituent is a mineral phase or a

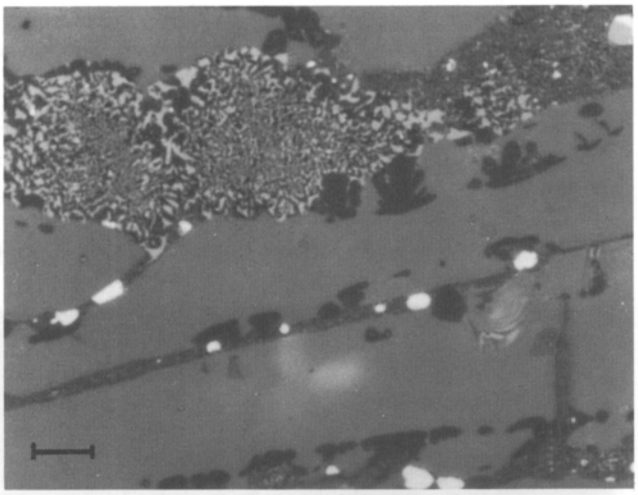

Figure 2. Reflected light micrograph of sample "A" showing fayalite laths (light grey) some of which incorporate dark rosettes of cristobalite or tridymite. The bright, rounded dots are iron sulfide; one shows a second, unidentified constituent. A fine intergrowth, barely resolved, of magnetite, fayalite, and glass forms the groundmass. The length of the scale bar is 0.01mm.

glass since the scale of the intergrowth is so fine that it is always opaque in thin section. It is too small to make reliable microprobe measurements on but appears to be composed largely of iron oxides and silica with minor aluminium, calcium, and sulfur. No phosphorus was detected in this or any other constituent.

Sample "B"
The hand specimen is a block that was broken from a larger piece of slag. The broken faces are coarsely crystalline and irridescent; individual crystals as large 5 x 1mm are visible on a cut surface. There are remarkably few gas cavities in comparison to most ferrous slags.

The microstructure is very similar to that of sample "A", but the primary fayalite laths are much larger, generally euhedral, and in random orientaions. A single, continuous, thin seam of magnetite divides two flows that are not apparent in the hand specimen. Many of the fayalite crystals are not fully developed and the interdendritic spaces are filled with other constituents. There is a higher volume percentage of magnetite in "B" than in "A". It is present as large rhombs (up to 0.8mm across the diagonal) and also as angular, faceted dendrites (Fig. 3).

Circular dots of iron sulphide generally 10-30 microns in diameter and are located in the interstitial groundmass and in the interdendritic filling in fayalite crystals together with small rounded masses of tridymite and cristobalite. The groundmass is very fine. At 1500x discontinuous, angular crystals of magnetite can be distinguished against a speckled background, the composition of which is uncertain.

Sample "C"
The hand specimen is a 30 x 10mm bun-shaped piece.

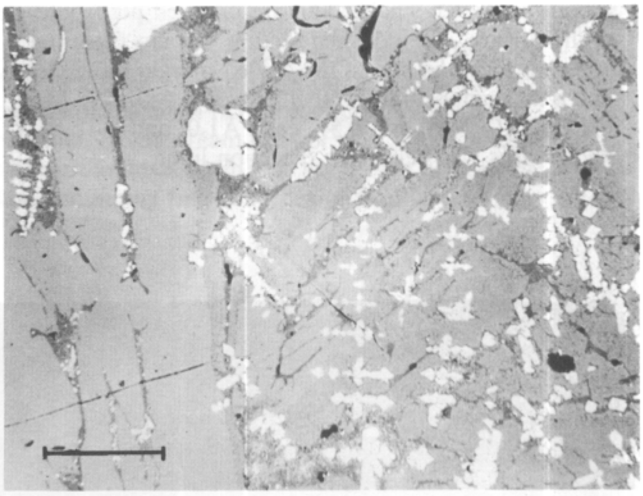

Figure 3. Reflected light micrograph of sample "B" from Fontley. Light grey laths of fayalite are the primary constituent; the bright rhombs and dendrites are magnetite. The groundmass (dark grey) is unresolved at this magnification. The length of the scale bar is 0.1mm.

The lower surface is flattened and pitted while the upper is smooth and displays folding; the texture resembles that of elephant hide. The crystals are too fine to be seen without magnification in a cut section, and the porosity (in the form of spherical cavities) is high. The average analysis determined with the microprobe is 46% SiO_2, 21% FeO, 18% Al_2O_3, 14% CaO, and less than 1% each of K_2O and S.

The microstructure and composition of this specimen are quite different from those of samples "A" and "B". The first phase to have formed is present as elongated, featureless, dark laths (Fig. 4). Semiquantitative microprobe analysis of this phase gives 51% SiO_2, 25% Al_2O_3, 20% CaO. The composition and optical properties suggest that it is anorthite ($CaAl_2Si_2O_8$).

The small laths, often skeletal, with medium grey tone in polished section are fayalite. The sample also contains many ragged rhombs of spinel. Often these are strongly zoned, as in Fig. 4. The inner grey portion is hercynite ($FeAl_2O_4$); the outer bright portion is titaniferous magnetite. Microprobe analysis of the latter shows that the magnetite contains about 10% TiO_2 and 8% Al_2O_3. Very fine dendrites of titaniferous magnetite are visible at high magnification in the groundmass together with numerous cream coloured dots of iron sulphide 1 to 5 microns in diameter. The groundmass is a deep brown glass speckled with tiny crystallites.

Mine Hill

Specimen "D"
The hand specimen is a flat-bottomed cake of slag 40 to 50mm thick with a domed and wrinkled upper surface It has been broken from a larger block; the broken surfaces are coarsely crystalline and irridescent. Crystals near the lower, flattened surface are up to 10mm long and in random orientation; crystals near the upper

surface are much smaller and are oriented perpendicular to the surface. The polished section was cut from the upper surface and shows the chilled margin quite clearly. The bulk composition is 60% Fe0, 34% $Si0_2$, 2% Mn0, 1% Ca0, 1% Mg0 and 0.5% each $A1_20_3$ and S. Phosphorus was below the detection limit.

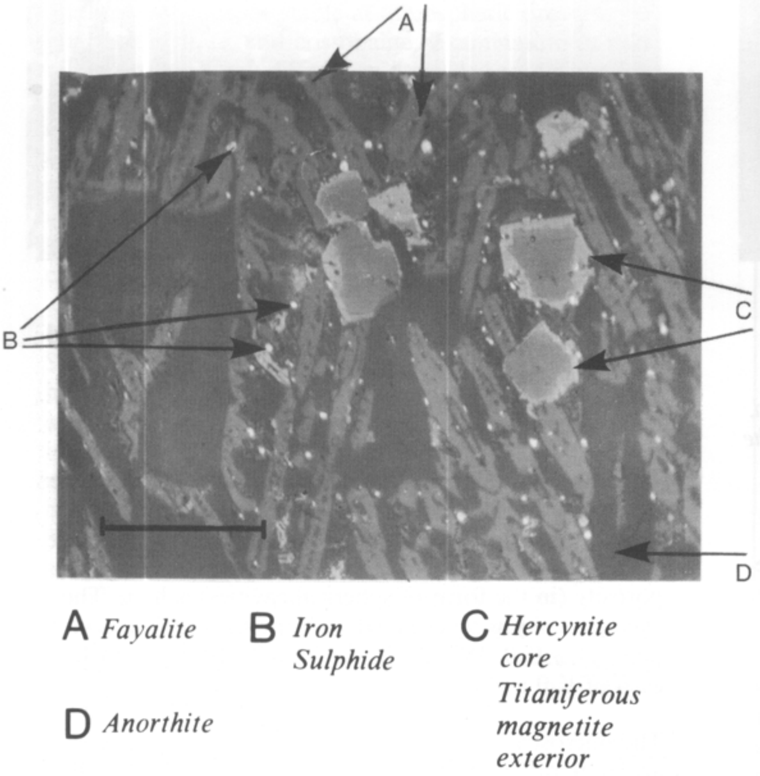

Figure 4. Reflected light micrograph of sample "C" from Fontley. The dark laths are anorthite; the light grey, skeletal laths are fayalite. The zoned crystals are spinels; the inner, dark zone is hercynite and the outer, light zone is titaniferous magnetite. The small bright dots are particles of iron sulfide. The groundmass is a glass. The length of the scale bar is 0.5mm.

The dominant phase is fayalite, which is present in stubby laths, invariably skeletal, with ragged ends. The outer portions of many fayalite laths are finely speckled with dots of another constituent (Fig. 5); examples of these dots examined with the microprobe were too small to provide dependable analyses but seem to be mostly silica. At 100x, the area between fayalite crystals are seen to be filled with a bright, feathery structure, which at higher magnification can be seen to be branching dendrites of magnetite. Almost all the magnetite in the sample is in dendritic form. A few rhombs with diagonal lengths up to 40 microns occur among the dendrites; they contain 1% $Ti0_2$, 2% $A1_20_3$ and 2% $Si0_2$.

Bright dots of iron sulphide occur in the groundmass between fayalite laths. Most are less than 5 micron in diameter but a few are as large as 15 microns. The microprobe showed one of these to contain approximately 68% Fe and 31% S. The optical properties are the same as those noted for the iron sulphide phase in the Fontley Forge samples and the same purple-grey isotropic second phase is present in a few examples. Rounded or rosette-shaped masses of tridymite or cristobalite are present in the groundmass and in the margins of the fayalite laths. They are up to 15 microns in diameter.

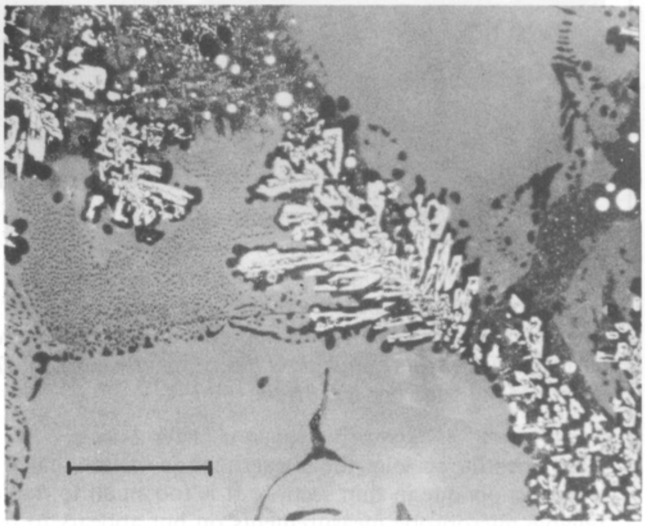

Figure 5. Reflected light micrograph of sample "D" from Mine Hill. The large, light crystals are fayalite; the outer margins are speckled with fine dots of a second constituent. The dark dots are tridymite or cristobalite; the white dots are iron sulfide. The bright, angular crystals and branched dendrites are magnetite. The groundmass is unresolved. The length of the scale bar is 0.05mm.

The groundmass consists of a very fine intergrowth of magnetite, fayalite and a third constituent, which is continuous, and usually no more than 2 to 3 microns wide. Although overlap of the electron beam of the microprobe onto adjacent phases prevented us from obtaining a reliable analysis, this appears to be mostly iron and silicon, with high levels of aluminium and calcium. It also appears to contain all the detectable phosphorus in the sample.

Sample "E"

The hand specimen, broken from a larger block, is a 2kg piece made up of several flows welded together. The flows at the base are flattened, and those on the top have a ropy texture. The boundaries of the flows are clearly visible as thin lines black lines backed by a chill zone. The core of each flow is packed with olive-coloured needles up to 3mm long. These are large gas cavities within the block.

The microstructure is similar to, but less coarse than that of "D". Flow boundaries are marked by continuous ribbons of magnetite 2 to 4 microns thick. The fayalite laths of the chill zone are much smaller than those in the core and tend to form arrays perpendicular to the surface. In the core the fayalite laths are stubbly and invariably skeletal. As in "D", the outer margins of the fayalites are densely speckled with dots of another constituent. The interstices between fayalite laths are filled with feathery intergrowths of fine, angular magnetite and a dark continuos matrix. Small rhombs of magnetite (up to 15 microns) and bright circular dots of iron sulphide (2-5 microns) are also dispersed in the interstices.

The rounded masses and rosettes of cristobalite or tridymite are much larger than in the other specimens. They are invariably cracked and show striking intergrowths with magnetite (Fig. 6). Both the wedge-shaped twin crystals of tridymite and the interpenetrant twins of cristobalite can be seen in thin section.

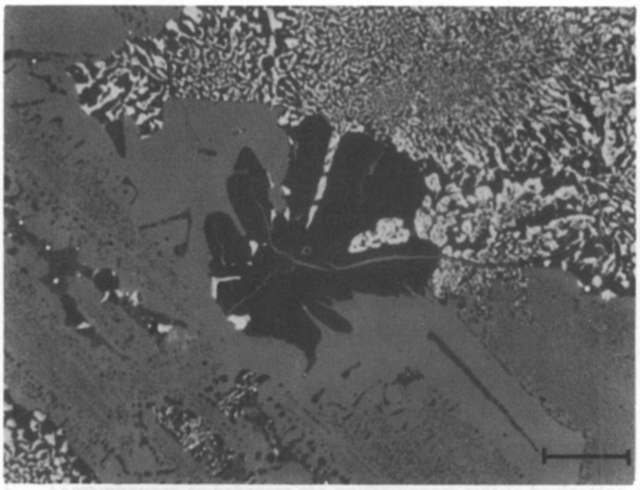

Figure 6. Reflected light micrograph of sample "E" from Mine Hill. The grey phase is fayalite, the outer edges of which are densely speckled with an unidentified constituent. The large, dark area is silica in the form of tridymite or cristobalite intergrown with angular, bright particles of magnetite. The cracks are filled with an unidentified iron oxide. The interstices between the fayalite laths contain a glass filled with feathery magnetite. The length of the scale bar is 0.05mm.

Sample "F"

The hand specimen is a polyhedral chunk about 30mm on a side. Only a small part of the original glossy, wrinkled exterior surface remains. The broken surfaces are coarsely crystalline and irridescent. Several flow boundaries are apparent in cut faces as thin, continuous dark lines backed by a smooth featureless zone a few millimeters thick. Slender laths of fayalite up to 5mm in length pack the cores of the flows. There are many small cavities, usually less than 0.5mm in diameter.

The dominant constituent in this section is fayalite. Flow boundaries are seen in the polished section to be marked by thin (2-4 micron), continuous seams of magnetite. The chilled margins adjacent to the magnetite seams contain small rhombs (15 microns) of magnetite and short, slender fayalite laths. There is marked coarsening of structure in the core of the flow, where fayalite laths are up to 5mm long and often display the same strikingly geometric patterns noted for sample "A".

Magnetite is dispersed through the groundmass as small rhombs (10-15 microns) and as branched, feathery dendrites. It also forms rings on, and intergrowths with, rosettes of the silica-rich phases cristobalite and tridymite. Bright cream dots of iron sulphide dispersed in the groundmass, which is composed of deep brown glass containing fine dendrites of fayalite and magnetite.

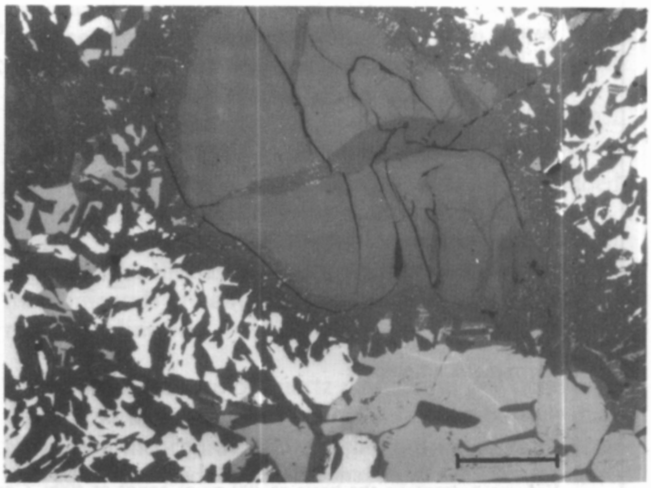

Figure 7. Reflected light micrograph of sample "G" from Mine Hill. The central, medium grey, heavily cracked constituent is a quartz grain. It is surrounded and penetrated by glass, and surrounded by an intergrowth of magnetite (white) and cristobalite or tridymite (dark grey). The light grey areas are fayalite. The unfilled cracks are formed during cooling and are due to the relatively large expansivity of quartz. The length of the scale bar is 0.1mm.

Sample "G"

This is a small finger of slag 15mm long by 5mm in diameter. The polished section reveals a black matrix containing many white particles of quartz up to 2mm long. They are invariably cracked, show the undulatory extinction characteristic of strained quartz, and are surrounded and penetrated by a darker material, which appears to be a glass. The outer fringes of the reaction rim surrounding the quartz particles are enclosed by a complex intergrowth of magnetite and cristobalite or tridymite (Fig. 7). The sample also contains ragged flakes of pyroxene and amphibole. It is clear from the texture visible in the thin section that the pyroxene and amphibole are not reaction products and so must have come from some material placed in the puddling furnace. There is little fayalite present in the regions of quartz/cristobalite/magnetite intergrowth, and the assemblage as a whole has clearly been arrested at the very early stages of reaction.

Magnetite has been altered to maghemite ($\alpha \mathrm{Fe}_2\mathrm{0}_3$) around the outer edge of the sample. Where the alteration is at an early stage, the maghemite can be seen as a grid of light blue lines along preferred crystallographic planes of the host magnetite, which appears brown in colour.

Table 1 Mineral Content of Puddling Slags

	Fontley			Mine Hill			
Mineral				Sample			
	A	B	C	D	E	F	G
Fayalite	69	66	35	70	70	61	8
Magnetite	2	22	4	12	9	5	29
Iron sulphide	3	1	3	2	2	2	—
Tridymite & cristobalite	3	*	—	8	8	12	24
Groundmass	23	11	16	8	11	19	10
Feldspar	—	—	39	—	—	—	—
Hercynite	—	—	3	—	—	—	—
Quartz	—	—	—	—	—	—	16
Pyroxene & amphibole	—	—	—	—	—	—	13

Notes:

Volume percent on the basis of 300 point count at 400x. Constituents unresolved at this magnification are recorded as groundmass.

* Present but less than 0.3%.

— Absent.

Summary

The mineral contents of the slags studied are summarized in Table I. Fayalite is present in all the slags and is the dominant constituent in all except "C" and "G". Iron oxide is also present in all and occurs only as magnetite. In specimen "B" magnetite is a primary constituent; it began to crystallize before the fayalite. In the others, it occurs in the groundmass between the fayalite laths and, in those samples composed of more than one slag flow, it forms the boundaries of the individual flows. The other constituent found in all the samples is iron sulphide. It is always in the form of small dots dispersed in the groundmass.

Silica in the form of cristobalite and tridymite is present in all the samples except "C"; in "G" it is also found in the form of quartz.

Hercynite is found in sample "C", the only slag to contain much alumina. Pyroxene and amphibole are present only in sample "G", but are impurities in the sand bed of the furnace rather than reaction products.

Interpretation

All of the samples except "C" and "G" have the composition and structure expected for puddling slags formed by the reaction of magnetite with sand. The dominant constituent is fayalite. Iron oxide is present only as magnetite; wustite, the principal form of iron oxide found in bloomery and finery slags, is absent. The only source of iron in dry puddling is the scale formed on the pigs as they are exposed to the oxidizing atmosphere in the furnace during melting. In wet puddling additional iron oxide (in the form of mill scale) is part of the furnace charge. The iron oxide remains magnetite in the puddling slag because oxidizing conditions are maintained in all parts of the hearth throughout the entire process. In a finery, both oxidizing and reducing zones surround the tuyere and slag brought into the oxidizing zone by the finer must pass through the reducing zone as it returns to the bottom of the hearth. Reducing conditions are required for the reduction of ore to metal in a bloomery. Hence, wustite is expected to be present in both bloomery and finery slags.

Since accumulation of slag must be avoided in dry puddling, slag would be tapped from the furnace during the process. The more or less steady tapping of small amounts of slag would account for the flow textures observed in the specimens from Fontley.

The details of the puddling process used at Mine Hill are not known to us from any independent source. The Mine Hill slags are remarkably similar to those from

Fontley in mineral content and structure and were probably formed in much the same way. Their manganese content is higher, however. According to Barraclough[23], manganese-rich slag was used in steel puddling to slow the rate of oxidation of carbon in the pig in the final stages of the conversion to steel so as to allow the puddler more time to adjust the composition of the heat. The Mine Hill puddling slag contains about 2% Mn, substantially less than the 9% manganese reported in samples of European steel puddling slag.[23] If duplication of the European steel puddling process was intended, then it appears that the puddlers at Mine Hill used too little manganese. This may be because no source of manganese other than that contained in the ore (see Table II) was conveniently available.

Table II

Analysis of Ore from Mine Hill

FeO	53.4 percent
CO_2	34.8
Al_2O_3	0.7
SiO_2	2.2
MnO	2.8
MgO	3.1
CaO	trace
S	0.4
P	trace

Source: Analysis by Simms & Wainwright, New York
27 February 1900

Additional characteristics of the puddling slags to be explained are the presence of iron sulphides and silica, and the absence of alkalis and phosphorus. Sulfur could enter the slag from the pig iron or the fuel. It is likely that the pig used at Fontley was from the charcoal-fired blast furnaces and so would have contained sulfur. There would have been sulfur in the mineral coal used to fire the puddling furnace and the products of combustion pass over the liquid slag on their way from the fire grate to the furnace stack. Some sulfur from these gases was retained by the slag.

Sample "G" is of special interest for the interpretation of the silica found in all of the slag samples. The quartz particle shown in Fig. 7 is in an early stage of a reaction with magnetite that has been arrested by the premature cooling of the slag. The high temperature polymorphs of quartz, tridymite and cristobalite, are also present but this cannot be used to estimate the temperature attained by the slag because the inversion temperatures are shifted by large amounts when aluminium together with divalent cations such as magnesium or calcium are present in the melt.[25] The unreacted quartz, amphibole, and pyroxene in "G" must have originated from the furnace refractories, the bed of the furnace, or some material added during the puddling process. Optical and microprobe analysis of a thin section of a part of a furnace wall found at the steel mill site at Mine Hill shows that the fire brick used consists of subangular particles of cristobalite or tridymite in a structureless matrix. Only Si and A1 are detected in the matrix by microprobe analysis. Mullite needles are present where the brick has been in contact with slag. We conclude that the brick was made of quartz grains in a clay binder and that if silica were to enter slag by decomposition of the brick, aluminium would also. Since the latter is not found, it appears that either a sand bottom was used (which would be contrary to usual practice in steel puddling) or that sand was added to the furnace charge at some point in the puddling process. The presence of amphibole and pyroxene suggests that the sand was from a local source because these minerals are abundant in the local metamorphic rocks at Mine Hill.

The principal source of quartz particles in dry puddling slag would be sand grains from the furnace bottom that have been incorporated in the slag during stirring of the charge by the puddler; additional sand may have entered the slag on the surface of the iron pigs used. The presence of anorthite in two of the samples from Fontley Forge suggests want of care in selecting appropriate sand for the bottom of the puddling furnace.

The alkalis usually found in bloomery slag and often responsible for the presence of leucite ($KA1Si_2O_6$), are absent in the puddling slags. The source of alkali in the bloomery is charcoal ash and, since in a puddling furnace the fuel is not in contact with the melt, there would be no source of alkali if the furnace were fired with wood or charcoal. The slag formed in wet puddling can remove up to about 80% of the phosphorus in the pig[26] but dry puddling slag, with its low content of iron oxide, probably would be less effective in dephosphorizing iron. This would account for the absence of phosphides in the slag samples.

Specimen "C" is distinctly different from "A" and "B" and does not have the constituents expected in puddling slag. We hypothesize that this may be slag that has been contaminated by inclusion of impure, locally obtained sand containing calcium carbonate, which is abundant in the geological formations near Fontley Forge. A trace of the same impurity is present in sample "A".

The results obtained on these two sets of slags suggest that while it is not possible to distinguish puddling slags from finery and bloomery slags on the basis of their bulk compositions, this distinction may be made from examination of their microstructures. The most diagnostic difference is the absence of wustite. When iron oxide is present in finery and bloomery slags, it is predominantly in the form of wustite. (Failed bloomery slags may contain small amounts of magnetite.[27]) The absence of alkali and of the mineral leucite is also characteristic; the presence of sulphides is suggestive of puddling. These generalizations need to be tested by examination of other examples from sites for which the process used is known.

Acknowledgement

We thank Alan Pooley for assistance with the microprobe analyses, Arthur Goodhue and Wallace Phelps for help with preparation of the specimens, and Kenneth Barraclough, Stig Blomgren, Erik Tholander, and William Rostoker for helpful discussion. The collection of slag samples at Mine Hill was made during an archaeological study of this site carried out by Raber Associates for the Roxbury Land Trust.

Note

The notation (N = 10, etc.) after the microhardness values is the standard notation for the number of individual determinations upon which the (average) microhardness value is based. As microhardness shows much greater variation with crystallographic orientation in silicate and oxide minerals than in metals, it is standard practice to indicate the number of points sampled. We sampled 10 points except in samples D and G, where we could not find enough magnetite crystals of sufficiently large size for a valid microhardness determination.

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The change from charcoal to coke in iron smelting

J E Rehder

Abstract

From the two bases of 19th century American experience with alternate blast furnace fuels and of modern knowledge of combustion, it is possible to construct with some confidence the changes that occurred when Abraham Darby in 1709 first operated an iron blast furnace on coke instead of charcoal as fuel. Production rate would have fallen by more than one third, nearly 80 percent more air would be required per ton of iron made, and the tapped iron would be at higher temperature, be more fluid, and would make machinable thin-sectioned gray iron castings. The need for more air proved to be a serious problem, which was solved finally by the use of steam power. The coke smelted iron made possible the castings that were essential for the construction of the new steam engines that were being developed, and there was a symbiosis that was productive but that took 40 to 50 years to mature. The new coke pig iron was not popular at the finery because the softer iron took longer to fine and had higher losses, but the correction for this was worked out and from the 1750s onward, charcoal furnaces were steadily and increasingly rapidly converted to coke fuel.

When charcoal is replaced by coke in a blast furnace, several considerable changes take place in the furnace operating parameters because of the quite different combustion characteristics of the fuels. These have been largely forgotten since the few charcoal furnaces still operating do not customarily change fuel. However change back and forth between charcoal and coke in the same furnace was a common practice in the eastern United States in the late 19th century, and was well recorded. This information combined with modern knowledge of solid fuels and their combustion makes it possible to reconstruct with some confidence the consequences of such changes in fuel.

This can be useful in the study of historical events which ocurred when few technical records were kept, and applies particularly to the original use of coke to replace charcoal in the blast furnace, by Abraham Darby in 1709. Few details of operating procedures or experiments were then recorded or at least survive, but reconstruction of what necessarily happened and had to be dealt with should be instructive, and can possibly help to explain the slow progress from initial use of coke to more general use 50 years later.

The procedure here will be to establish the kinds and extent of operational change produced by the change from charcoal to coke, for which an excursion into the physics and chemistry of combustion in fuel beds will be necessary. It will then be established what a normal charcoal fueled operation would likely have been in Darby's furnace in 1709, and on this basis to then show what changes the operation of the same furnace on coke would produce. The changes can then be compared to what actually happened as shown by the surviving record. The subsequent progress to general acceptance of coke smelting can then be examined, and comment made on further development of furnace design. The historical record is based principally on Raistrick[1] and Mott[2].

Combustion of Charcoal and of Coke in Packed Beds

A blast furnace is basically a device for oxidizing carbon in lump form as a packed bed, the conditions of combustion depending on the physical and chemical properties of the fuel, and the reduction of metal oxides being ancillary. In modern blast furnaces with high air preheat temperatures and high tuyere velocities a tunnel or raceway is formed at the nose of each tuyere and combustion takes place within the raceway very largely to carbon monoxide and nitrogen. However with ambient temperature air and lower blowing rates such as were used up until the first quarter of the 19th century, raceways are not formed and the sequence of combustion events is extended physically into the fuel bed.

In such circumstances combustion is characterized by a very high temperature zone of oxidizing gas close to the tuyere nose (a few lump diameters distance), followed by a considerably longer zone of gas of decreasing temperature and increasing carbon monoxide content as the initially high carbon dioxide content is reduced by surrounding fuel. The length of these zones and the rate of reduction of carbon dioxide are strongly affected by the chemical reactivity and the lump size (surface area) of the type of carbon being burned. This process has been extensively explored by Hiles and Mott[3].

Charcoal is a highly reactive form of carbon, in the order of ten times that of coke, and initial combustion with cold blast is to 10 to 12 percent carbon dioxide, which creates an adiabatic flame temperature of about 1,920°C within a few cm. of air entry. This carbon dioxide is then rapidly reduced to carbon monoxide by passage through more fuel, the reduction being complete typically within 40 to 60 cm. of air entry at the the velocities used in early 18th century furnaces. However with coke which is much less reactive, the maximum initial carbon dioxide on combustion is about 17 percent, which creates an AFT of about 2,070°C, and the zone of carbon dioxide to carbon monoxide reduction is much longer because of more carbon dioxide to be reduced and lower reactivity of the carbon.

These high initial temperatures are in fact closely approached in considerable volume in large furnaces with low heat losses, but in the small 18th century funaces the volume approaching such temperatures would be in cu. cm., not cu. m. The important point is that when charcoal is replaced by coke, the working high temperature zone above a tuyere i.e. from about 1,700 to about 800°C, where melting of iron and slag and reduction of ore occur, starts from a higher temperature and extends much farther. This increases the superheating of melted iron and slag and increases the effective furnace volume by stretching it farther up the stack. In essence a coke fueled blast furnace works at a higher initial temperature, but reduction is less intense over a longer distance than when the fuel is charcoal. This was noted by turn-of-the-century writers on blast furnace practice, such as Forsythe[4]. These changes affect the amount of air consumed per unit weight of fuel burned, the amount of fuel needed per ton of iron made, and the temperature of the tapped iron. In the operation of an iron-melting cupola, coke fuel will produce iron at about 150°C higher tapping temperature than will charcoal at the same fuel ratio.

19th Century Comparative Experience

In the eastern United States in the 19th century, wooded areas covered fields of bituminous and anthracite coals, and the rapidly growing iron industry became accustomed to using charcoal, coke, or anthracite coal as fuel, changing as local price and availability changed. In the latter half of the century air was generally supplied by steam-driven piston blowers, moderate hot blast temperature was used, and record keeping was good. There are several reports of alternate use of fuels but one of the best was made by Birkinbine[5], and is of particular interest because the furnace size and shape was not greatly different from 18th century practice. In the following summary all quantities have been converted to metric.

The furnace was built originally at Pine Grove in Pennsylvania in 1770 and was remodelled in 1877 with steam-driven cast iron blowing cylinders replacing a water wheel and wooden tubs. The bosh was 2.8 m. in diameter, with working height 11.3 m. The top was 1.5 m. diameter and the crucible was 1.3 m. diameter and 1.5 m. high, with three tuyeres 0.9 m. from the bottom. Hot blast temperature averaged 316°C. Campaigns of a month or more each were made consecutively on several fuels and mixtures of fuels, but only the two on coke and on charcoal are reported here. The figures in Table 1 are averages for about one month, and the production rate data on coke have been decreased to the same blowing rate as with charcoal, since the coke campaign averaged 28 percent higher blowing rate. Blowing rates were reported from engine revolution counts and so are comparable, but they are here decreased by 20 percent to compensate for leakages at the air pump, in the air heater, and in pipe joints. No data were given on fuel lump size or composition.

Table 1 American Operating Data, Charcoal and Coke, Same Blowing Rate

	Chcl.	Coke	Ratio
Production rate, MT per week	97.4	55.9	0.57
Fuel per MT iron, kg	1,120.0	1,550.0	1.38
Air blown per MT iron, cu. m.	4,220.0	7,350.0	1.74
Air blown per kg. fuel, cu. m.	3.8	4.7	1.26

A modern charcoal blast furnace with hearth diameter 2.4 m. and height of 16 m., using charcoal made with the best of modern practice, reported a specific air consumption of 3.9 cu. m. per kg of charcoal, which is a reasonable check.

The Furnace at Coalbrookdale

The charcoal blast furnace leased by Abraham Darby in 1708 was rebuilt and put in blast in January 1709. The rebuilding was very likely to the dimensions and lines commonly used at the time[2]. The height would have been about 6.7 m., with a square or rectangular crucible about 0.3 sq. m. when new and about 1.5 m. high to the start of the bosh. The single tuyere would enter about 0.5 m. from the bottom and internal volume would be about 9.1 cu. m. Combustion air was supplied by two bellows driven by a water wheel whose diameter and bucket capacity are apparently now unknown.

Fuels

Wood was charred in earth-covered heaps with recovery of usable charcoal of only 15 to 20 percent. The amount of charcoal necessary per ton of iron made would obviously vary with ore grade due to the different amounts of slag then made and the limestone necessary to flux it to acceptable fluidity, but average consumption data are available for the period. In 12 furnaces between 1680 and 1705 the average was 1.6 tons of charcoal per ton of iron made, with a minimum of 1.2 and a maximum of 2.0[7].

Coal was carbonized to coke in the same manner with a yield of about 33 percent[2]. The coke made would be more reactive than modern coke because of the low coking temperature, but the wood charring was also at low temperature so the coke would still be much less reactive than the charcoal. The clod coal measure which outcropped near Coalbrookdale was an important factor in Darby's favour because it was suitable for coking in heaps, which many coals are not, and it contained unusually low sulphur and ash contents. The coke necessary per ton of iron made, based on the ratio given in Table 1, would be 2.2 tons.

Ore

The iron measures that lie between the coal seams containing the Clod coal in Shropshire were apparently the source of iron ore supplied to Coalbrookdale by contractors. The ores are carbonates containing an average of 36 percent iron, detailed analyses being available[8]. Since there was no technology available for adequate cleaning, the ore as delivered for the necessary roasting probably contained at least 15 to 20 percent shale, giving the roasted ore a yield of about 30 percent which was typical of the time and locality[9]. Roasting in heaps probably decomposed not more than 75 percent of the carbonate so that about 2.4 tons of roasted ore would be necessary per ton of iron made. The gangue in the ore, plus the shale, the fuel ash, and the limestone necessary to flux them, would produce about 1.3 tons of slag per ton of coke iron made. With coke smelting the iron content of the slag should not be more than about 2 percent, representing in this case a loss of about 2.6 percent of the iron charged, which was negligable in view of the inaccuracies of weighing.

Burden Density

The bulk density of the burden affects the time of travel or resistance in the furnace, and it is higher with a coke than with a charcoal burden. This is shown in Table 2, where the ore charged is that to the furnace after roasting. Extra limestone is necessary to flux the coke ash. The basis is one ton of iron made.

Table 2 Burden Bulk Density

		Charcoal		Coke	
	cu. m.	kg.	cu.m.	kg.	cu. m.
Iron ore	1,600	2,400	1.50	2,400	1.50
Charcoal	240	1,600	6.67	---	---
Coke	480	---	---	2,200	4.58
Limestone	1,280	600	0.47	---	---
Limestone	1,280	---	---	1,200	0.94
Totals		4,600	8.64	6,010	7.02

Bulk density, kg. per cu. m. 532

Furnace Operation

It is now possible to compare the operation of the furnace at Coalbrookdale as it typically would have been when on charcoal fuel, and as it would have been on coke fuel. It is assumed that the rate of air supply is constant.

Charcoal Fuel

On charcoal the production rate of iron is taken as the average of such furnaces at the time, which would be consistant with the average fuel consumption discussed above. Three separate estimates are available for the period 1680 to 1720, not all of which include the same furnaces. 29 furnaces in Schubert[10] averaged 2.46 tons per day, 44 in Mott[11] averaged 2.12 tons, and 44 in Hyde[12] averaged 1.92 tons, all excluding the Weald. The overall average is 2.16 tons per day. With a smelting rate of 2.16 tons per day and a charcoal consumption of 1.6 tons per ton of iron, the rate of charcoal combustion is 2.4 kg. per minute. As noted above in Table 1, 3.8 cu. m. of air are required per kg. of charcoal, so the air supply rate to the tuyere must be 9.1 cu. m. per minute, and the air required per ton of iron made is 6,080 cu. m. Residence time in a furnace of 9.1 cu. m. volume with the burden occupying 8.6 cu. m. per ton of iron as in Table 2, will be 11.8 hours. This is in good agreement with contemporary observation[13].

Coke Fuel

It is now assumed that the same furnace, ore, and air supply are used, but with coke replacing charcoal as fuel. From Table 1 the air required per kg. of coke is 4.7 cu. m., and at an air supply rate of 9.1 cu. m. per minute, the rate of combustion of coke will be 1.9 kg per minute. Since from Table 1, 38 per cent more fuel is required, or 2.2 tons per ton of iron, the rate of production of iron will be 1.24 tons per day. Residence time at 7.0 cu. m. of burden per ton of iron will be 25.0 hours, and the air required per ton of iron made will be 10,900 cu. m.

These figures are collected and compared in Table 3

Table 3 Comparison of Charcoal and Coke Fueled Operations

	Charcoal	Coke	Change %
Production rate, tons per 7 day week	15.1	8.7	-42
Fuel required, tons per ton iron	1.6	2.2	+38
Air required, cu. m. per ton iron	6,080	10,900	+79
Residence time, hours	11.8	25.0	+112

Comment

In Table 3 the extent of the changes produced when coke replaced charcoal as fuel in the same furnace are evident. Production rate decreased seriously, much more air was needed per ton of iron made, and residence time in the furnace was more than doubled.

As noted earlier, operation of a shaft furnace on coke fuel produces higher temperature tapped metal than with charcoal fuel, and this has important secondary effects. Higher temperature iron will reduce silicon from the slag into the iron and dissolve more carbon in the iron from fuel in the hearth. The resulting increase in carbon and silicon contents make the iron more fluid at a given temperature, and this added to the effect of temperature itself on fluidity makes a molten iron much more fluid than that from a charcoal furnace. This makes transfer of iron in foundry ladles easier and the iron will fill much thinner sections in a mold. In the addition the higher carbon and silicon contents of the iron make it solidify as gray cast iron free of hard carbides and easily machinable, in thin cast sections. All of these effects of higher iron temperature made the coke smelted iron very well suited to the gray cast iron foundry business, which after all was a prime original objective of Darby with his patent on sand molding thin-walled kettles. Of course no one at that time knew of the existence of carbon or silicon in iron or their effects, but the coke smelted iron must have been a welcome surprise to Darby and would compensate for shortage in production rate, putting him into a foundry business that was immediately profitable. Before long Coalbrookdale became the principal supplier of machinable gray cast iron cylinders, pistons, and pipes for the various steam engines that were being developed.

The invisible higher silicon content of the coke smelted iron was likely the reason that as pig iron it was unpopular with finers for conversion to bar iron. The silicon would have to be oxidized in the fining operation before the carbon, and so unaccountably the iron would be very slow to come to nature. More fuel and labour would be required, and iron losses would be higher to flux the increased silica in the slag, all of which would increase costs.

Sulphur content of the coke iron would be appreciably higher than that of charcoal iron, coming from the fuel. It would have no effect on the grey cast iron made since by chance most of the ores used contained enough manganese, whose presence and existence were unknown , to neutralize the sulphur as the compound manganese sulphide. However if the pig iron were to be fined to bar iron, most of the manganese would be oxidized out and the resulting iron sulphide would produce hot shortness (poor forgeability) in proportion to its amount. Fluxing of slag in charcoal smelted iron was essentially the use of limestone to decrease the melting temperature of the usually high silica gangue in the ore, to workable fluidity, which was neutral or moderately acid slag which had low ability to absorb sulphur. This practice probably continued into coke smelting.

It is possible that at first the higher temperature of coke iron which would give higher slag fluidity, was taken advantage of by decreasing limestone flux to save money and fuel, since the resulting more acid higher melting point slag could then be handled, and nothing was known about desulphurizing ability. It appears likely however that as time passed, experience accumulated, and higher grade ores lower in gangue content were used, the higher temperature iron made it possible to use an increased limestone to ore ratio to make a higher melting point slag on the basic or higher lime side, which could do some desulphurization. These questions would be worth exploring in the historical record.

Phosphorus in grey cast iron increases fluidity moderately, increases internal shrinkage, and decreases machinability, but when less than about 0.5 per cent is present none of these effects are serious. However in bar iron phosphorus creates cold shortness markedly in smaller amounts. Most of the coal measure iron ores that were widely used contained appreciable amounts of phosphorus, varying from ore field to ore field. There was no effective way of removing it so ore selection was important, and this put charcoal and coke smelted iron in the same position.

Operating Experience at Coalbrookdale

There is apparently no surviving record of what Abraham Darby did at the furnace during the first weeks and months of operation. He would have soon found out that production rate was less than two thirds of what we would have expected from general charcoal experience, but it would not take long to also realise that the iron made was higher in temperature and made thin castings without chilled or white iron edges. The sale record for the first year's operation shows averages per week of only 1.55 tons[14], which after allowing for about 60 per cent yield of poured metal to good castings, would require 2.6 tons of smelted iron. This is only about 30 per cent of what should have been possible.

These considerations and figures suggest that the year was one of trial and error and the building of sales of grey iron castings, and by the end of the first year it should have been apparent that with the new iron unexpectedly so well suited to castings, a future of relatively low production rate making saleable iron castings in a market with almost no effective competitors, since charcoal furnaces do not make grey iron easily, was very acceptable. This is a likely explanation why Darby apparently made a financial profit from the first year and continued to make primarily castings.

There is a gap in the record of sales as shown by Mott, and then in 1718 saleable goods for the year amounted to 258 tons. This would represent nearly the full production of the blast furnace, since an air furnace was in use at least by 1718 to remelt sprues and scrap castings for pouring new castings. If a 45 week year is assumed as suggested by Mott this represents a blast furnace production rate average of 5.7 tons per week, or about two thirds of what would have been possible with enough air. In 1715 a new furnace was blown in, working with a separate dam and pond but fed by the same stream. Evidently the market for grey iron castings was increasing steadily, and by 1734 four other furnaces had been leased or purchased and converted to coke operation.

Materials

The record of materials consumed at Coalbrookdale from 1718 to 1737 is shown in Figure 1[14] and the record of production in four-week totals is shown in Figure 2[15]. From Figure 1 it is clear that ore grade was poor for several years, at its worst in 1722 corresponding to only 17 per cent yield. This implies that the ore used was about half ironstone and half shale, and the resulting slag volume including necessary flux must have been about 4.0 tons of slag per ton of iron made. This is a large slag volume, three times the volume used in the operations analysis above, and the increased heat necessary required considerably more coke with

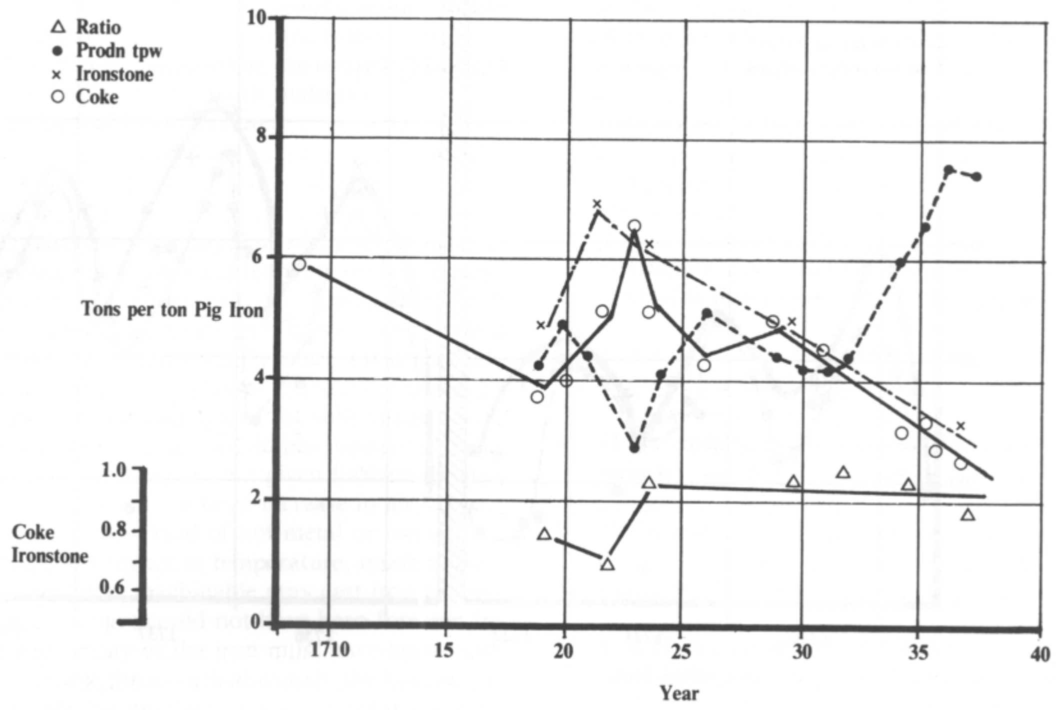

Figure 1 - Materials Consumed and Iron Made, Coalbrookdale 1709-1737

corresponding decrease in iron production rate; about 4.5 tons of coke being necessary to smelt a ton of iron instead of 2.2 tons.

After 1722 something successful was evidently being done with ore cleaning and by 1737 the ore required per ton of iron was down to 3.3 tons, implying a grade of 30 per cent. Coke consumption decreased from about 6.5 tons per ton of iron in 1723 to 2.7 in 1737 and production rate, subject to wet and dry years, varied around an average of about 4.5 tons per week until 1732. Maximum short term rate was 8.8 tons per week in January 1720 which is close to projection in Table 3, and maximum yearly production was 273 tons. This indicates again that on occasion when there was enough water, i.e. air supply, the furnace would produce at the predicted rate.

Air Supply

The rate of air supply for blowing the furnace was directly controlled by the waterflow over the wheel, and in Figure 2 the large variation in iron production rate with water seasonally available is clear, supporting the frequent complaints in the record of not enough water. The water flow was not enough even at best, to fully utilize the furnace capability with either charcoal or coke as fuel.

The installation in early 1734 of a water pump driven by one horse[16] to return about 50 gallons of water per minute from below the water wheels to above them, made a major difference in furnace production rates by increasing their air supply. This was year-round, the effect being visible in Figure 2, and it is clear how starved the furnaces were of air. The pumping rate was not large enough to eliminate all of the summer dificit but when added to winter higher water, gave enough air to reach for short periods production of 10 tons per week, somewhat more than the projection in Table 3. The average production rate over three years was 340 tons per year which is more than 50 per cent above that before use of the horse-driven pump, but still well below the possible 400 tons because of the low water flow rate in summer.

Further Development

Following the clear lesson on the importance of more air for coke operation, in 1742 a Newcomen steam engine replaced the horse on a larger pump[16] and enough water became available to obliterate seasonal variation and to increase production rate to 800 tons per year per furnace[17]. This is more than double that with the horse pump because of elimination of the summer fallow, and double that to be had from the same furnace on charcoal operation, and there would be a marked decrease in the cost of iron made. The demonstration was final that the key limiting factor in production rate was air supply.

800 tons per year is an average of about 17 tons per week, which is about double that in the operations analysis in Table 3. This would require a similar increase in air rate which in turn would need more power. The power required from the wheel is a function of the air rate per minute times the resistance against which it

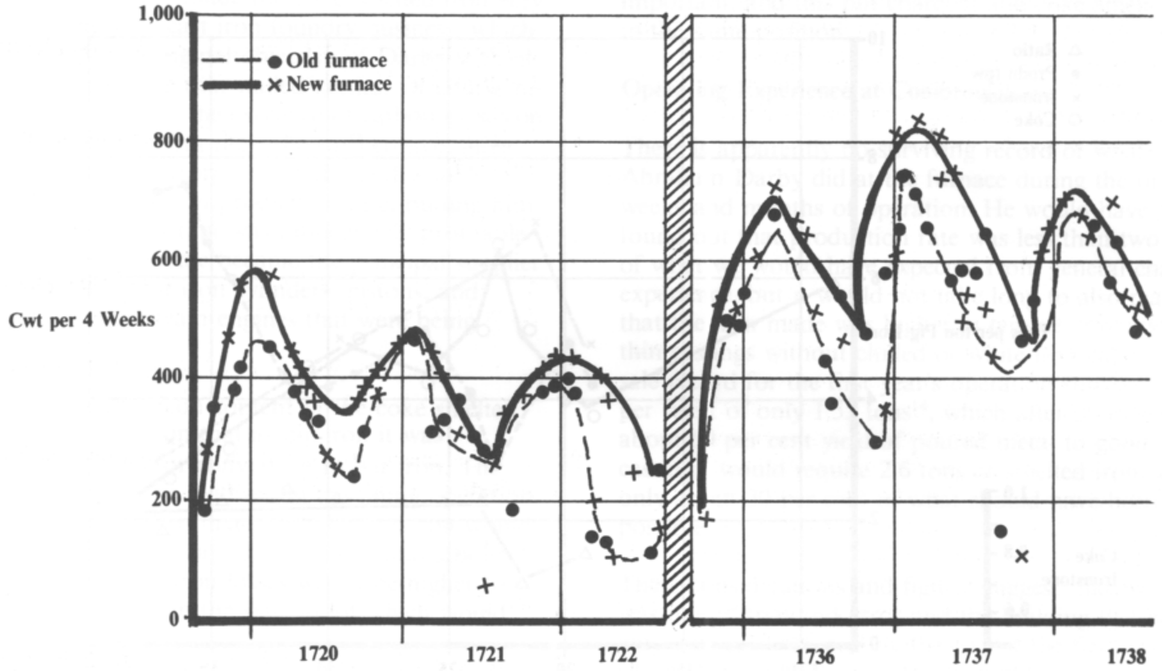

Figure 2 — Production of Iron at Coalbrookdale 1719-1737

works, and the resistance of a given burden is in turn a function of the square of the air rate. Doubling the air rate will therefore require 8 times the power. There is no record of a major rebuild of the water wheel so something else must have been changed, and this must have been the gas flow resistance in tuyeres and burden in the furnace.

Furnace operators must have been aware in a practical way of the considerable effect of tuyere diameter on resistance to air flow, since the resistance increases with the inverse of the fourth power of the tuyere diameter. Also in the furnace profiles typical of the 17th and early 18th century, it can be shown that the gas flow resistance in the narrow crucible created a large part of the total burden resistance. This for example, increasing the tuyere diameter from 6 cm to 8 cm and increasing the crucible dimensions by about 20 per cent or 11 cm. on sides and ends, can be shown to pass twice as much air with no increase in resistance. The increase in power required would then be simply double. It is possible that further adjustments were made to tuyere and hearth size so that no extra power was required from the water wheel, but it is not possible with present evidence to determine what was in fact done. These changes in furnace dimensions are small and within the changes produced by normal erosion during a campaign, so they were unlikely to be recorded.

When still higher production rate were required power requirements inevitably increased further, and in retrospect it does not seem fortuitous that the development of the steam engine occurred parallel to the development of coke smelting. The engines were constructed of thin-walled machinable gray iron castings for cylinders and other parts, which were best made from coke-smelted iron and Coalbrookdale was primarily in the castings business. In the period 1739 to 1748, 43 cylinders and 987 pipes were cast weighing a total of 403 tons[18]. This symbiosis was fruitful for blast furnace practice, leading first to elimination of low production rate in the summer, then independence from stream flow rates since only a recirculated pool was in principle necessary, and finally in 1776 to replacement of both water wheel and bellows by cast iron cylinders in engine and air pump (Raistrick 1970). The blast furnace was then independent of both stream flow and seasonal variation in fuel supply, and could be located wherever coal field and associated ironstone were in good geographical relation to markets.

The success of the steam pump in 1742 with the resulting decrease in the cost of making iron could well have been the signal to other ironmasters that the crucial question of air supply had been effectively answered. By 1760 there were 14 coke blast furnaces[12], by 1775 30, and by 1780 43.

At the same time furnace lines and dimensions were being changed for easier gas and burden flow, and as noted above more attention was very likely being paid to using the higher lime content slags which could be carried in the higher temperature hearths. It should be noted that such slags would produce iron lower in both sulphur and in silicon because of the higher basicity, which would make the pig iron easier and faster to fine and the resulting bar iron less hot-short. It is possible that the 'happy thought' of Abraham Darby II mentioned by his widow in a letter quoted by Mott[19] on how to make pig iron acceptable to the finers, was a realization that higher limestone in the furnace burden would do this. Exploration of such matters on the basis here presented would be interesting.

Summary

The reconstruction of what happens when an iron-making blast furnace is changed from charcoal to coke fuel seems to be on a solid basis from American operating experience in the late 19th century and present day knowledge of combustion, and when this is applied to the original change by Darby in England in 1709, seems to increase understanding of the subsequent events. The principal changes inevitably produced by change from charcoal to coke in a given furnace were decreased production rate, a large increase in air requirement, and a new kind of hot metal or molten cast iron which was higher in temperature, much more fluid, and solidified as machinable gray cast iron in thin sections. These changes could not have been foreseen by Darby, and the quality of the iron must have been most welcome since it by chance suited exactly the kind of product he originally intended to make. Coalbrookdale soon became the leading gray cast iron foundry in Europe. The pig iron was not very welcome at a finery, but this was largely due to the element silicon that made such good iron castings possible.

The ensuing problems were primarily those of air supply, and secondarily those of controlling the amount of sulphur in the iron and making the pig iron easier to fine to bar iron. The first was eventually solved by use of the steam engine, which throughout its development had to have machinable thin-walled gray iron castings, and there was real interdependance.

The second set of problems was soluble only by the use of more lime in slags for pig iron that was going to be fined, to remove sulphur and to decrease reduction of silicon from the slag. This took time because the chemical elements involved were simply not known, but essential to this was the higher hearth and slag temperatures of the coke-smelted iron.

Increased air rates and iron production rates forced changes in tuyere practice and in furnace lines to limit the power necessary for the air supply, and a series of changes ensued which in fact are still going on today, with furnace lines almost straight and vertical and great attention being paid to the resistance of the burden.

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Biography

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.

He is now Senior Research Associate in the Department of Metallurgy and Materials Science, University of Toronto.

Wrought iron again: The Blists Hill Ironworks officially opened

Stuart B Smith and W K V Gale

The official opening of the Blists Hill Ironworks by HRH The Prince of Wales on Friday March 6th 1987 marked the culmination of the first phase of the development of the Ironbridge Gorge Museum, When it was conceived twenty years ago, the Museum set itself six major objectives: to restore the Iron Bridge, establish the Coalport china Museum, conserve Abraham Darby's Furnace at Coalbrookdale, build a Museum of Iron, excavate the Bedlam Furnaces and to create a living museum at Blists Hall which would include a working Wrought Ironworks.

Wrought iron was used by Thomas Telford for the Menai Suspension Bridge and by Brunel for the SS Great Britain; it is the fabric of the Eiffel Tower and of the Statue of Liberty. The manufacture of wrought iron is one of the most spectacular industrial processes, last carried out in this country by Thomas Walmsley of Bolton in 1976. The machinery from Walmsleys has been re-erected at the Blists Hill Museum, within an historic building which once formed part of the Woolwich Dockyard and the manufacture of this most adaptable of structural and decorative materials is about to start again.

The construction of the Ironworks has been the largest civil engineering project ever undertaken by a museum in Great Britain. It has been achieved through the inspiration of the late Reg Morton, first honorary Curator of the Museum, the financial support of the numerous donors, the determination of the staff, Board and Friends of the Museum and the hard work of more than four hundred men employed by the Manpower Services Community Programme Scheme over the last five years.

The short paragraphs above were written by HMS Council member, Stuart Smith (Director of the Ironbridge Gorge Museum) as an introduction to the Press-Pack for the opening ceremony. A more specific piece about the importance of wrought iron to metallurgical and technological history, added by Keith Gale, currently, President of the Historical Metallurgy Society, who co-ordinated the iron-making part of the proceedings and briefed Prince Charles on the practicalities of the process.

We are reprinting Keith's article and adding a couple of illustrations as The Journal's tribute to the importance of this occasion and to the memory of Reg Morton, founding father of our Society.

Keith Gale explains the process to Prince Charles.

The ironworks at Blists Hill will be making wrought iron, which was formerly the principal metal of commerce. Wrought iron was known more than 4000 years ago but for centuries it was made only in very small quantities. Technology developed slowly but by the end of the 18th century new production methods has been introduced and wrought iron making had become an industry instead of a village craft.

By the early 1800s Britain was producing more than 250,000 tons of iron a year, most of which was wrought iron. In the 1850s the annual production of wrought iron was in the region of 3 million tons. But from 1856 onwards the Bessemer and Siemens processes for making steel in bulk began to compete with wrought iron. Steel was just as good as wrought iron for most purposes and it could be produced faster, cheaper and in large quantities than wrought iron, the older metal was soon fighting a losing battle. Wrought iron took a long time to die out but by 1900 its production was about 1 million tons, against steel at 6½ million tons.

By the 1930s wrought iron had virtually ceased to be of any real significance. A few companies continued to make it for a time but in 1973 the last wrought ironworks in Britain - and in the world - closed down. This was the Atlas Ironworks, Bolton, Lancashire, of Thomas Walmsley and Sons Ltd.

The equipment at Atlas Ironworks was all of the 1860s type. It was due to be scrapped and Ironbridge Gorge Museum took the unique opportunity of acquiring the major items for preservation. The objectives at Blists Hill is not simply to preserve plant wholly typical of the wrought iron trade in its heyday. It is also intended to run the works on a regular basis and to produce and sell wrought iron, for which there is still a demand, especially from craftsmen makers of ornamental and architectural ironwork. This involves the re-learning of techniques and the training of workers skills which had been virtually forgotten. There are many technical problems, not all of which have yet been solved, and those responsible for running the Ironworks have no illusions about the challenge which remains.

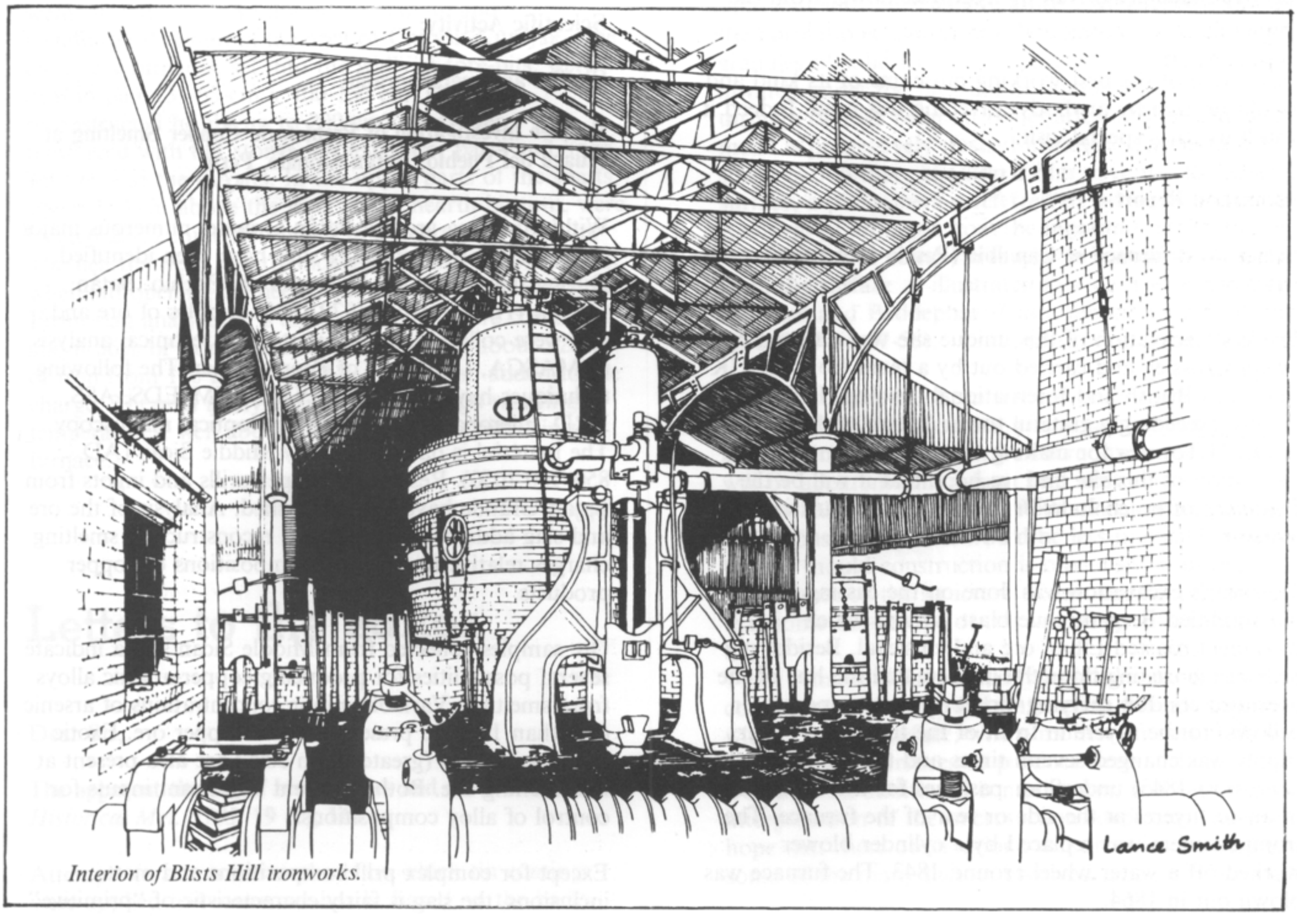
Production of wrought iron is a complicated process and it is only possible to summarise it here. The raw material is cast iron, which contains certain impurities. These are removed by heating it in a coal fired furnace (the 'puddling' furnace) with fluxes. About 5 cwt of cast iron is converted to wrought iron in a working cycle of two hours (the 'heat') and the iron is removed from the furnace in five spongy, shapeless balls. These are taken immediately to the steam hammer and consolidated ('shingled') into rectangular pieces ('blooms') about 4in. square by 2ft 6in. long. The blooms pass, while still red hot, to the first rolling mill (the 'forge train') where they are rolled down to flat bars, 3 or 4in. wide and 10 or 12ft long an allowed to cool. When cold the bars are cut in a steam driven 'shear' to shorter lengths, which are then reheated and rolled to finished sizes and shapes in the second rolling mill (the 'finishing mill').

The furnaces are connected to a steam boiler, which recovers some of the waste heat and the gases then pass to a 60ft. high chimney stack.

Blists Hill Ironworks is small when compared with typical works of the 19th century. It has two puddling furnaces and one 'ball' furnace (which is similar but is used for reheating iron, not making it). Walmsleys had 18 puddling furnaces; some works had 50 or more. But the works is wholly typical in all other aspects.

The forge train rolls are 20 in diameter and they are driven by a steam engine of traditional pattern. Also a traditional pattern are the steam hammer (which has a falling weight of 3 tons), the steam driven shear and the steam pumps for circulating cooling water. The second mill, for finishing iron, is not yet erected, but all the parts, including a steam engine to drive it, are on the site. Erection and commissioning of this mill will be the next stage of development.

The building which houses the works is also of historical interest. It is of cast and wrought iron and is mainly the anchor forge building from Woolwich Dockyard, built in 1816. Some small additions - modern in character - have been made to adapt the building to its present purpose.



Interior of Blists Hill ironworks.

Notes and News and Work in progress

The Iron Museum in Vallorbe, Switzerland

Vallorbe is a small village in the Swiss Jura on the road from Pontarlier to Lausanne. Its connection with the iron industry goes back to 350 BC and there are the remains of bloomeries dated up to the 6th century AD. Documentary evidence shows that there was a revival by the monastery of Romainmôtier in the 13th century. By the 16th century Vallorbe had many bloomeries and forges and by 1670 had three blast furnaces.

This tradition has been documented in a number of books by Prof. P L Pelet who has been instrumental in setting up a museum amongst the old forges along the River Orbe. This gives full details of the growth of the industry, the ores, and the technique used. The forge is still working, and the smithing processes are demonstrated. Naturally the tool-making side was orientated towards the needs of Swiss industry, and file making figures large in the techniques shown. There is a double smith's hearth, a chain and nail smith's hearth, and five machines driven by hydraulic power from the river.

This is one of the best working museums of its kind and should be seen by anybody travelling this road. Indeed it is well worth a special visit.

Excavation Report

Italian Blast furnace at Capalbio (Pescia Fiorentina) Tuscany

The first excavation of this unique site was directed by David Crossley and carried out by a team from the UK with both British and International funding (ICCROM). We are exceedingly grateful to the Italian authorities and to Dr. G Torraca for making the arrangements for the excavation of this site and we hope that it will be the beginning of much Italo-British work on industrial remains.

This year's excavation was done on the casting floor of this modified Bergamesque blast furnace which consumed roasted Elban ore and charcoal. Besides pig beds in the casting floor the dig revealed the line of the overhead conduit carrying air from the trompe (water bellows) to the tuyere in front of the furnace. The air supply was changed several times and the dig revealed later (post 1843) underfloor passages for the conduction of air to tuyeres at the side or rear of the furnace. The trompe system was replaced by a cylinder blower worked off a water wheel around 1843. The furnace was blown out in 1864.

The water exiting from the trompe had fed a large quenching tank at the right of the casting floor; it was a normal practice to quench the cast metal to ensure that it solidified as white iron which was more suitable for conversion to wrought iron.

The buildings are extensive and even contain the remains of a vertically shafted water wheel now modified to drive an olive mill. It is hoped that details of the lower part of the trompe will be found during further work.

December 1986 (from D W Crossley's interim report)

Research Group

The Groupe DHistoires des Mines et de la Métallurgie, Paris, was established at a meeting held on 12th October 1985. It publishes a Bulletin which has several times been quoted in these pages. The president of the Group is D Woronoff, the vice-president F Pichon, the secretary P Benoit. The provisional working programme that has been defined comprises a research guide to the history of mining and metallurgy (D Woronoff), a technical vocabulary of metallurgy (P Fluzin), the iconography of mines and metallurgy (P Benoit), and the conservation and treatment of technological and merallurgical monuments (P François).

After P Benoit, Paris

Scientific Activity:

Studies and metallography:

Further Investigation of Prehistoric Copper Smelting at Huaca del Pueblo, Batán Grande, Peru

Within the area around Batán Grande, numerous major prehistoric copper smelting sites have been identified. During the excavation of Huaca del Pueblo, Batán Grande (HPBG) from 1979-1985, samples of ore and slag were collected and submitted for technical analysis to MASCA, University of Pennsylvania. The following techniques have been used: PIXE, SEM/EDS, ASS, XRD, microhardness testing, and optical microscopy. The material is dated primarily Middle Sican (AD 850/900-1050). Results on copper prills and ingots from Batán Grande have been published. Analysis of the ore and slag adds new data toward reconstructing smelting charges relative to observed compositions of copper products.

Ore samples collected from Middle Sican strata indicate several possibilities for producing copper-arsenic alloys from smelting. Variable minor concentrations of arsenic (less than 1%) are present in local copper ore. Exotic arsenic-rich ores (greater than 30%) are also present at the smelting site. Both represent significant inputs for control of alloy compositions.

Except for complex prill compositions and matte inclusions, the slag is fairly characteristic of "primitive" copper smelting utilizing an iron ore as flux. Major slag phases are fayalite, wustite, magnetite, and a complex Fe, Si, Al matrix. Slag compositions indicate a melting point range from 1150° C to 1250° C. Based on chilled layers of wustite observed on slag surfaces, the smelting process evidently included raking some quantity of viscous slag out of the furnace. However, most of the slag containing copper prills remained in the furnace as previously reported.

Simple mass balances for the slag from smelting and the associated ore specimens account for most inputs and relate copper product quantities to published furnace dimensions. Results from previous copper smelting experiments supply additional comparative data in support of the generally accepted model for a 'prill extraction' technology.

J F Merkel Peabody Museum, Harvard University
S J Fleming MASCA, The University Museum, University of Pennsylvania
I Shimada Department of Anthropology, Harvard University

Iron Metallurgy and Blacksmith's Work among the Altai Turks in the 6th—10th Centuries AD. A scientific programme on early iron metallurgy, was recently started by a team from the University of Kemerovo, Siberia, USSR. About 30 bloomery sites have been discovered in the SE part of the Altai range, which seems to have been an important mining and metallurgical region in the area of Chuysk-Kureysk. The bloomery furnaces, set into the walls of fore-pits, were oval in plan (35-65 cm x 100-150 cm, with a reconstructed height up to 200 cm). They were reinforced with flat stones in their lower parts and lined with clay at the throats. In the upper parts of the shafts, about 100 cm above the level of the hearth bottom, were located 20-22 multiple tuyeres in a horizontal position. The hearths were slightly inclined towards the front wall, where an opening connected the furnace with its fore-pit. From slag analyses it is assumed that the ore contained about 56% of iron, and that the yield was about 22 kg of iron from 100 kg or ore. No fluxes were added to the charge. Thermal analyses indicate that high working temperatures, well above 1300° C, were attained in the furnace.

CPSA

Letters to the editor

Dear Sir,

The apparent tinning of bronze axes and other artifacts *J Historical Met. 1985,* **19 (2), 169**

Attempts to assess the methods by which tin coatings were applied to bronze axe-heads, based on the badly corroded specimens described by several investigators, would appear to be an almost impossible task, although it is evidently regarded as a challenge by dedicated archaeologists. The author refers to experimental investigations of the reaction between tin and copper, principally those of G L J Bailey and H C Watkins, who, however did not display any microsections showing the reaction products. He failed to notice my earlier paper *(J Inst. Met. 1938* **62 (1)** 277-295) with microsections showing the growth of the ϵ, η and ς phases, with plots of alloy film growth over a temperature range of 100° to 500° C, and times ranging from 5 seconds to 3,000 hours. Prolonged contact between molten tin and copper resulted mainly in thickening of the n phase, and the author's suggestion that diffusion would result in 'the tin layer finally becoming a bronze layer' seems unlikely.

I found quite a high rate of diffusion at 100° C, and almost certainly this continues at ambient temperatures as can be readily observed in tinned copper wire after 20 to 30 years storage. How far this might proceed after several centuries can only be guessed.

A study of the Vaughan review covering 84 published papers on inverse segregation, offers a somewhat daunting task to readers of Historical Metallurgy. (Incidentally the reference is incorrect). I accumulated a great deal of evidence, from work on large vertically cast slabs of zinc, copper and brass, as well as very large slabs cast into horizontal moulds, that inverse freezing is the normal mechanism of solidification. Crystals or granules of solid form at the chilled surface, and move inwards under the pressure of liquid metal feeding down through cavities or grain boundaries, and solidified metal is progessively pushed inwards. Throughout solidification there is a liquid film covering the ingot surface, a phenomenon referred to by many observers. Removal of an ingot from the ingot mould before solidification is complete results in liquid metal weeping from the surface as illustrated in a discussion of a paper by Allen and Puddephat *(J Inst. Metals 1935* **57** 88-90. Also 1937 **61** 57-58).

Inverse freezing has been noticed only in those alloys where solidification occurs over a range of temperatures, as in the tin bronzes. Furthermore inverse segregation will be apparent only where heat abstraction is entirely from a chilled mould wall. With more complex mould conditions segregation would be less predictable, and the type of mould construction is obviously of great significance to the structure of cast bronze artifacts, so that some knowledge of this would be invaluable.

These remarks relate natually to ideal reproducible conditions of casting and tin coating. Rough castings with a porous surface, where molten tin may flow into cavities and interstices to produce deep surface alloying would be an additional complication, and confuse the interpretation of the microsections depicted. However I hope that these observations will provide clarification of some of the many factors involved.

Richard Chadwick

Book reviews

Tom Greeves: **Tin and Mines of Dartmoor: A photographic Record**
Devon Books, Exeter, 1986, £4.95. Paperback, 86pp., 4 figs., 75 plates

This is no mere collection of old photographs. Tom Greeves has spent the last fifteen years painstakingly researching the tin industry and has presented us here with a superb book which has an impact and authority not immediately indicated by its format and style of publication.

After a brief introduction, the main part of the booklet is devoted to three of the high moorland mines — Hexworthy, Birch Tor and Vitifer and Golden Dagger. In the words of the author, the book 'is an attempt to illustrate something of the environment and way of life of the Dartmoor tin miner between sixty and one hundred years ago'.

Each of the mines is introduced by a brief historical note but the meat of the book consists of the 75 plates and their extended captions. 'Captions' seems hardly an adequate word to use since many of them are small essays, not only describing the photographs but skilfully blending history, oral information, technological detail, critical observation and interpretation in a way which can rarely have been bettered. The text is so well written, well integrated and well referenced that it both reads easily and fulfils the most exacting requirements of scholarship — a rare combination in a book which must by its nature appeal to a wide audience for it to be economically viable.

Many publications have appeared dealing with mines and mining but none succeed as well as this in actually reminding us that these exciting, dark, damp holes were the workplaces of men. Tom Greeves' success in doing this is entirely due to his skilful use of oral information. His list of acknowledgements is a reminder of how dispersed this information is, how much energy and skill is required to collect it and how easy it could be lost. Although the book is only 86 pages long there is a tremendous amount of information packed into it and the good production and design make it easy to follow. There are clear maps of the sites, a useful glossary, a full bibliography and an index — items all too often dropped from publications of this nature 'in the interests of economy'.

The impact of this book is, quite simply, overwhelming and it will be of value and interest to a wide readership, not least to the descendents of the tin miners themselves. Tom Greeves and his publishers are to be congratulated.

Peter Crew

Geoffrey Tweedale: **Giants of Sheffield Steel**
ii plus 85p, 210mm x 150mm, Sheffield City Libraries, 1986 £3.95

This little book provides biographical detail of ten leaders of industry in the Sheffield of the nineteenth and early twentieth centuries: it carries a sub-title 'The Men who made Sheffield the Steel Capital of the World'. It accordingly complements the technological history of Sheffield steel as set out in 'Steelmaking Before Bessemer'. Details of the careers of Harry Brearley, John Brown, William Butcher, Mark Firth, Robert Hadfield, Thomas Jessop, Samuel Osborn, Tom and Albert Vickers and George Wolstenholm are set down in a well organised style. The choice of these ten as 'giants' is, of course, an arbitrary one and reflects, it would seem, the extensive research the author has carried out as regards the impact of Sheffield steelmaking on the American scene. The list could obviously be greatly extended; the inclusion of Huntsman, Sanderson, Cammell and Doncaster would, one feels, have made for a more rounded whole and perhaps these could form the basis for a subsequent volume. For the reader wishing to know something of the motivation of the Victorian entrepreneur, however, this nicely produced publication will provide well researched detail set out in a very readable manner and it could well stimulate further study. The technical detail is somewhat sparse but what is there has the merit of being reliable, which is more than can be said of a number of other and more pretentious industrial histories put out by economic historians.

K C Barraclough

Messrs Coste & Perdonnet.
Smelting of Lead Ores in Reverberatory Furnaces as performed in Great Britain 1830 *£5.80*

H W Hixon
Notes on the Blowing of Copper in Converters as practised at Anaconda, Montana, USA 1900
Metallurgical Reprint Series, De Archaeologische Pers, Eindhoven. £5.50

These are reprints of two important papers on 19th Century metallurgy. The first is one of the reports used by Dufrénoy in his Voyage Métallurgique en Angleterre and it is useful to have an English version. The authors compare the new reverberatory with the older Scottish ore hearth, and the higher rate of lead recovery compared with continental practice is noted. Lead recovery is improved by the use of iron as a flux. It is concluded that there is not much difference between the low shaft (ore hearth) and the reverberatory. It depends on availabilty of fuel and power for blowing.

The other report relates to copper smelting practice some 70 years later when the lessons of the Bessemer process had penetrated to the copper industry. It was not without its problems due to the high iron content of the basic slag which stayed in contact with the lining for a considerable time and fluxed it. But basic refractories were not successful. One had to accept that lining consumption was considerable. In fact one plant in Mexico used low grade siliceous copper ore as a lining.

Both booklets give practical information with a good many detailed drawings, and practical details on plant and its ancillaries such as blast furnaces and cupolas. These two books will help the understanding of plant remains on 19th century smelting sites and will be a useful key to the interpretation of the relevant metallurgical texts.

R F Tylecote

R Lansdown and W Yule (eds.), The Lead Debate: The Environment, Toxicology and Child Health
(Croom Helm, London and Sydney, 1986, pp. 286, £14.95 paperback, ISBN 0 7099 1654 X)

In 1747, *The London Tradesman,* a widely used guide for those who were contemplating apprenticing children, stated:-

> There are works at *Whitechapel,* and some other of the suburbs, for making of White and Red Lead....the work is perfomed by....Labourers, who are sure in a few years to become paralytic by the Mercurial Fumes of the Lead; and seldom live a dozen years in the business.

In 1895 lead poisoning was made a notifiable industrial disease. In 1978 the Department of Health and Social Security set up a Working Party 'To review the overall effects on health of environmental lead from all sources and, in particular, its effects on the health and development of children and to assess the contribution lead in petrol makes to the body burden'. Drs. Lansdown and Yule were expert members of that Working Party.

While there has long been awareness of the toxic qualities of lead (long before any action was taken to minimise the risk of poisoning) it is only within the last two decades that concern has developed about the possibility of physical impairment of the brain at levels of lead burden below those which produce clinical symptoms of poisoning. There is still no conclusion to this debate, little discussion as to whether or not a threshold level of lead burden exists below which there is no effect, and only a limited political willingness (as earlier with regard to poisoning) to take action aimed at reducing environmental lead levels.

This book, which adds nothing new in any factual sense to the debate, contains a magisterial survey of the subject and recent literature on it. It contains chapters, all by medical experts writing for the layman, on lead as a metal, its use both in history and today, how its incidence in the body is measured and how the body takes up lead, studies of the incidence of lead in various populations and the sources from which populations are exposed to lead. The final section deals with the effects of lead. Experiments with animals are described but are shown to have limited bearing on human populations, while with the latter it is, of course, not possible to undertake experiments controlling lead dosage. As a result the studies on population groups (chiefly children are regarded as most at risk from brain impairment) have only been able to show, at best, an association between high lead burden and low I.Q., although a high correlation has often been assumed by the media to show cause and effect. The book contains a scrupulously careful analysis of the statistical problems and shows that the most recent medical studies have taken cognisance of many of them (they broadly involve the possibility that high lead burden is a crude index of a collection of factors relating to social deprivation which is the actual cause of the retarded development in children). Despite the fact that some evidence is beginning to appear which suggests that children from higher socio-economic backgrounds show no correlation between lead burden and I.Q. the general drift of research suggests that an increase in burden is likely to affect mental development.

While this book has little to offer with regard to the history of metallurgy it is thoroughly to be recommended to those involved in that subject as a contribution to our understanding of the social impact of lead.

David Rowe

Dabieshan
Donald B Wagner. *Traditional Chinese iron-production techniques in Southern Henan in the twentieth century. Scandinavian Institute of Asian Studies Monograph Series No. 52*
Published 1985, Curzon Press: London. Price £5.50.

The main contention of the monograph is that the study of 20th century traditional techniques will provide a basis for interpretation of archaeological remains and documentary records.

In that the core of our understanding of the ancient processes is based on ethnographic and historical records, this monograph provides an excellent addition to the literature. It is a valuable contribution particularly as it provides a wealth of technical information often overlooked, such as the materials used in construction of the furnaces, composition of the furnace lining, along with analyses of ores and products.

The research concentrates on the Dabieshan mountains in parts of the provinces of Henan, Hubei and Anhui, on localised, small scale production of pig-iron. Small blast furnaces, approximately two metres high, were employed to smelt small iron-sand deposits using charcoal as fuel and small 'hole in the ground' refining hearths.

Detailed description of numerous furnaces is provided along with technical diagrams. There is also reproductions of early photographs depicting blast furnaces, refining hearths, iron-sand sluicing and other activities related to the industry.

The volume is divided into six chapters:

1 Looks at literature sources relating to the early industry.

2 On traditional iron-production techniques of the southern Henan.

3 Ironsand. The geographical location of industries based on sand and processes of mining and beneficiation.

4 Forestry and charcoal production provides quantitative information on the production of charcoal and the practice of forest management to preserve resources.

5 Blast furnaces. The largest section of the monograph is devoted to blast furnaces and their variation throughout 20th century China. This also includes a section on BF's in ancient China.

6 Refining Furnaces. This chapter considers refining furnaces in the Dabieshan region and variations from other parts of China. This is then used to understand refining techniques in ancient China. Finally, a comparison is drawn with Western refining techniques.

In the section on blast furnaces, Wagner sees the development of both the BF and the bloomery, related to the Chinese experiences with copper smelting and bronze casting techniques. A liquid would have been expected, and given certain conditions in the furnace, cast iron would have been produced. However, a solid lump would (at times) have been left in the furnace, and this, unlike the cast iron would have been malleable.

Although these early furnaces would have resulted in the production of both types of iron, it is likely that knowledge of the bloomery process had arrived in China before the advent of the BF. It is also the case that the bloomery can result in the production of both cast iron and malleable iron. At present the evidence from China is too limited to reconstruct the early history of the iron industry, while on the west it suggests that the earliest phases of iron production were dominated by the bloomery furnace.

R E Clough

African Iron Working — ancient and traditional
Randi Haaland and Peter Shinnie (Eds.) *Norwegian University Press, Oslo, 1985; pp. 205; A5 hardback; Price £22.50.*

A long-awaited book consisting of ten contributions by archaeologists and anthropologists specialising in this field. After an introduction by the two editors. F Kense opens the book with the thorny problem of the diffusion of iron to and in Africa. He seems to accept its arrival from the North — Mauny's original theory. But the recent discovery of copper working in a second millennium BC context in Niger by Grébenart, Bernus, and their colleagues has put a different complexion on the sequence of metal working in sub-Saharan Africa and seems to indicate that the arrival of iron smelting in the first millennium BC was a natural development of what went before and did not necessarily need ideas from the Mediterranean.

But the spread of iron working over the whole of Africa by the Bantu migration is now being challenged since the expansion of Bantu-speaking groups is now estimated to have occurred around 3000-2000 BC. This is a well-presented summary of the problem of iron in Africa and acts as a good introduction to what follows and fills the gaps in the overall coverage.

The next paper is by the second editor, Peter Shinnie and is devoted to iron working at Meroe on the Nile. This subject has had much exposure in metallurgical journals and does not need detailed explanation here. Generally iron working is in evidence towards the end of the first millennium BC and smelting proper in the first 4 centuries AD, i.e. before it was conquered by the Axumites. The metallurgical evidence is impressive and detailed and seems to compare closely with that in Roman Europe suggesting an independent diffusion path in this instance.

Randi Haarland's paper is more amorphous and she deals with the Darfur area of Western Sudan which has always had a fascination for anthropologists in regard to its furnace types. The furnaces discussed here are the slag-pit type which seems to be the most common type in the Sahara today. The blacksmiths here have a stigmatised status which makes certain that the skill is maintained in the family. This aspect is given much discussion.

Central Africa has given us many surprises and the paper by de Maret is no exception. Here again we get a more ethnographic approach dealing with an area where the smith is buried with a complete set of tools. Not only the smiths are so buried but often the tribal chief had tools buried with him denoting the prestige of the smith — a point that must be kept in mind when interpreting burials generally.

Moving over to East Africa we have a paper by Judith Todd on the Dimi of Ethiopia. This has been well-discussed in these pages. The author believes that with sufficient information we can provenance artifacts over a restricted area by their composition.

Further south, in Zaire, Ruwanda and Burundi, van Noten brings us back to furnace typology with the slag pit furnace and multiple tuyeres. Here we have large shaft furnaces 0.9 m dia with many tuyeres which penetrate towards the centre of the furnace just leaving room for the bloom to form. These are built of individual sun-dried bricks in this respect resemble furnaces recently found at Laxton Hall in Northants. The African examples date from 200BC to 500AD, while the British are late Roman.

Childs and Schmidt describe iron smelting experiments based on furnaces excavated in NW Tanzania. They still believe that long tuyeres give considerable advantages through achieving preheat temperatures of the order of 200-500° C although they now state that they 'were not able to argue for a causative link between preheating and high furnace temperatures'. It is a pity that they do not seem to have passed air through the tubes heated to the above temperature range at the expected rate of air flow and measured the air temperature attained.

L M Pole gives us a good survey of furnace design in West Africa. The types used here are mostly tall shaft furnaces with big outputs but there are some 'Catalan' types, and others with very strange tuyere designs. John Sutton concludes the book with comments on the significance of the variability of African furnaces. There is more on the argument of bowl vs. shaft and it is clear that there is no continuous development in any one area, mainly because new groups of people with different traditions have entered the area.

This book is pioneering new territory and is an absolute essential for anybody teaching or researching into the subject. The editors and authors have managed to make some sense out of a difficult subject and provide us with a good introduction and a good bibliography, although the latter is not as comprehensive as it might have been.

R F Tylecote

Errata

Vol. 20 (Part 1)

Donald Wagner points out that there are errors in his paper that could be misleading. In Table 4 on page 6 the headings have been misaligned and "Fe" should be Fe_3O_4, and the headings, "Fe" to "no." should be moved one column to the right. Table 11 should be modified as follows:-

Table 11 Analyses of samples of the ore charged in experimental furnace no. 2 (22,p. 66)

sample no.	Cu	FeO	Fe_2O_3	SiO_2	CaO	MgO	S	Al_2O_3	TiO_2	Calculated Fe
1	7.08	2.60	72.81	7.12	—	0.16	0.06	0.76	0.12	52.99
2	8.07	2.50	71.92	6.51	0.22	0.08	0.03	0.76	0.12	52.29
3	11.30	2.43	66.35	6.78	—	0.08	0.03	0.85	0.10	48.34
4	8.77	2.44	59.20	11.49	1.93	0.08	0.11	1.14	0.13	43.34
mean	8.81	2.49	67.57	7.98	0.54	0.10	0.06	0.88	0.12	49.24

Table 7. Under SiO_2 and T-37 the entry should be 34.32, and the last entry under Al_2O_3 should be 6.30.

Table 10. "Cuprite" should be moved one column to the right.

Contents list. Delete "Edited and translated".

Bryan Earl notes that there are several errors in his paper on Melting Tin in the West of England; Part 2:-

p.18, the right hand column, and p.29 reference 12. The date of Dr Cotton's account should be 1664.

p.23, Table 1. The temperature plot mentioned under "Col. 5th" is in Fig. 12; that mentioned under "Col. 6th" is in Fig. 13.

p.24, Table 2. A more complete analysis of the products of the 6th Experimental blow is given in the appendix under BE14. The 5th experimental blow is under BE8a in the appendix where the figure for K_2O should be 0.64. The Hexworthy site is locally known as Week Ford.

p.25. The left hand column. Delete reference to Fig. 14.

p.29. Acknowledgements. For "Donald" Read "Douglas".

A further paper by Miss E. Photos on the significance of the analyses given in the Appendix will appear in a future issue.

Abstracts

General

W Emrich. Handbook of charcoal making: the traditional and industrial methods.
Book. Solar Energy R & D in the European Community Series E. Energy from Biomass. *Vol 7 D 9, Dordrecht, Netherlands, 1985*

A comprehensive review and handbook, containing the following chapters: History and fundamentals of the charcoal process; Traditional methods of the smallholder charcoal-maker; Concepts and technology for the industrial charcoal-maker; Techniques for recovering commercial products from pyrolysis oil; Raw materials supply; End use markets for charcoal and charcoal by-products; Planning a charcoal venture and selection of equipment; Charcoal briquettes and activated charcoal manufacturing; Safety precautions and environmental considerations; Charcoal and laboratory work.

AATA

S J Fleming. The application of PIXE spectrometry to bronze analysis: Practical considerations. *Masca 1985,* **3** *(5) 142-149.*

The principles, advantages and disadvantages of compositional analysis by PIXE (proton-induced X-ray emission) spectrometry, with particular reference to copper-based artifacts, are described in a manner understandable to the non-specialist.

AATA

K Igaki. Investigation of high quality ancient iron. *Kobunkazai no Kagaku, 1984,* **29,** *18-26. In Japanese.*

Through the measurement of anodic polarisation curves very large differences in corrosion resistance are observed between the high quality ancient iron alloys and modern steels, mainly due to the soundness of the passivation film formed on the metal surface. Compositional analysis shows the substantial differences are in the concentration of manganese, silicon and sulphur, usually in the level of several tens of wt ppm for high quality ancient iron alloy, far less than for modern steel. Superior corrosion resistance is observed on the specimen prepared by a traditional iron-making process using a clay furnace of nearly 1 m in height. This process has been kept in secret in the family group named Kurabayashi for several hundred years at least. In spite of the low carbon concentration (0.4%) carbon is in the form of vermicular graphite. This iron alloy is not only corrosion resistant but also easily workable. Recent technology succeeded in diminishing the sulphur concentration to the level of a few wt ppm. The next step to approach the high quality ancient iron alloy would be to decrease the concentration level of manganese and silicon.

AATA

H Frere. Le temoignage des pieces de monnaie (The testimony of coins). In book: Le Temps. Des Milliards d'Années au Milliardième de Seconde. *Université de Liège 1984, 188-205 (in French)*

There are many physical clues to the provenance of a coin: weight, homogeneity of composition, trace minerals in the composition, imprint. There are also iconographic clues to a coin's age: subject, inscription, date (although coins have been reissued with original dates). A coin with a good provenance can be used to establish the provenance of a treasure hoard or to date a site.

AATA

G B Kauffman. The role of gold in alchemy. Part 1. *Gold Bulletin, 1985,* **18,** 31-34.

Since ancient times and in every culture, gold has been valued for its beauty as well as for its unique physical and chemical properties. The pseudo-science of alchemy arose almost everywhere from earliest times in an attempt to convert base metals into gold. This review traces the history of alchemy and the role of gold in it, through Chinese, Greek, Arab and European cultures.

AATA

G B Kauffman. The role of gold in alchemy. Part 2. *Gold Bulletin, 1985,* **18** *(2) 69-78.*

The search for the philosopher's stone, the agent for transmuting base metal into gold, laid the groundwork for modern chemistry. The origin, both in time and place, of the stone which was known by innumerable fanciful names, is obscure. Writers disagree in describing its powers, properties and colour, as well as the time required for transmutation.

AATA

G B Kauffman. The role of gold in alchemy. Part 3. *Gold Bulletin 1985,* **18,** *(3), 109-119.*

Through the centuries goldmaking has been alternately encouraged and banned by rulers and clergy, and the number of alleged transmutations is considerable. With the advent of nuclear physics and chemistry, the alchemists' goal of transmutation has finally been realized, although the process is far from cost-effective.

AATA

C McCombe. One hundred years of aluminium. *A review article in the Fuel and Metallurgical Journals Technical Supplement. March 1986.*

Other brief references to historical developments are included in other articles which review fabrication processes and the evolution of the secondary aluminium industry.

APG

N D Meeks. Tin-rich surfaces on bronze: some experimental and archaeological considerations. *Archaeometry, 1986,* **28***(2) 133-163.*

Tin-rich surfaces found on bronze antiquities may be the result of man-made or natural processes. The difficulties encountered in distinguishing between these processes are discussed and illustrated with reference to the surface structures obtained on experimentally tinned copper and bronze. Heat treatments were carried out on the experimental material to allow observation of the growth of the intermetallic compound layers on the surface, and of changes that occur at various significant temperatures. The experimental reduction of cassiterite directly onto the surface of copper and bronze is illustrated for the first time. Examples of tin-rich surfaces found on various antiquities are illustrated and are compared with the experimental material interpretation. Scanning electron microscopy and micro-analysis were the primary tools used in the study.

RFT

J Patscheider and S Veprek. Application of low-pressure hydrogen plasma to the conservation of ancient iron artifacts. *Studies in Conservation, 1986,* **31,** *29-37.*

Claim effective removal of chlorides while preserving original structure of iron; results from over 50 artefacts.

BAA

E E H Pitt. X-ray fluorescence analysis of non-ferrous archaelogical metalwork. Part 1. Analytical technique. *Anal. Proc. 1985,* **22,** *(3) 72-73.*

Method of sampling metallic museum objects are discussed. X-ray fluorescence analysis of brasses, bronzes, and pewter is outlined, and the analysis of samples from a pewter spoon handle is detailed.

AATA

R J Rosenberg. Determination of the silver content of ancient silver coins by neutron activation analysis. *Journal of Radio-analytical and Nuclear Chemistry 1985,* **92,** *171-176.*

A rapid analysis procedure requiring two and one half minutes per coin was devised. A reactor activation of one second duration was followed by 'cooling' for 85 seconds and counting of the resultant activity for 60 seconds with a Ge detector. 110 Ag and 108 Ag were measured for Finnish coins of the 14th and 15th centuries. An average precision of ±2.1% is reported.

AATA

M Rousset and M Fedoroff. Multi element instrumental neutron activation analysis of silver-copper coins. *Journal of Radio-analytical and Nuclear Chemistry, 1985,* **92** *(1) 159-170.*

Analysis conditions were optimized for purposes of avoiding high radioactivity of major elements and overcoming shielding effects in heterogeneous silver-copper coinage of the proto-historic La Tène period. Major and 12 trace elements were determined.

AATA

G Sperl. Montanarchaometrie. Wiener Berichte über Naturwissen-schaft in der Kunst. *1984,* **1,** *175-185. (In German)*

Montanarchaeometry is the field of research dealing with the historical aspects of mining and metallurgical engineering. The author reviews measuring methods and their application in research programs concerning especially the past metallurgical operations of copper and iron in Austria.

AATA

H M Storch and G Watzinger. Microscopical and microspectro-analytical investigations of archaeological artifacts. *Jena Rev. 1984,* **29** *(4), 182-183.*

The archaeological bronze ewer of Borsch and the bronze fibula of Ostheim from La Tène in Western Switzerland were analysed and trace elements detected and microscopic structures were presented. The examinations were used in identifying the manufacturing techniques employed in the production of artifacts.

AATA

J Wolters. Zur Geschichte der Lotung von Edelmetallen: Historische Entwicklung der Lotlegierungen. (The history of soldering of noble metals: 1, Historical development of solder alloying). *Zeitschrift fur Archäometrie, 1983,* **1** *(2), 48-64.*

Introduction to a bibliography (to follow).

BAA

Claude Blair, John Blair and R Brownsword. An Oxford brasiers' dispute of the 1390s: Evidence for brass making in Medieval England. *The Antiquaries Journal, 1986,* **66** *(1) 83-90.*

A contract of 1392 between two Oxford brasiers provides important evidence for the organisation of the medieval brasier's craft and for technical aspects of his

S Gerrard. Retallack. A late Medieval tin-mining complex in the Parish of Constantine, and its Cornish context. *Corn. Arch. 1985,* **24,** *175-182.*

Remains of at least six separate mills were surveyed: four crazing mills, two stamping mills and a blowing house are probably of 16th century date.

BAA

S Gerrard and A Sharpe. Archaeological survey and excavation at Wheel Prosper Tin Stamps, Lanivet. *Corn. Arch. 1985,* **24,** *196-211. Pls. figs.*

Survey and partial clearance (before destruction) of late 19th century tin processing works.

BAA

H S Green. A Bronze Age stone mould from New Mills, Newtown, Powys. *Bull. Board Celtic Stud, 1985,* **32,** *273-274.*

BAA

W S Harvey. An examination of bolts found at the Wanlock lead mines. *Ind. Arch. 1983,* *17 (2-4),* **130-137, 141-151.**

Wrought iron bolts, most of which probably date from about 1780, were examined metallographically to determine how they were made. The thread profiles are recorded.

APG

S P Needham, A J Lawson and H S Green. British Bronze Age metal work associated finds series, *A1-6, 1985, 40. Price £7.50 (loose cards in folder: 07141 1380 8). Available from Brit Mus Publ. only.*

The first set of cards covers hoards from, Castell Coch (Glam S), Oddington (Glos), Castle Rising (Nfk, Mile Cross, Norwich, Wold Farm, Willerby (Yorks N), and Arreton Down (IoW). Includes analyses.

BAA

C McCombe. Aluminium bronze — a Victorian wonder metal. *Foundry Trade Journal 1968, March 13,* **160** *(3322), 186-188.*

The properties of copper-aluminium alloys were known a few months after aluminium metal was first produced in 1855, but commercial exploitation began in 1885 when the Cowles process (described and illustrated) considerably reduced the cost of the alloy; soon afterwards, due to the availability of cheap aluminium from the Hall-Heroult process, the alloy was made from pure metals.

APG

C McCombe. What price an eight-foot cast-iron walrus? *Foundry Trade Journal, 1986, June 5,* **160,** *(3325), 472-473.*

APG

T I Molleson, D Eldridge and N Gale. Identification of lead sources by stable isotope ratios in bones and lead from Poundbury Camp, Dorset. *Oxford Journal Arch. 1986,* **5** *(2), 249-253.*

Two sources; three from local British ores (Mendip). One (child) from Laurion, Greece which suggests immigration of the child.

RFT

G Tweedale: Metallurgy and technological changes. A case study of Sheffield speciality steel and America 1830-1930. *Technology and Culture, 1986 April,* **27** *(2), 189-222.*

The article traces developments in the crucible steel process for making plain carbon steels, alloy tool steels, manganese steel and stainless steel in the light of American industrial requirements and shows that the US steel industry did not fully emerge until the end of the first World War.

APG

Europe

A Burnett, P T Craddock and N Meeks. Italian currency bars In: Italian Iron Age artefacts *(Ed. J Swaddling) Brit. Mus. Publ. 1986, 127-130*

A typological and metallurgical examination of these highly unusual pieces. They regularly contain 20-40% of iron. This iron was deliberately introduced during the smelting of the copper.

PTC

H Born. Technische und analytische Untersuchungen an der bronzenen Reiterstatuette von Klein-Steinheim. (Technical and analytical research of a bronze equestrian group from Klein-Steinheim, Germany) *Trierer Zeitschrift, 1985,* **48,** *247-260 (In German).*

Since the statuette was found discussion centered on whether it is a cast bronze from antiquity or not. The author deals with the technical and analytical aspects which date the group between the Roman period, the Renaissance and the 19th century.

AATA

P T Craddock. The metallurgy of Italian and Sardinian bronzes. In: Italic artefacts in the British Museum. *(Ed. J Swaddling) Brit. Mus. Publ. 1986, 127-130.*

Contains the quantitative analyses of some 80 bronzes. The Sardinian bronzes are principally unleaded, in trade. References to the importation of **calamys** and **calamin** in 1384 provides the first evidence yet found for the making of brass in England from its raw materials.

Authors (abridged)

J Wadsworth, D W Kum and O D Sherby. Welded Damascus steels and a new breed of laminated composites, *Metal Progress, June 1986,* **129** *(7), 61-67.*

Work at Stanford has shown that fine grained ultra-high carbon steels can be readily solid-state welded to one another or to other ferrous metals, bonding taking place at temperatures below A_1. Laminated mixtures of superplastic high carbon steel and low carbon steel are superplastic. These observations are believed to account for some of the good properties of some early products.

APG

Britain

R D Van Arsdell. An industrial engineer (but no Papyrus) in Celtic Britain. *Oxford J Arch, 1986,* **5** *(2), 205-221.*

Coin making in Iron Age Britain. Cast bronze coins in Kent. Demonstrated the development of coin-making processes to optimise the casting process.

RFT

J Bayley. Brass and brooches in Roman Britain. *Masca J, 1986,* **3** *181-191.*

Brass makes a sudden appearance in the early 1st century, eg in 3 unfinished Colchester type brooches from Baldlock. The subsequent reversion to leaded bronze may indicate official (?mint) takeover of the brass supply.

BAA

N Beagrie. A bronze 'ox-hide' ingot from Cornwall. *Corn. Arch. 1985,* **24,** *160-162.*

Diver's find off Looe Island, no context (?medieval).

BAA

D Brooke. The advent of the steel rail; 1857-1914. *Journal of Transport History, 1986,* **7** *(1) 18-31.*

The records of five railway companies and other contemporary publications are used to show how the declining quality of wrought iron nails, their rapid wear under heavy traffic, and the decreasing cost of steel eventually led to the universal use of steel for railmaking.

R Brownsword, E E H Pitt and J Wilkin. A technical note on the 'Gloucester candlestick'. *Journal British Arch. Ass. 1985,* **138,** *168-170.*

BAA

R Brownsword and E E H Pitt. A technical note on a skillet handle fragment from Ripe. *Sussex Arch. Coll. 1985,* **123,** *265-267.*

PTC

O V Clarke and M M B Kemp. A hoard of Late Bronze Age gold ornament from heights of Brae, *Ross & Cromarty District, Highland Region. PSAS 1984,* **114,** *189-198.*

A brief description of a hoard of gold objects from the 8th-7th centuries BC. Paper includes XRF analysis of each object in terms of gold, silver, and copper content.

EAS

J H Lewes. The charcoal fired blast furnaces of Scotland: a review. *PSAS, 1984,* **114,** *433-479.*

An updated survey based on McAdam's work of 1887 and includes reports of recent excavations at Red Smiddy, and Bonawe furnaces and short notes on other sites.

EAS

J Collins. Iron Age 'Coin moulds'. *Britannia, 1985,* **16,** *237-238.*

Defends the traditional interpretation of these indented ceramic flans as coin moulds in which precious metals of the required likeness were weighed out and melted to produce a flan which could then be struck. Recent papers have raised objections to this theory. However, it is pointed out here that there is little else that the small flan, if gold or silver, could be used for, and proof that some Iron Age coins were not produced in this manner does not mean that none of them were.

AAS

R M Ehrenreich. Blacksmithing technology in Iron Age Wessex. *Oxford Journal Arch. 1986,* **5,** *(2), 165-184.*

503 artefacts were examined to determine the capability of Iron Age blacksmiths. Mainly from Danebury. Discusses the role of phosphorus and agrees that it is not as detrimental as was thought.

RFT

D Elkington and D Viner. A Roman pig of lead found at Syde, Glos (Vespasianic, from Mendip) *Trans. Bristol & Gloucester Arch. Soc., 1985,* **103,** *209-211.*

BBA

L S Garrard. Snaefell Mines, Lonan, Isle of Man, part II: Surviving remains other than those on the main washing floors and about the shaft. *Ind. Arch. 1983,* **17** *(2-4), 114-119.*

BAA

contrast to the leaded bronzes from the mainland and there was one brass possibly the earliest in Europe. The iron content of the Sardinian metal is much higher, suggesting a more sophisticated process.

PTC

R B Gordon and T S Reynolds. Medieval iron in Society — conference report — Norberg, Sweden. *Technology and Culture, 1986 January,* **27** *(1), 110-117.*

The conference was organised following the discovery of an iron manufacturing facility believed to have been in operation between AD 1150 and 1350, which included a blast furnace and waterpower works. Three themes were considered — waterpower — Metallurgical processes and socio-economic consequences. The proceedings are outlined in this report. (See next abstract).

APG

Medieval Iron in Society.

Papers presented at the symposium in Norberg, Sweden, May 6-1, 1985. *Jernkontoret and Riksantikvarieabetet, Jernkontorets Forskning, H34.*

This is the first volume containing the papers presented at the conference, the second volume which mainly contains discussion became available at the end of 1986. (H39).

The contents were as follows:-

Sven Fornander, Introductory comments on the iron district of Norberg; Gert Magnusson, Lapphyttan — an example of medieval iron production in the blast furnace; T S Reynolds Iron and water — the technological context and the origins of the water-powered iron mill; R B Gordon, Hydrological analysis of water power used at medieval ironworks; Ninina Cuomo, traditions of the water wheel in Italy; David Crossley, the construction and installation of water wheels: medieval to post medieval; R Maddin, The technology of iron making; R F Tylecote, the early history of the iron blast furnace in Europe: a case of east-west contact?: G Sperl, Die Technologie der direkten Eisenherstellung in Alpenraum (der Stuckofenprozess); N Bjorkenstam and Sven Fornander, metallurgy and technology at Lapphyttan; Inga Serning, Vinarhytan and Juteboda — two medieval blast furnaces in middle Sweden; J Gomori, spread of blast furnaces in post medieval Hungary; E M Nosek and W Mazur, Iron smelting in medieval bloomery furnaces on Castle Hill at Muszyna, Poland: J Piaskowski, iron and steel technology on the territories of Poland on the 11-14th century; B G scott, the blast furnace in Ireland; a failed industry; R Hodges, the beginnings of the medieval iron industry in Western Europe; craft specialization and the domestic mode of production; R Sprandel, Der Export von Schwedischem Eisen im Spatmittelalter und seine Bedeutung fur Handel und Gewerbe in Nord - und Westeuropa; R Francovich, Rocca san Silvestro: an archaeological project for the study of a mining village in Tuscany; L Karlsson, Cistercian iron production; Ake Hyenstrand, Early medieval mining and iron production in Sweden: some spatial aspects.

Besides the discussion, Vol II contains J F Belhoste, the diffusion of the blast furnace in France in the 15-16th century: Peter Crew and M Williams, early iron in NW Wales; R Pleiner, the blast furnace in Bohemia; A Espelund, Ironmaking in Norway; Hans Hagfeldt, the weight distribution of slag from Lapphyttan.

RFT

C Mortimer. The early use of brass in silver alloys. *Oxford Journal. Arch. 1986,* **5** *(2), 233-242.*

22 silver finger rings. In some Roman rings brass had been added instead of copper a misleading surface composition tended to give lower copper and higher Ag, Au, and Zn contents than destructive analysis of the core.

RFT

C Moyer. September meeting: the Gundestrup cauldron — identification of tool traces. *Washington Conservation Guild Newsletter, 1985,* **9** *(4), 5-6.*

Discusses the study of the tool marks on the surface of a silver cauldron in an attempt to determine its age and provenance.

AATA

M Nisser. Documentation and preservation of Swedish historic ironworks. In: Ironworks and iron monuments/forges et monuments en fer. *Rome 1985, 67-87.*

Paper presented at the Ironbridge Symposium (1984) on the history of the manufacture of iron in Sweden since the 17th century, on the policy of conservation of ironworks since the beginning of the 20th century, on availble documentation in the legal field and on financial support and legal measures taken in favour of industrial heritage in Sweden.

AATA

A Pasch. Rekonstruktion einer Goldblechscheibenfibel und Untersuchungen zu den Herstellungstechniken. (Reconstruction of a gold-plated disc-shaped tin brooch and analysis of production.) *Restaurierung und Museumstechnik, 1985,* **6,** *5-22.*

The brooch was decorated in coloured stone inlays with filigree dating from the 2nd half of the 7th century AD. The original was in a severely damaged condition. The method of reconstruction is described in detail.

AAS

B Jovanovic. New discoveries at Rudna Glava — the earliest shaft and gallery copper mine in Eastern Europe. *IAMS Newsletter, 1986,* **8,** *1-2.*

Carbonate ores, following along veins (not cutting rock), in 16-20 m deep shafts; over 200 grooved mauls, antler picks, pottery and votive altars cum lamps. Pottery and dates 14 C combine to suggest exploitation in 4200-4000 BC (Early Vinca culture).

BAA

M Kis Varga and L Kolto. Analysis of archaeological objects by X-ray emission spectrometry. *Tomki Koz, 1985,* **27** *(1),85-90. (In Hungarian)*

The composition of 15 silver coins from the Hungarian Arpad dynasty and six foreign coins from the same period was determined. Earlier coins had a higher silver content than the later ones. Some coins contained 0.1% bismuth, and all coins contained lead (0.2-1.2%) 3 gold coins from the same period were also analysed. Analysis of 14 Roman bronze fibulae indicated that they were probably made in the same workshop. Six ceramic examples were also analysed.

AATA

H L Knau and M Sonnecken. Karierung con Massenhutten-Wustungen im oberen Einzugsgebiet der Agger, Oberbergischer Kreis. (Mapping of furnaces of the Massenhutte type, in the river basin of the Agger, Bergisches Land, W. Germany). *(In German). Der marker, 1986* **35** *(1), 50-52.*

In an area now flooded by dam waters there were 24 sites of abandoned iron smelting places recorded known as 'Massenhutten', denoting furnaces for bloomery and cast iron production. The earliest date from AD 1300.

CPSA

D Liebel. Rekonstruction des bronzeschwertes von Stenn in originalgetreuer Technik. (Reconstruction of a bronze sword found in Stenn according to original production techniques). *Restaurierung und Museumstechnik, 1985,* **6,** *39-53. (In German).*

Reconstruction of a bronze sword dated to the 12th century BC is described: the molten process, melting procedures and the alloys used. Demonstrates the practical aspects of the reconstruction process.

AATA

E Macnamara. The construction of some Etruscan incense — burners and candlaebra. In: *The Italian Iron Age artefacts in the British Museum (Ed. J Swaddling) British Mus. Publ. 1986, 81-86.*

Includes a technical appendix by P T Craddock and M I Hockly giving the analyses and other details . Analyses are used to show which of the candelabra were made up from unassociated pieces in recent times. Also suggests that the components used were made together in one workshop, contradicting Pliny, who suggested that diverse towns specialised in particular components.

PTC

D Molenda. Der Erzbergbau Polens vom 16. bis 18. Jahrhundert. (Ore mining in Poland from the 16th to 18th centuries). *Der Anschnitt, 1985,* **37,** *(5-6), 196-205.*

From the 16th to 18th centuries Poland was an important mining district in Europe. The main centre was the lead-zinc district of Silesia, where a galena with a high amount of silver was mined from 1528 to 1628, 20,000 shafts were built, 2,000 tons of lead and 600 kg of silver were produced annually. Besides galena, galmei (calamine) was mined. The second important mining district was in the Swietokrzyskie mountains with mines for copper and lead. Similar deposits were mined in the Tatra mountains. In lower Silesia there were mines for gold and tin.

AATA

E Pernicka and G A Wagner. Die metallurgische Bedeutung von Sifnos im Altertum. (The metallurgical importance of Siphnos in antiquity). *Der Anschnitt, 1985, special publication,* **3** *200-211. (Germ. W. Engl. Sum).*

Since the 3rd mill. BC argentiferous lead ores have been mined at Siphnos. The lead can be characterised by its isotopes which are different from those from Laurion and other deposits in Greece.

AATA

E Pernicka and G A Wagner. Alte Goldgruben auf Sifnos. (ancient gold mines at Siphnos). *Der Anschnitt, 1985, special.publication,* **3,** *174-184 (germ. W. Engl. Summ).*

Since the 3rd mill. BC lead and silver were extracted from ores of lead, silver, copper and zinc. The slags were analysed chemically, microscopically and by phase analysis. The data for the metallurgical activicty are compared with the thermolummescence esence of pottery found together in slags.

AATA

J Riederer. Metallanalysen an Erzeugnissen des Mittelalters. (Metal analysis from products of bronze casting during the Middle Ages and later periods). *Der Anschnitt, 1984, Beiheft 2, 153-158. (Germ. W. Engl. Summ.)*

A large number of bronze and brass objects from the Middle Ages and the 16th-17th centuries have been analysed. From the trace element pattern it should be possible to deduce the deposits from which the metals come; evidence not yet sufficient.

AATA

J Riederer. Metallanalysen römischer Bronzen. (Metal analysis of Roman bronzes). In: Toreutik und figürliche Bronzen römischer Zeit. Akten der 6. Tagung über antike Bronzen, Staatliche Museen, *Preussischer Kulturbesitz Berlin, Antikenmuseum, Berlin, 1984, 220-225 (In German).*

The large number of Roman objects made of copper alloys shows that the term bronze for this group of alloys is not correct in many cases. It is proposed to define the copper alloys more precisely i.e. copper tin bronze, lead tin bronze, brass, adding if there are low, medium, high amounts of tin, lead or zinc. From that, 23 classes of copper alloys which were used during the Roman period can be distinguished.

AATA

J Riederer. Die Metallanalyse des Braunschweiger Löwen. (The metal analysis of the lion of Braunschweig). *In: Der Braunschweiger Lowe. (Ed. G Spies). Braunschweig, 1984, 167-179 (In German).*

From a brass monument cast in 1166 about 60 samples were analysed. Though the lion appears to be homogeneous (apart from numerous repairs) it was found that quite different compositions of brass occur. A detailed examination of the sculpture revealed vertical boundaries, which on some places had been broken up. It is obvious that the lion was cast from small portions of molten brass of varying composition, which were heated separately and poured one after the other into the mould.

AATA

C H Roden. Montanarchaologische Quellen des ur und fruh geschichtlichen Zinnbergbaus in Europe: ein Uberblick.(Archaeological sources of prehistoric tin mining in Europe: A survey). *Der Anschnitt, 1985,* **37** *(2-3), 50-80. (Germ. W. Engl. summary).*

From all regions where prehistoric tin mining is proved by archaeological evidence, the metallurgical finds are described with the aim of discussing the question whether tin oxide or metallic tin was used for the production of bronze during the early periods. The tin deposits of Ireland, Cornwall, western, central and southern France, Tuscany and the German, Polish and Czechoslovakian ore mountains are discussed.

AATA

U Sieblist. Der vergoldete Spangenhelm von Stössen, Kr. Hohenmolsen. (The goldplated helmet clasp found in Stossen). (In German). *Restaurierung und Museumstechnik, 1985,* **6,** *23-38.*

The original clasp dating from the late migration period was found in 1920 in a grave. Technological examination of the helmet's construction etc. is described, as well as a detailed description of the stages involved in reconstructing the clasp.

RDB and IBCOM. (transl).

S Shennan. Central Europe in the 3rd millennium BC: an evolutionary trajectory from the beginning of the European Bronze Age. *Journal. Anthropol. Arch. 1986,* **5,** *115-146.*

In copper-bearing areas, the metal began to appear in grave goods, not especially highly valued; in the Bell Beaker phase the metal began to undermine existing differentials and set up new ones, leading to competition, wider exchange networks, diffusion westwards and probably the prestige use of riding horses. Patterns of competition alliance and exchange continued and expanded until late 2nd millennium.

BAA

M Sonnecken: Die mittelalterlich-fruhneuzeitliche Eisenerzeugung im markischen Sauerland. Ergebnisse industrie-archälogischer Forschungen. (Medieval and post-medieval iron working in Sauerland — results of industrial archaeological research. *Der Marker, 1985,* **34** *(4), 193-199. (In German).*

A survey of bloomeries and early blast furnaces (13th-17th centuries). About 1350 smelting sites recorded.

CPSA

M Stantscheva. Thrakische Goldgewinning bei Sofia in Bulgarien. (Thracian gold mining at Sofia in Bulgaria). (In German). *Der Anschnitt, 1985,* **37** *(4), 122-127.*

Remains of gold mining in alluvial deposits were found near Sofia where gold-bearing sand was obtained and washed. From archaeological evidence it is supposed that Thracians exploited these deposits during the Roman period.

AATA

M Vavelidis, I Bassiakos, F Begemann, K Patrearcheas, E Pernicki, S Schmidt-Strecker and G A Wagner. Geologie und Erzvorkommen. (Geology and ore deposits). *Der Anschnitt, Beiheft* **3,** *1985, 59-80 (Germ. W. Engl. summary).*

On the Cycladic Island of Siphnos ore mines which were worked in prehistory have been studied. In a series of marbles and metamorphic rocks with silver-bearing ores, first of all a lead-zinc mineralisation occurs, connected with secondary ores in the upper zones. Chemical analyses of the ores, and the lead isotope data of the lead ores, the slags and lead oxides are given.

AATA

M Vickers. Metalwork and Athenian painted pottery. *Journal Hellanic Soc. 1985,* **105,** *108-128.*

Suggests that Greek silver may usually have been patinated black in antiquity rather than polished, especially if pattern-gilded. Thus the Athenian red figure ware could be seen as copies of silver prototypes. There is warning to conservators cleaning black patination off ancient silver and it is asked why black patination is removed but green patination is left on contemporary bronzes.

AATA

G A Wagner and G Weisgerber. Andere Blei-Silbergruben auf Sifnos. (Other lead-silver mines at Siphnos.) *Der Anschnitt, Beiheft* **3** *1985, 159-173. (Germ. W. Engl. summary).*

Besides the ancient mining centre of Agios Silvestros at Siphnos there are a certain number of other ore deposits which were mined since prehistoric periods.

AATA

G Weisgerber. Der Eisenbergbau des 19.A. Jahrhunderts auf Sifnos und seine Technischen Denmaler. (The mining of iron ores during the 19th-20th centuries at Siphnos and its technical monuments. *Der Anschnitt, Beiheft* **3,** *1985, 212-221. (Germ. W. Engl. summary).*

In places where earlier metal ores were found at Siphnos during the 19th-20th centuries iron ores were mined without the use of electricity or modern sources. The ores were separated by hand and transported by a combined cable railway and a railway for mule-drawn carts to the next habour.

AATA

G Weisgerber. Die Blei und Silbergruben von Agios Sostis. (The lead and silver mines at Agios Sostis). *Der Anschnitt, Beiheft* **3,** *1985, 113-158. (Germ. W. Engl. summary).*

On the Greek Island of Siphnos some places are known where lead has been mined since prehistoric periods. The old mines are mostly intact and ancient mining techniques could be studied in detail.

AATA

A R Williams. The knight and the blast furnace. *Metals and Materials, 1986, August,* **2** *(8), 485-489.*

Citing examples from the Royal Armories at the Tower of London and from those of Turin, Italy, the author gives an overview of the evolution of armour from the simple mailshift to elaborately etched coloured and gilded suits of hardened steel.

Author (abridged)

Ferrum, *No. 57, 1986.*

This issue of the house magazine of the Eisen-bibliotek at Schaffhausen contains a number of important papers on experimental iron smelting arising from a conference held on the 6/7th September 1985:-

H Luling, Remarks on the theme of the conference. p3.

T Eisenblatter, The value of technical reconstructions to historical research.

C Eibner, Archaeometric methods used on early iron smelting sites.

A Hauptmann, Aims of archaeometallalurgical investigations; reconstructions of the earliest iron smelting process.

P F Tschudin. Ore from heaven; iron production in the old cultures of the Mediterranean up to Medieval times.

E Sprandel, The production capacity of Medieval iron furnaces from written sources.

H Straube, Critical comparisons of theories on the metallurgy of the bloomery.

H J Kostler, The change from the Stuckofen to the Flussofen as seen from metallurgical examples.

G Sperl, Problems and results of smelting experiments.

H P Britt, Introduction to the bloomery process 'ELIGIUS'

T Geiger, The metallurgical investigation of a small piece of bloom.

L von Mackensen, Archaeometry and the history of science.

All the papers are in German.

RFT

Asia

K T M Hegde, P T Craddock and V H Sonawane. Zinc distillation in ancient India. In: Proceedings of the 24th Internations Archaeometry Symposium (Ed. J Olin and M J Beachram). *Smithsonian Inst. Washington, 1986, 249-253.*

Description of the production of zinc in India during the last millennium as exemplified by the excavation of extant furnaces still containing their full charge of retorts at Zawar in Rajasthan.

PTC

T N Lung. The history of copper cementation on iron. The world's first hydrometallurgical process from medieval China. *Hydrometallurgy, 1983,* **17,** *113-129.*

Evidence and description of hydrometallurgy from texts dated to AD 1086, some evidence that process began in China during the Han period a 1000 years earlier. Also gives a good general history and description of hydrometallurgy.

PTC

G F Bass. A Bronze Age shipwreck at Ulu Burum (Kas); 1984 campaign. *Amer. Journal. Arch. 1986,* **90** *(3), 269-296*

Bronze tools and weapons, 84 copper ingots in rows. 15th-14th centuries BC. Also a lump of brittle grey material of 99.5% Sn. The wreck is less well preserved than that of Cap Gelidonya. The Cu has helped to corrode the tin. 19 Cu bun ingots 20-28 cm diam. Other artefacts were lamps, glass ingot and a bronze dagger. Also a silver bracelet, a lugged bronze axe and a bronze knife. Believes that Cyprus is the most likely source of the ox-hide ingots. Pithos No KW251 had some small fragments of tin in it (?octopuses). The destination of the ship was west of the site; probably Rhodes, Mycenaean Asia Minor, or Greece.

RFT

V N Bhoraskar, S Y Mahajan, S S Jayanthakamar and V D Gogate. Analysis of ancient iron objects with 14 MeV neutron activation analysis. *Journ. of Radioanalytical and Nuclear Chemistry, Letters, 1985,* **95** *(2). 73-80.*

The relative activities of Cu, A1, Mn, Mg, and Si were used to characterise iron from the Naikund site in Maharashtra State, India, a smelting site dating to the 17th century BC. Iron artefacts from five megalithic sites were found to have corresponding activity ratios and are felt therefore to have come from this smelter. It is suggested that copper was added to reduce rusting of the iron.

AATA

G F Carter. Chemical compositions of copper-based Roman coins. *Israel Numismatik Journ. 1983,* **6-7,** *22-38.*

X-ray fluorescence analysis and chemical analysis of 25 bronze coins from Antioch dating from AD 14-37 and AD 98-117 for the elements iron, nickel, cobalt, copper, zinc, silver, arsenic, tin, antimony and lead provide information as to their intrinsic metallic value, gradual debasement, the remelting of previously struck coins, quality control in minting, and authenticity.

AATA

N H Gale, Z A Stos-Gale and G R Gilmore. Alloy types and copper sources of Anatolian copper alloy artifacts. *Anatolian Studies, 1985,* **35,** *143-173.*

Lead isotope and neutron activation analysis of Chalcolithic and EBA bronzes from the Aegean and Anatolia (Kastri, Beycesultan, Yortan, Mersin and Yumuk Tepe) made in an attempt to group together various metalworking traditions and possibly locate the EB II material from Troy from local sources.
Arsenical copper was common and tin bronze rare in Chalcolithic period of Anatolia.

AATA

A Hauptmann, G Weisgerber and E A Knauf. Archäometallurgische und Bergbauarchäologische Untersuchungen im Gebiet von Fenan, Wadi Arabah, (Jordanian.) Archaeometallurgical examinations in the region of Fenan, Wadi Arabah (Jordon). *Der Anschnitt, 1985,* **37** *(5-6), 163-195 (Germ. W. Engl. summary).*

Wadi Arabah in Jordon was important for its copper mining from prehistoric times. 150,000-200.000 tons of slagheaps prove that this was one of the largest mining districts in antiquity. In the early periods copper silicates and malachite, later copper manganese ores, and in Roman periods manganese-free copper ores were mined. The shafts and the smelting sites are described in detail. Analyses of slags and ores are given.

AATA

V C Pigott. Pre-industrial mineral exploitation and metal production in Thailand. *Masca Journ. 1985,* **3** *(5), 170-174.*

The archaeometallurgical project conducted in 1984-1985 produced evidence of copper/bronze production on the Khorat Plateau in Northeast Thailand from ca. 2000 BC into the late 1st mill. BC. The region is, however, virtually devoid of deposits of copper or tin and the province of Loci, off the northwest edge of the Plateau, was investigated. Two relevant major complexes were identified in 1984, and one, a copper mining site at Phu Lon excavated in 1985. Prehistoric mining and mineral preparation was found at the site. Work for the 1986 season is adumbrated.

AATA

J Merkel. Ore beneficiation during the Late Bronze/Early Iron Age at Timna, Israel. Masca 1985, 3 *(5), 164-169.*

Experiments on effect of beneficiation (enrichment of an ore between mining and smelting) on element concentrations in copper smelting at Timna's Site 2 were carried out in connection with an elucidation of ancient smelting methods. Analysis was by emission spectroscopy (inductively coupled plasma). The beneficiation method was handsorting, and it is shown that element concentrations (including minor and trace element) are markedly influenced by using it. If trace element patterns in excavated artefacts are to be related to those of the ore, the effects of beneficiation need to be recognised and eluciated.

AATA

B Prakash and V Tripathi. Iron technology in ancient India. *Metals & Materials, 1986, September,* **2** *(9), 568-579.*

The study of societies in remote areas, still practising traditional ironmaking processes is discussed.
Incorporates new archaeological and ethno-technological findings to draw a cohesive picture of the evolution of iron in India.

Authors (abridged)

J D Muhly, R Maddin, T Stech and E Ozgen. Iron in Anatolia and the nature of the Hittite iron industry. *Anatolian Studies, 1985,* **35,** *67-84.*

The general development of iron working is traced with special reference to Anatolia from the first use of meteoric iron in the 3rd millennium BC on. Fragments of some corroded Hittite iron artifacts were analysed and examined metallographically. One from Bogazkoy was of speiss (iron arsenide) and matte (iron sulfide). It is suggested that they may be associated with iron smelting. The remainder were too corroded or small to enable firm conclusions on the special nature of Hittite iron to be made.

AATA

J Riederer. Materialanalysen an Bronze und Messingstatuetten des Staatlichen Museums für Völkerkunde in München. (Analysis of bronze and brass statuettes of the Staatliche Museum für Völkerkunde in Munich). In: Skulpturen aus Indien. (Ed. C Mallebrein). *Munich, Federal Republic of Germany, 1984, 231-236 (In German).*

Some 48 Indian bronze and brass statuettes have been analysed by atomic absorption spectrometry. Some 12 different types of copper alloys, characterised by the large variation of the amounts of lead, tin, and zinc, distinguishable as objects from southern India, are mostly made of tin bronze and lead-tin bronzes, while in northern India copper-zinc alloys are more frequent.

AATA

T Stech, J D Muhly and R Maddin. The analysis of iron artefacts from Paleopaphos-Skales. *Reports of the Department of antiquities, Cyprus, 1985, 195-202.*

15 iron artefacts were investigated from a Cypro-geometric cemetery (different phases between 1050-750 BC). Many badly corroded objects produced relic carbides of decomposed pearlitic mild steel. The possibility of deliberate carburization is still under discussion.

CPSA

G Wranglen. The rustless iron pillar at Delhi. *Corrosion Science, 1970,* **10,** *161-770.*

History and technical study of the old forge-welded wrought-iron pillar at Delhi.

AATA

Changhu Tian. Analytical study of the foundry technology of Chinese ancient bronze mirrors. *Chengdu Keji Daxue Xuebao, 1984,* **3,** *145-151.*

The bronze foundry technology in ancient China used very delicate moulding methods and melting practices. The development of the bronze mirror stretched from the late stage of the New Stone Age to the Quing Dynasty. The origin and development of bronze mirrors are disussed and chemical analyses, metallographic structures, and hardness studies are given.

AATA

Africa

C J Davey. Crucibles in the Petrie collection and hieroglyphic ideograms for metal. *The Journ. of Egyptian Arch. 1985,* **71,** *142-148.*

Six crucibles from the Petrie collection, University College, London are described and illustrated. X-ray fluorescence analysis of slags from the crucibles is reported briefly. Archaeological, historical, and philological evidence is also used to determine the manufacture, use, and significance of the crucibles. The crucibles seem to have been used in the production of copper and tin bronzes, except for one which may have been used for precious metals.

AATA

America.

H R Schenck and R Knox jr. Valley Forge: the making of iron in the 18th century. *Archaeology, 1986, January-February,* **39** *(1), 26-33.*

Techniques of archaeometallurgy were employed to examine two cast iron and three wrought iron artefacts from the upper forge of Valley Forge. Quantitative analysis of the major and minor elements in each piece of proton-induced X-ray emission (PIXE) spectroscopy indicates a mediocre quality wrought iron. Its high carbon content raised the possibility that the site was actually a steel forge and not a finery forge.

AATA

H R Schenck and R Knox jr. Wrought iron manufacture at Valley Forge. *Masca 1985,* **3** *(5), 132-142.*

Valley Forge in south eastern Pennsylvania is a site for the refining of cast iron dating back to 1742. Five pieces of iron (2 pig iron, 3 wrought iron) were studied by metallography, microhardness measurements and compositional analysis using proton-induced X-ray emission (PIXE). The pieces are all of good quality in being low in deleterious elements such as sulphur and phosphorus but the wrought irons are markedly heterogeneous and of high carbon content. This last feature has led to speculation that attempts at steel rather than wrought iron manufacture may be implicated. The appendix gives full detail on detection limits and errors for the PIXE method.

AATA

F Buchwald, G Mosdal. Meteoric, telluric and wrought iron in Greenland. *Man and Society, 1985,* **9,** *49pp. (68 figs.)*

Investigation of 74 artefacts (knives, harpoons, adzes etc.) from Eskimo Greenland. Those from known meteorites contain at least 5% Ni and many inclusions; objects made of telluric iron (Disco) are heterogeneously carburised (0.87-4%). Wrought iron artefacts date to AD 1100 and later. No heat treatment was used, only drilling and cold hammering.

CPSA

B R Gordon. Laboratory evidence of the use of metal tools at Machu Picchu (Peru) and environs. *Journ. Arch. Science, 1985,* **12** *(4), 311-327.*

An interpretation of use-wear marks on artefacts is developed from the principles of metal cutting and brittle fracture and applied to surface markings and microstructural damage on bronze tools. Most of the tools have blunt edges, relatively low tin contents and were not workhardened before use. Further details are discussed. Many of the tools are broken and study of their microstructures shows that the bronze used has poor mechanical properties because of porosity and bands of sulphide inclusions.

AATA

W W Vernon. New perspectives on archaeometallurgy of the Old Copper industry. *Masca 1985,* **3** *(5), 154-163.*

The Old Copper industry flourished in the Great Lakes region of the USA from about 3000 BC to 1000 BC. Thirty five artefacts and three native copper pieces were sectioned and studied by metallography. Cold-working and annealing of native copper was used. The results are discussed in anthropological terms.

CPSA

J R White and R W Jones. Metallurgical analysis of the Eaton (Hopewell) furnace iron. *Masca 1985,* **3** *(6), 182-185.*

A blast furnace at the site near Youngstown, Ohio, was in operation from 1803 to about 1808. Eleven specimens of iron were investigated. The results plus site investigations show that coal was used for smelting. The pig iron produced was of high quality despite the apparent absence of added flux, probably because of the ore was both rich and self fluxing.

A Sutulov. Early history of Chilean mining from the Inca period. *Bulletin of the Metals Museum, 1978,* **3,** *4-15.*

The earliest history of metal working is based upon archaeological evidence: the artefacts, the mines and the furnaces. The production of various ores and their relative importance inder the Spanish conquest are discussed. After independence in 1810, European investments were responsible for the expansion of mining activities. New techniques, such as the Swansea process increased production of copper. During the last half of the 19th century silver production and export were important to the economic stability of the country.

AATA

M L Wayman, R R Smith, C G Hickey and M J M Duke. The analysis of copper artefacts of the copper Inuit. *Arch. Science, 1985,* **12** *(5), 367-375.*

Metallography and neutron activation analysis have been used to investigate copper artefacts from 19th century archaeological sites associated with the 'copper Inuit' of the west central Canadian Arctic. A knowledge of the source of copper is important to studies of the effects of European contact on the utilisation of native copper and on the general lifestyle of the copper Inuit. Significant microstructural differences exist between native copper and the 19th century smelted copper. It was possible to differentiate between artefacts of native copper and those produced from smelted copper.

AATA (abridged)

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