BRITISH MUSEUM
Occasional Paper 17

Aspects of Early Metallurgy

HISTORICAL METALLURGY SOCIETY
Occasional Paper 1

Edited by
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Department of Scientific Research 1991

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Editorial Note

The papers contained in this volume were, for the most part, presented at a symposium on early metallurgy organised by the Historical Metallurgy Society and the British Museum Research Laboratory and held at the British Museum in April 1977. This symposium was arranged to coincide with the major exhibition called 'Wealth of the Roman World - Gold and Silver AD 300 - 700' which opened at the British Museum on 1st April 1977. It seemed an opportune occasion to organise a gathering of those interested in the investigation of ancient metallurgy, and the wide range of subjects covered by the papers in the following pages bears this out.

The first edition of Aspects of Early Metallurgy was prepared as a bound set of preprints for distribution at the 1977 symposium. In all about 220 copies were printed and distributed to those attending the symposium, with the remainder being sold soon afterwards so that the book has been out of print since the Autumn of 1977. Since then there has been a continuing demand for copies and this has encouraged the British Museum, with the agreement of the Council of the Historical Metallurgy Society, to print a second edition in the format of a British Museum Occasional Paper.

All the papers are the same as those in the first edition, although the opportunity has been taken to correct a number of typing errors, and, in addition, three new papers have been included.

At the 1977 symposium, Dr. M.G. Spratling gave a paper on the metallurgical finds from the Iron-Age Site of Gussage All Saints in Dorset. This paper has now been published in the official site report, and so an introduction to the site has been written by Jennifer Foster especially for this volume, and is accompanied by a report on the crucibles by Hilary Howard. Finally, part of Dr. Spratling's original paper which dealt with weighing in prehistoric Europe is also included.

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December 1979

SUMMARY OF RESULTS OF EXPERIMENTAL WORK ON EARLY COPPER SMELTING

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We have now smelted seven mineral ores and two artificial ores mainly to determine the trace element distribution between ore, slag, raw metal and refined metal. The real ores came from Timna (Israel), N'Changa (Zambia), Avoca (Ireland), Rudna Glava (Yugoslavia), Parys Mountain (Wales, UK) and Rio Tinto (Spain). The real ores were found to be of rather high purity and were capable of giving high purity metal by quite simple techniques. It seemed that we needed some artificial ores that might reflect to some extent the lower purity of some of the orebodies used in antiquity. For this reason two artificial ores were made up, from reagent grade oxides and sulphides respectively, to see how really impure ores behave. Figure 1 is a flow sheet which indicates the inputs and outputs of the process. The main results are discussed briefly below.

Furnaces

Forced draught bowl furnaces without slag-tapping facilities were used which are similar to furnaces found near Timna in the Negev and belonging to the Chalcolithic period(1). It was found that when one tuyere was used the copper formed mainly as droplets on the bottom, while with two tuyeres higher temperatures were attained and the metal formed a more compact "plano-convex" ingot. Iron enters from the slag by reduction and can diffuse from the slag when the copper, slag and charcoal are in intimate contact at temperatures over 1100°C. Normally the reduced metal globules fall through the slag layer into the cooler bottom regions of the furnace and end up with an iron content of 2 - 3%. But if they get "hung up" in the higher temperature regions in contact with slag and charcoal they then can absorb iron up to 30% and become very viscous.

The 2 - 3% Fe can be refined out by remelting in a crucible under either oxidising conditions or reducing conditions due to its existence as a separate phase with a lower density.

Fluxing

Real ores are either siliceous or ferruginous. Generally the sulphides have excess iron and need to be fluxed with silica, and the oxide ores have excess silica and need to be fluxed with iron oxide. In both cases therefore, the liquid slag will be mainly fayalite ($2FeO.SiO_2$), with a free running temperature of 1150 - 1250°C, through which the reduced copper will pass by virtue of the difference in density, and low solubility.

Fluxing was known from the 4th millennium B.C. and probably much earlier. Only pure minerals such as cuprite, malachite and chalcocite can be smelted without fluxing. Early people probably found out whether to use iron oxide or sand as flux by trial and error. We analysed the ores first and added the necessary flux to give a fayalite slag and it is therefore not surprising that all the slags are similar in composition. But, in order to prove our point we smelted two ores, an oxide and a sulphide, without a flux. The results were failures - the reduced copper in the first being virtually microscopic in size.

Oxide versus sulphide

The successful smelting of oxide ores merely requires the correct flux and enough charcoal to produce a reducing atmosphere. This results in a copper containing iron and a good proportion of the more volatile elements, As, Sb, Bi, Pb etc. Sulphide ores either require a prior roasting under oxidising conditions, in

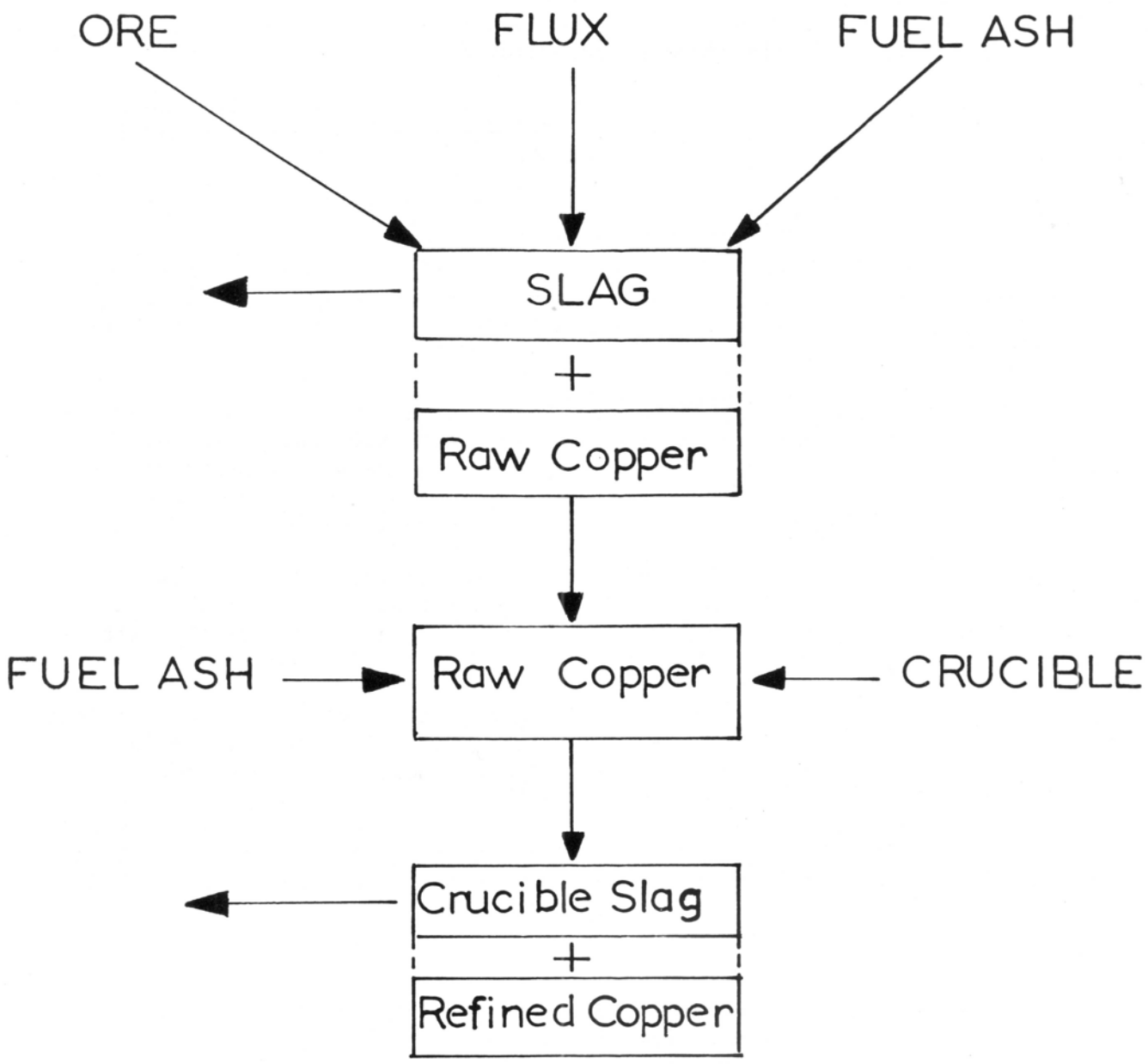
ORE
FLUX
FUEL ASH
SLAG
+
Raw Copper
FUEL ASH
Raw Copper
CRUCIBLE
Crucible Slag
+
Refined Copper

Figure 1

which case much of the volatiles is removed, followed by charcoal reduction to metal, or they may be smelted to matte (a solution of iron and copper sulphides) which also removes a good deal of the volatiles. This requires a further oxidation process before the oxidised matte can be reduction-smelted to metal, when further amounts of the volatile elements are removed.

It is now certain that sulphide ores were being smelted in MBA Ireland and in Roman Cyprus. This process would result in pure metal without refining and is probably responsible for the rather pure LBA ingots of Britain.

Distribution of main impurities

Most of the real ores mentioned in the first section gave rather pure copper apart from iron as they were low in the main impurity elements. For this reason impure oxide and sulphide furnace charges were made up to see how much of these impurities could be recovered or eliminated.

The results on the oxide "ore" are given in Table 1. We see that, as 50% of the "ore" is oxygen or slag-producing elements which are therefore removed, the amount of some of the elements in the raw copper such as As and Ni is increased while much of the Pb, Zn and Bi is lost. Losses of Ni, As and Sb subsequently take place during refining in a crucible under oxidising conditions.

The results for the sulphide "Ore" are shown in Table 2. Here we see that the losses during matte smelting are much greater and that even the nickel is partly eliminated. Further losses can be expected to take place when the matte is roasted to allow it to be reduction smelted.

While it is not surprising that much of the As, Sb and Bi have gone, the loss of the Pb is rather unexpected. Overall loss of Ni is negligible. There is little doubt that the increased loss during sulphide smelting explains the enormous improvement in copper purity from the LBA onwards. To a first approximation, in sulphide smelting the losses are in step with the vapour pressures of the elements (see Table 3) but, of course, this picture is complicated by dilution, the presence of the slag, and other factors. The presence of lead in Welsh EBA bronzes can only be explained by very high lead contents in the ores used if we preclude the possibility of intentional additions of metallic lead.

Summing up, then, we can explain the purity of the early coppers as being the result of low-temperature smelting and the frequent use of pure (except for As etc.) oxide ores. Later, higher temperatures were achieved with multiple tuyeres and, although the ores were probably less pure, the elimination of impurities such as As was then possible. By the LBA, sulphides were being smelted and the inherent purification of the roasting and matting process led to a large increase in the purity of the metal produced from impure ores. Even so, the high purity found in the British LBA ingots would not be expected without some specific purification process.

The ox-hide shaped ingots from Cape Gelidonya which date from the Late Bronze Age contain about 10% of iron.(2) We would not expect this from a sulphide copper deposit but it is perfectly possible for oxide smelting. It would seem that there were ample reserves of oxide ores in the Near East at this time.

Most of the iron and other impurities can be reduced in amount by controlled remelting in a crucible. The degree of refining will depend on the time and care given to the refining operation (Table 4).

In connection with the iron removal problem, it is clear that the iron and sulphur contents of the raw copper from the reduction-smelted oxide ores are very different from those of the roasted sulphides. (Table 5). In the case of the oxide ores the Fe/S ratio exceeds 5 while in the roasted sulphides it is about 1.

The relatively high residual sulphur level of the roasted sulphides may assist the removal of iron as FeS (which melts at 1000°C) by some segregation process. Probably the molten sulphide floats and is absorbed by the slag, while in the oxide smelts, the solid iron, with its greater density, is held in contact with the copper and produces a more viscous melt. (Fig. 2).

References and Footnotes

1. Details of the process using oxide ores were given at the 1976 Symposium on Archaeometry and Archaeological Prospection at Edinburgh, March 1976. Proceedings forthcoming.

2. R. Maddin and J. Muhly. Some notes on the copper trade in the ancient mid-east. J. of Metals, (1974) May, 7pp.

Acknowledgement

The main part of the work presented here was carried out by H.A. Ghaznavi and formed part of the work for his M.Sc. degree. His thesis is entitled "Trace element partitioning in Early Copper Smelting", University of Newcastle-upon-Tyne, October 1976. This has since been published as R.F. Tylecote, H.A. Ghaznavi and P.J. Boydell, 'Partitioning of trace elements between the ores, fluxes, slags and metal during the smelting of copper', J. Arch. Sci. 4 (1977) 305-333.

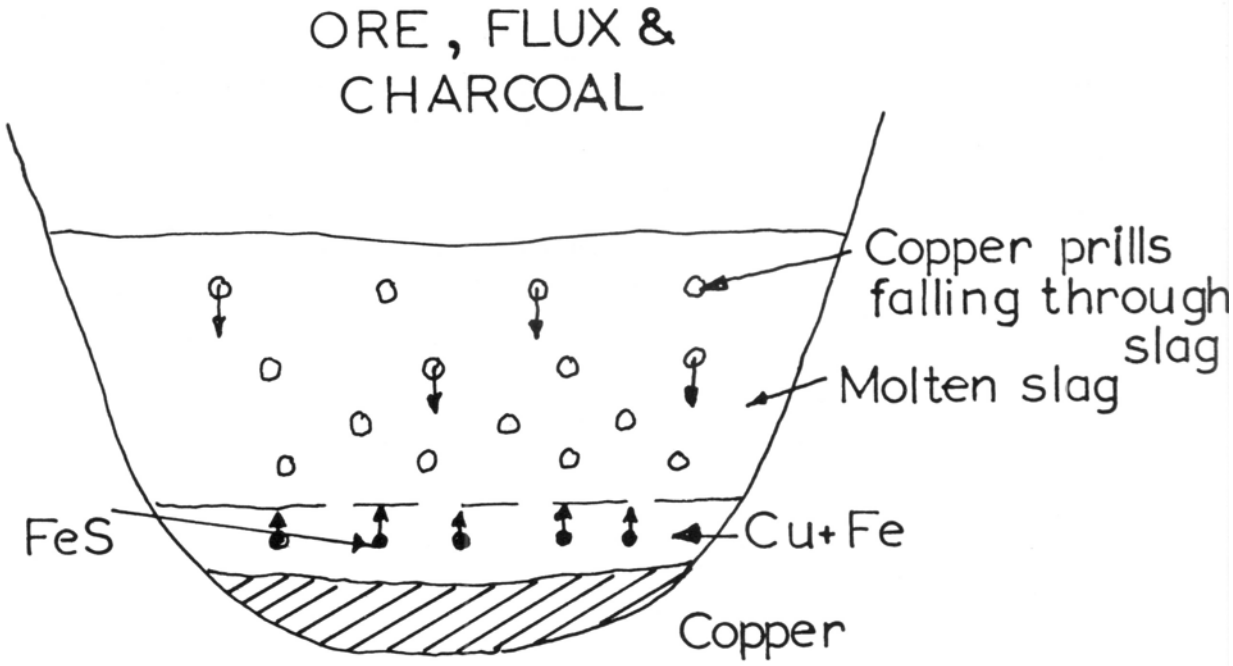

Figure 2

Table 1

Artificial Oxide Ore - Smelt No.14

Composition %			Metals in Ore From (1)	% Calc. to 100	Raw, smelted metal %	Loss or gain %	To:
Ore		Slag					
1		2	3	4	5	6	
CuO	50.0	0.08	Cu 40.00	59.5	73.15	-	-
MnO_2	5.0	4.75	Mn 3.16	4.8	0.05	-99	slag
As	2.88	nd	As 2.88	4.4	4.20	-0.5	-
ZnO	5.00	2.50	Zn 4.03	6.1	2.20	-64	slag
NiO	5.00	nd	Ni 3.89	5.8	9.75	+68	-
PbO	5.00	1.34	Pb 4.65	7.0	2.02	-71	slag, fume
Sb	4.20	nd	Sb 4.20	6.3	5.30	-16	-
Bi_2O_3	(3.72 Bi)	0.09	Bi 3.72	5.6	1.01	-82	fume
FeO		49.5	Fe -	-	2.32		
Fe_2O_3		1.86					
Al_2O_3		1.40					
CaO		7.20					
K_2O		1.50					
Na_2O	2.34	1.20					
SiO_2	15.00	27.4					
			67.3	99.5	100.0		

nd = not detected

Table 2

Artificial Sulphide Ore - Smelt No.15.

Composition % Ore		Slag	Sulphides and metals in ore from (1) %		Calc to 100	Smelted matte %	Loss %	To:
	1	2		3	4	5	6	
Cu_2S	30.0	2.16	Cu_2S	30.0	35.4	45.0	-	-
MnO_2	4.0	2.84	Mn	4.0	4.7	0.19	-95	slag
As	1.15	0.13	As	1.2	1.4	0.26	-82	fume
ZnO	4.00	1.97	Zn	4.0	4.7	1.81	-62	slag
NiO	4.00	0.16	Ni	4.0	4.7	3.84	-18	-
PbO	4.00	0.40	Pb	4.0	4.7	1.48	-69	fume
Sb	4.00	nd.	Sb	4.0	4.7	1.01	-78	fume
Bi_2O_3	(2.98 Bi)	0.15	Bi	2.98	3.5	0.12	-96	fume
FeS	30.00	-	FeS	30.00	35.4	24.80		
SiO_2	12.00	26.00	Si	-		2.50		
FeO	-	42.7	Fe			10.03 (Fe_3O_4)		
CaO	-	7.25	Ca			0.60		
Al_2O_3	-	1.55	Al			-		
Na_2O	1.43	1.45	Na			-		
K_2O	-	0.85	K			-		
Fe_2O_3	-	7.40	Fe			(Fe 3.2)		
MgO	-	0.62	Mg			0.40		

nd = not detected

Table 3

Vapour pressures of main impurities (pure metal) state) at 1500 K (1227°C).

	log mm Hg.
Sb_2	10.13
As_4	5.70
Bi	5.00
Zn	4.66
Pb	1.31
Cu	- 1.92
Sn	- 2.07
Co	- 3.98
Ni	- 4.45

(after Smithells, Vol.1, p.262-3)

Table 4

Effect of refining by crucible melting on the metal produced from Artificial Ore 14

	Composition - %		
	Metal in "Ore"	Raw copper	Refined copper
Cu	-	(73.2)	(85.9)
As	2.88	4.2	2.0
Sb	4.20	5.3	3.0
Mn	3.16	nd	nd
Ni	3.84	9.75	5.3
Pb	4.65	2.02	1.5
Zn	4.03	2.20	1.0
Bi	3.72	1.01	0.8
Fe	-	2.32	0.5

Table 5

Iron and sulphur contents of raw metal - %

	Tuyeres	Ores		Fe	S	Fe/S	Fe/S Mean
OXIDE ORES	1	CuO	1	2.6	0.35†	7.4	5.5
	1	Timna	2*	3.0	0.40	7.5	
	1	Timna	3*	2.5	1.0	2.5	
	1	Rio T	4*	2.86	0.6	4.7	
	2	Art	14	2.32	some†	high	
ROASTED SULPHIDE ORES	2	RioTR	12	1.0	0.9	1.1	1.1
	2	NCR	8	0.81	0.8	1.0	
	2	RT2R	9a	0.8	0.6	1.3	
	2	RT2R	9b	0.45	0.35	1.3	
	2	AVR	11	0.75	1.5	0.5	
	2	AMLR	13a	0.01	0.02	0.5	
	2	AMLR	13b	0.275	0.1	2.75	
	2	AMLR	13c	0.50	0.72	0.7	

* Residual sulphide - not roasted

† Sulphur probably came from haematite flux (0.17%)

Key
CuO Reagent grade cupric oxide
Timna. Oxide ore from Timna, Palestine
Rio T. Oxide ore from Rio Tinto, Spain.
Art. Artificial oxide ore.
Rio T R. Rio T ore roasted to remove some of the residual sulphur.
RT2R. Sulphide ore from Rio Tinto; roasted.
AVR. Sulphide ore from Avoca, Ireland; roasted.
AMLR. Sulphide ore from Parys Mt.,Amlwch,Wales;roasted.

INVESTIGATIONS ON THE EXTRACTIVE METALLURGY OF Cu/Sb/As ORE AND EXCAVATED SMELTING PRODUCTS FROM NORSUN-TEPE (KEBAN) ON THE UPPER EUPHRATES (3500-2800 B.C.)

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Introduction

During the 1974 excavation by Prof. Dr H Hauptmann(1) at Norsun-tepe, a hill near the copper belt which stretches from Iran via Anatolia and Cyprus to Sinai (Fig. 1), in the river valley of the Upper Euphrates where the dam of Keban is intended to provide a 64 000 km^2 water reservoir, a small heap of ore and many pieces of copper slag were found in a level dated 3500 B.C. As this early date could give some valuable information on early copper and copper alloy production, samples of the ore and from the slag were investigated in the laboratories of the metallurgical department of the materials science section of the University of Erlangen-Nürnberg. The composition of the ore was investigated together with the possibility of a reduction of this ore to metal and its usefulness for producing copper alloys. The slag was also investigated for distribution of the different phases involved and for their composition.

Investigation of the ore

There was a crystalline type of ore containing blue azurite, green malachite, white quartz and barite and red brown antimony-ochre (from an area NO 74 K19 I/II S // Room AB) consisting of particles from powder up to 4 cm diameter, and also one large piece of the same type of ore (10x8x5cm) (from J 18 III/IV//41 R.M.a) found in a burned area (27.7.74). Small pieces (2x3x0.5cm) of another ore of sandstone type were found together with copper slag in a different area (NO 74 J 18 III/IV//30 Room M) (15.6.74).

Crystalline type of ore

In order to find out the metal constituents of the ore, selected pieces and two samples of powder of the crystalline type were investigated by X-ray analysis. The powder was fixed on adhesive plastics and a 10x10 mm square of this sample was analysed. Two other particles of this ore of about 17 mm diameter were fixed in plastics, ground on dry emery paper and polished in water free solution by diamond paste. These two samples were also analysed and the results are given in Table 1 (no. 1-9). A sample of the large piece of crystalline ore found in the burned area (no. 10+11 of Table 1) was found to be a similar type of ore. Maximum imp./min was in all cases copper followed by barium. Other constituents were As, Cd, Fe, Ni, Pb, Sb, Sr and Zn.

One of the polished samples was investigated by electron microprobe analysis. Dark blue azurite areas and light green malachite areas contained the highest copper content. In dark brown areas barite and small inclusions of cuprite containing arsenic and antimony were present. A green area of malachite included areas containing a dark phase. These areas contained antimony with a content of arsenic which was less than that in the cuprite. Many white areas consisted of quartz. Dark coloured quartz contained antimony in small particles. One of the results of this analysis can be seen from figure 2 a-c. Between the grains of malachite and azurite an area containing antimony is present.

Several samples were taken for spectroscopic analysis. They were dissolved as far as possible in four parts of 30% nitric acid and one part of 25% hydrochloric acid of high purity. The liquid was dried on graphite electrodes which were investigated by spectrographic analysis and compared with samples which were investigated in powder form by means of a crucible shaped electrode. Results of the spectroscopic analysis are given in Table 2. The lines of Cd coincide with other lines, therefore Cd could not be analysed by this method. Besides the other elements found in the X-ray analysis, Ag, Al, Ca, Mg and Si were detected, whilst Co, Mn and Mo were present at the trace level. This semi-quantitative investigation revealed no significant difference between the ore samples A and B and the large piece of ore from the burned area.

All these samples were characterised by relatively large amounts of crystalline barite, sometimes occurring in crystals with a diameter of more than 0.5 mm. Besides deep blue veins and nodules of azurite, $Cu_3(CO_3)_2(OH)_2$, and bright green malachite, $Cu_2CO_3(OH)_2$, yellow redbrown antimony-ochre containing oxides of stibiconite, $Sb_3O_6(OH)$, and cervantite, Sb_2O_4, also arsenolith, As_2O_3, isomorphous with senarmontite, Sb_2O_3, and schafurzicite, $FeSb_2O_4$, isomorphous with trippkeit, $CuAs_2O_4$ and also isomorphous with lead oxide, Pb_3O_4, may occur. In one area a mixture of very small plate-like particles of<2 µm thickness of chalcopyrite and arsenopyrite, FeAsS, and tetrahedrite $Cu_3(SbAs)S_3$ was found. During the investigation of this area by microprobe analysis some part of this substance was evaporated by the heat of the electron beam.

Sandstone type of ore

The small samples of the sandstone type of ore which were found together with copper slag (in the area NO 74 J 18 III/IV//30 Room M) (15.6.74) had an appearance like green sandstone. As X-ray analysis (Table 1) and spectroscopic analysis (Table 2) show, this ore did not contain barium. Antimony, and a very small amount of arsenic, were found only by spectroscopic analysis. By using scanning electron microscopy with an element detector, black cubic particles included in the green sandstone ore were found to consist of quartz containing chromium oxide. The matrix contained, besides copper, a high content of iron. The sandstone ore was used for the smelting of copper. The same constituents as in this ore were found in the slag of the same level. Due to magnetite production by smelting of the ore many pieces of the slag were ferromagnetic. Such ferromagnetic slag was also observed in slags of early working at Ergani Maden(2).

The composition of the ore is similar to the sandstone ore from Helgoland which can be reduced easily to copper balls with charcoal in a claypot (15 cm diameter) placed in the middle of a pit (70 cm diameter and 40 cm in depth) on a layer of charcoal in a 4 h smelting process(3).

Reduction of ores in laboratory experiments

The easiest way to test the smelting of ore to metal is to take two pieces of charcoal and to put the ore between these pieces and then to heat it up with the aid of compressed air. This method may have been used also in prehistoric times and was used to investigate the possibilities of a reduction of the ores. For other laboratory tests small reduction furnaces were used.

Reduction of the crystalline ore

To investigate the influence of reduction time on the smelting products of the crystalline ore, especially on the content of antimony and arsenic in the reduced metal and in the slag, one sample of the crystalline ore (about 2 g) was reduced by the charcoal method for 7 minutes and a second sample for 3 minutes. After the reduction the samples cooled between the pieces of charcoal. They were embedded into plastics and investigated by X-ray analysis and by microprobe analysis. The results of the X-ray analysis (Table 3) show that antimony and

arsenic were still present in the smelting products. In the micrograph (Fig. 3) of the seven minutes reduction product, slag and round metallic balls can be seen. In the sample reduced for three minutes similar metallic balls were observed.

Two other samples of the ore were reduced in a small furnace (Fig. 4). Air was blown into the bottom of a graphite crucible of 70 mm interior diameter by means of three stainless steel tubes. The volume of air was measured by a gasometer. The ore was crushed to a particle diameter of less than 1 mm and mixed with charcoal particles of the same size and weight. In the beginning 200 g of glowing charcoal was inserted into the furnace. Then the ore-charcoal mixture (200 g ore and 200 g charcoal) was added in six portions. The reaction lasted 1 h and needed 2.6 m^3 air. In a second reaction 3.3 m^3 of air were blown into the furnace and the reaction time was also 1 h. The reaction products consisted of an agglomeration of slag with different appearance (crystalline and glassy) and of metallic balls. A temperature of $\sim$1200 ^{o}C was achieved.

The micrograph of figure 5 was prepared from a piece of the smelting product of the reaction which was done with 2.2 m^3 air. The phase labelled P1 contains the maximum content of Sb (Table 4) found in this sample. The other metallic phases, P2 and P3, also contain Sb and As. P2 consists of a metallic mixture of Ni and Cu with the highest Ni-content of all phases investigated. Maximum Cu-content of the metallic phases containing Sb and As is found in P3, on the border between metallic and sulphur-rich phases P4 and P5. No Sb and As were found by the microprobe analysis in the sulphur-rich phases.

Four different areas are shown in figure 6 from the reaction product which was reduced with 3.3 m^3 air. Between the black area of barium silicate containing Ca, Cu, Fe, K and Sb (P1 in Table 4) and the metallic bead, a dark grey area (P2 in Fig. 5) consists of copper-sulphide. The metallic ball (P3-P5) contains different Cu-base intermetallic compounds with different amounts of Sb, Pb and As. No Ni was found. Similar Cu-base intermetallic compounds containing Sb and As, and in addition Ni, also occur. Also in this sample, areas containing sulphides were found to contain no arsenic or antimony. In the micrograph illustrated in figure 7, copper sulphide (P1 and P2) is surrounding a Cu-Sb compound (P3) containing Ni and a high content of As. The bright centre of the metallic ball (P4) consists of another compound of Cu with a lower content of As. Other balls of metallic appearance contain As and Pb besides Cu, but no Sb. Many copper beads contain copper sulphide, as a dark grey inclusion, and other inclusions containing As, Ba, Ca, Fe, K, Mn, Si and Sb. No Ni is observed in these beads. Therefore it seems that by this reduction method, which may be similar to that used 5000 years ago, intermetallic copper compounds containing arsenic and antimony, metallic copper which contains small amounts of As and Pb, and copperstone could be produced simultaneously. Melting these products in a second melting process produces a very brittle Cu-Sb-As-alloy.

Reduction of sandstone ore

As was shown in a former smelting experiment with copper ore on Helgoland(3) there may be a large variation in the copper content of this type of sandstone ore. Also in the three reduction experiments performed with charcoal, very different amounts of metallic Cu and Fe were obtained, varying from 1 - 25% of the weight of the reaction products. By X-ray analysis (Table 3) of the slag the same elements were found as in the ore. The spectrographic analysis of a copper bead (Table 5) shows that no As could be detected, but a distinct line of Sb was observed. Ni and Co were detected. Neither the line of Zn nor that of Pb was observed, whilst in the ore Zn was detected in a very small amount.

Investigation of excavated smelting products

Smelting products dated to about 3500 B.C. were found in three different levels of the excavation. Each contained a different amount of slag, ore and burned clay.

Investigation of sample 2, from level NO 74 J 18 III/IV//30 Room M (15.6.1974)

This small slag heap (1.5 kg) contained about 50 pieces of slag with a diameter up to 8 cm, and also burnt clay arising from the contact of hot slag with earth or furnace lining. Most of the slag pieces were ferromagnetic. There were also some small particles of ore (∽1 cm diameter) which have already been described as sandstone ore. X-ray analysis of many pieces of this slag heap revealed the presence of only Cu and Fe. Only these two elements were observed in the burned clay. In one piece of broken slag (no. 9 of Table 3) strontium was detected.

The microprobe analysis showed that the magnetic behaviour of most pieces of this slag heap was caused by magnetite. In figure 8a-c typical areas of these slag pieces and in Table 6 the corresponding impulses/min of the elements detected are clollected. Figure 8a shows primary magnetite (P1, P2) in glassy slag (P3). In figure 8b Cu-Fe-oxide is present in P1, sulphide in P2 and silicates in P3 and P4, the latter containing potassium. In figure 8c, representing a larger area around figure 8b, P5 contains oxide and P6 chloride.

Investigation of sample 3 (2 pieces of slag 1x3 cm and 2x2.5 cm) from level K 18/19 I/II//41 R.Y. (7.8.74)∽3500 B.C.

The investigation of the two pieces of slag by X-ray analysis (Table 3) showed that in these samples only Cu and Fe could be detected. Microprobe analysis of a metallographic specimen (Fig. 9a + b and Table 6) showed that the light areas can be of very variable composition. In figure 9a, P1 consists of Cu-Fe-oxide and P2 contains a much higher content of iron and sulphur. Also within the white ball of figure 8b there are compounds of different composition. In the area of P3 a sulphide is present and the area of P4 contains Cu-Fe-oxide and in area P5 Cu-Fe-chloride. No Ni, As or Sb could be detected.

Investigation of sample 4, from level J 18 III/IV//41 R.M.-a (burned area) (27.7.74)∽3500 B.C.

This sample consisted of a large piece of crystalline ore, already described, a large piece of slag (2.5x2.5 cm) and four small pieces of slag (2.5x1 cm). The X-ray analysis showed (Table 3) that in some of the samples Pb or As and also Zn is present. These elements were not found in the slag of sample 2 and 3. In the microprobe analysis (Table 6) Cr was detected, as can be seen from the area P1 of figure 10a and P10 and P11 in figure 10b. In P6 of figure 10a and in P8 of figure 10b, copper chloride containing a small amount of Fe was found. This chloride is also observed in many other areas. Figure 11 shows a scanning microscope photograph of such colourless chloride plates. As these chlorides are observed within the slag, chlorides must have been an addition for the smelting of the ore.

Investigation of slag samples from level L 19a/G16 (20.7.74) and levels L 19a/G36; L 19a/K19b/G37 (9.8.74) dated∽2800 B.C.

Other slag samples, from a level dated to∽2800 B.C., showed a higher content of Co, besides Pb and Zn, in X-ray analysis, and a large amount of sulphide by microprobe analysis so that one may suggest that ore of a higher sulphur content was smelted during that time than in the levels dated∽3500 B.C. Also in these samples a large amount of chloride was present. No nickel was detected.

Alloying influence of the addition of crystalline ore and charcoal on copper at 1200 °C

As 1200 °C is a temperature which could be achieved in early days of metallurgical development 3 g of filings of pure copper were melted under charcoal in a crucible (60% Al_2O_3) at this temperature both with and without addition of 7 g of the crystalline ore smelting product arising from the 3.3m^3 air reduction already

described. On the two resulting metallic beads HV 0.015 was measured. The hardness HV increased from 88±2 for the copper to 116^{+4}_{-5} for the copper after alloying together with the reduction product of the crystalline ore. In this case the copper matrix contained about 0.5% Sb and a precipitate of small particles of CuS and of the intermetallic compound Cu_3Sb.

Summary and discussion

It may be suggested that the crystalline type of ore was found in tertiary volcanic rocks which have been mineralized locally. The copper carbonates and the compounds of Sb, As, Pb and Zn occur as fissure fillings together with quartz and barite. Similar ores can be found in the Azerbaijan mineralized area(4), which is a continuation of the north-east Turkish mineralized area. Although the high content of Sb and As would be suitable for an improved copper product in the diagrammatic tree of the development of metallurgy(5) there was no evidence of Sb or As in the slag of the same level. The ore used for the production of the excavated slag was an easily reducable sandstone type of ore found between the excavated slag.

The crystalline type of ore could not have been used for copper smelting because the resulting copper alloy would contain too much Sb and could not be fabricated into tools and weapons. It may have been used as a raw material for an alloying reaction with copper to produce an alloy containing Sb and As. As has been shown in a simple laboratory test, the hardness of copper could be increased from HV 88 to HV 116 by such an alloying procedure. Such alloys containing Sb and As were found in chalcolithic copper knives, in a dagger and in needles found in Cyprus(6) and in a bronze axe found in Ugarit(7).

Another excavation at Cayönii Tepesi, near Ergani Maden, the major copper mining area of Turkey and fifty km south of Keban, also produced striking evidence of early experimentation with several copper minerals(8) for copper smelting, so that the Ergani Maden mining area is believed to have had a great influence on the development of the metal industry of the Near East(9).

In all slag samples investigated, chloride was found in the interior of the slag so that one can assume that chloride fluxes were used for smelting this oxidized ore. In two other Bronze Age copper smelting sites, Enkomi in Cyprus(10) and Timna (Negev)(11), chlorides have also been found in copper slag samples. It seems that at 3500 B.C. in Norsun-tepe an oxidized copper ore was smelted and that first trials with a more complicated Sb and As containing ore were intended. At a later time (2800 B.C.) sulphide ore was smelted. From the small heaps of slag one may suggest that the smelting of copper within the town could be votive smelting in a temple for worshipping an unknown deity. A similar worshipping is suggested for Enkomi and Kition in Cyprus for male and female deities(12) and for Hathor in Timna (Negev)(13) and Aphrodite in Tamassos (Cyprus)(14).

Acknowledgements

X-ray analysis done by Mrs M. Kühl, microprobe analysis by Mr H. Rollig, spectroscopic analysis by Mr K. Nigge. The laboratory smelting of the ore was performed by Mr L. Endl.

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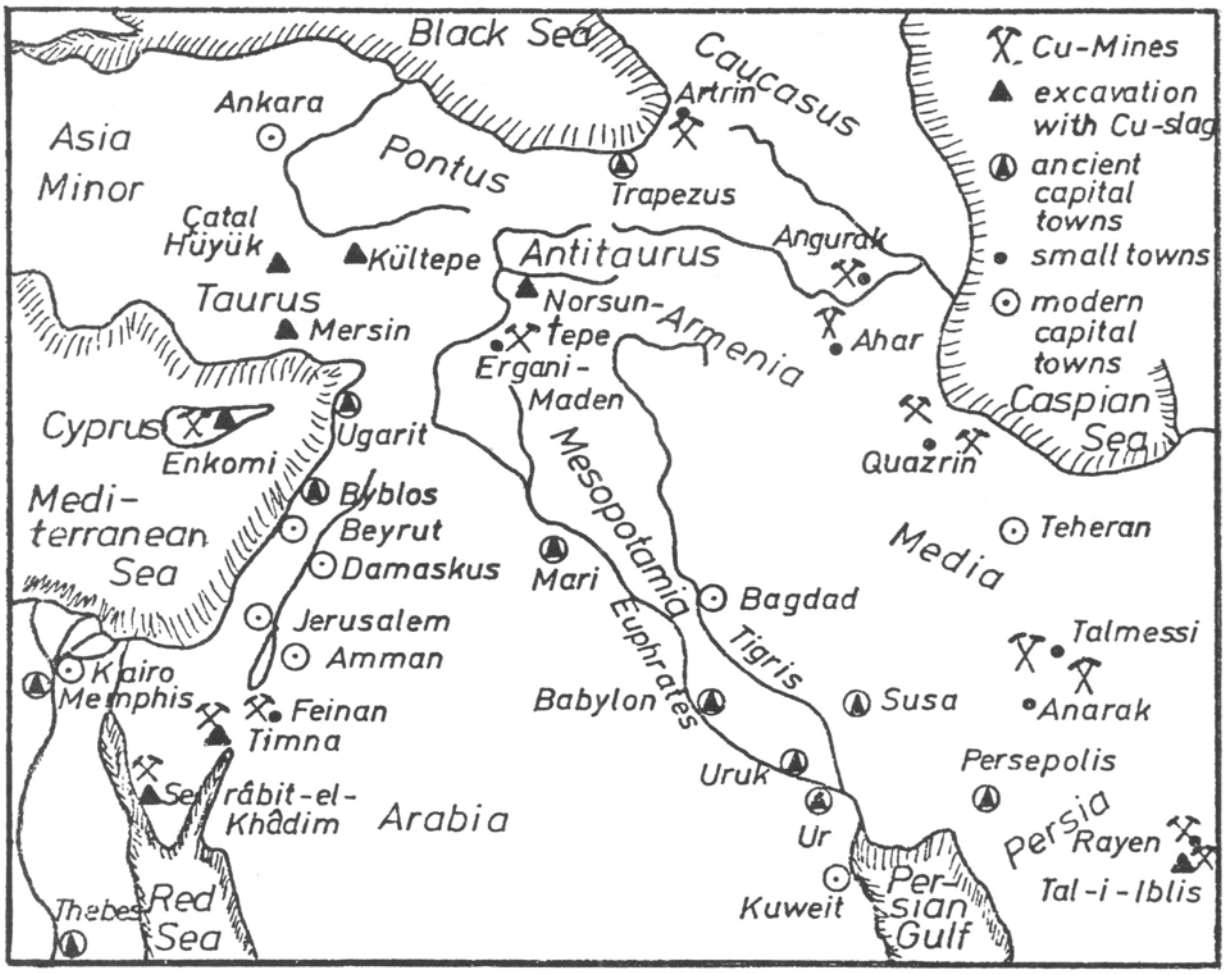


Figure 1: Situation of Norsun-tepe in copper bearing areas of the Middle East

Table 1

X-ray analysis of ores found in Norsun-tepe excavation 1974, ~3500 B.C.

no.	1	2	3	4	5	6	7	8	9	10	11	12	13
sample	crystalline ore									large piece burned layer		sandstone ore	
+++) element	powder A1	powder A2	powder B1	powder B2	met.+) A1	met.+) A1	met.+) A2	broken A	broken B	broken	met.+)	met.+)	broken
X-ray tube	W	Cr	W	Cr	W	Cr	Cr	W	Cr	Cr	Cr	Cr	Cr
Cu ++)	1526,6	122,8	1284,0	118,0	612,7	111,6	95,3	821,7	111,0	60,8	13,5	31,7	35
As/Cu	0,03	0,05	0,01	0,04	0,04	0,05	0,09	0,05	0,05	0,23	0,69?	nd	nd
Ba/Cu	0,25	0,44	0,28	0,62	0,57	0,55	0,12	0,45	0,42	1,07	2,27	nd	nd
Cd/Cu	0,02	0,03	0,03	0,03	nd	nd	nd	nd	nd	0,10	nd	nd	nd
Fe/Cu	0,01	0,05	0,08	0,06	0,07	0,04	0,08	0,08	0,04	0,11	0,12	0,28	1,27
Ni/Cu	nd	nd	nd	nd	0,02	nd	nd	nd	nd	0,03	nd	nd	0,04
Pb/Cu	0,03	0,04	0,09	0,04	0,04	0,05	0,08	0,05	0,05	1,02	0,69?	nd	nd
Sb/Cu	0,27	0,41	0,27	0,36	0,22	0,27	0,53	0,24	0,50	0,99	1,30	nd	nd
Sr/Cu	0,03	0,07	0,05	0,08	nd	0,10	nd	nd	nd	nd	nd	nd	nd
Zn/Cu	0,02	0,01	0,02	0,02	nd	0,02	0,04	0,02	0,01	0,08	nd	nd	nd

+) metallographic specimen nd = not detectable

++) Imp/min x 1000

+++) 50 kV, 10 mA

all elements $K\alpha_{11}$, As $K\beta_{11}$, Pb $L\beta_{11}$, As? $K\alpha_{11}$, Pb? $I\alpha_{11}$

Table 2

Spectrometric analysis of ores found in Norsun-tepe excavation 1974, ~3500 B.C.

wave length in Å	2287,08	2288,12	2335,27	2382,04	2516,12	2576,10	2802,00	2802,70	2816,15	2877,92	3273,96	3282,32	3361,21	3382,89	3453,51	3464,46	3933,67	3944,03
sample / element	Ni	As	Ba	Fe	Si	Mn	Pb	Mg	Mo	Sb	Cu	Zn	Ti	Ag	Co	Sr	Ca	Al
crystalline ore, sample A small piece	nd	++++	+++	+++	++++	tr	++	+++	tr	+++	ms	+	+	++	+	+	+++	+++
crystalline ore, sample A malachite + azurite, dissolved in HNO_3+HCl	nd	++++	+++	++++	+++	tr	++	++++	nd	+	ms	++	tr	nd	tr?	+	++++	+++
crystalline ore, sample A malachite	nd	++++	+++	++++	++++	+	+++	++++	tr	+++	ms	++	+	nd	tr?	+	++++	++++
crystalline ore, sample A azurite	nd	++++	+++++	++++	++++	+	+++	+++++	+	+++	ms	+++	++	+	tr?	++	++++	++++
large piece of crystalline ore, burned layer, samll piece	nd	++++	+++	+++	+++	tr	+++	+++	tr	+++	ms	+	+	++	nd	+	+++	+
sandstone ore	nd	tr	nd	++	+++	+	nd	++++	nd	+	ms	+	tr	tr	nd	nd	+++	+++

nd not detectable
tr trace
\+
++
+++ | increasing content
++++
+++++
ms main substance

working conditions: Q 24 (Zeiss)

Feussner Sparking
sparking time: 100 sec
capacity: 3000 cm
selfinduction: 815 000 cm
transformer indication: 3

slit height: 4 mm
slit width: 8 µm
electrode distance: 2,5 mm

Table 3

X-ray analysis of experimental smelting products of crystalline and sandstone ore and of slag samples no. 2 - 4, Norsun-tepe excavation 1974, ~3500 B.C.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
sample	c.o. R 21a (7min)	c.o. R 21a (7min)	c.o. R 22 2,6m³ air	c.o. R 32 3,3m³ air	s.o. R 57	s.o. R 58	e.s. 2/1	e.s. 2/2	e.s. 2G	e.s. 2	e.s. 3/1	e.s. 3/2	e.s. 4/1	e.s. 4D	e.s. 4E	e.s. 4F
X-ray tube	broken slag	met. +)	broken slag	met. +)	broken slag	broken slag	met. +)	broken slag	broken slag	burned clay	broken slag	broken slag	broken slag	broken slag	broken slag	broken slag
element	W	W	W	Cr	Cr	Cr	W	W	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr
Cu Imp/min x 1000 ++)	864,0	498,7	138,4	268,9	141,7	4,3	52,0	302,0	131,3	3,2	159,3	60,0	7,5	266,1	149,1	108,7
As/Cu	0,02	0,01	0,18?	0,05?	nd	nd	nd	nd	nd	nd	nd	nd	0,24?	nd	0,01?	0,02?
Ba/Cu	0,30	0,52	1,66	0,20	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fe/Cu	0,05	0,09	0,19	0,04	0,37	3,22	2,62	0,36	0,05	2,14	0,16	0,80	2,12	0,08	0,26	0,54
Ni/Cu	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0,01
Pb/Cu	0,03	0,01	0,18?	0,05?	nd	nd	nd	nd	nd	nd	nd	nd	0,24?	nd	0,01?	0,02?
Sb/Cu	0,35	0,71	0,50	0,12	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sr/Cu	0,05	0,07	nd	0,05	nd	nd	nd	nd	0,02	nd	nd	nd	nd	nd	nd	nd
Zn/Cu	0,03	0,02	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0,004

+) metallographic specimen
++) 50 kV, 10 mA, all elements $K\alpha_{11}$, As $K\beta_{11}$, $PbL\beta_{11}$, As? $K\alpha_{11}$, Pb? $L\alpha_{11}$

nd = not detectable
c.o. = crystalline ore-reduction
s.o. = sandstone ore-reduction

e.s. = excavated slag

Table 4

Microprobe analysis of experimental smelting products of crystalline ore of excavation Norsuntepe 1974, ~3500 B.C., 25 KV, ~70×10^{-9} A+)

sample	area	Al mica $K\alpha_{11}$	As LiF $K\alpha_{11}$ ($K\beta_{11}$)	Ba mica $L\alpha_{13}$	Ca mica $K\alpha_{13}$	Cu LiF $K\alpha_{11}$	Fe LiF $K\alpha_{11}$	K mica $K\alpha_{13}$	Ni LiF $K\alpha_{11}$	Pb LiF $L\alpha_{11}$ ($L\beta_{11}$)	S mica $K\alpha_{21}$	Sb mica $L\alpha_{13}$	Si mica $K\alpha_{11}$
R 22	P1	nd	2,79	nd	nd	0,88	nd	nd	nd	nd	nd	31,6	nd
(2,6 m^3 air)	P2	nd	2,48	nd	nd	14,45	0,11	nd	20,18	nd	nd	19,7	nd
Fig. 5	P3	nd	1,70	nd	nd	49,2	nd	nd	0,21	nd	nd	13,3	nd
	P4	nd	nd	5,79	nd	36,1	6,65	nd	nd	nd	25,2	nd	nd
	P5	nd	nd	nd	nd	62.3	0,60	nd	nd	nd	19,3	nd	nd
R 32	P1	nd	nd	10,9	1,55	0,39	2,67	0,39	nd	nd	nd	0,28	14,4
(3,3 m^3 air)	P2	nd	nd	nd	nd	30,3	nd	nd	nd	nd	22,35	nd	nd
Fig. 6	P3	nd	0,66?	nd	nd	38,1	nd	nd	nd	0,66?	nd	0,76	nd
	P4	nd	4,32 (0,55)	nd	nd	40,2	nd	nd	nd	4,32 (0,39)	nd	6,00	nd
	P5	nd	1,31?	nd	nd	40,2	nd	nd	nd	1,31?	nd	8,54	nd
	P6	0,87	nd	nd	nd	26,9	0,40	nd	nd	nd	23,3	0,48	1,86
R 32	P1	nd	nd	nd	nd	49,2	nd	nd	nd	nd	23,0	nd	nd
(3,3 m^3 air)	P2	nd	nd	nd	nd	45,3	nd	nd	nd	nd	22,1	nd	nd
Fig. 7	P3	nd	3,44	nd	nd	39,1	nd	nd	0,26	nd	nd	6,32	nd
	P4	nd	1,32	nd	nd	52.2	nd	nd	nd	nd	nd	2,39	nd

+) for all samples impulses/minute detected, not detected elements: Ag, Au, Cr, Cl, Co, Mg, Mo, P, Sn, Ti, Zn.
nd = not detectable

Table 5

Spectrometric analysis of experimental smelting products of crystalline and sandstone ore and of chalcolitic slag, sample 2, Norsun-tepe excavation 1974, ~3500 B.C.

wave length in Å	2287,08	2238,12	2335,27	2382,04	2516,12	2576,10	2801,00	2802,70	2816,15	2877,92	3273,96	3282,32	3361,21	3382,89	3453,51	3464,46	3933,67	3944,03
element / sample	Ni	As	Ba	Fe	Si	Mn	Pb	Mg	Mo	Sb	Cu	Zn	Ti	Ag	Co	Sr	Ca	Al
Reduction of azurite from crystalline ore, slag (R 55)	nd	+	++	++	+++	++	nd	++	nd	+	++++	nd	nd	tr?	+	tr?	++	tr?
Reduction of azurite from crystalline ore, copper ball (R 55)	tr	+	+++	++	+++	++	nd	++	tr?	++	ms	nd	+	++	nd	tr	+++	++
Reduction of crystalline ore in small furnace, sulfide (R 22)	nd	+	++	++	++	+	nd	+++	nd	++	ms	+	tr	+	nd	nd	+++	+
Reduction (R 22) " " sulfide with white area	nd	+	+++	++	+++	+	+	+++	tr?	++	ms	++	tr	+	nd	tr	+++	+
Metallic ball (R 22) " "	nd	+++	+++	++	+++	++	++	+++	nd	+++	ms	+++	tr	++	nd	tr	+++	+++
Reduction of large piece of ore (burned layer) slag	tr	+	++	++	++++	++	tr	+++	tr?	+	++++	nd	nd	nd	+	+	+++	+
Red. sandstone ore, slag (R 58)	nd	nd	nd	+++	++	+	nd	+++	nd	tr	+++	nd	nd	tr	+	nd	+++	++
Red. sandstone ore, slag (R 62)	nd	nd	nd	+++	++	++	nd	+++	nd	tr?	+++	nd	nd	tr?	+	tr?	+++	++
Red. sandstone ore (R 58) metallic ball	+	nd	nd	+++	+++	+	nd	+++	nd	+	ms	nd	+	+	++	nd	+++	+++
Slag, sample 2 A	tr?	tr	nd	++++	++++	++	nd	++++	nd	nd	ms	+++	+	tr?	+	nd	++++	+++
Slag, sample 2 B	nd	+	nd	++++	++++	+	nd	++++	nd	tr?	ms	++	tr	tr?	+	nd	ms	+++
Ferromagnetic slag, sample 2	nd	tr	nd	++++	++++	++	nd	++++	nd	tr?	++++	nd	+	tr	++	nd	ms	+++
Slag, sample 2, powder	nd	nd	nd	+++	+++	++	nd	++++	tr?	nd	++++	nd	++	nd	nd	nd	ms	+++
Burned clay, sample 2	nd	nd	nd	++	+++	++	nd	+++	nd	nd	+++	nd	tr	nd	nd	nd	+++	++

nd = not detectable
tr = trace
ms = main substance

\+ ++ +++ ++++ ↓ increasing content

working conditions: Q 24 (Zeiss)

Feussner sparking
sparking time: 100 sec
capacity: 3 000 cm
selfinduction: 815 000 cm

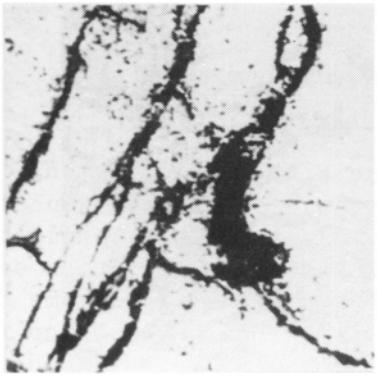
transformer indication: 3
slit height: 4 mm
slit width: 8 µm
electrode distance: 2,5 mm

Table 6

Microprobe analysis of slag, sample 2 - 4, excavation Norsun-tepe 1974, ~3500 B.C. 25 kV, ~ 70×10^{-9} A, for all samples impulses/minute detected

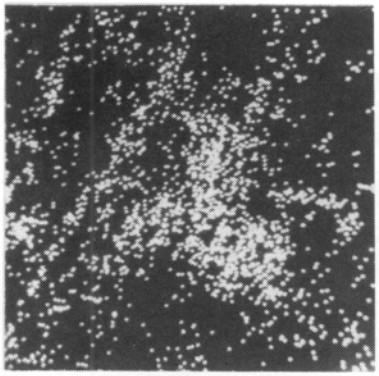
sample	area	Al mica $K\alpha_{11}$	Ca mica $K\alpha_{13}$	Cl mica $K\alpha_{11}$	Cr LiF $K\alpha_{11}$	Cu LiF $K\alpha_{11}$	Fe LiF $K\alpha_{11}$	K mica $K\alpha_{13}$	Mg mica $K\alpha_{11}$	Ni LiF $K\alpha_{11}$	S mica $K\alpha_{21}$	Si mica $K\alpha_{11}$	Zn LiF $K\alpha_{11}$
slag sample 2/1	P1	1,29	4,04	nd	nd	2,00	2,46	0,09	0,15	nd	nd	21,3	nd
Fig. 8a	P2	0,15	nd	nd	nd	7,06	24,2	nd	0,08	nd	nd	0,89	nd
	P3	0,16	nd	nd	nd	1,52	28,7	nd	0,11	nd	nd	nd	nd
slag sample 2/2	P1	nd	nd	nd	nd	49,3	0,35	nd	nd	nd	nd	nd	nd
Fig. 8 b+c	P2	nd	nd	nd	nd	64,27	0,71	nd	nd	nd	3,14	nd	nd
	P3	0,17	4,86	nd	nd	0,70	6,05	nd	0,57	nd	nd	16,0	nd
	P4	0,96	1,60	nd	nd	2,37	4,02	0,22	nd	nd	nd	24,1	nd
	P5	nd	nd	nd	nd	6,26	27,9	nd	nd	nd	nd	1,59	nd
	P6	nd	nd	16,0	nd	31,3	0,40	nd	nd	nd	nd	nd	nd
slag sample 3	P1	nd	nd	nd	nd	55,1	1,92	nd	nd	nd	nd	nd	nd
Fig. 9 a+b	P2	nd	nd	nd	nd	48,0	3,76	nd	nd	nd	3,50	0,89	nd
	P3	nd	nd	nd	nd	46,7	2,39	nd	nd	nd	24,3	nd	nd
	P4	nd	nd	nd	nd	25,5	25,6	nd	nd	nd	nd	0,47	nd
	P5	nd	nd	3,00	nd	25,5	26,2	nd	nd	nd	nd	nd	nd
slag sample 4	P1	nd	nd	nd	0,13	0,32	49,3	nd	nd	nd	nd	nd	nd
Fig. 10 a+b	P2	1,62	2,42	nd	nd	0,66	6,46	0,20	0,19	nd	nd	29,7	0,10
	P3	0,24	0,60	nd	nd	0,44	13,7	0,16	0,65	0,11	nd	21,6	nd
	P4	nd	nd	nd	nd	60,6	2,91	nd	nd	nd	nd	nd	nd
	P5	nd	nd	nd	nd	62,1	1,90	nd	nd	nd	nd	nd	nd
	P6	nd	nd	22,8	nd	37,0	0,86	nd	nd	nd	nd	nd	nd
	P7	nd	nd	19,3	nd	42,7	0,84	nd	nd	nd	nd	nd	nd
	P8	nd	nd	nd	nd	48,0	1,83	nd	nd	nd	19,1	nd	nd
	P9	nd	nd	nd	nd	2,90	0,85	nd	nd	nd	nd	57,3	nd
	P10	nd	nd	nd	19,2	0,32	14,2	nd	0,33	nd	nd	nd	nd
	P11	nd	nd	nd	0,30	0,15	54,0	nd	nd	0,16	nd	nd	nd
	P12	nd	nd	nd	nd	0,44	8,00	nd	nd	nd	nd	56,8	nd

nd = not detectable; not detected elements: Ag,As Au,Ba,Ca,Cl,Co,Mo,P,Pb,Sb,Sn,Ti



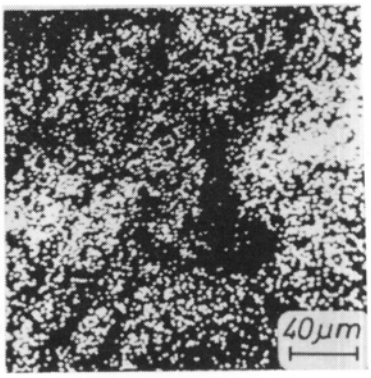
2a

Backscattered electron Image



2b

Sb-image



2c

Cu-image

Figure 2a-c: Microprobe analysis of crystalline ore

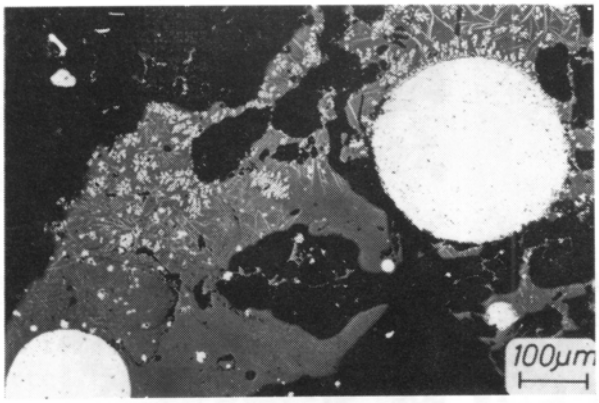


Figure 3: Micrograph of slag and Cu-balls of reduced crystalline ore (R21a)

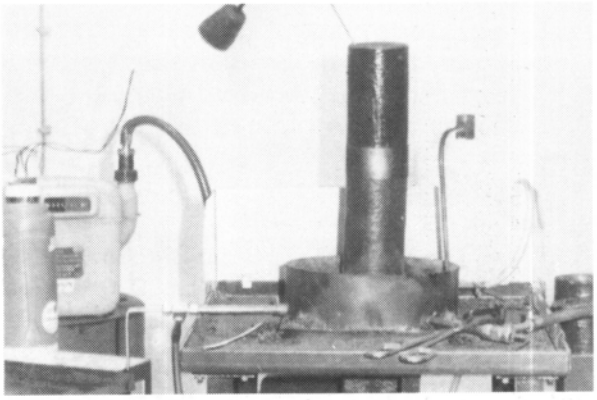


Figure 4: Laboratory smelting furnace for copper ore

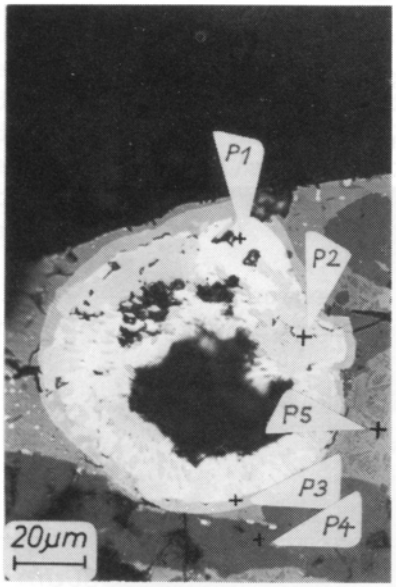


Figure 5: 2.6 m^3 air crystalline ore

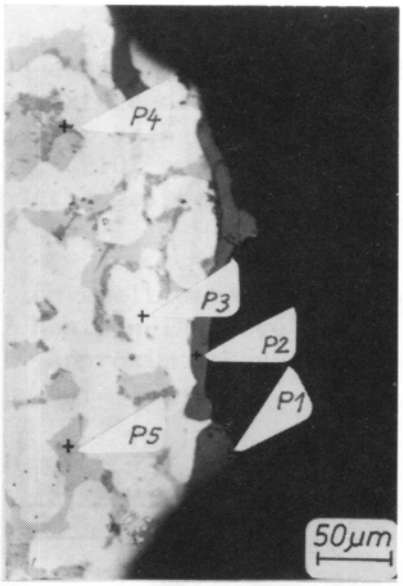


Figure 6: 3.3 m^3 air crystalline ore

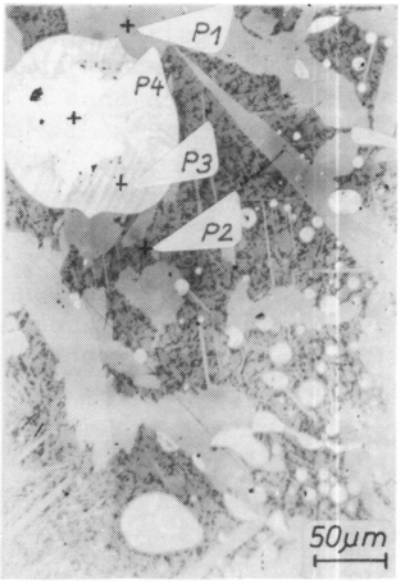
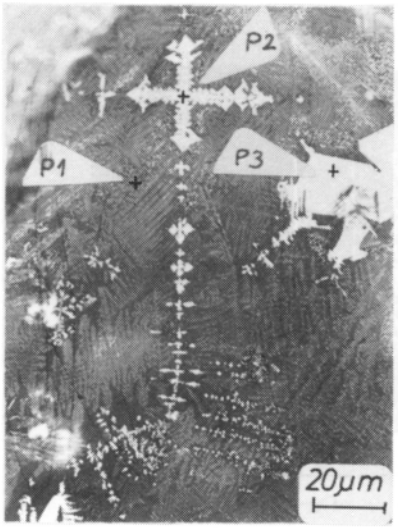
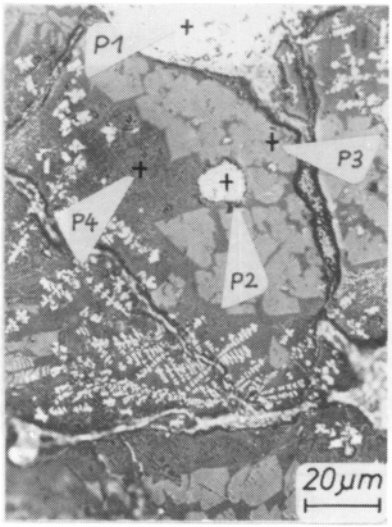


Figure 7: 3.3 m^3 air crystalline ore

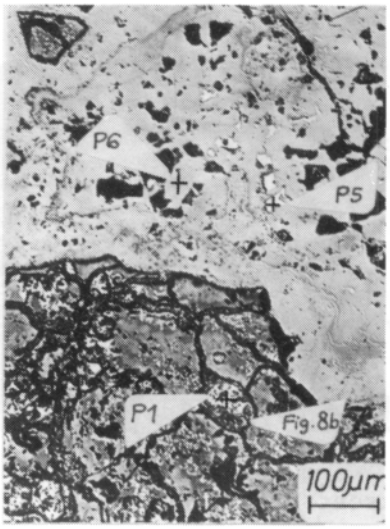
Figure 5-7: Micrographs of laboratory smelting products



8a



8b

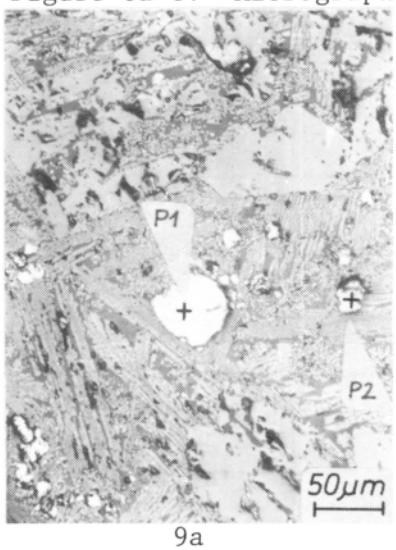


8c

Slag sample 2/1

Slag sample 2/2

Figure 8a-c: Micrographs of excavated slag, sample 2



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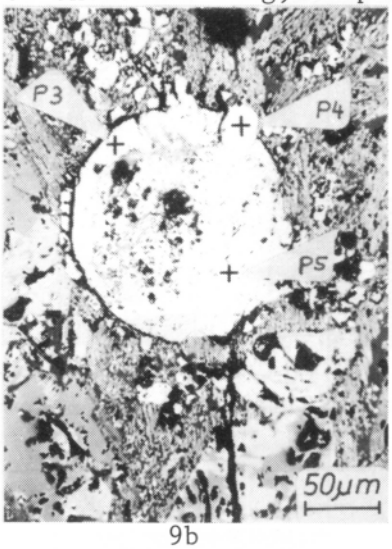

9b

Figure 9a-b: Micrographs of excavated slag, sample 3

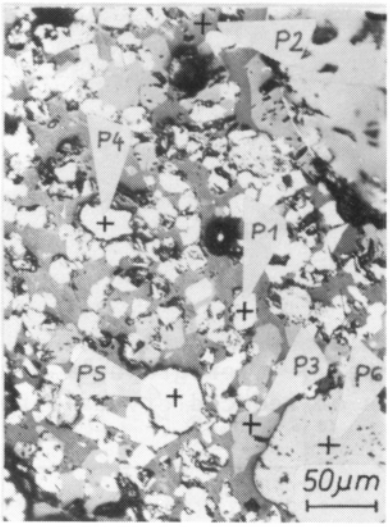

Figure 10: Micrograph of excavated slag, sample 4

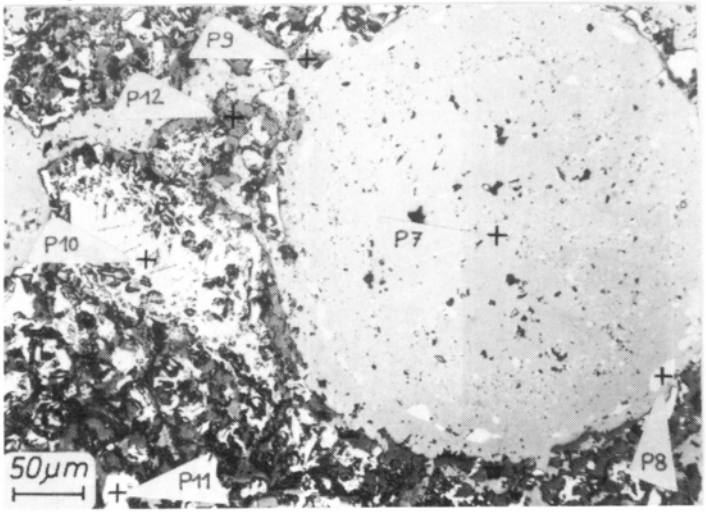

Figure 10b: Micrograph of excavated slag, sample 4

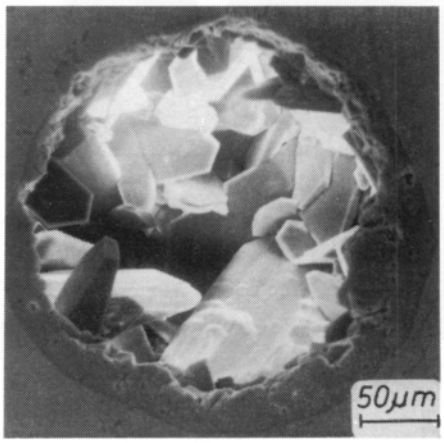

Figure 11: Scanning electron micrograph of chloride in slag sample 4

INVESTIGATIONS INTO PRIMITIVE LEAD SMELTING AND ITS PRODUCTS

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The purpose of this paper is to describe a series of lead smelting experiments carried out to produce material under primitive, yet controlled and recorded conditions. This material could then be examined for features that relate to those conditions and then ultimately compared with archaeological material from lead smelting sites around the world. The results of some preliminary analytical work on the slag and some of the "lead" produced are also included. However it must be stressed that this work is still continuing. At this stage the results are far from complete and the conclusions drawn from them are only tentative.

Modern materials and equipment were used to simulate primitive conditions in the smelting experiments. The use of entirely "authentic" primitive materials would not have allowed the necessary degree of control and variability of conditions required. It is intended that the results of these experiments could be used in comparison with similar results from an archaeological lead smelting site, and from this a hypothetical reconstruction of the process used at that site could be made. Then this hypothetical process could be tested by itself, using only equipment and material which could have been used at that site.

Equipment and materials used

The furnace was designed and built as in figures 1 and 2. It basically consisted of a deep bowl of approximate dimensions 0.23m. diameter and 0.3m. deep. Facility for tapping the furnace was made at the bottom of the furnace by providing a removable brick. A tuyere end consisting of a piece of mullite tube was inserted through the furnace wall above the tap hole at an angle of about 60° to the horizontal and three probe holes to allow temperature and gas composition measurements to be made were inserted in a vertical plane at an angle of 80° to that of the tuyere. Tuyere II whose position is indicated in figures 1 and 2 was only used in two of the preliminary smelts and was found to be unnecessary. Air to the tuyere was supplied by an electrically driven rotary compressor, the flow rate being monitored by a conventional rotameter. A furnace lining was used to prevent attack on the furnace wall by the charges used in the smelting and this, after the preliminary smelts had established that a refractory cement lining tended to crack, consisted of a mixture of bentonite, silica sand and charcoal powder, moistened and re-applied for each smelt. Temperature measurements were made using chromel/alumel (Ni90%, Cr10% v Ni94%, Al2% + Si&Mn) thermocouples protected by silica sheaths, and the gas measurements were made using an "Orsat" apparatus.

The smelting charges for each smelt were mixtures of galena concentrate, ferruginous flux consisting of "Newfoundland Ore" and siliceous flux consisting of normal, foundry silica sand. Approximate analyses for these materials are given in Table 1:-

Table 1

Analyses of ore and fluxes

	SiO_2	Fe_2O_3	Pb S	Pb	Al_2O_3	Total
Galena Concentrate	2.26	3.0	78.3	-	1.83	85.4
Silica Sand	88.5	0.21	-	nil	6.95	95.66
Newfoundland Ore	3.48	83.0	-	0.013	7.6	94.093

The remaining 15% for the galena concentrate probably consisted of lime (CaO) and fluorspar (CaF_2). For the mixing of the charges these materials were used in coarse powder form (maximum particle size about mesh size 10).

The fuel used was normal charcoal as supplied in lumps (maximum size about 50mm cube).

Experimental

Four preliminary smelts were carried out in order to establish a successful procedure for working the furnace and from which a programme of smelts could be planned which would eventually provide as much information as possible. Thus a programme was designed in which the effect of altering the following variables, on the nature of the products, could be investigated :-

Series A - charge composition (nine smelts)

Series B - air-flow rate through the tuyere (three smelts)

Series C - running time (two smelts)

Series D - charging time (one smelt)

Series E - height of tuyere above base of furnace (one smelt)

The "charging time" was the time taken to charge the prepared charge (always being 5kg. in weight) and the "running time" was the time after charging had finished when the furnace was allowed to run on just charcoal before tapping of the furnace was attempted.

The basic procedure used was as follows :-

The furnace was preheated for two hours using a gas/air burner.

The furnace was then filled with charcoal and the air supply connected at the predetermined flow rate (normally 150$dm.^3$ $min.^{-1}$).

Thirty minutes after the start of charcoal addition, addition of the prepared charge with charcoal was started at a predetermined rate so that it would all be added at the end of the prescribed time, (normally 60 minutes).

After this, the furnace was run on charcoal only, for a predetermined time (normally 60 minutes) and finally tapping was attempted by removing the removable brick, punching a hole in the furnace lining, and raking out material that was able to flow, into a steel mould.

Temperature measurements were made just before charging the prepared charge was begun, and again just before tapping was attempted. Gas measurements were made just before charging the prepared charge was begun and again just after charging of the prepared charge had finished.

The charge composition, charging time, running time, air-flow rate and tuyere height for each smelt is given in Tables 2 and 3. The charge compositions for series A were chosen so that charges with galena contents of about 60% (smelts PbA1,2 and 3), 40% (smelts PbA4,5 and 6) and 20% (smelts PbA7,8 and 9) were tested with iron oxide to silica ratios of 3:1 (smelts PbA1,4 and 7), 2.4:1 (smelts PbA2,5 and 8) and 1.5:1 (smelts PbA3,6 and 9). The charcoal consumption rates given in Tables 2 and 3 were not predetermined but depended on other factors, mainly the air-flow rate.

In addition, three dry runs were made using just charcoal, no prepared charge being added at all. This allowed for further investigation of the effect of

different air-flow rates and the possible effect of a different preheat time (which was not altered in the actual smelting experiments).

Temperature and atmospheric conditions present during the smelts

The information on this relating to each individual smelt is collected in Tables 2 and 3. Generally these conditions were reasonably constant for each smelt in series A, though in smelt PbA7 the fusion of the charge into a solid mass round the tuyere end appears to have affected the air-flow through the furnace so that the temperature distribution while the furnace was running on charcoal alone, was altered. It must be pointed out that proper gas analysis was not introduced until smelt PbA5, however the figures after that tend to show (with the exception of smelt PbA9) that conditions after charging had finished were more oxidizing (i.e. smaller CO/CO_2 ratio) than before charging.

The changing of the air-flow rate in smelts PbB2 and PbB3 led to a reduction in temperature. Also the reduction in the CO/CO_2 ratio indicated that reduction of the air-flow rate created more oxidizing conditions. This may seem rather surprising but it is discussed later when more eivdence is presented. Accompanying these changes brought about by the reduction in air-flow rate is a dramatic decrease in the charcoal consumption rate.

As would be expected, the alteration of the running time had little effect on conditions within the furnace. Alteration of the charging time (and therefore rate of charging) might be expected to have affected conditions immediately after charging had finished and conditions do appear to have been rather more oxidizing at this time with a faster charging rate. The raising of the tuyere appears to have had little effect (rather surprisingly) on temperature distribution. It appears though, that it did lead to rather more oxidizing conditions in the vicinity of probe hole ii just before charging was begun.

As mentioned above, three "dry" runs were made to give further information on the temperature distribution and atmospheric conditions at different flow rates and different preheat times. The results from these showed that a fair region in the middle of the furnace was above 1300°C, hot enough to produce a fluid slag of any normal composition (see Fig. 3). However this region of highest temperature tended to move up the furnace with time, probably due to the build up of an ash layer on the bottom of the furnace. Lowering the air-flow rate tended to produce lower temperature (maximum 1100°C at a rate of $50 dm.^3 min.^{-1}$) and rather more oxidizing conditions as indicated by the CO/CO_2 ratios, though these did tend to be rather erratic indicating that conditions were never very stable in the furnace. Lengthening the preheat time appeared to have little effect on general conditions. A temperature profile for the first "dry" run (D.R.1) 180 minutes after the start of charcoal addition is shown in figure 3. Its rather asymmetrical appearance is probably due to the plane of measurement (that of the probe holes) being at an angle of 80° to that of the tuyere (see Fig. 2).

On cleaning out the furnace after the first and third "dry" runs, a vitreous material was found adhering to the furnace lining at the bottom. This probably came from the fuel ash and was analysed along with the slag material produced in the smelts.

The results of the smelting experiments

This information is presented in Table 4 . Unfortunately, at this stage it is impossible to give the weight of lead produced in each smelt separate from that of the slag. This is because much of the lead is entrapped as small particles within the slag and to retrieve it, the slag would have to be crushed up. It is hoped that some time in the future it will be possible to examine fragments of the slag under the microscope both as thin sections and metallographically under

reflected light. Only when this work is completed, will it be possible to crush the slag completely to obtain all the lead metal.

An obvious feature of the figures in Table 4 is that the combined weights of tapped and untapped material in each smelt are very much less (20-50%) than the total weight of charge smelted. The fact that the combined weight of tapped and untapped material increases as the galena fraction of the charge was reduced (smelts PbA1-9) suggests that it was the more volatile fraction that was lost. In this context it can be noted that as the air-flow rate was reduced, and thus the temperatures reduced (smelts PbB1-3), the fraction of material lost was reduced. Also, a shorter running time (smelt PbC1) and a shorter charging time (smelt PbD1) reduced the amount of material lost in this way. That no material was tapped in smelts PbA7 and PbA9 may be due to the composition of the slag, as derived from the charge, being such as to produce an insufficiently fluid slag at the temperatures present.

At this stage it is difficult to assess whether the amount of lead that was tapped is related to any of the experimental conditions, or whether it depended on the skill of the operator. The latter is probably very important but it would seem that the greater the lead content of the smelted material is, then the easier it is to tap the lead off from the less fluid slag.

The nature of the slag produced does appear to be rather variable. However it would seem that the greater the lead content of the charge, then the more non-crystalline is the nature of the slag.

Analysis of the products of the lead smelts

Again it must be stressed that this work is far from complete. It is hoped to be able to do further analyses on these products in the near future and that they will be ready by the time this paper is read. The analyses of the slags and the vitrified products of D.R.1 and D.R.3 are presented in Table 5 and the less complete analyses of some of the "lead" produced, are presented in Table 6.

The slag samples were crushed and sieved to a particle size smaller than 72 mesh. However, as a check, a sample of the untapped slag from smelt PbA2 which did not pass through the 72 mesh sieve was kept and analysed with the rest of the samples. For the silica, alumina and lead determinations, samples of the slag were fused with lithium tetraborate in a platinum crucible and then this mixture was dissolved in dilute hydrochloric acid. Often a small amount of precipitate formed which on being tested by evaporation with hydrofluoric acid proved to be silica. These solutions were appropriately diluted and tested against standard solutions for silicon, aluminium and lead on an atomic absorption spectrophotometer (Shandon Southern A3400). The precipitate was added to the spectrometrically produced figure for silica to give the total silica content. Metallic iron was determined by boiling the slag sample in 10% $CuSO_4$ solution, precipitating excess copper with aluminium and titrating against standard potassium dichromate solution. Iron II was determined by digesting the slag in hydrochloric acid containing sodium fluoride and titrating against standard potassium dichromate solution. Total iron was determined as for silica, alumina and lead on the spectrophotometer and iron III was determined by subtraction from this.

The samples of tapped "lead" were dissolved in dilute nitric acid and iron and lead were determined using the atomic absorption spectrophotometer.

At this stage there is little to be said about the samples of lead except that they obviously contain much impurity and they appear to be very variable in composition. It is possible that they contain slag inclusions.

More comment can be made on the slag analyses as they stand. A general feature is that most of the tapped samples are less rich in silica than the corresponding untapped samples, yet more rich in iron and lead oxides. This may be significant as one might expect the tapped material to be the more fluid component of the material in the furnace while it was running.

At this stage it is impossible to judge with any reliability whether there is differential pick-up or loss of elements (apart from the lead fraction). Until the weight of lead produced in each smelt is known separately and there is a full analysis of this lead, there is not enough information on this aspect. However the FeO: SiO_2 ratios appear to be generally rather low (see Table 7) and this may indicate that iron oxide has been lost in the smelting process along with the lead as fume.

The analyses of smelts PbA2, PbA3 and PbA4 may well be affected by the incorporation of material from the failed protective ends to the mullite tuyere. Otherwise it would be expected that there will be a little pick-up of alumina and silica as the charges attacked the tuyere.

As for charge compositions and their bearing on slag compositions, the expected general trends are shown in the figures for series A but there is great variability. For example Table 7 shows the FeO: SiO_2 ratios as present in the charge against the mean values of these ratios in the slag (tapped and untapped) for each smelt of series A.

Clearer relationships are shown between slag composition and some of the other variables. The decrease in metallic iron in the slag as the air-flow rate is decreased (smelts PbB1-3) gives further evidence of more oxidizing conditions with the lower air-flow rate. Also the higher lead content of the slag at the lower air-flow rate may also be indicative as it is reasonable to expect that the lead present in the slag exists as lead oxide rather than lead metal which would have been sieved out. There is a proper discussion of the air-flow rate and its relationship to the CO/CO_2 ratio in the next section.

Figure 4 shows how altering the running time affected the composition of the slag with respect to iron and lead. The lead content of the slag decreases with increased running time. Two effects may have caused this. Lead oxide being relatively volatile tended to vapourize off and be lost. The longer running time would allow more lead oxide to vapourize. Alternatively, it has already been pointed out that conditions immediately charging had finished were relatively oxidizing. It is reasonable to expect that the furnace would tend to return to relatively reducing conditions the longer it was run without further charge being added. Thus a longer running time would mean that for a greater time, conditions within the furnace were relatively reducing and thus more of the lead oxide would have been reduced to lead metal and separated from the slag. That this may have been the case is also indicated by the decrease in iron II content of the slag as the running time was increased and the corresponding rise of the iron O: iron II ratio as shown in figure 4.

The shorter charging time of smelt PbD1 appears to have caused an increase in the lead content of the slag. The probable explanation of this is that the shorter charging time meant a shorter time for the smelt as a whole, giving less time for volatalization of the lead oxide and less time for the lead oxide to be reduced to the metal.

As already said, raising the tuyere height (smelt PbE1) altered conditions little and there is no obvious feature of the slag analysis that can be related to this.

The vitrified products of the "dry" run, as might be expected, are highly siliceous. The lead content of the product of D.R.1 was probably absorbed from the furnace which had absorbed lead during the smelting experiments. This is supported by the absence of lead from the vitrified product of D.R.3. Further analysis of these products will be useful.

Air-flow rate and its effect on the CO/CO_2 ratio

An aspect that has emerged from the above work is that the air-flow rate through the furnace did have a considerable effect on the nature of the atmosphere present. This is to be expected. However, the fact that a reduction in air-flow rate led to more oxidizing conditions, is at first rather surprising. This effect can be explained if one considers the kinetics and thermodynamics of the charcoal burning reactions. The three main reactions in this respect are normally considered to be :-

$$2C + O_2 \longrightarrow 2CO \quad -(1$$

$$C + O_2 \longrightarrow CO_2 \quad -(2$$

$$2CO + O_2 \longrightarrow 2CO_2 \quad -(3$$

They are all strongly exothermic. It would appear though, that the rate at which oxygen arrives at the reactive sites is rate determining for each reaction. Thus, lowering the air-flow rate means that the reactions occur more slowly and the temperature drops (as has been noticed). However, reaction (1 has a positive entropy change which means that the Gibbs Free Energy for the reaction (which is a measure of the extent to which the reaction will occur) becomes less negative as the temperature drops and thus the reaction is less favoured. Reaction (2 has a negligible entropy change and so its relative favourability is affected little by alteration in temperature. Reaction (3 has a negative entropy change and thus the reaction becomes relatively more favourable as the temperature drops. Thus in the smelting experiments, as the air-flow rate was decreased, so the temperature of the furnace was reduced and the reaction producing carbon monoxide became relatively less favoured thermodynamically to those producing carbon dioxide. Thus the CO/CO_2 ratio was reduced and conditions became more oxidizing.

It is interesting to note the relationship of the slag composition to the CO/CO_2 ratio. Figure 5 shows how, with increasing CO/CO_2 ratio (i.e. more reducing conditions), the lead content of the slag was reduced, probably as more lead oxide was reduced to lead metal and separated from the slag. On the other hand, the metallic iron content increased, as did the ratio of iron O to iron II.

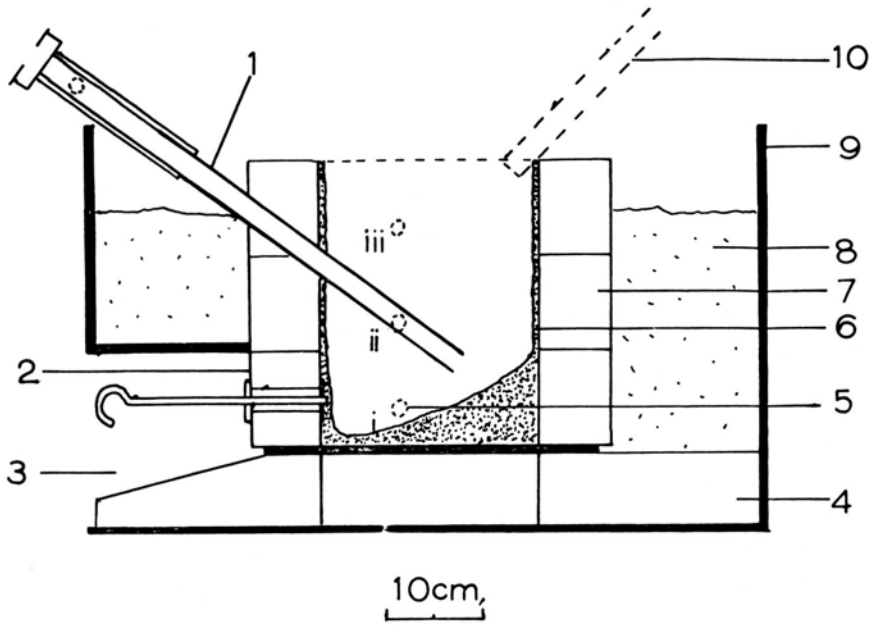
Conclusions

There will be more to say under this heading when the work is more complete. However there are one or two points that do stand out from the work so far.

These experiments have shown that it is relatively easy to reduce lead from a sulphide ore under primitive conditions. However, due to the high temperatures that are involved, (which are needed to produce a fluid slag), a large proportion of the lead component of the charge will be lost through volatalization.

There is though, quite a variability in nature and composition of the products of these smelts which shows little obvious relationship to the controlled variables. However, altering variables such as air-flow rate, running time and charging rate does have noticeable effects on the nature and composition of the products over and above this inherent variability.

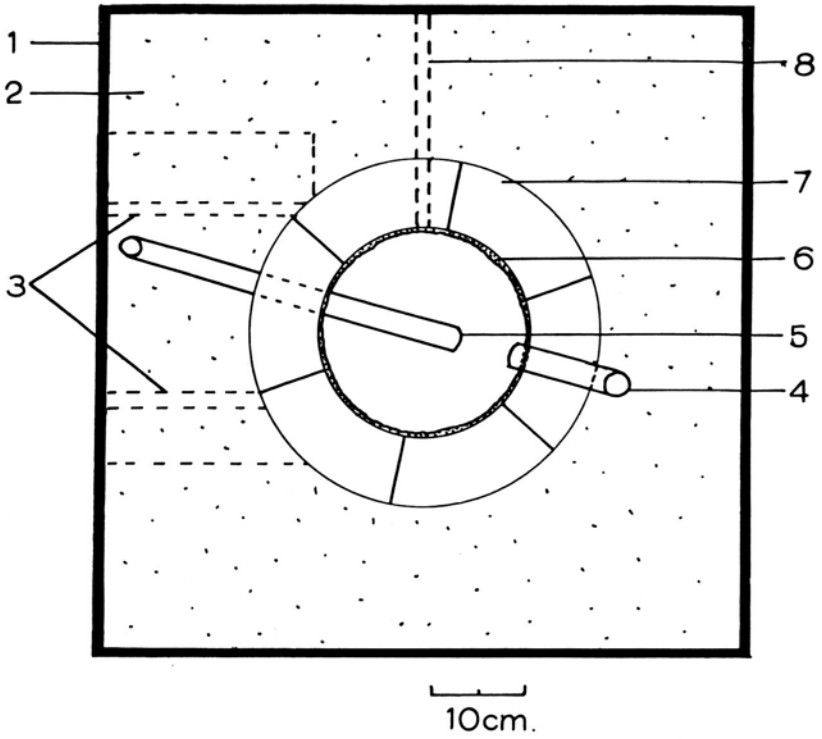
Finally, it bears repeating that a reduction of air-flow rate through the furnace lowers the temperature and, contrary to what one might expect, creates a more oxidizing atmosphere.



1 tuyere I
2 removable brick
3 tapway
4 "kieselghur" insulating bricks
5 position of probe hole
6 furnace lining
7 refractory fire bricks
8 sand seal
9 asbestos board
10 position of tuyere II

Figure 1

Furnace-section through plane of tuyeres



1 asbestos board
2 sand seal
3 position of tapway
4 tuyere II (used twice only)
5 tuyere I
6 furnace lining
7 refractory fire bricks
8 position of probe holes

Figure 2

Plan of Furnace

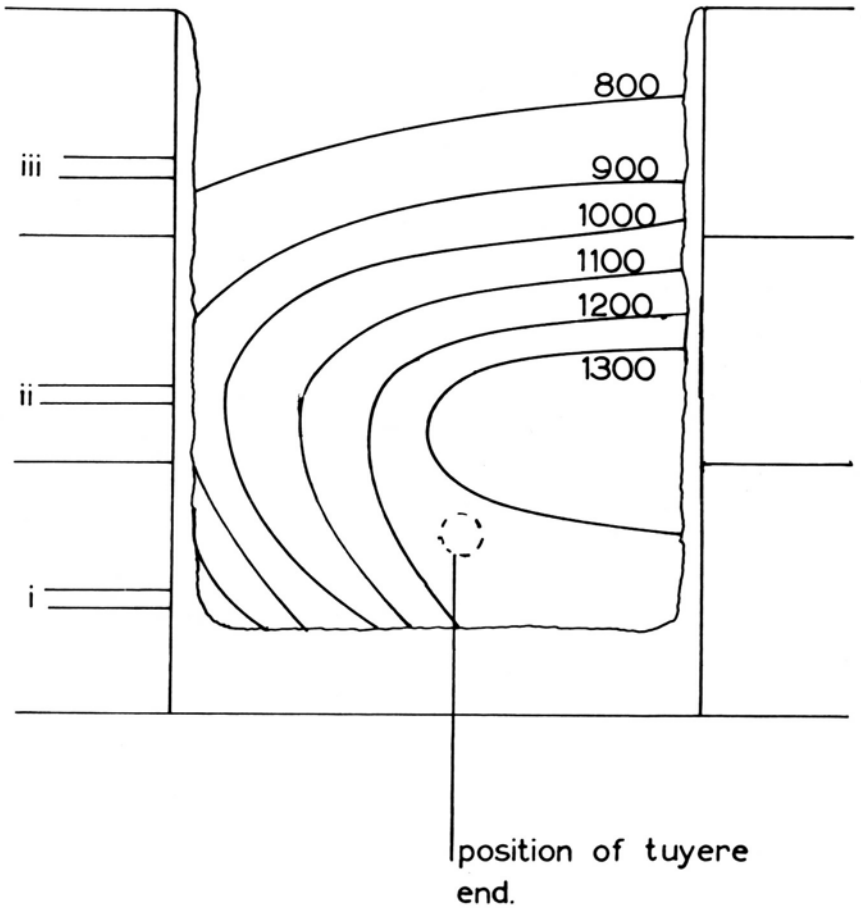


Figure 3

Temperature profile of D.R.1 after 180 minutes.

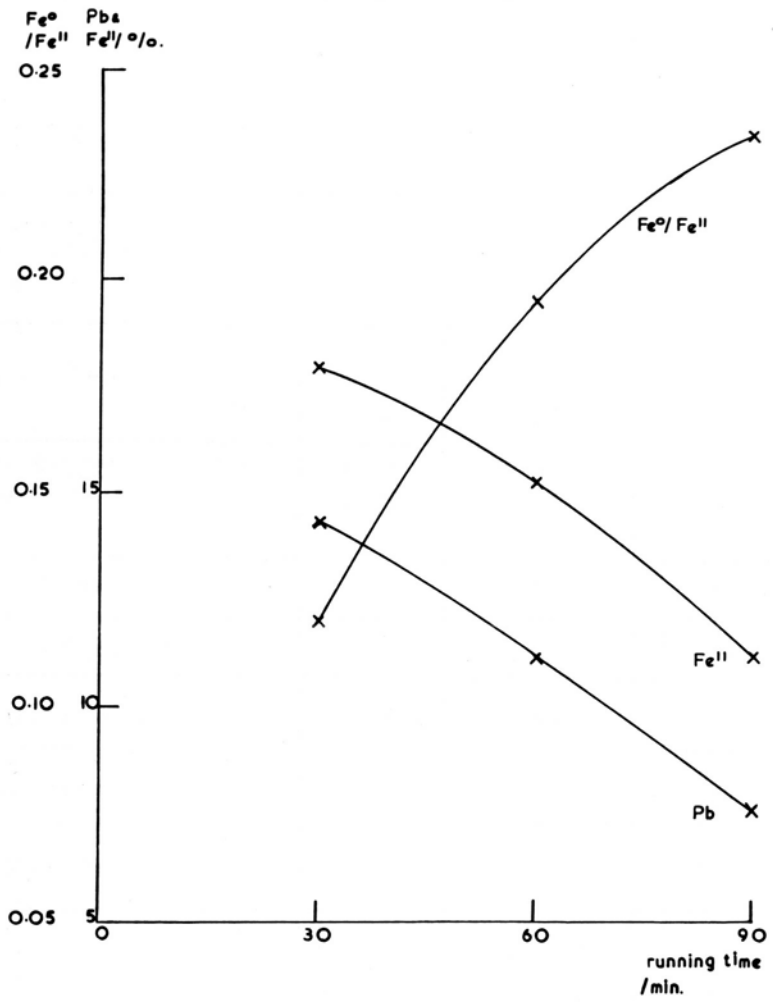


Figure 4

Pb content, Fe'' content and Fe°/Fe'' ratio of slag against running time.

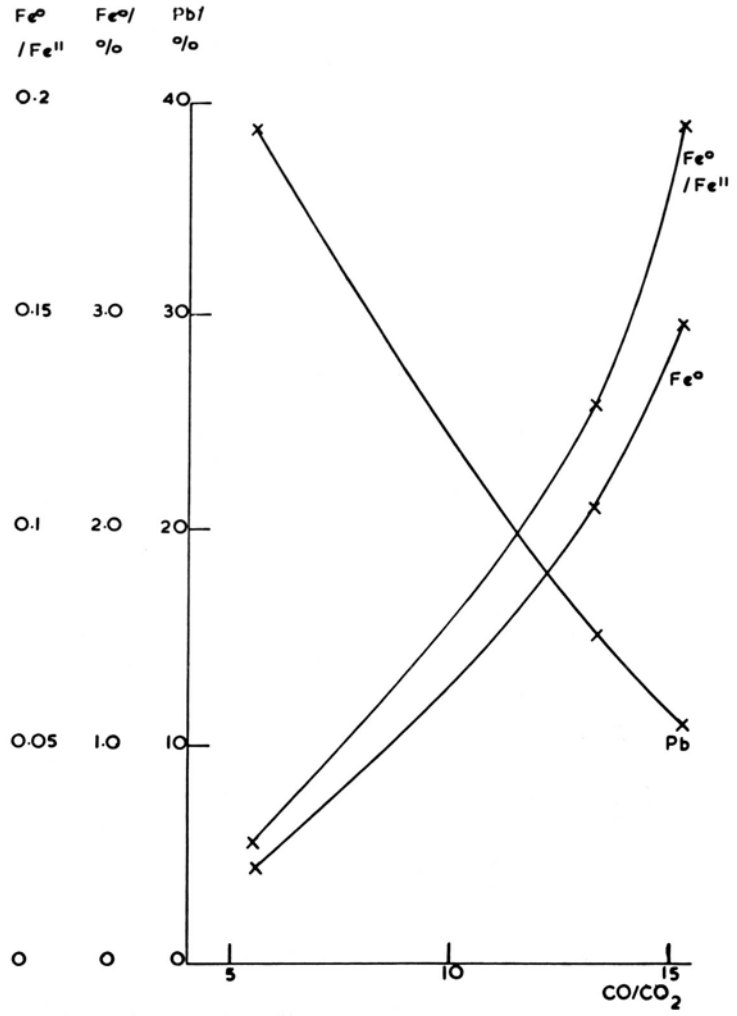


Figure 5

Pb content, Fe° content and Fe°/Fe'' ratio of slag against CO/CO_2 ratio.

Table 2

Experimental conditions presented in the smelts of series A.

Smelt		PbA1	PbA2	PbA3	PbA4	PbA5	PbA6	PbA7	PbA8	PbA9
Charge/kg.	G.C.(1)	3.78	3.78	3.80	2.68	2.68	2.70	1.24	1.24	1.26
	S.S.	0.20	0.26	0.40	0.42	0.52	0.78	0.72	0.88	1.28
	N.O.	1.02	0.96	0.80	1.90	1.80	1.52	3.04	2.88	2.46
		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Flow rate/$dm.^3$ $min.^{-1}$		150	150	150	150	150	150	150	150	150
Running time/min.		60	60	60	60	60	60	60	60	60
Charging time/min.		60	60	60	60	60	60	60	60	60
Ht.of tuyere/m.m.		40	40	40	40	40	40	40	40	40
Charcoal rate/$kg.hr.^{-1}$		2.3	2.0	2.0	2.1	2.0	1.9	1.9	2.0	2.1
Temps	iii	1000	980	970	930	950	970	900	940	830
before	ii	1250	1150	1030	1170	1140	1210	1190	1265	1130
charging./°C.	i	1250	1250	1230	1250	1300	1190	1190	1300+	1300
Temps	iii	1180	1050	1120	1050	1100	1050	1070	1150	1050
while	ii	1300+	1300+	1300+	1300+	1200	1300+	1070	1300+	1300+
running./°C.	i(2)	-	-	-	-	-	-	-	-	-
CO/CO_2										
before charging	ii	-	-	-	-	11.3	10.88	13.05	21.4	7.88
after charging	ii	-	-	-	-	2.4	3.74	1.43	8.77	9.84
Comments			Refactory clay on tuyere end which was lost.	As for PbA2.	"Zircosil" on tuyere end which was lost.			Charge fused as solid mass round tuyere end.		Tuyere end poked out twice while charging.

Table 3

Experimental conditions present in the smelts of series B,C,D and E.

Smelt		PbB1	PbB2	PbB3	PbC1	PbC2	PbD1	PbE1
Charge/kg.	G.C.(1)	3.78	3.78	3.78	3.78	3.78	3.78	3.78
	S.S.	0.26	0.26	0.26	0.26	0.26	0.26	0.26
	N.O.	0.96	0.96	0.96	0.96	0.96	0.96	0.96
		5.00	5.00	5.00	5.00	5.00	5.00	5.00
Flow rate/$dm.^3$ $min.^{-1}$		150	95	50	150	150	150	150
Running time/min.		60	60	60	30	90	60	60
Charging time/min.		60	60	60	60	60	30	60
Ht.of tuyere/m.m.		40	40	40	40	40	40	100
Charcoal rate/$kg.hr.^{-1}$		2.1	1.4	0.5	2.0	2.2	1.9	2.1
Temps before charging/°C.	iii	950	640	580	920	960	900	940
	ii	1225	1255	970	1275	1300+	1140	1300+
	i	1300	1300	950	1300+	1300+	1300+	1300+
Temps while running/°C.	iii	910	1000	815	1030	1200	955	1000
	ii	1300+	1300+	1130	1300+	1300+	1300+	1300+
	i(2)	1180	-	-	1290	-	1280	1260
CO/CO_2								
Before charging	ii	15.3+	13.3+	5.55	14.6+	20.9+	13.7+	7.05+
After charging	ii	6.37+	5.66+	3.54	4.65	9.5	2.47	6.40+
Comments:			Tuyere end poked out 3 min after charging finished	Tuyere end poked out 4,13 37 min after charging finished.				

(1) G.C.=galena concentrate
S.S.=silica sand
N.O.=Newfoundland ore

(2) Probe hole i often blocked by this time.

Table 4

Products of smelts.

Smelt	Wt. of tapped material/kg.	Wt. of untapped material/kg.	Tapped lead?	Nature of tapped slag.	Nature of untapped slag.
PbA1	0.460	2.282	a little	crystalline, porous	green,vitreous
PbA2	1.726	0.876	all	grey, crystalline	green,vitreous
PbA3	1.234	1.219	all	vitreous	green,vitreous
PbA4	1.400	2.290	none	partly vitreous	fine grained.
PbA5	0.620	2.590	some	lustrous & porous	fine grained
PbA6	0.690	2.773	none	fine grained, porous	fine grained
PbA7	nil	3.61	none	-	fine grained, porous
PbA8	0.870	3.187	a little	fine grained lustrous	fine grained
PbA9	nil	3.715	none	-	fine grained
PbB1	1.427	1.469	some	vitreous, porous	fine grained, porous
PbB2	0.225	3.040	none	vitreous	semi vitreous
PbB3	0.283	3.254	a little	fine grained porous	crystalline, porous
PbC1	1.853	1.358	most	vitreous, porous	fine grained
PbC2	0.612	2.362	very little	vitreous	fine grained
PbD1	2.047	1.466	all	vitreous	fine grained
PbE1	1.841	0.970	all	vitreous	fine grained

Table 5

Analyses of slags from lead smelts and vitrified products from dry-runs

Slag	SiO_2	Al_2O_3	Fe	Fe O	Fe_2O_3	PbO
Pb A1 tapped	7.6	1.05	1.83	56.82	0.54	22.47
untapped	46.6	10.93	2.88	9.52	0.59	2.25
Pb A2 tapped	13.8	0.17	3.54	57.84	-	23.92
untapped < 72 mesh	48.4	9.46	1.84	11.55	0.47	3.89
untapped >72 mesh	49.8	9.35	1.47	9.12	4.22	6.04
Pb A3 tapped	47.7	7.92	2.91	15.62	2.17	10.71
untapped	47.5	8.41	1.41	12.83	1.66	6.92
Pb A4 tapped	36.3	6.50	3.33	32.70	6.53	7.64
untapped	42.8	7.40	5.43	22.31	6.33	5.70
Pb A5 tapped	33.4	7.50	6.02	27.83	6.43	6.82
untapped	24.8	7.45	7.31	33.89	2.10	9.10
Pb A6 tapped	42.9	7.78	3.27	24.60	4.20	9.08
untapped	43.1	6.76	4.25	26.44	0.67	11.85
Pb A7 untapped	22.2	6.16	4.01	37.62	7.59	16.50
Pb A8 tapped	32.9	7.32	4.77	43.42	-	4.10
untapped	40.5	7.21	8.97	32.43	-	4.27
Pb A9 untapped	50.0	7.14	4.90	31.81	-	7.42
Pb B1 tapped	34.3	5.53	1.32	20.92	2.26	17.71
untapped	44.8	7.43	4.62	18.33	4.35	6.23
Pb B2 tapped	29.5	6.03	1.62	20.47	0.39	20.30
untapped	32.2	6.37	3.59	21.52	-	12.84
Pb B3 tapped	24.2	4.76	0.47	23.75	1.83	39.14
untapped	25.8	3.23	0.43	16.84	6.88	44.88
Pb C1 tapped	32.3	5.61	1.81	23.32	2.00	18.17
untapped	39.3	6.11	2.49	22.87	4.93	12.67
Pb C2 tapped	37.6	8.83	2.92	14.32	2.45	5.71
untapped	40.7	6.82	2.32	14.36	2.92	8.63
Pb D1 tapped	35.9	5.36	1.63	18.38	5.42	21.50
untapped	37.1	6.04	3.28	20.16	3.83	14.64
Pb E1 tapped	28.8	6.96	2.15	21.19	0.21	16.53
untapped	30.0	6.17	1.47	22.68	3.02	9.57
D.R.1. vitrified product	59.2	3.41	0.66	1.42	2.85	1.72
D.R.3. vitrified product	76.4	3.83	0.37	1.71	4.29	-

Table 6

Analyses of tapped "lead" from lead smelts

Lead sample	Fe	Pb
Pb A1	1.48	34.25
Pb A2	1.33	94.31
Pb A3	1.13	93.50
Pb A5	0.73	45.60
Pb A8	-	80.96
Pb B1	0.65	81.11
Pb B3	1.18	37.95
Pb C1	0.35	94.53
Pb D1	4.54	88.46
Pb E1	1.89	94.20

Table 7

$FeO:SiO_2$ ratios for the charge and the slag of the lead smelts of series A.

Smelt	$FeO: SiO_2$ ratio in charge	Mean of $FeO:SiO_2$ ratio in slag
Pb A1	3.0	1.224
Pb A2	2.4	1.116
Pb A3	1.5	0.299
Pb A4	3.0	0.695
Pb A5	2.4	1.060
Pb A6	1.5	0.593
Pb A7	3.0	1.694
Pb A8	2.4	1.033
Pb A9	1.5	0.636

THE ANALYSIS OF ROMAN TIN AND PEWTER INGOTS

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1. Introduction

In the 19th century six pewter ingots were recovered from the River Thames at Battersea (British Museum, 1964 and Franks, 1863). They are roughly oval in shape except for one which is circular, all are plano-convex and resemble the bun-shaped ingots of copper which are very common in Bronze Age Britain. A distinctive feature of these ingots is that they are stamped with Chi-Rho monograms and the name Syagrius.

Ingots of pure metal are quite common in Britain during the Roman period, since Britain was a source of metals for the Empire. In addition to the bun-shaped copper ingots, the metals tin, lead and silver were produced. Mixed-element ingots are rare however, and seem to be confined to tin/lead alloys. Lumps of pewter weighing a few pounds are known from various sites, but more frequent are small shapeless lumps probably of solder. The Battersea ingots are unique in being properly stamped blocks of pewter. A remarkable find of fourteen stamped ingots of pure tin (Colls et al, 1975) was recently made in a Mediterranean shipwreck at Port-Vendres, S. France. They were probably from the tin-producing areas of Spain or Portugal. These ingots had a clearly defined, unusual shape which included a carrying handle as part of the original casting. Some of the ingots were 'twins' of double size; in all, the weights ranged between 3.1 and 8.8 kg. The Port-Vendres group sheds light upon the way in which quite small cargoes of raw metal were being shipped around the Roman Empire (the total weight of the fourteen ingots was 83.6 kg). The ingots bore stamps of the names of officials, marks which would enable the origin of the metal to be identified during transport and distribution from the production areas.

The group of Battersea ingots weigh a total of 15.8 kg, that is about one fifth of the Port-Vendres total. It would not be unreasonable to suppose that the Battersea group formed part or even the whole of a shipment of raw metal, in this case pewter, from the metal producing province of Britain being sent to the Continent via the River Thames.

The present study concentrates on a scientific examination of the six ingots including the analysis for major and trace elements, their weight, shape, stamps, possible method of manufacture and relationship to other Roman metal ingots. The study is part of a wider examination of lead in Roman Britain and connects with work currently being undertaken to analyse a large number of examples of Roman silver, some of the preliminary results of which are given elsewhere in this volume (Lang & Hughes, 1977).

2.1 Quantitative analysis of the ingots

In order to provide reasonably full analyses of the metal, small shavings of bright metal, roughly 20 mg in weight, were removed from each ingot after discarding the corroded surface material. The metal was then analysed by atomic absorption spectrometry using the method previously described by Hughes et al (1976, section 4 'lead alloys'). In addition to the major elements tin and lead, the following trace elements were measured: silver, iron, nickel, copper and antimony, and the results are given in Table 1, in which for convenience a number is assigned to each ingot. The accuracy of the lead and tin results should be within $\pm$ 2% lead/tin (for lead in ingot 1 it should be $\pm$ 0.1% lead), while for the trace elements, as a percentage of the ppm results one would expect not worse than $\pm$ 10% and probably $\pm$ 5% for most of the trace elements.

Table 1

Quantitative atomic absorption analysis of Roman pewter ingots from the Thames

Ingot number (this paper)	British Museum Registration No.	Tin %	Lead %	Silver ppm	Iron ppm	Nickel ppm	Copper ppm	Antimony ppm
1	91,2-17,3	94.0	4.59	18	1870	27	1150	900
2	91,2-17,1	68.4	31.5	52	170	17	640	530
3	64,3-15,2	67.6	30.9	29	580	20	670	390
4	62,3-21,1	67.4	31.1	104	940	50	520	600
5	68,9-14,1	54.0	43.3	56	180	15	510	390
6	91,2-17,2	50.4	43.9	98	850	24	750	620
for comparison:-								
Eleven Roman lead pigs	(Schubiger, 1972) (The Fe and Ni analyses are by Hughes, unpub.)	-	-	18-103	50-260	6-58	19-269	38-347
Four Bronze Age tin artefacts	(Coghlan and Case, 1957)	-	-	<100	-	-	100-390	<100
Damaged mount, LBA, Anglesey	65,10-13,22 (Craddock, unpub.)	99	0.7	-	300	100	1000	450

2.1.1 Major elements

The list of ingots in Table 1 is drawn up in order of descending tin content. It is immediately obvious from the results that the ingots fall into three groups: three ingots contain ca 67% tin, two contain ca 52% tin and one contains 95%. A comparison with previous analyses of Roman pewter can be conveniently made by considering the list of analyses prepared by Tylecote (1962). His collected data have been plotted in figure 1, together with the analyses of the Battersea ingots. It is interesting to note that there is a cluster of pewters containing 95% tin (cf. ingot 1 from Battersea), and Tylecote has suggested that the presence of 5% lead may slightly increase the hardness of the alloy. The three pewter ingots with ca 67% tin fall roughly in the centre of the 62-80% group in Figure 1, this group indicating that the 62-80% tin content was a favoured composition for Roman pewter. When we turn to the two ingots with ca 52% tin, they are seen to fall just below the spread of the 62-80% group. In fact there is a distinct break in figure 1 between 46 and 62% tin, except for these two examples.

In attempting to explain both the occurrence of a significant number of Roman pewters with 62-80% tin, reference will be made to the tin-lead phase diagram (see Lyman (1948), page 1238). The phase diagram shows that the tin-lead eutectic mixture contains 61.9% tin/38.1% lead and melts at 183°C; when this metal is cooled from the molten state it passes straight from the liquid to the solid state. Above and below this percentage tin in the alloy, an intermediate stage is introduced and as the metal cools it first forms a pasty mass containing either solid tin or solid lead crystallised from solution. This stage continues until 183°C is reached when the liquid eutectic which remains then solidifies. The length of the pasty stage (in terms of °C) depends upon the deviation from 61.9% tin in the original alloy. In the light of this it is then possible to suggest some significance in the fact that the Roman pewters with 62-80% tin have as their lower limit to the group a value corresponding exactly to the eutectic composition. The 'pasty' stage for

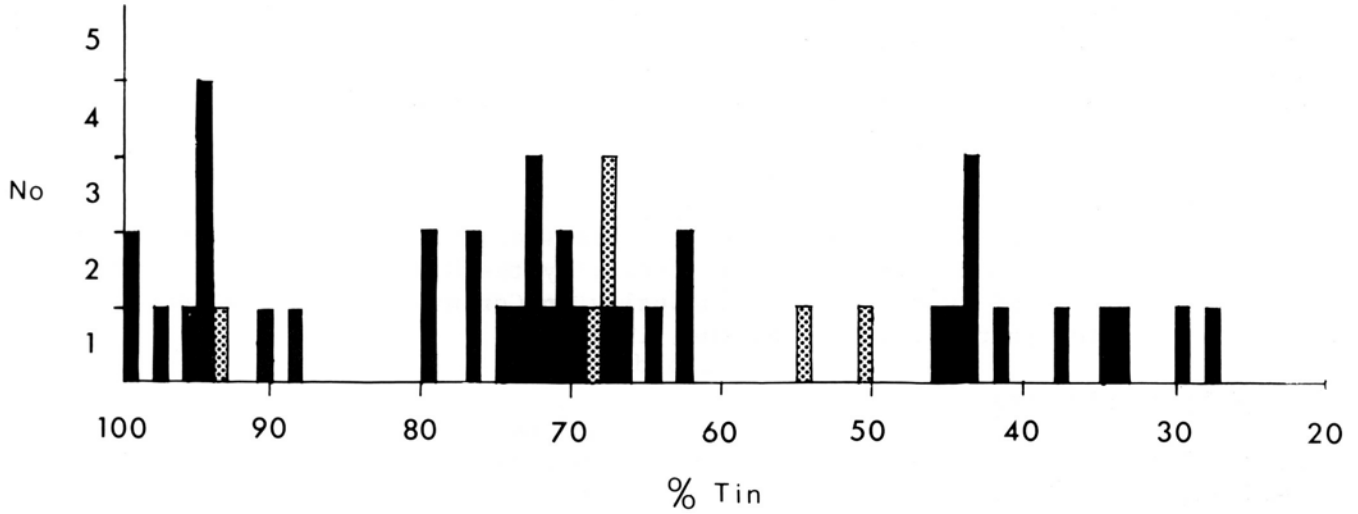

Figure 1 Histogram of analyses of Roman pewter objects

The stippled areas represent the Battersea ingots. Other data is from Tylecote (1962) tables 25 and 26.

62-80% tin alloys has a temperature range of between 0 and 20 degrees Centigrade respectively, viz. a relatively narrow range. For alloys of 40% tin, i.e. 20% lower than the eutectic mixture, however, the pasty stage covers about 50 degrees Centigrade. The Romans may therefore have aimed at pewters containing between 62 and 80% tin because they had a narrow semi-solid range, and might therefore be expected to produce superior castings. It would have been relatively easy to gauge the composition of a piece of pewter simply by melting it and observing its behaviour as it cooled. If it solidified more or less instantaneously from liquid to solid, it was clearly near the eutectic point (unless it was pure tin or lead). The possibility of detecting an alloy of the eutectic composition fairly easily may have influenced its choice as the lower limit for pewter alloys in general use. Below 61.9% the melting curve rises steeply so with decreasing tin content one rapidly develops a lengthy (in degrees Centigrade) intermediate 'pasty' stage.

A further explanation which is applicable to both the 67% tin and the 52% tin ingots from Battersea relates to the composition of solders mentioned by Pliny (Book 34, 160-161): 'at the present day a counterfeit stagnum is made by adding one part of white copper (i.e. brass) to two parts of white lead (i.e. tin); and it is also made in another way by mixing together equal weights of white and black lead (i.e. lead): the latter compound some people now call 'silver mixture' (Lat., argentarium). The same people also give the name of 'tertiary' (Lat., tertiarium) to a compound containing two portions of black lead and one of white; its price is 20 denarii a pound. It is used for soldering pipes. More dishonest workers add to tertiary an equal amount of white lead and call it 'silver mixture' (Lat., argentarium), and use it melted for plating by immersion any articles they wish' (trans. Rackham, 1968). The first form of argentarium contains equal parts of lead and tin and corresponds to the 52% tin ingots from Battersea. The composition of the second form of argentarium, containing equal parts of tertiary and of tin, is 1 part of lead to 2 parts of tin (i.e. 67% tin/33% lead) and therefore similarly

corresponds to the 67% tin ingots from Battersea. The quotation from Pliny is usually taken to refer as a whole to solders although only the pipe solder is specifically designated as such and the second argentarium is said to be for plating articles. It would therefore appear that we have the option of calling the five Battersea ingots nos. 2 to 6 either pewter or solder, since they do correspond in composition to solders actually mentioned by Pliny, allowing for slight deviations from the mixtures he specified. Could this group therefore be a shipment of solder, a very necessary material for example for the bronze and brass working industries? What of the 95% tin ingot (no. 1)? Possibly the latter is to be classed as a slightly impure tin, deliberately made to this specification nevertheless. That very pure tin was being produced quite freely by the Romans is of course evident from the analyses of ingots found principally in Cornwall, which frequently show purities greater than 99.5% tin (Smythe, 1937).

2.1.2 Trace elements

As regards the trace elements iron, nickel, copper and antimony, the five ingots 2 to 6 seem to have broadly similar ranges of values, while no. 1 which has 95% tin contains about twice the average of the others for iron, copper and antimony, a nickel value about the same as the others, but a silver content significantly lower than the others. The trace element composition of the 95% tin ingot will reflect the tin smelting process in use and indicates how various trace elements are carried through the process, which would involve a straightforward reduction smelting of cassiterite at a low temperature to produce tin metal directly. The low trace element values correspond to those listed in Table 1 for Roman lead pigs and Bronze Age tin artefacts from Ireland (Coughlan and Case, 1957).

The question of the desilvering of Roman lead in Britain has been discussed by several authors e.g. Tylecote (1962) and Smythe (1940). One point which has emerged from the analysis of lead ores (galena) in Britain which were exploited by the Romans is their low natural abundance of silver, compared to the Continental leads; see Schubiger (1972) and Wyttenbach and Schubiger (1973) for an analytical study of Continental Roman lead objects. It would appear that desilvering was carried out where the silver level was above 100 ppm: this figure has been partly derived from the silver contents of the Roman lead pigs analysed by Gowland (1901) and Schubiger (1972) which all had less than 100 ppm silver except one with ca 440 ppm, which may have escaped the desilvering process by an oversight.

With respect to the possible desilvering of tin, we have the statement of Pliny (Book 34, 158) that 'white lead (i.e. tin) yields no silver, although it (i.e. silver) is obtained from black lead (i.e. lead)'. Further, there appears to be no archaeological evidence, viz. cupellation hearths, etc., for the desilvering of tin. From a technical point of view as well, it would be a difficult process, not as easy as that practised for lead. Again, tin had a higher commerical value than lead and losses of tin during a desilvering process would probably outweigh the value of the silver recovered. It would therefore appear, on this evidence, that tin ores were not desilvered by the Romans.

When the trace element results for the Battersea ingots (see Table 1) are looked at in the light of this, the silver results are all seen to be low with ca 100 ppm being the highest. The tin ingot no. 1 has the lowest silver content with 18 ppm and is distinctly lower than the others - no. 3 is the next with 29 ppm. For the tin ingot this means that the tin ores from which it was derived were low in silver; this would be an additional reason for not desilvering tin ores. As the tin incorporated in the pewter ingots is low in silver, this means that the added lead probably accounts for the bulk of the silver in the pewter and since this amount is low, either a galena low in silver was used or else the lead was desilvered.

3. Ingot Stamps

This will be dealt with only briefly, to illustrate the basic coherence of the group of six ingots. Examination of the upper plane surface of the plano-convex ingots shows that four difference stamps were used; type 1: the name Syagrius written as a single continuous word; type 2: a second 'Syagrius' split into two vertical registers forming a rectangular stamp; type 3: a circular stamp with 'Spes in Deo' around the circumference and a small Chi-Rho monogram in the centre; and type 4: another circular stamp with a plain Chi-Rho monogram. Because of the importance of establishing the relationship between the six ingots, silicone rubber moulds were taken of the stamp impressions on each ingot and compared. The occurrence of the impressions on each ingot is as shown in the following Table:-

Table 2

The occurrence of stamp impressions on the Battersea ingots:

Ingot Number	Tin (%)	Type 1*	Type 2	Type 3	Type 4
1	94		X		X
2	68.4	X		X	
3	67.6		X		X
4	67.4	X		X	
5	54.0	X		X	
6	50.4	X		X	

*see above for description of stamp types

The links between the ingots on the basis of the stamp impressions produces two groups: (nos. 1 and 3) and (nos. 2, 4, 5 and 6). This clearly does not correspond to links based upon metal composition. Conversely it does indicate that both the high tin ingot (no. 1) and one of the 67% tin ingots (no. 3) are associated and the most probable explanation is that they originated at the same production centre. Similarly two of the 67% tin ingots and the 52% tin ingots carry the same stamps and hence these also came from the same centre. The occurrence of two stamps on each, one with the name Syagrius and one circular stamp with a Chi-Rho monogram does further show that all six ingots belong together and that we are dealing with the products of a single centre.

4. Method of manufacture and ingot shape

The ingots are plano-convex in shape and the stamps were impressed on the plane upper surface left as a result of the cooling of the molten metal. The shape of each ingot is shown in figure 2 which compares them with Roman metal ingots in general.

It is reasonable to infer that the metal was not produced by a single direct smelting either of impure cassiterite or of a cassiterite/galena mixture. Impure cassiterite would not be expected to yield tin containing as much as 45% lead, although 5% lead (cf. ingot no. 1) might be achieved. Further, since the smelting conditions required for cassiterite and galena to yield their respective metals are different, with mixed ore smelting it would certainly be very difficult to exercise any control over the resulting metal composition. For stamped ingots one assumes that some control over composition is being exercised so that the quality of the metal is of a known grade.

If the tin and lead were produced separately from their respective ores, with tin ores in Cornwall and lead ores in Somerset or Derbyshire etc, then some more

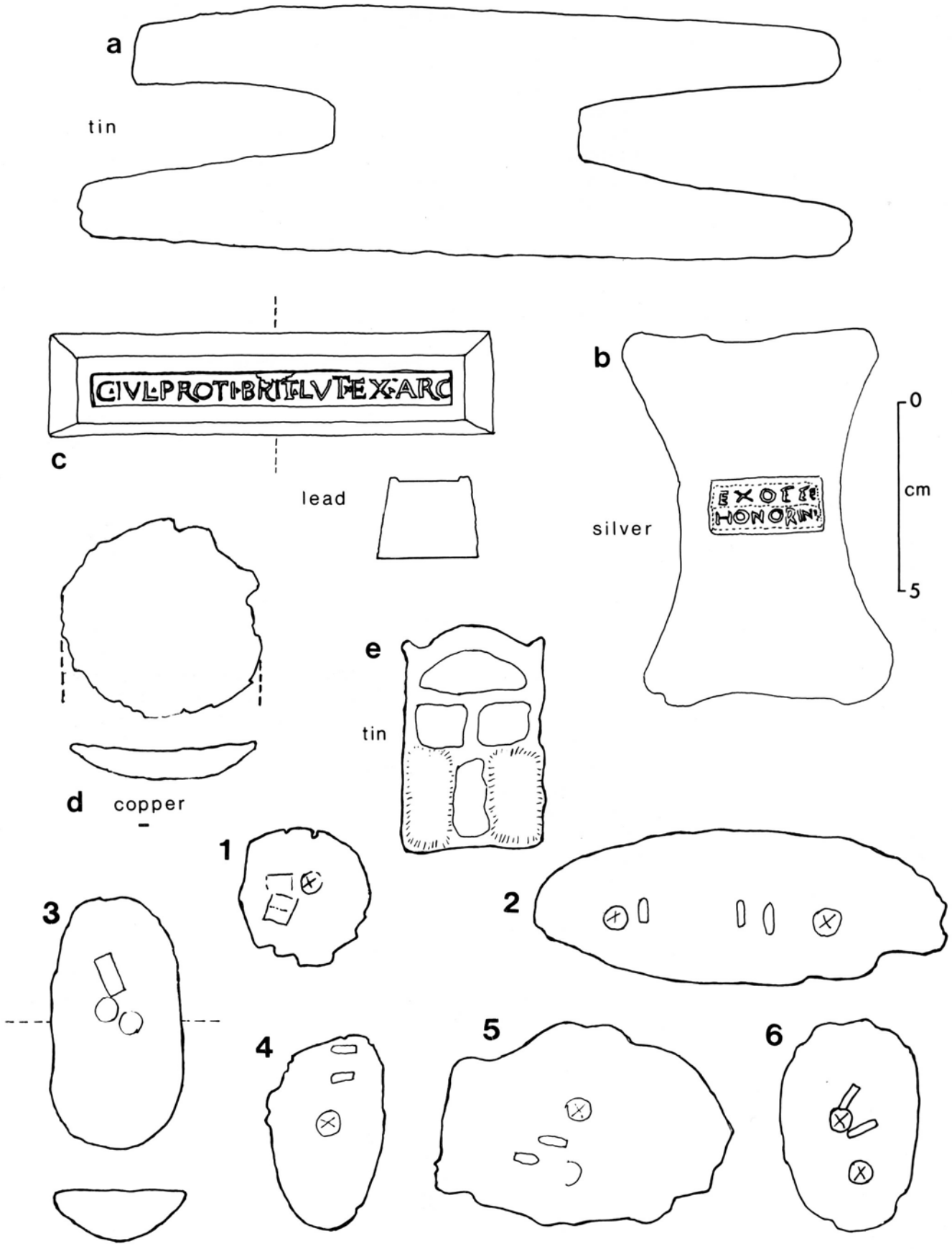

Figure 2 Typical shapes of Roman metal ingots; scale 1:5 (except b)

a. Gowland (1899); b. Painter (1972); c. Gowland (1901); d. British Museum, from Anglesey; e. Port-Vendres, Colls et al (1975); 1-6: Battersea ingots

central area would be most probable for the melting of the pure metals in fixed ratios to produce these ingots. Evidently very pure tin was obtained since the very low trace element contents compares with those obtained on Cornish pure tin ingots analysed in the past. For lead, direct smelting also produces a high quality metal with low trace element content. After melting the metals together in the correct ratio they were then cast into an oval shaped hollow, probably in sand judging from the roughness of the convex underside surface. After cooling, the stamps were impressed into the plane surface with a single or possibly multiple hammer blows. Stamping while hot was not necessary as laboratory tests on plumber's solder have shown that the relatively soft metal can be impressed to the depth found on the ingots using hard metal stamps and a moderate hammer blow.

Setting aside the Battersea ingots for a moment and considering other stamped Roman metal ingots we can discern certain criteria in their manufacture. The first criterion is that the imperial stamps indicate an authenticated metal composition - pure lead, pure silver etc. - rather than some random composition. Secondly, these ingots are of a standardised shape: see figure 2 for examples of the standard shapes adopted. Copper and tin are found in circular bun-shaped forms. Tin ingots have also been found which have an astragal (knuckle bone) form. The heavy lead pigs of which quite numerous examples are known are in a rectangular bar form of trapezoidal cross-section. These bear an inscription cast into and filling the upper surface. The inscription commonly includes the Emperor's name, the origin of the pigs (e.g. BRIT for Britain) and 'EX ARG' which has been taken by some to mean 'from the silver mines' - an optimistic description since British lead ores are generally poor in silver - (Smythe, 1940), although another interpretation is that EX ARG means that the silver has been removed (Tylecote, 1962). The silver ingots have a double-axe or ox-hide shape (Painter 1972), and the unusual form of the Port-Vendres tin ingots (Colls et al, 1975) has already been described. A third criterion is the making of these ingots to some sort of standard weight. This is obviously linked up with making to a standard shape and the practice clearly varies between the different metals. Thus the silver ingots which appear to be payments made to members of the Imperial army correspond quite closely to one Roman pound in weight (Painter, 1972). On the other hand, while all the lead ingots are roughly the same in dimensions, their weights vary with a standard deviation of 20lbs about a mean of 175lbs (data for 39 Roman lead pigs, Tylecote (1962) Tables 33 and 34) - which corresponds to 250 $\pm$ 28 Roman pounds.

When these criteria are applied to the Battersea ingots, they seem to fit in reasonably well. Firstly, the stamped Battersea ingots do indeed have apparently standardised compositions, although it appears to be a series rather than a single composition; there is one with 95% tin, three with 67% tin and two with 52%. Reasons have been given above why these compositions were chosen (viz. tin/lead ratios of 95:5, 67:33 and 50:50).

Secondly, the shape of each ingot is not random. Of the six, no. 1 is circular in shape and the other five are oval. The length and breadth of each are given in Table 3. If the maximum length vs. maximum breadth ratio for each ingot is calculated from their dimensions, an interesting pattern emerges (see Table 3). The length/breadth ratio falls into the following three groups: ingot no. 1 is virtually circular; ingots 2-4 are oval and have ratios between 1.75 and 2.71 and ingots 5 and 6 have ratios 1.45 $\pm$ 0.02. Considering these ratios as round numbers, ingots 2, 3 and 4 have a length twice or three times their breadth and 5 and 6 have a length which is 1½ times their breadth. The immediate point which strikes one about the division of the ingots by shape is that they correspond to the compositional groups. Thus the three ingots with more tin (67%) are more elongated than those with a 50:50 composition, and the high tin ingot is circular. By analogy with the circular ingots of Cornish tin (though admittedly caution is needed because the latter are not strictly closely dated) and of copper, a circular shape may indicate purity of the metal. Thus the circular shape of the ingot no. 1 may indicate that it is of tin rather than pewter, although it does contain a few percent of lead.

Table 3

Maximum size dimensions and length/breadth ratio of the Battersea ingots

Ingot Number	Max. length (cm)	Max. breadth (cm)	Ratio length/breadth	% Tin
1	12	11.1	1.08	94.0
2	35.5	13.1	2.71	68.4
3	21.4	11.3	1.89	67.6
4	17.4	9.9	1.75	67.4
5	24.8	17.4	1.43	54.0
6	18.0	12.2	1.47	50.4

The other five ingots are oval possibly to indicate that they were not of pure tin but were alloyed with lead, with the more elongated form for the higher tin content. The shape could therefore be indicative of composition and thus the different types of tin/lead alloy could be recognised in the hand.

A third point to note is their weight. One can be reasonably sure only in the case of silver ingots (Painter, 1972) that a specific weight was intended, although the lead pigs are reasonably consistent at about 250 Roman pounds (see above). However, tin was a more valuable metal than lead since having secure tin sources was of great importance for bronze-using civilisations. It might therefore be expected that more attention would be paid to the quantity of tin in each ingot; Pliny (34, 161) gives the price of tin as 80 denarii per pound, and of lead as 7 denarii. The six ingots have been reweighed and the results are as shown in Table 4. Merely as a suggestion, some round figures have been given in the two

Table 4

Weight of Battersea pewter ingots and a possible interpretation

Ingot Number	Weight (grams)	Weight (total) (Roman lbs)*	Weight of tin (Roman lbs)	Possible scheme Weight (total) (Roman lbs)	Possible scheme Weight of tin (Roman lbs)
1	821	2.56	2.43	3	3
2	5074	15.85	10.57	15	10
3	3090	9.65	6.44	9	6
4	1228	3.83	2.55	4.5(?3)	3(?2)
5	3503	10.94	5.47	12	6
6	2098	6.56	3.27	6	3

*assuming that 1 Roman pound = 320 grams.

right hand columns of Table 4 which seem to show some sort of pattern as regards the weight of each ingot. The possible pattern is suggested on the grounds that for a 2:1 tin/lead alloy, having the ingots in units of 3lbs makes the calculation of their tin content (i.e. value) quite easy: 3lbs ingot contains 2lbs tin. Only no. 4 seems to deviate badly from the scheme. Whether this idea has any validity will depend to a large extent on the finding of other Roman pewter ingots and their scientific examination. Analogy with the Port-Vendres tin ingots may however indicate that there was no specific intentional weight. The fourteen ingots from that ship ranged from 3.1 to 8.8 kg in weight and the excavators could suggest no systematic pattern to the weights (Colls et al, 1975).

It may be helpful at this stage to briefly note examples of pewter 'lumps' quoted in the literature which although not stamped or inscribed do date from the Roman period. From Silchester comes a 'lenticular' fragment of 'solder' which weighed about 2.5 kg, viz. 7.8 Roman pounds and contained 38.01% tin and 61.83% lead (Gowland, 1901). The weight of tin, 2.97 Roman pounds, does have a weight very close to 3 pounds and is comparable to that for the Battersea ingots 1, 6 and possibly 4. From Corbridge came a lump described by Smythe (1937) as an 'oblate spheroid', probably cast in a closed mould of dimensions 6.5 x 3.5 cm and weighing about 450 grams, viz. 1.4 Roman pounds. Its analysis showed 94.78% tin and 5.37% lead, so the weight of tin would be about 1.4 pounds; this composition is very similar to Battersea no. 1 but its weight and shape are quite different. Although other analysed fragments as opposed to vessels of pewter are known, in general they are small odd pieces, probably of solder, and could not be classed as ingots.

5. Conclusions

The six Roman pewter ingots found at Battersea in the River Thames may represent part or the whole of a shipment of metal from the British mines, the total weight of metal being 15.8 kg. One ingot was shown by analysis to contain 95% tin and 5% lead while three others contain ca 67% tin and the remaining two ca 52% tin. It is suggested that these compositions were not random but deliberately produced. Comparison with written sources suggests that the heavily leaded ingots may be raw solder, since they correspond to two alloys both known as 'argentarium' and mentioned by Pliny. The stamps impressed into the ingots demonstrate that all six of the ingots form an associated group and therefore may be taken as the products of a single manufacturing centre. As regards elements other than lead and tin, the ingots are very pure, and correspond to known levels of trace elements in Roman ingots of pure lead and tin respectively. They have a low silver content. It is suggested that the distinctive oval shape of the ingots is deliberate in order to indicate to those involved in handling and transporting the ingots which alloy compositions were represented by each. The three ingots with ca 67% tin are distinctly more elongated than the two with ca 52% tin. The circular ingot (95% tin) seems to correspond with the circular forms of Roman ingots of pure metals, viz. tin and copper, found in Britain. In general, the Battersea ingots have factors in common with the Port-Vendres group: the ingots are stamped; they are of some sort of standardised shape; they were found together - in the case of the French ingots they are obviously a cargo of metal being shipped from the Empire's metal producing areas, for the Battersea ingots we can only surmise that this is why they were found as a group; their weights are not all exactly the same but vary by a factor of 2 to 3. The Battersea ingots are however unique at the present time being of pewter and bearing official stamps.

Acknowledgements

The author wishes to thank Mr. K.S. Painter of the Department of Greek and Roman Antiquities, British Museum who originally made the request for the analysis of the ingots to be carried out. A joint paper with Mr. Painter is in preparation which will deal more fully with the archaeological aspects including the inscriptions, as well as the scientific work. Mr. Derrick Giles of the Department of Conservation and Technical Services, B.M., very kindly made the silicone rubber moulds of the stamp impressions which were used for comparative purposes.

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THE COMPOSITION OF IBERIAN BRONZE AGE METALWORK IN THE BRITISH MUSEUM

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This study of the nature of the alloys used in the Iberian Bronze Age is part of a much more comprehensive study, "A catalogue of Prehistoric Bronze Metalwork from the Iberian Peninsula in the British Museum", which is being published in the journal Ampurias (Barcelona) in 1980 jointly by the author of this paper and Richard J Harrison of Bristol University.

The principal analytical work on Iberian bronze has been published by the Sirets (1887 and 1913), Ferreira (1961) and Junghans, Schröder, and Sangmeister (1962 and 68). Some other analyses do exist but have often been published without the vital details of sampling and analytical technique necessary to interpret the results.

For this project, the samples were taken with a 12 volt portable jeweller's drill with a size 60 bit; about 10 milligrams of sample were removed for analysis. The surface metal and any corrosion were avoided, and only bright metal turnings were collected. A few of the artifacts were totally corroded and these were not analysed as the composition of corroded metal usually bears no relation to that of the original metal (Caley 1964). A full discussion of the problems of sampling and reporting the analyses of ancient metalwork has been published elsewhere (Craddock 1976).

The samples were analysed by Atomic Absorption Spectrometry, the elements bismuth and arsenic being analysed using the spectrometer with a flameless atomiser and deuterium arc background corrector. The results are expressed in percentages; most elements could be detected down to 0.005% in the metal except for tin which could only be detected down to 0.05%. The standard deviation of the result is $\pm$1% for the major elements and $\pm$30% for the elements present in amounts below 0.2% of the metal. This may seem an unduly pessimistic estimate of the precision, especially for the trace elements, but the results of recent interlaboratory comparisons (Chase 1975) shows this to be a realistic estimate. For a fuller discussion of the use of Atomic Absorption Spectrometry in archaeology see Hughes, Cowell & Craddock (1976).

The Pre-Beaker metalwork is represented here by six flat axes, five of which are of relatively pure copper, and one is arsenical copper (see Fig. 1). These results are similar to those obtained by Junghans et al, (1962 and 1968). Blance (1961) and Almagro and Arribas (1964) have maintained that metalworking was introduced into the Iberian Peninsula by colonists or traders from the Eastern Mediterranean. They claimed that daggers like those from Alaca with pronounced midribs on both faces must have been cast in two piece moulds, and that this Pre-Beaker metallurgy was more sophisticated that that which followed it. Piggott (1962) suggested that the indigenous Beaker peoples overthrew the coastal trading settlements and there actually learned metallurgy, although of a primitive kind.

However, Renfrew (1967) radically disagreed and maintained that the cultural similarities between the pre-Beaker metallurgists and the Eastern Mediterranean were more apparent than real. He and Charles (1967) further pointed out that the Alaca daggers could have been produced by hammering up from a single mould casting, and that the vast majority of the contemporary metalwork was definitely cast thus. A comparison of the analyses published here with those of contemporary axes from the Aegean shows they are completely different (Craddock 1976). The Aegean axes are of arsenical copper whereas the pre-Beaker axes are usually of copper (see Fig. 2). This strongly suggests the two metalworking traditions are not at all related.

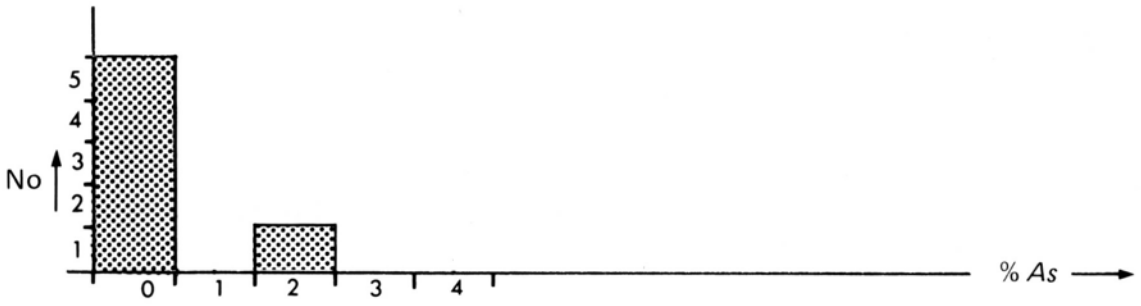

Figure 1 *As* content of Pre-Beaker axes

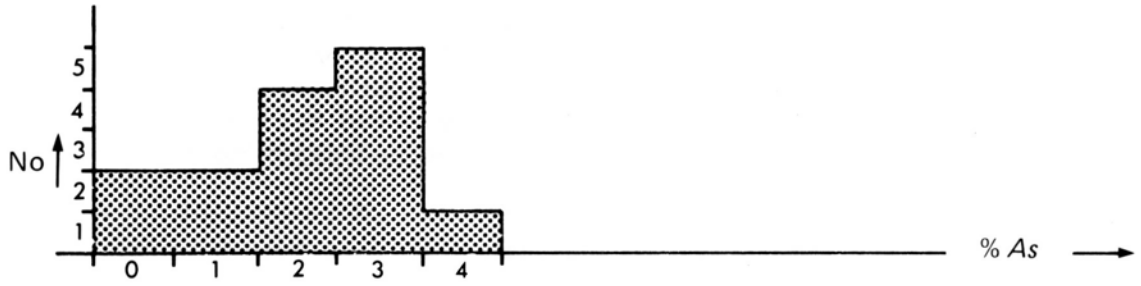

Figure 2 *As* content of contemporary Aegean axes

The succeeding Beaker metallurgy, far from being technically inferior, regularly used arsenical copper alloys, and even occasionally tin bronze. The amount of arsenic alloyed with the copper seems to have been carefully controlled. The arsenic content of the ten Palmella points lies within narrow bounds (Fig. 3). The arsenic content of the succeeding Argaric metalwork seems to be similarly carefully controlled. The Beaker and Argaric daggers of arsenical copper have much higher arsenic contents than the axes or points (Figs. 4 and 5). The average arsenic content of the daggers is 4.1%, against only 2.1% for the points and axes. Increasing the arsenic content increases the hardness and brittleness of the metal, and thus the daggers which need a hard edge to retain their sharpness have a much higher arsenic content than the axes and points which need to be tough to withstand shock during use. These figures show that the smiths realised the hardening properties of alloys and could control them to within narrow limits. There is little direct evidence to suggest how the arsenic or tin was introduced into the copper. Allan (1970) believed the arsenic was introduced either deliberately or accidentally by using copper ores rich in arsenic, such as Chalcopyrite or Chalcocite, but it has been shown by Charles (1967) that the arsenic was a deliberate addition, and to have just relied on the fortuitous retention of the arsenic in the ores during smelting would not produce the narrow range of arsenic content found in particular classes of metelwork. This rather suggests that arsenic was used either in the form of metal, or of a relatively pure compound, such as realgar (AsS) or orpiment (As_2S_3). Arsenic is unknown from antiquity; indeed it would have been virtually impossible to collect owing to its extreme volatility and the avidity with which it oxidises. Thus it is almost certain that arsenic was added to the copper as a compound and reduced to metal in situ. There is a strong possibility that tin bronzes were formed in the same way using cassiterite (SnO_2) and copper, for although a very few tin artifacts are known from antiquity, no tin ingots or droplets of tin have ever been found in metal working areas, whereas copper ingots and droplets are common. This absence of tin has led Charles (1974) to speculate that it was normally added to copper as cassiterite.

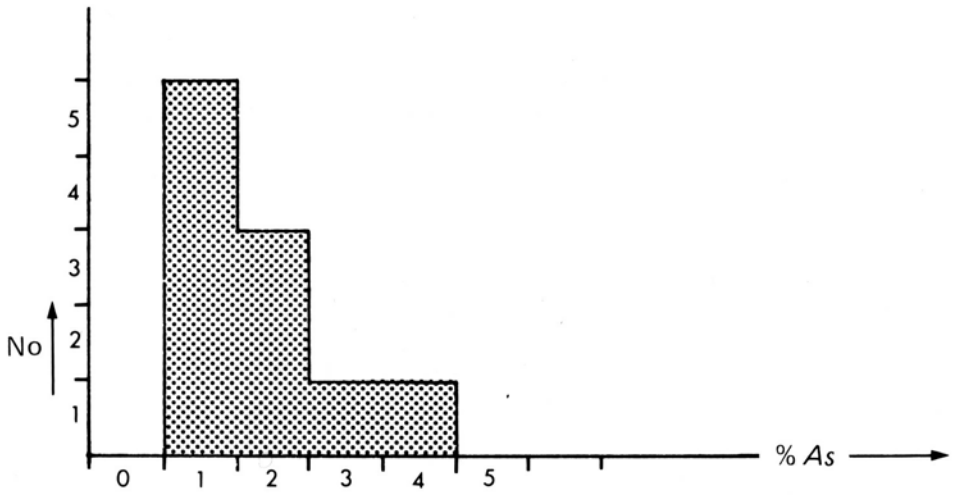

Figure 3 *As* content of Palmela points

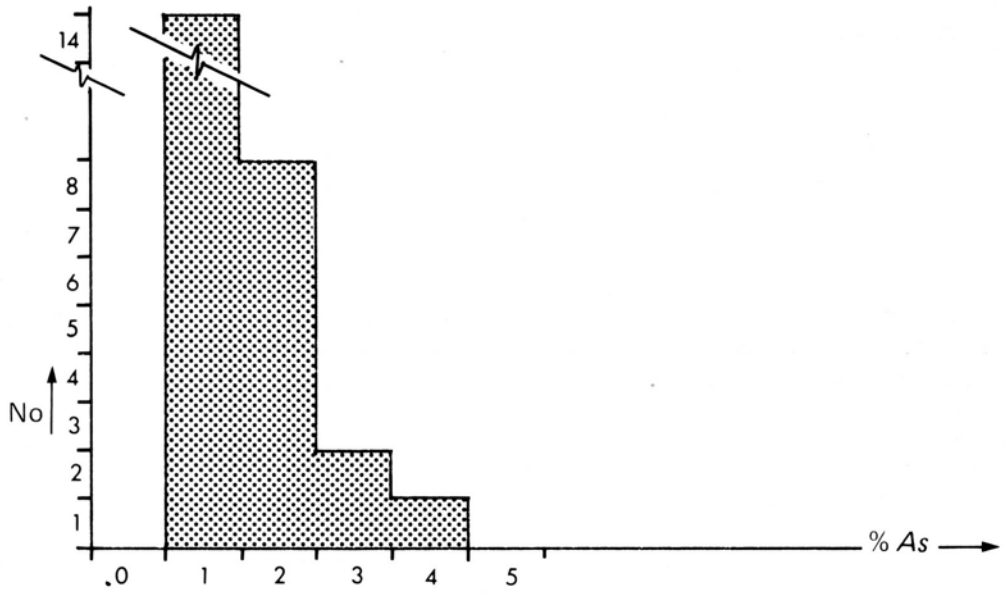

Figure 4 *As* content of Beaker and Argaric points and Axes of arsenical copper.

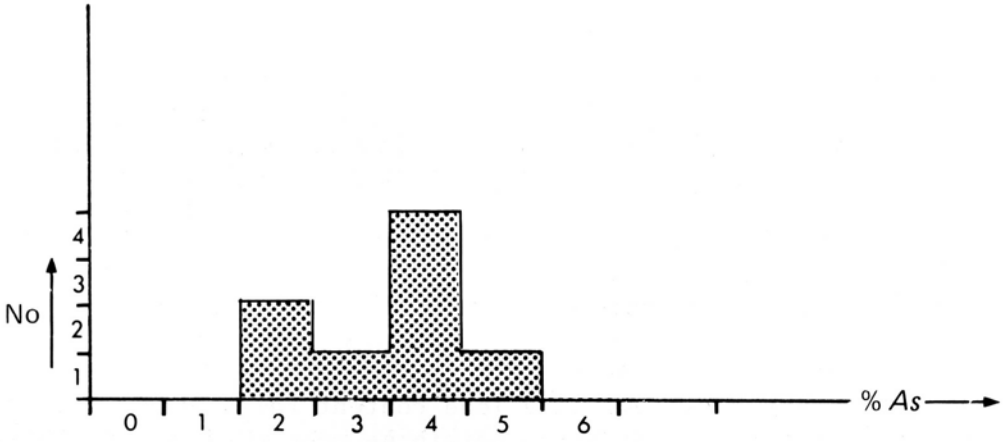

Figure 5 *As* content of Beaker and Argaric daggers of arsenical copper

In the European Bronze Age tin replaces arsenic as the main alloying metal around the beginning of the second millenium BC. However, this does not appear to have been the case in Iberia where, although some tin bronzes from the Beaker period are known, arsenical copper continued in use for over a thousand years later until the beginning of the first millenium BC. The reasons for this are obscure, Harrison (1974) suggests that as tin only occurs in several scattered deposits in Southern Iberia the supply was liable to be erratic, and not until the Late Bronze Age, when the larger North West Iberian deposits were exploited, could a regular supply of tin be guaranteed, and arsenical copper be dispensed with. This argument works well for Iberia, but if applied to the rest of Europe then only Bohemia and Southern Britain should have had tin bronze at all during the second millenium whereas its use became rapidly universal except in Iberia. Whatever the real reason it does again demonstrate the isolation of the quite rich cultures of Southern Iberia in the Bronze Age.

During the Argaric period of the second millenium BC silver became popular and silver rivets are quite common. Iberia is rich in silver deposits, normally associated with lead. A very little silver metal occurs native, and rather more occurs as electrum, a natural alloy with gold. The most common ore of silver is glance, the sulphide (AgS), which occurs by itself and with lead. Another ore common in Spain is horn silver, the chloride (AgCl), which also occurs with lead. The Iberian lead deposits have been exploited for their silver since at least the time of the Phoenicians. The two metals are separated by cupellation, leaving the silver behind as a button of metal. It is interesting to note that the rivets of the dagger (no. 55 in the table below) contain about half a percent of lead, but no gold, suggesting that the silver had been produced by cupellation, but the rivets of the sickle (no. 53) contain no lead but three percent of gold suggesting they may well be of native silver.

A consequence of the introduction of silver production from lead ores was to vastly stimulate lead production, and during the Late Bronze Age leaded bronzes and lead artifacts became common. The Atlantic Bronze Age metalwork especially, is often highly leaded. Figure 6 shows the lead content of the Late Bronze axes

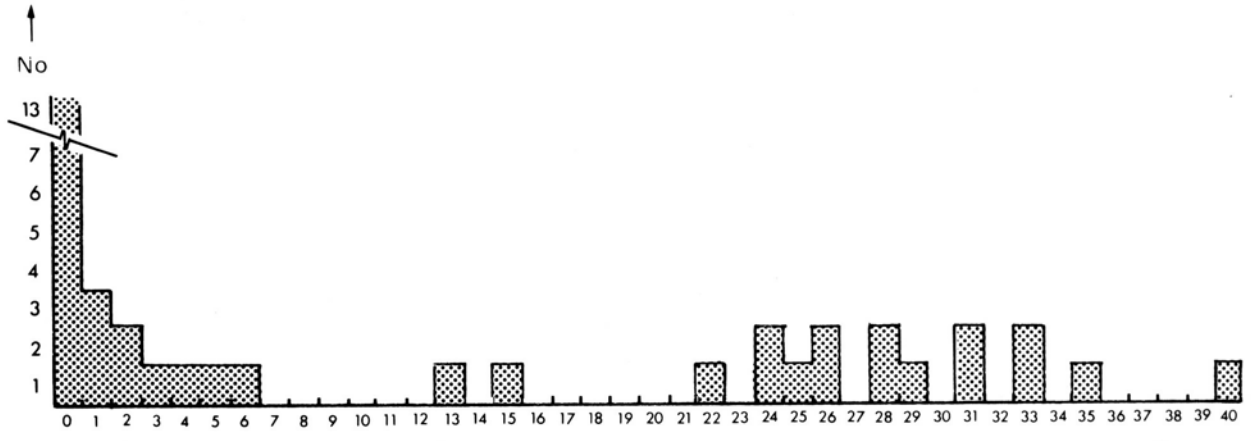

Figure 6: Lead content of Atlantic axes

published here and by Siret (1913). The lead content falls into two groups, those containing under six percent, and those containing more than twenty percent of lead. Many of the heavily leaded bronzes are very rough castings, and it is obvious from the unfinished state of the blades that they were not intended for

use. Lead does not dissolve in copper, and its presence in such large quantities, although making the metal easier to cast, would render the metal very liable to tearing along the lead-copper boundaries during use.

Highly leaded bronzes are rarely met with in the European Bronze Age generally, but do occur in the Late Bronze Age, notably in North West Iberia and Brittany, where many deposits of often large numbers of unused highly leaded or lead axes have been found carefully arranged. The reason for the high lead content is puzzling. Lead has been added to copper to de-silver it at least from Roman times onwards, and may have been introduced by the Phoenicians. The legendary account in the Timaeus of the first Phoenician traders to Spain acquiring so much silver that they threw away the lead anchor stocks and replaced them with silver ones in order to carry away yet more of the metal may have a grain of technological truth in it, reflecting the Phoenician introduction of the lead de-silvering of copper, i.e. bringing lead to produce silver. But the highly leaded axes do not contain much silver, and anyway the copper left after de-silvering should not have a high lead content. The colour and appearance of these axes would make it impossible to deceive a potential customer that these were ordinary tin bronze axes and thus fraud seems out of the question as a motive. As the lead-copper alloy of these axes was useless to the Bronze Age smiths it is also impossible to interpret them as ingots. Contemporary Archaic Greek and Etruscan statuettes and decorative metalwork occasionally contained large amounts of lead, and the later Hellenistic and Roman statues regularly had a high lead content (Craddock 1977), but the few analyses of Iron Age statuettes or decorative metalwork shows they were not highly leaded. The careful burial of many of these axes suggest they may have been made for votive deposit connected with some ritual now lost to us.

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PRE-BEAKER AXES

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
1	100.		.15	.005	.320		.020			.02	.001	
2	98.0			.015	.008					2.3	.006	
3	99.0		.10	.030	.004					.80	.002	
4	99.5			.080	.006		.015			.60	.006	
5	100.			.030	.050		.020		.004	.025	.003	
6	99.5			.010	.015					.015	.001	

BEAKER AXE

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
12	92.5		5.9	.025	.007	.1100	.200		.060	1.45		

BEAKER DAGGERS

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
29	94.5			.040	.020					4.4		
31	94.5		.09	.004	.040		.003			5.8	.0100	

PALMELA POINTS

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
32	98.5	.100		.005	.010		.003			1.9	.002	
33	97.0			.020	.008					2.7	.002	
34	95.5			.010	.006		.006			4.6	.009	
35	98.0	.030		.200	.010	.040	.005	.005		1.9	.007	
36	99.0	.010		.013	.008	.015				1.6	.004	
37	99.5			.075	.009	.040	.035			1.2	.005	
38	96.5	.010		.020	.010	.030	.005	.005		2.6	.002	

PALMELA POINTS CONTINUED

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
39	98.0		.1	.005	.015		.004			2.1	.001	
40	97.0			.010	.025					3.3	.005	
41	98.5		.15	.020	.100	.260				1.5	.001	

E.B.A. / M.B.A.

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
27	88.5	.480	8.8	.050	.010	.10	.03			1.2	.008	
28	100.			.085	.008	.07	.05			.02	.001	
30A	94.5		.55	.100	.030					4.8	.008	
30B	97.5		.05	.090	.005	.06	.04			1.0	.005	
42	98.0			.070	.020	.04	.13			1.7	.003	
44	95.5	.040		.010	.010					3.6	.010	
45	99.0			.020	.060					1.5	.004	

ARGARIC AXES

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
7	97.5			.010	.010		.005			2.6	.013	
8	99.5			.080	.015					1.2	.008	
9	98.0			.006	.010				.005	2.3	.006	
10	98.5	.220	1.5	.030	.015	.05	.130			.40	.002	
11	98.0		.05	.020	.015	.05	.0025			1.4	.002	
13	97.5			.002	.015		.004			2.0	.001	
14	97.0			.010	.020		.004			3.0	.0035	
15	97.5	.015		.150	.002					2.3		

ARGARIC AXES CONTINUED

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
16	96.0			.020	.020		.005		.010	3.9	.008	
17	97.0			.010	.008					1.9	.004	
18	97.5		.1	.025	.010	.04	.007			1.8	.005	
19	91.5	.850	6.3	.035	.010	.02	.050	.002	.003	1.1	.001	
20	96.5		.1	.006	.003					2.4	.005	
21	99.0		.2	.045	.020		.006		.006	1.4	.005	
22	99.0			.035	.010		.003			1.2	.003	.450
23	99.0			.010	.030					1.4	.002	.003
24	98.5	.015	.45	.075	.012		.010			1.9	.006	
25	99.0			.010	.010	.02	.003			1.9	.012	
26	89.0	.19	9.1	.020	.010	.035	.050	.005	.010	.45	.0015	

ARGARIC DAGGERS

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
49A	97.0			.040	.014		.010			2.7	.008	
49B	96.5		.10	.020	.002		.002			3.0	.004	
52	96.0			.015	.008		.020			4.7		
55A	97.0	.040	.60	.020	.007				.015	2.2	.012	
55B	0.200	.600		98.5	.030	.04	.010				.005	
55C	0.200	.530		99.5	.100		.030		.013		.002	
56	96.0			.020	.040	.055			.015	4.5	.008	
57	89.5	2.20	7.8	.040	.300		.040		.007	.30	.002	.040

ARGARIC SICKLE, CHISELS, AND SAW

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
53A	95.0		.07	.090	.015		.003			4.7	.005	
53B	2.70			93.0	.014		.008	3.50				
53C	2.60			94.0	.015	.02	.003	3.00				
61	95.5	.010		.008	.035		.004			3.3	.005	
62	96.0		.20	.020	.020					2.9	.002	
96	99.0	.110	.11	.070	.007	.08	.040	.005	.004	.20	.001	
94	99.0			.010	.012				.010	1.8	.005	

ATLANTIC AXES

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
63	61.5	31.3	6.10	.040	.030	.14	.015			.35	.0015	.010
64A	62.5	30.2	6.30	.075	.015		.005			.02	.001	
64B	62.5	29.5	6.80	.025	.015		.005			.03	.001	.005
65	84.0	5.80	10.0	.045	.008	.05	.065			.20	.0025	
66	88.0	2.00	9.40	.060	.025		.020			.06	.001	
67	89.0	1.20	10.3	.045	.020	.05	.045			.05	.0025	
68	89.0	1.30	8.50	.060	1.00	.065	.030		.004	.08	.002	
69	89.5	1.80	9.10	.060	.020	.07	.015			.10	.0015	
70A	62.5	30.0	7.00	.030	.006	.025	.015			.025	.001	
70B	65.5	26.2	8.00	.040	.004	.02	.020			.03	.002	
71A	62.0	31.2	6.90	.050	.045		.010			.03	.002	.005
71B	59.0	35.1	6.40	.050	.030		.010			.025	.002	
72	62.0	31.1	6.50	.085	.025	.03	.005			.02	.001	.020
73	90.0	.060	8.40	.055	.010	.15	.015			.15	.002	
74	91.0	.130	8.50	.009	.040	.07	.020			.20	.010	

ATLANTIC AXES CONTINUED

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
75	82.5	2.80	13.7	.060	.007	.045	.035			.70	.0025	
76	90.5	.110	8.70	.070	.010	.09	.020			.11	.0015	
77A	67.5	24.6	8.30	.060	.025	.07			.008	.015	.001	.010
77B	66.5	24.5	7.70	.070	.030	.07	.002		.008	.10	.001	.008
78A	72.5	26.5	.500	.040	.008		.005			1.1	.003	
78B	72.0	26.6	.500	.040	.005	.03	.010			.80	.003	
79A	80.5	12.6	6.50	.030	.007		.010		.005	.01	.0015	
79B	76.5	16.3	6.20	.025	.005		.010			.01	.0015	
79C	77.0	16.4	6.10	.030	.010		.005			.02	.0015	
80	66.8	22.9	4.75		.180							.010
81	90.5		9.90	.015	.025		.010			.015	.002	
82	88.5	.060	9.80	.070	.025	.20	.045		.004	.20	.001	.003
83	89.5	.070	9.90	.020	.010	.015	.0100			.1000	.0020	
84	83.5	6.00	8.80	.085	.004	.08	.0400		.0100	.3500	.0030	
85	90.0		10.4	.120	.015	.10	.0450			.0400	.0020	
86	91.5	.030	7.10	.050	.025	.25	.0350			.0400	.0010	
87	87.0	.370	10.1	.270	.010	1.0	.0400			.4000	.0350	
88	86.5	3.00	8.60	.070	.010	.06	.0350			.3000	.0040	
89	83.5	4.10	11.0	.060	.009	.07	.0400			.1500	.0040	
95	91.0		8.40	.010	.015	.02	.0070			.0250	.0015	

ATLANTIC SPEARHEADS

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
91	90.5	.600	9.5	.070	.025	.07	.050			.25	.005	
92	89.0	.900	10.4	.050	.035	.06	.040			.05	.002	

ATLANTIC SPEARHEADS CONTINUED

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
93	92.0	.550	8.3	.060	.003		.020			.30	.003	

ATLANTIC SICKLE

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
90	67.5	20.5	10.40	.250	.015	.05	.300		.015	.15	.002	

ATLANTIC ARROWHEAD

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
48	85.0	.120	15.4	.035	.020	.07	.005			.04	.001	

ATLANTIC SWORDS

RJH	CU	PB	SN	AG	FE	SB	NI	AU	CO	AS	BI	ZN
97A	91.5		7.3	.005	.020	.015	.005			.15	.001	
97B	93.5		5.5	.005	.010					.02	.001	
97C	93.5		5.3	.005	.020					.04	.001	
97D	93.5		5.4	.001	.020					.03	.001	
97E	99.0		.10	.003	.015					.015	.001	
97F	99.0			.006	.010		.002			.015	.001	
98A	85.5	.40	.13	.110	.007	.015	.020			.10	.001	
98B	87.5	.20	11.4	.110	.010	.03	.015		.030	.10	.001	.003

BRONZE IN THE BRITISH BRONZE AGE

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The purpose of this paper is to provide a background to the discussion of copper and bronze metallurgy in the Welsh Bronze Age by giving a general description of copper and bronze in the British Bronze Age, as far as it has been illuminated by compositional analysis. Unfortunately there are considerable areas and periods still unexplored, but a coherent narrative is still possible.

Copper Age

The term 'Copper Age' is used as a descriptive convenience. During this period British metallurgy is dominated by the products of Ireland, by virtue of their great number and distinctive forms and composition. In Ireland there are evolutionary sequences for the numerous copper axes and halberds and the less numerous copper daggers. However all have the same pattern of impurities with arsenic, antimony and silver but no nickel (Coghlan & Case 1957; Allen, Britton & Coghlan 1970; SAM 2,3 & 2,4; Case, unpublished).

Some Irish copper objects, notably most of the halberds and a considerable proportion of the largest thick butted flat axes, show signs of deliberate enrichment, rather than accidental or deliberate depletion for the remainder. Study of several hundred results suggests 1.25% arsenic as a reasonable boundary between the two classes.

There are almost no other composition types present in the Irish Copper Age. The use of metal of this distinctive Irish type continues into the Bronze Age, bronze appearing during the currency of thin/broad butted flat axes, Breaghwy halberds and the earliest rivetted daggers.

The pattern in Wales and Scotland is related to that in Ireland but there are differences in the popularity of the various implement types. In both countries thick butted axes are uncommon but, where found, they appear to be of Irish type and metal (Coles 1968-9). With the arrival of thin butted flat axes the importance of Irish metal begins to decline and there are the first signs of native metal production. The characteristic impurities, if any, now tend to be arsenic and nickel with low levels of antimony and silver. In Scotland difficulties of interpretation arise because there seem to be some Scottish ore sources producing metal similar to that from Ireland. However, there is a much smaller range of composition and nickel is more common as an impurity. Arsenic and antimony results outside this range, particularly if showing enrichment, would suggest Irish origin.

In the whole of the mainland of Britain the problem of halberds is of some complexity as there is a wide range of non-Irish types and compositions. Some, with arsenic, antimony, nickel and silver impurities, appear to originate in Scotland and to occur there and in Wales. For the rest there is an exotic variety of compositions for which continental parallels need to be reviewed.

In England only one or two copper axes have been analysed but they seem to fit the Welsh and Scottish pattern. The copper daggers, which represent a different tradition in English metal-working, have varied compositions, some of which are similar to metal in Dutch and Breton Bell Beaker contents (Butler & Van der Waals 1966).

It has often been suggested that halberds, having a presumed ritual or ceremonial function, were made of copper long after the use of that metal had ceased elsewhere, because of a conservatism associated with ritual practices.

This is possible, but it must be emphasised that the compositions of halberds are generally of types that died out early in the bronze using period. At present, known associated finds do not permit any conclusions as to the degree of overlap between the use of copper and tin bronze.

Early Bronze Age

In Wales, Ireland and Scotland there appears to be a natural local progression from copper to bronze and from broad to narrow butted axes and outside influences need not have contributed very greatly to this. In Ireland and Scotland the earliest narrow bronze axes, respectively of Killaha and Migdale types (Harbison 1969; Coles 1968-69), continue the use of metal containing arsenic, antimony and silver as impurities with the same distinction between Scottish and Irish compositions. There is some interchange of types between Ireland and Scotland, but plain axes of 'Migdale' type in Ireland tend to follow the Irish pattern of impurities.

In Wales both Killaha and Migdale axes of Irish metal occur, but only in those areas of South and Mid-Wales most accessible to Ireland. Elsewhere regional industries begin to appear and have a lifetime extending into the later phases of the Early Bronze Age. These are situated in South and Mid-Wales, North-West Wales, and North-East Wales and the Marches. The last named group illustrates one of the problems of sorting bronze implements by analysis. The metal is of very high purity with no distinguishing characteristics and is of a type which appears in a number of places and at a number of times. However, the distribution and the types involved suggest that there is a local industry, based probably in Shropshire. There is also, in South-East Wales, an area where there is penetration by an apparently English-based industry. This extends across Southern England as far as Kent and up into East Yorkshire and has strong connections with Bush Barrow metalwork (Britton 1961 & 1963). Its life includes the introduction of more developed forms of axe with central bevels and decoration.

Other English axes show a variety of compositions, often derived from the sources mentioned above, but with many others whose origins, in the present state of knowledge, it is impossible to locate. In general the daggers follow the same compositional patterns as the axes, but, as might be expected, their distributions indicate that they are often much more mobile than the axes.

The big divide in the evolution of Early Bronze Age metal-working in Britain comes not, as might be thought, at the end of the copper using period, but with the introduction of more developed forms of flat axe. The old composition groups based on arsenic, antimony and silver disappear abruptly and completely, and new types of metal appear with equal suddenness.

In Ireland the principal impurity types are now arsenic/silver or very low impurity levels, with a smaller contribution from arsenic/nickel types. These groups last for the rest of the Early Bronze Age covering developed flat axes, hammer flanged axes and cast flanged axes and their associated weapon types. It is important to note that the arsenic/silver composition groups are entirely confined to developed axes and to Ireland, whereas the others have a wider circulation, although they are not sufficiently distinctive to be easily separated from similar groups in other areas.

In Scotland the same transition occurs with the introduction of developed flat axes as does the same disappearance of arsenic/antimony/silver metal groups. They are replaced by high purity metal or by arsenic/nickel or arsenic/antimony/nickel combinations.

This last is the typical metal of the Arreton flanged axe industry in Southern England, although it has earlier roots. As the arsenic/silver group is confined to Ireland, so this is confined to the British side of the Irish Sea.

Other groupings occur, notably arsenic/nickel and high purity types continuing from previous stages, and a high nickel group confined to the South of England which seems to have a continental origin, but our ignorance of British ores is still too great for any certainty.

Clearly, the bronze industry during the Early Bronze Age in Britain and Ireland moves from the early domination by the Irish copper industry to a succession of local production centres and implement typologies. Some of the changes may be sufficiently sharply defined to have a wider archaeological significance, and the causes of these should be sought. Also the period of importance of a number of metal groups is so short and their association with particular types of implement so strong that it is possible to construct an evolutionary chart as shown in figure 1, and use it to place other analyses as they are performed.

Middle Bronze Age

The typological sequences defining the introduction of recognisably Middle Bronze Age implements is not well described for all areas (Rowlands 1976), nor have many of the objects intermediate between flanged axes and palstaves and haft-flanged axes been analysed, but a shadowy outline can still be constructed.

The dominant feature of the start of the Middle Bronze Age is the radical change in impurity types that takes place in a very short space of time. There is little sign of continuity with most of the Early Bronze Age metal groups.

At present, Wales is the only area where analytical attention has been paid to the early stages of the Middle Bronze Age. The bar-stop axes which represent one of the strands in the evolution of the palstave have a variety of compositions of either the high purity or nickel/arsenic types. The former may come from Irish or Welsh sources; if Irish, they are then related to the Irish haft-flanged axe series which are often of this composition. The Welsh distribution of the haft-flanged axes follows that of earlier Irish imports despite a long hiatus in Irish influence.

In Wales these few early specimens are followed by the dominant group of the early Middle Bronze Age, named after the Acton Park hoard and centred round 0.7% arsenic and 0.35% nickel with up to seven or more per cent lead. This leaded bronze so far appears confined to the Welsh area with occasional exports, but this pattern may well change after more English material is analysed. The source of the metal is unknown, but N. Wales or Shropshire are the strongest possibilities. It is noteworthy that the contemporary hoard of very similar palstaves from Voorhout in The Netherlands shows very similar analyses. We can no longer say that substantial concentrations of lead are diagnostic of the Late Bronze Age.

The next phase of the Middle Bronze Age in Wales is commonly labelled Cemmaes and its most typical product is the looped low-flanged palstave. The compositions of these are similar to those of the preceding Acton Park phase, but with reduced lead and sufficiently different nickel and arsenic contents to produce a separate composition group (Fig. 2). It is surprising that such uniformity of composition occurs, particularly with arsenic, but proximity to the ore source and standardisation of smelting technique from a fairly uniform ore deposit are probably responsible. Evidently the Middle Bronze Age is a more attractive area for metallurgical study than has hitherto been thought.

The corresponding phases in Southern England have all been analysed to some extent (Brown & Blin-Stoyle 1959). Analyses with medium levels of arsenic and nickel are almost universal, but lead occurs only rarely. The proportions of nickel and arsenic vary from place to place and will depend on the differing types of fresh metal and the amount and type of scrap available to the founders of each area. However, the importance of scrap is probably not large.

There is also a correlation with implement type; for example, the palstaves from the Somerset hoards form a fairly tight cluster of analyses which is fairly similar to that of the Cemmaes phase and is outlined on figure 2. However weapons and ornaments from the Somerset hoards have compositions outside this area. This difference is typical of other areas, including Wales, and suggests a different industrial organisation for making these products and also a greater mobility for the finished product. Areas, such as the South-East of England which are remote from copper deposits, show a greater variety of analyses. Part of the reason for this appears to be the import of bronze of high nickel content from North-Western France. There are other analyses which do not fit into the general pattern and there is some evidence, at least in Wales, of a small number of industries of purely local significance.

In Ireland there are at least two separate metal groups in use (Brown & Blin-Stoyle 1959; Allen, Britton & Coghlan 1970; SAM 2,4). The high purity group continues to be steadily used for at least the first half of the period. There is also an arsenic/nickel group appearing where nickel has previously been very uncommon; this differs from other British groups of the type in having more antimony and silver. These groups penetrate the Western seaboard of Britain; among these groups the arsenic/nickel types appear to have the longer lifetime.

Another variable in Middle Bronze Age metalwork is tin content. It is difficult to see the complete picture at present but the variations appear to have both geographical and typological significance.

Hawkes and others (Hawkes 1960; Burgess 1974, 1976) have defined a Middle Bronze Age III phase to take account of objects such as Taunton-Hade-Marschen socketed axes, early swords, transitional palstaves and imports such as the Ffynhonnau knife.

This concept is certainly valid in those parts of Southern England and Wales where an analytical record exists. In Wales the typical hoards are those of Penard and Ffynhonnau which contain most of these types of implements. The typical impurities are again arsenic and nickel but antimony and cobalt are also commonly present. This group forms another distinct cluster on the arsenic-nickel diagram in figure 2. This group also contains other Welsh and English transitional palstaves and slender socketed axes. In a wider context all British and Irish Ballintober swords that have been analysed (Eogan 1965; Britton, unpublished) seem to belong to this group. There are a number of associated imports which have exotic compositions such as the 8% nickel and 40% lead in the barbed and tanged arrowhead from Penard.

The most important development in this period is the evolution of the flange-hilted sword from imported Erbenheim and Hemigkofen proto types. A good number of these have been analysed (Britton, unpublished) and generally present compositions differing from those of native Middle Bronze Age III products. Some can be identified on the continent in succeeding phases and in later continental metal imported as scrap, particularly that involved in the Wilburton industry. The presence of significant amounts of lead is not observed in any of these swords until those of the Wilburton phase become established. In general lead levels during this phase are very low.

Late Bronze Age

In a large part of Southern, Eastern and Midland England the first phase recognised as Late Bronze Age is that characterised by the material in the Wilburton hoard. This group has a particularly distinctive composition, possessing high levels of arsenic, antimony, nickel and silver. This appears to be the result of the importation of scrap from the continent as there are no similar compositions in material that is recognisably British, and the corresponding French phase, St. Brieuc-des-Iffs (Giot, Bourhis & Briard 1966; Burgess 1968),

has similar impurities at still higher levels. These will have been reduced on re-melting and dilution with additions of lead, up to 40% in some delicate castings; however such large lead contents do not occur in Northern France. The area of the Wilburton industry is mainly remote from copper sources and the recourse to imported scrap and lead dilution may be a result of political pressure on the normal metal supply, although the lead may equally result from technological experiment.

In the North of England the Wallington phase continues the traditions of the Middle Bronze Age, without the addition of lead. It is unfortunate that no Wallington material has yet received detailed analysis. In Wales and the South-West it is difficult to identify the products that are contemporary with Wilburton, especially if Middle Bronze Age traditions prove to be particularly conservative, but socketed axes of Burgess's Gwithian type are a possibility. There is slight evidence of a return to lead additions in Welsh tools after their absence in the Penard phase (Burgess & Tylecote 1968; Burgess 1976).

These socketed axes are probably ancestral to the South Wales type which is common in South Wales and South-West England in Late Bronze Age II. Study of a large number of metal analyses (Brown & Blin-Stoyle 1959; Allen, Britton & Coghlan 1970) confirms the impression that by this time scrap has become a universal factor in the organisation of the metal supply.

Much, if not all, of the ingot copper of the Late Bronze Age which has been analysed is of great purity, in contrast to the varying pattern of impurities in preceding phases. This, coupled with the progressive purification of scrap by successive re-meltings, will tend, assuming that the two are habitually mixed, to produce a large pool of metal with progressively lower and more uniform impurity contents. Thus it may be possible to make a crude ordering of metalwork in the Late Bronze Age by composition as well as by typology. This uniformity is universal as far as analysis has progressed, and covers all the regional industries such as Yorkshire socketed axes and Broadward spearheads as well as more widely dispersed types such as Ewart Park swords. Indeed this composition (0.10 to 0.20% for arsenic, antimony, nickel and possibly silver) has a wider distribution, appearing in imported Carp's Tongue material and in Ireland. The lead content is usually around 7%, this level being adequate for securing good casting properties, although there are occasional implements with considerably higher lead contents.

There are a number of interesting exceptions to this general pattern. Firstly, there is some evidence of the continuance of metalworking centres of purely local significance. The best example is the collection of tools found at the Breiddin hill-fort in the Marches (Musson, forthcoming). This has a distinctive composition containing considerably more antimony than arsenic, a feature unusual at any stage in the British Bronze Age. Other implements are now being identified as belonging to this group such as a sword from the River Severn in Shropshire. We have here a small concern making products for local use and we have been lucky enough to find them before they had disappeared into the common metal pool. We must also conclude that the makers were relying on freshly smelted metal without a large admixture of scrap; lead additions were still being made. Such local groups must occur elsewhere in the Late Bronze Age but they have not yet been identified.

The second source of deviant compositions is imported scrap. As pointed out above, such metal need not be distinctive, but some remarkable compositions are found, particularly in such complex finds as the Parc-y-Meirch hoard of harness fittings and the very late Wilburton hoard from Isleham (Britton, unpublished).

Analyses in the latest phases of the Late Bronze Age are rather scarce, but the trend towards increasing dilution continues. This is shown in the Cardiff and Llyn Fawr hoards from South Wales where the impurity content has almost vanished and lead contents have fallen to 2 to 3% or less. It is likely that the

deliberate addition of lead had fallen out of favour. These hoards are often associated with objects of sheet bronze; this appears to be of similar composition to that used for castings.

In Wales iron is first used at this time, for objects that are replicas of cast bronze types. Blades of cutting tools are already being carburized, and the metal work is of a high standard.

These various programmes of analysis have demonstrated strong correlations between implement typology and composition, and the existence of clearly defined regional industries, and suggest that it would be useful to attempt to determine possible connections between these regional groups and their probable ore resources.

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Key to Figure 1

Provisional Designation of Early Bronze Age Composition Groups

A : Impurities arsenic, antimony and silver.

A1	As > Sb > Ag; As, Sb > 0.42%
A1*	Similar to A1 but enriched in arsenic
A1a	As ≏ Sb > Ag; As, Sb > 0.42%
A2	As < Sb > Ag; Sb > 0.42%
A3	As ≏ Sb ≏ Ag; All < 0.42%
A3*	Similar to A3 but enriched in arsenic
A3a	Similar to A3 but all < 0.10%

B : Impurities arsenic and nickel.

B1	As > 0.65%, Ni > 0.10%) * indicates enrich-
B2	As > 0.65%, Ni < 0.10%) ment in arsenic
B3	0.65% > As > 0.20%, Ni > 0.10%
B4	As < 0.20%, Ni < 0.10%
B5	As variable, Ni > 0.40%

C : Zero or trace impurities.

C1	No impurities
C2	Trace arsenic
C3	Trace antimony
C4	Trace nickel
C5	Trace silver

D : Arsenic, antimony, nickel and silver impurities.

E : Arsenic, antimony and nickel impurities.

F : Arsenic and silver impurities.

No individual groups yet defined under these headings.

Pb, Fe, S are permissible impurities in all groups as they are not significant for classification purposes.

This classification may prove to be too refined and some groups should perhaps be combined, e.g. A1* and A3*, B1 and B2.

Axe Type \ Metal Group	A	B1, B1*	B3	B4	C	D	E	Associations
Copper, Thick butted	●●●							Halberds
Copper, Thin butted	●●●● ●●			●	●	●●		
Killaha	●●							Rivetted daggers
Migdale, large	●●●	●●●				●●		Rivetted daggers, awls, Bush Barrow
Migdale, small	●●●	●●●●	●●●●	●●●●● ●●●	●●			
Rain pattern		●●●			●			
Plain bevelled		●●			●		●	Aylesford
Decorated & bevelled			●●●	●	●●●			Knife daggers
Hammer flanged			●●	●	●		●	
Cast flanged, plain			●		●●			Razor
Arreton					●●●●	●	●●●	Ogival daggers, Early spearheads
Haft flanged				●	●●●●● ●			
Early palstaves			●●		●			

Figure 1 Evolution of Welsh Early Bronze Age Metallurgy (see page 69 for Key)

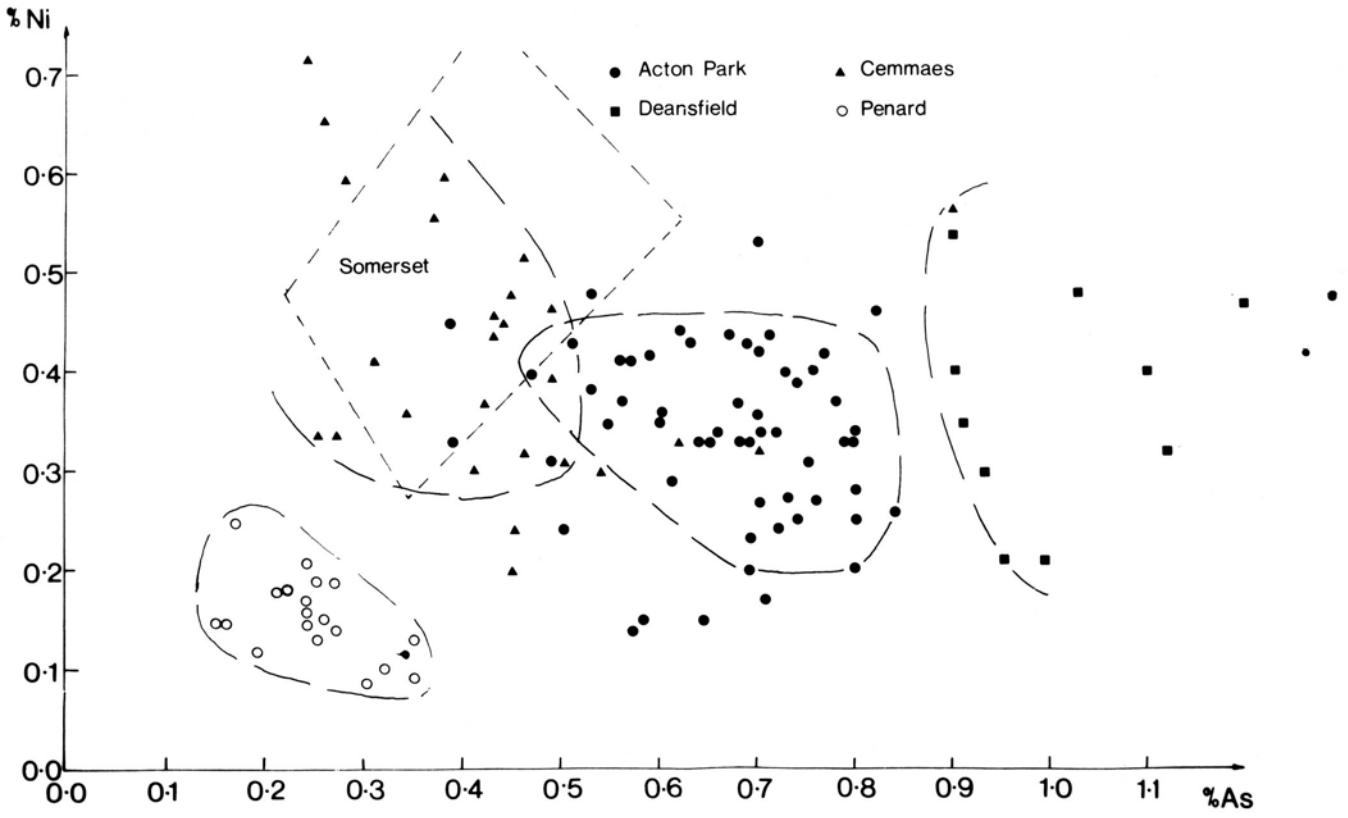

Figure 2 Evolution of Welsh Middle Bronze Age Metallurgy

METALLURGICAL INVESTIGATION OF THE BRONZE CRATER OF DERVENI

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A bronze crater and several other bronze vases with an attractive golden appearance were found at Derveni, near Thessaloniki, in 1962. They are ascribed to the 4th century B.C., a period during which metalworking in Greece had reached an amazingly high standard of performance.

Sampling of the crater was obviously very difficult, and therefore, the number of samples was relatively limited, and their size extremely small. Nevertheless, their chemical analysis and metallographic investigation led to interesting conclusions regarding the composition and fabrication techniques of the crater.

The research work was undertaken in close cooperation with the archaeologist Mrs E Youris.

Samples and their Origin

The samples examined in this study were taken from the following parts of the crater: (a) perforated lid, (b) section somewhere below Pentheas, (c) Dora (skin) of Silinos, (d) base of the crater, and (e) statuette of Satyr. Four of them are of particular interest, because it was possible to examine them under the microscope, and to reach some important conclusions which are referred to below.

Crater Examination

The large crater (Fig. 1), a unique masterpiece of ancient Greek art and technology, has a height of about 90 cm, and an approximate weight of 40 kg. Its helicoidal cast handles are richly ornamented with snakes, and masks of Heracles, an unspecified god (Mrs Youris calls him a "tavrokero God"), and of Hades, God of the underworld; the lower part of the handles ends in the shape of a thorn. The passions of Dionysus are represented in fine relief all round the main body of the crater. Among them are the weddings of Ariadne and the young god, the orgiastic dances of Maenads, which dances, according to Mrs Youris, represent the God's rebirth, and signify also the deep belief in the immortality of the soul. In her paper (1) she states also that these representations of Dionysian passions are unique in the artistic tradition of the period. In Attic pottery, Dionysian themes predominate, but we have not yet met a decoration representing the god's passions. The same applies to Italian pottery, whose topics are developed from ancient tragedies.

According to the archaeologist, Mr Ch. Makaronas (2), who was in charge of the excavations, the large crater and many other interesting finds were buried in six box-like tombs, made of large limestone slabs; they were discovered accidentally by a scraper during road works.

As mentioned above, the crater and most of the bronze vases have an attractive golden appearance, which led Mr Makaronas to believe that they were gold plated.

In the present report the crater was examined chemically and metallographically. X-ray investigation of the crater was carried out in order to look for the existence of joins and to assess the original number of bronze sheets used in fabrication.

Figure 1: The Crater of Derveni of the 4C B.C.

A description of the probable process of making and decorating the crater is presented on the basis of (a) the present study, (b) our knowledge of present-day Greek traditional copper and silver-smithing, and (c) our laboratory experiments to shape a relatively hard brass disc into a simple vase by hammering.

Chemical Analysis and Metallographic Examination of the Derveni Crater

(1) Perforated Lid:

Chemical analysis of this sample gave the following results :

Sn %	Cu %	Pb %	Zn %	Fe %	Ni %	Au %	Ag %
14.95	84.90	---	0.005	0.046	0.050	---	0.005

Sb %	Mn %	Co %	Ti %
0.040	---	trace	---

As can be seen, there is no trace of gold; the golden appearance is not due to the presence of this precious metal, but to the unusually high tin content. The same applies to all the bronzes found in the Derveni tombs, and it is surprising that the ancient artist-craftsmen had worked such a hard copper-tin alloy. Normally, ancient metalworkers used softer alloys in similar cases, especially to make cauldrons. Why then did they use an alloy so difficult to shape? Did they intend to obtain merely an attractive appearance or was the composition meant to increase corrosion resistance - since the crater would contain the remains of some high-born personage - or did they have both aims? One thing is certain, whatever the object it was done deliberately. We must not forget, that among the vases with a golden appearance were also some common bronze objects (cauldrons etc.) of minor artistic value, covered as usual by a dark or light green patina. This suggests that ancient metalworkers were always careful in choosing the right metal or alloy. The Eleusis technical specifications (3) of the same historical period, concerning the composition of bronze fittings between the drums of the Philonian stoa columns, show clearly how the ancient Greeks were aware of the mechanical properties of copper alloys in relation to their composition, and in particular their tin content. Certainly metalworkers would have to face many difficulties in shaping a hard bronze sheet into a crater, and furthermore, in producing the fine relief designs. Nevertheless, we must remember that time productivity did not play an overriding role in those days; after all, they were creating works of exceptional art.

The low content of foreign impurities suggests that the copper was of Cypriot origin.

Metallographic Examination of the Lid

Metallograhpic investigation proved that the lid was hot worked. Micrographs (illustrated in Figs. 2 and 3 at a magnification of x 200) show the hard δ-phase in a matrix of α-solid solution. The δ-phase is still elongated in some parts in the direction of hammering, while many α-crystallites show twinning.

An attempt was made in the laboratory to assess the final or annealing temperatures, at which the metalworkers might have shaped the crater's individual parts, especially the embossed thin sheet forming its main body, and the lid. For this purpose a cast sample of bronze, containing about 14% tin (i.e. very similar to the metal of the crater) was treated as follows: first, beaten hot, then reheated to 650°C, and finally cooled in still air. This was done in order to homogenize the metallic mass of the cored cast bronze. After cooling, it was hammered cold from 4.5mm down to 2.5mm, i.e. a reduction of more than 44% in

Figure 2

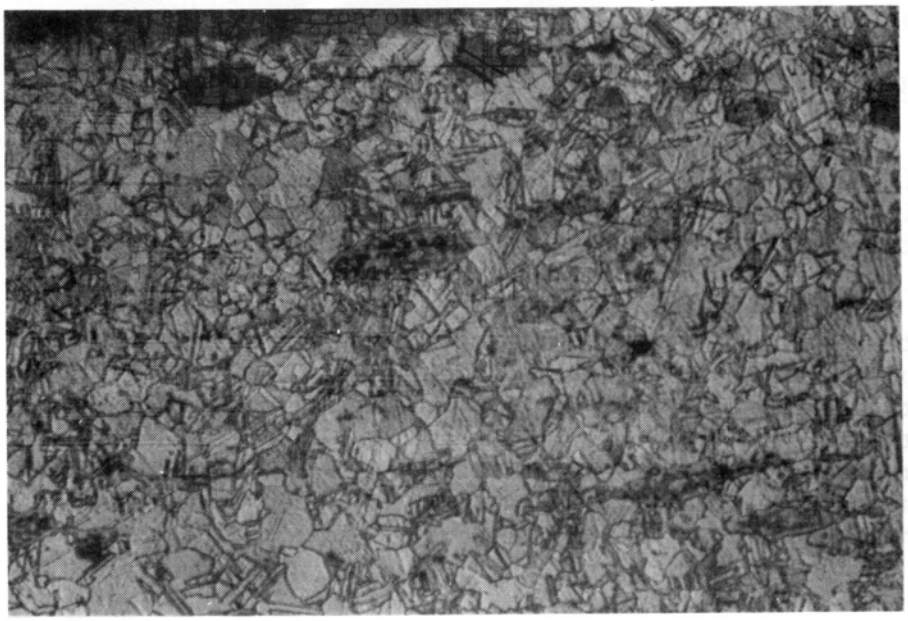
Micrograph of the Crater lid. Mag. x200

Figure 3

Micrograph of the Crater lid. Mag. x200

Figure 5

Micrograph of Pentheas sample showing deformed δ-crystallites in a matrix of twinned ∝ grains. Mag. x200



thickness; then annealed progressively from room temperature up to 800°C. It is notable that Brinell hardness increased after hammering from 96 to 240. Micrographs at intervals of 50°C were taken showing recrystallisation and gradual grain growth. Matching the micrographs of the crater to the sample, the final hammering, or reheating temperature could be estimated to an accuracy of about ± 50°C. The same experiment was undertaken on an electrolytic copper sample in order to find the final shaping temperature of the copper Silinos skin. Details are given below.

Admittedly, one cannot expect to achieve results identical with those of the past because, as is well known, grain size of alloys with similar compositions, depends not only on final temperature, but also on original casting, heating time, degree of cold work, etc. Nevertheless, such studies can help a great deal to elucidate problems connected with ancient metalworking and fabrication processes. Comparing, therefore, the micrographs of the lid with those of the laboratory sample described above, we arrive, as a first approximation, at a final hammering, or reheating, temperature of the order of 550°C to 600°C (Fig. 4). Whether it concerned the one or the other final treatment is difficult to define, but smiths usually heat the alloy for a short time in a heap of white hot coal after forging and then they let it cool in still air. I think that the lid was treated in the same way and its grain size is related to its final heating temperature.

Sample below Pentheas

This sample was taken from the thin sheet of the main crater body, which is decorated with the fine embossed Dionysian scenes. Its study was, therefore, very interesting for both composition and fabrication techniques. The specimen itself was very small (about 0.06g), and this caused many difficulties in preparing the metallographic sample, and then in determining its chemical analysis. Nevertheless, both examinations were quite successful, and led to important results reported below.

Chemical Analysis

Chemical analysis has shown the following results :

Sn %	Cu %	Pb %	Zn %	Fe %	Ni %	Au %	Ag %
14.88	85.03	---	0.009	0.10	---	---	---

Sb %	Mn %	Co %	Ti %
---	---	---	---

The above composition is not very different from that of the lid, and its relatively high purity again favours the idea of Cypriot origin for the copper. The tin content is unusually high for such a thin sheet, and it is remarkable that the artist-craftsman worked this hard bronze, and produced the fine relief representations which decorate the crater's main body. Any carelessness on his part would lead to a fatal tearing of the sheet, very difficult, if not impossible, to repair.

Metallographic Examination of Pentheas Sample

The sample, as mentioned above, was taken from a point below Pentheas, where I observed an indication of some descaling, or rather a splitting into two different layers, the one shinning, and the other dull. At first I thought that there might have been a thin gold alloy leaf over the bronze sheet. Nevertheless, both examinations, chemical and metallographic, proved that (a) no trace of gold existed, and (b) corrosion was responsible for the apparent splitting. Micrographs, on the other hand, showed that beyond the visible tearing, the alloy was

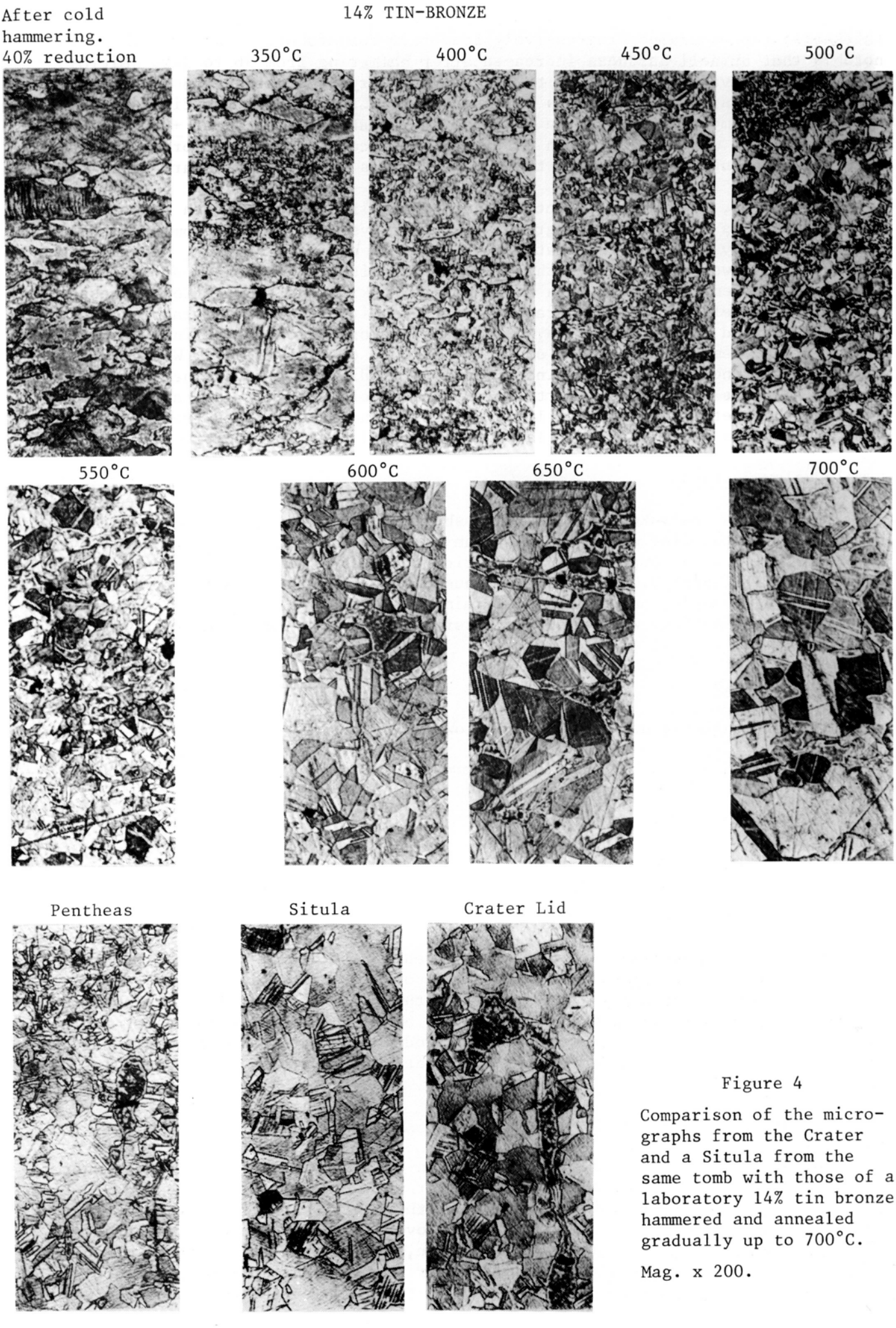


Figure 4

Comparison of the micrographs from the Crater and a Situla from the same tomb with those of a laboratory 14% tin bronze, hammered and annealed gradually up to 700°C.

Mag. x 200.

homogeneous, excluding therefore, the possibility of any metal plating. Figure 5 (mag. x 200) indicates a more pronounced deformation of the δ-phase, while α-crystallites are smaller there than those of the lid. This means that the final heating temperature was somehow lower in this part of the crater. Comparing this micrograph with those of the laboratory sample set (Fig. 4) we conclude that it would be of the order of 550°C. A thorough metallographic examination, near this point, showed a slight grain size differentiation, which was probably due to uneven heating, and which could be a good reason for a corrosive micro, or macro-galvanic cell development between regions of low and high mechanical stresses.

Probable Fabrication Methods

The crater of Derveni consists of cast and forged parts. The heavily decorated helicoidal handles, the statuettes on the shoulder, and the base are cast. The lid, the neck, and the main body with its rich Dionysian relief representations are, as mentioned above, forged. From a technical point of view the latter operation is the most impressive, because the material consists of a hard thin bronze sheet, very difficult to shape, and to emboss. The questions to ask, therefore, are (a) how did the metalworker fabricate the crater, and (b) how did the artist work out the relief designs?

There are two alternative methods of shaping a thin metal sheet into a vase : (a) Spinning, and (b) Hammering.

Embossing always follows after the initial shaping, as described below.

Spinning

The lathe has been known since the Geometric period, and even before, but only for the shaping of wood. The use of this tool for machining metals is mentioned for the first time in the history of metals in Greece in the 4th century B.C. The Eleusis stele (3), as mentioned above, refers to the making of bronze fittings. Consequently, it is not unlikely that ancient craftsmen had used the lathe to fabricate, at least, small size cups, or other simple metal artifacts. Smaller bronze and silver bowls, or vases with flat bottoms, of this period show clear signs of spinning, i.e., indentation of some sharp bearing tool in the middle of the flat base and all around it concentric rings up to the outer rim. Further research in Greece may elucidate this subject (Figs. 6-8).

In the case of the Derveni crater, hammering would be the most probable process used by the ancient metalworker, because its considerable size and the spherical shape of the base exclude the use of the lathe.

Hammering

Shaping by hand-hammering constitutes an old metalworking technique in forming metal objects. Nowadays, this old-fashioned process has been replaced by modern mass production automatic machines, which have considerably increased productivity, but have killed any meaning of what we call art. Fortunately in Greece there are still some old smiths who continue to use traditional fabricating methods; I am greatly indebted to them for their help in my understanding of old metalworking techniques; personally, I believe that the latter does not differ much in principle from that applied in antiquity. A highly skilled smith, Mr George Louskos, now retired, was kind enough to show me in practice, how a thin metal sheet can be shaped by hammering into a spherical vase. Such comparative studies are not only interesting from a technical point of view; they are valuable also for keeping alive records of a dying technique.

A description of the method follows: when a small central circular area of a thin metal disc is beaten (Fig. 9) the central part becomes thinner and deeper, while the rims and the rest of the disc, which still keep the original thickness,

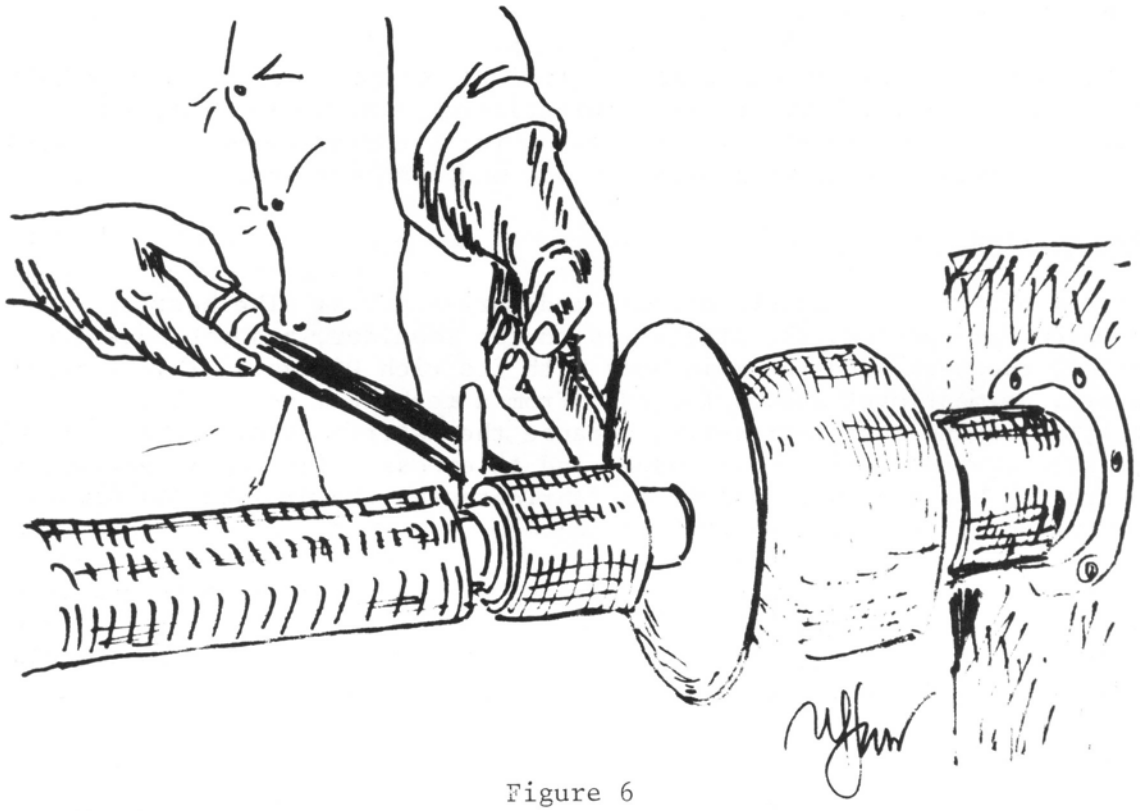


Figure 6

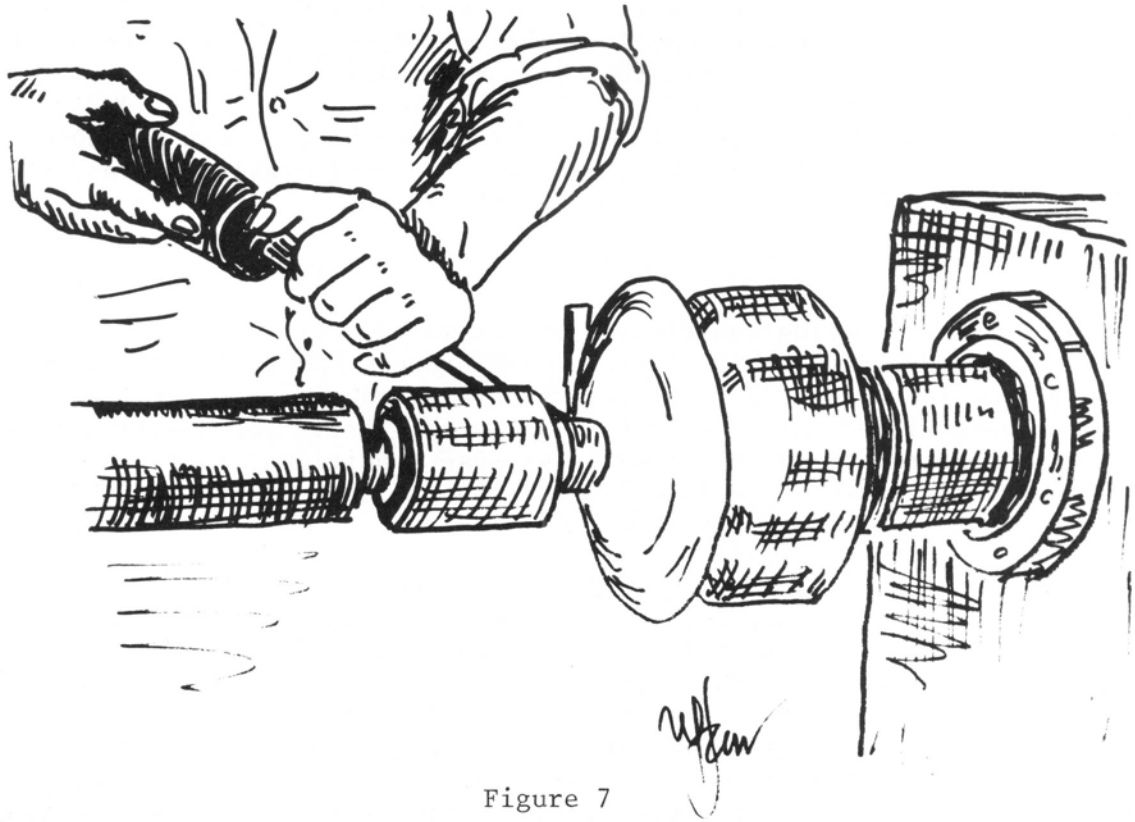


Figure 7

are raised upwards. A small depression is thus produced in the centre, whose diameter increases gradually until the original flat disk changes first into a shallow, (Fig. 10) and then into a deep dish, (Figs. 11 and 12) which can finally be worked into a vase.

The disc used to make a simple vase was brass with 36% zinc, and 64% copper. The reason for choosing a relatively hard copper alloy was to identify what difficulties our smith would face, since the crater was also made of a hard bronze material. Its original thickness was 2mm, and its diameter 250mm.

The modern smith started to beat cold a circular area in the middle of the disc, but he was forced to anneal it very often, because it hardened too fast, and he was unable to proceed easily. Even so, it was difficult to shape, and finally he decided to heat the disc to about 650°C, and hammer it while hot, reheating every time he felt this necessary. It was an unusual task for him, because normally he worked soft copper, or mild-bronze (or brass) which did not need to be shaped hot. He succeeded in producing a vase-like form, with a height of 115mm, and a thickness of 0.9mm (from the original 2mm). During hammering, the disc diameter fell from 250mm to 235mm, and then increased gradually to 253mm. It would have increased more, if the smith had continued to shape it up to the neck; however, our main object was not to make a real vase, but to show how the ancient smith fabricated the Derveni crater from a single sheet. Finally, this experiment proved that hard copper-tin alloys, similar to those used to fabricate this crater, could be worked only while hot, and never cold, even if more frequent intermediate annealings were applied.

X-ray Investigation

As mentioned above, a metallic vase can be produced more easily from two or more separate components (nowadays by spinning) which are then joined together, than from one single sheet. Mrs Youris and I had a feeling that the crater might have been made in this way, and we decided, therefore, to examine it with X-rays. My friend Dr M Comninos kindly arranged for Mr D Constantacopoulos, a brilliant and enthusiastic radiographer and electronic engineer, to come to Thessaloniki. He took some exceptional radiographs whose examination led to the surprising conclusion that the whole crater, without of course considering its cast components, was shaped from only one bronze sheet. Taking into account its height (90 cm) and its hard composition, we can appreciate the difficulties the ancient metalworker and artist had to overcome in order to produce this masterpiece of ancient Greek art. Another larger crater of the 6th century B.C. (about 525 B.C.), was found at Vix (4), (5). It is kept at the Chatillon-sur-Seine Museum, France. The Vix crater has a height of 1.64 m, and a volume of 1200 l, and was also formed from one single bronze sheet. Nevertheless, there exist some significant differences which indicate considerable technological development between the corresponding historical periods of these craters. Two are worth mentioning: (i) the hard composition of the Derveni crater, and (ii) the artist's high skill in producing on it the superb embossed Dionysian representations. On the contrary, the Vix crater was made out of soft bronze (8% Sn) and worked cold. Metallographic examination showed that no annealing followed the cold shaping. The second and most important difference is the fact that its main body is plain, i.e., without any relief decoration; this was probably the reason why it was not heat treated after shaping, an important condition for embossing.

Figure 13 shows the position of X-ray films in the interior of the crater. Four long films (39 x 10 cm) covered longitudinally all the vase surface from rim down to the base on two opposite sides, and two short ones (20 x 10 cm) covered the interior of the neck. With this arrangement it was impossible to miss the presence of any joining, which, if it existed, would normally cross the films perpendicularly. In fact, we located only one welding join in the middle of the neck, having a width of about 12mm, while the rest of the crater proved to be of one single piece. Just above the rather rough welding zone the artist-craftsman

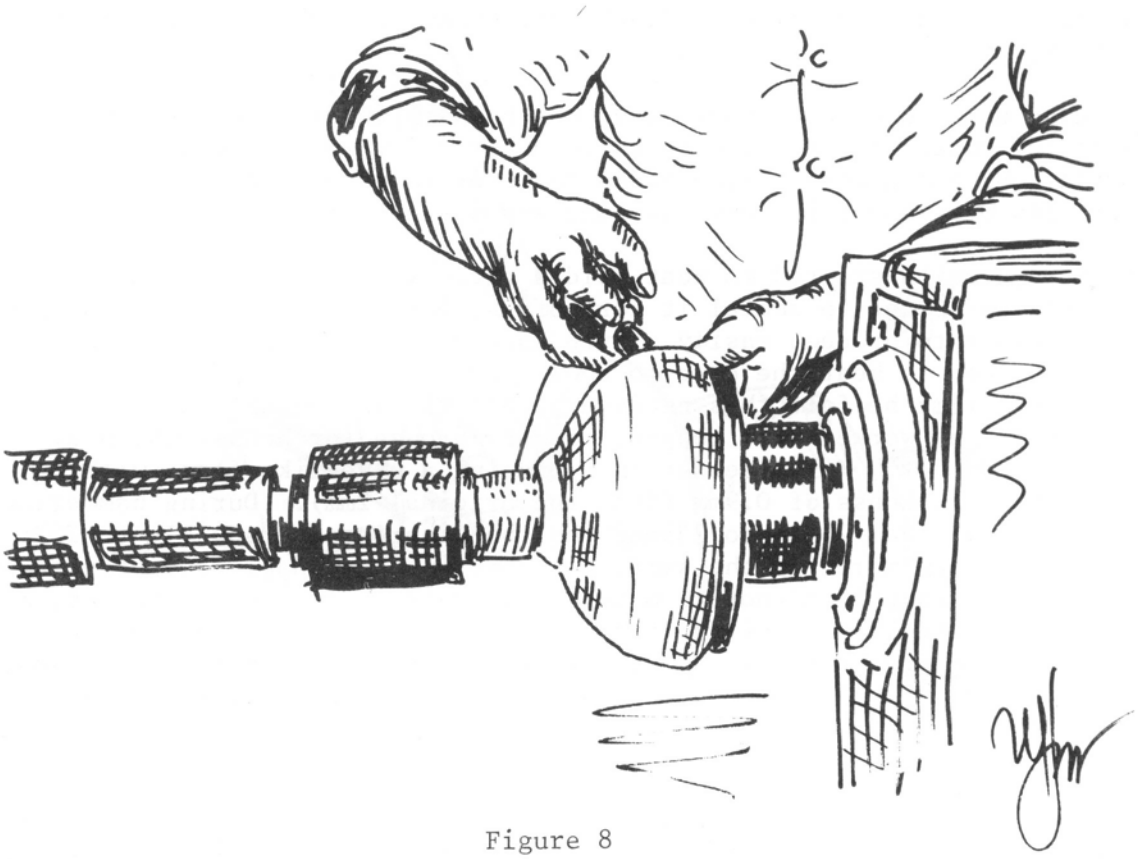


Figure 8

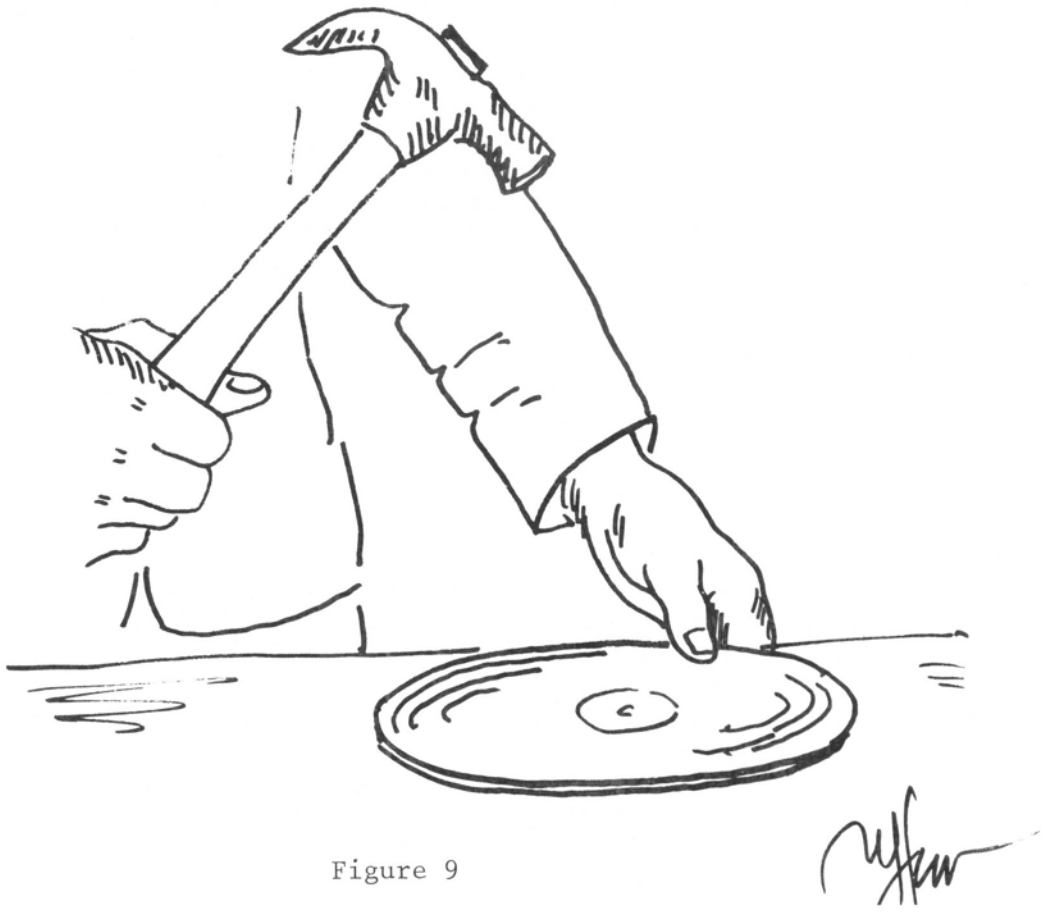


Figure 9

had soldered representations of wild and domesticated animals, looking as if they are moving on an irregular ground. In this way he dispels one's attention from the welding area, and according to Mrs Youris he follows the 4th century B.C. fashion of a double zone of decoration on the neck. Nevertheless, I would like to point out that in ceramic art the upper decorated zone is, as far as I know, covered with floral designs, and the lower one with animal or human representations. It is obvious, therefore, that the artist wished to hide the bad appearance of the welding; if he had used a band of floral decoration it would not hide, but on the contrary would emphasise, the existence of a join.

X-ray investigation of the four statuettes, which lie on the shoulder, showed that they are solid and not hollow. A slight piping in the middle of the sleeping Maenas and Satyr can be seen in the radiographs.

Description of present-day Embossing Techniques

I believe that in many cases there are no essential differences between ancient and present-day handicraft techniques, especially as far as embossing is concerned. Beeswax found in the interior of the crater (some on its surface, and some stuck on pieces of cloth, which covered once mortal remains), and a careful study of its relief decorations do not leave any doubt about this conviction. A description, therefore, of present embossing techniques will give an idea of how the artist-craftsman produced the superb relief representations in that remote time.

Preliminary Embossing

A long iron bar is fixed at one end. An assistant beats the bar, making it vibrate as vigorously as possible (Fig. 14). Another worker introduces the vibrating end into the interior of the metallic vessel, allowing it to be stuck at points indicated by a previously drawn design. The thin sheet rises up at the beaten area thus forming the first rough embossment. In the case of the crater, his colleague would have had to be careful during this stage, because, as already mentioned, the thin bronze sheet was hard and, therefore, very liable to tear.

Filling with Wax

After this treatment metalworkers place into the vase small pieces of tar, which they subsequently melt by heating. This is repeated until the vase is completely filled with tar, which they allow to cool. The vase is now ready for its final embossing stage.

Although tar was known in Anatolia, and probably in Greece, ancient Greek metallurgists and metalworkers normally used beeswax in metal castings, and presumably also in embossing techniques as the presence of beeswax in the crater indicates.

Final Embossing Stage

The smith, following the original design, now completes the relief decorations. For this purpose he hammers very lightly and carefully the fine metal sheet, which is backed by the solidified tar, with the help of chisels and other fine tools (Fig. 15). After completion of this stage he removes the tar (or wax in ancient times) by melting, and finally he polishes the whole vase surface.

I believe that the ancient artists did not follow a procedure much different in creating the unique decorations of the Derveni crater.

Figure 10

Figure 11

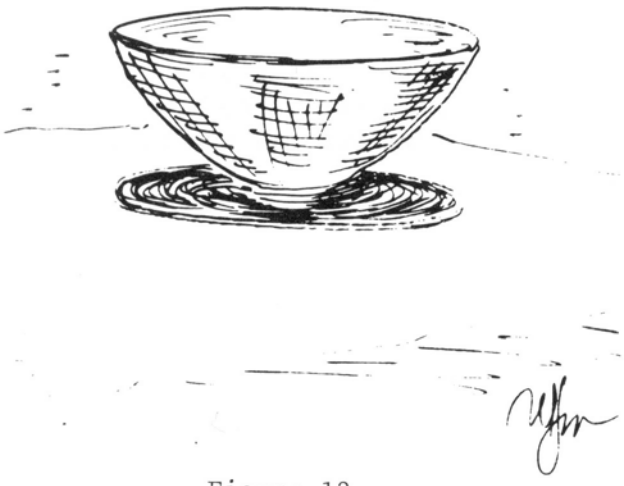


Figure 12

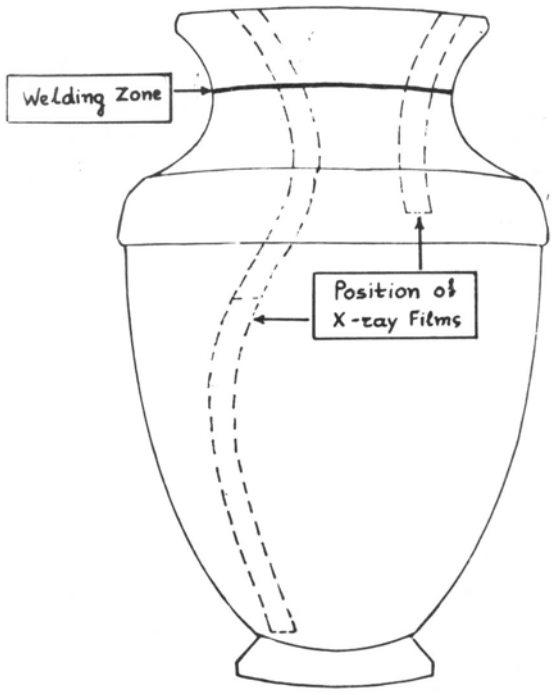


Figure 13

Crater Base

This heavy component has in the middle a hole, in which the crater's body is accommodated. Both were welded together with pewter, traces of which are still visible. At present they are fixed with resins.

Chemical analysis gave the following analysis :

Sn %	Cu %	Pb %	Zn %	Fe %	Ni %	Au %	Ag %
12.80	85.68	0.16	0.07	0.36	0.061	---	0.018

Sb %	Mn %	Co %
0.67	---	0.050

Its composition differs slightly from previously examined samples; relatively high in tin content, and low impurity concentration are again its main characteristics.

Metallographic Examination of the Crater Base

It was impossible to cut out even a very small piece for metallographic purposes without causing some visible injury to the antiquity. It was also impossible to use a portable grinding and polishing machine without avoiding the danger of destroying its rich decoration; on the other hand its shape would not allow a satisfactory microscopic examination. I therefore tried with success a new chemical polishing technique I had developed some years ago, a description of which is in the press.(7) Micrographs taken in this way showed clearly that the base is cast; nevertheless, there is in the middle of the replica an islet - (and there may exist more of such areas), of small twinned α-crystallites surrounded by δ-phase; this proves that some parts were beaten hot, probably to correct casting imperfections, or for decorative purposes.

Silinos Skin

Chemical Analysis and Metallographic Investigation

For colour contrast effect the artist-craftsman used fine red copper sheet to make the Silinos skin. Its chemical analysis is the following :

Cu %	Fe %	Ni %
97.5	2.10	0.20

Sn, Pb, Zn, Au, Ag, Sb, Mn, Co.....nil. Except for the unusually high iron content the absence of other impurities favours the idea that the copper was imported from Cyprus.

Micrographs from the Silinos skin show small crystallites grown at random; this means that it was either hot worked, or heated briefly after cold shaping. Comparing, as in the case of the hard bronzes, the grain size of the skin sample with that of laboratory standards of known annealing temperatures, I deduce that its final heating temperature corresponds to 450°C; as copper recrystallises at lower temperatures than bronze; this indicates that it did not need to be worked at higher temperatures, as was the case for the other hard bronze components of the crater.

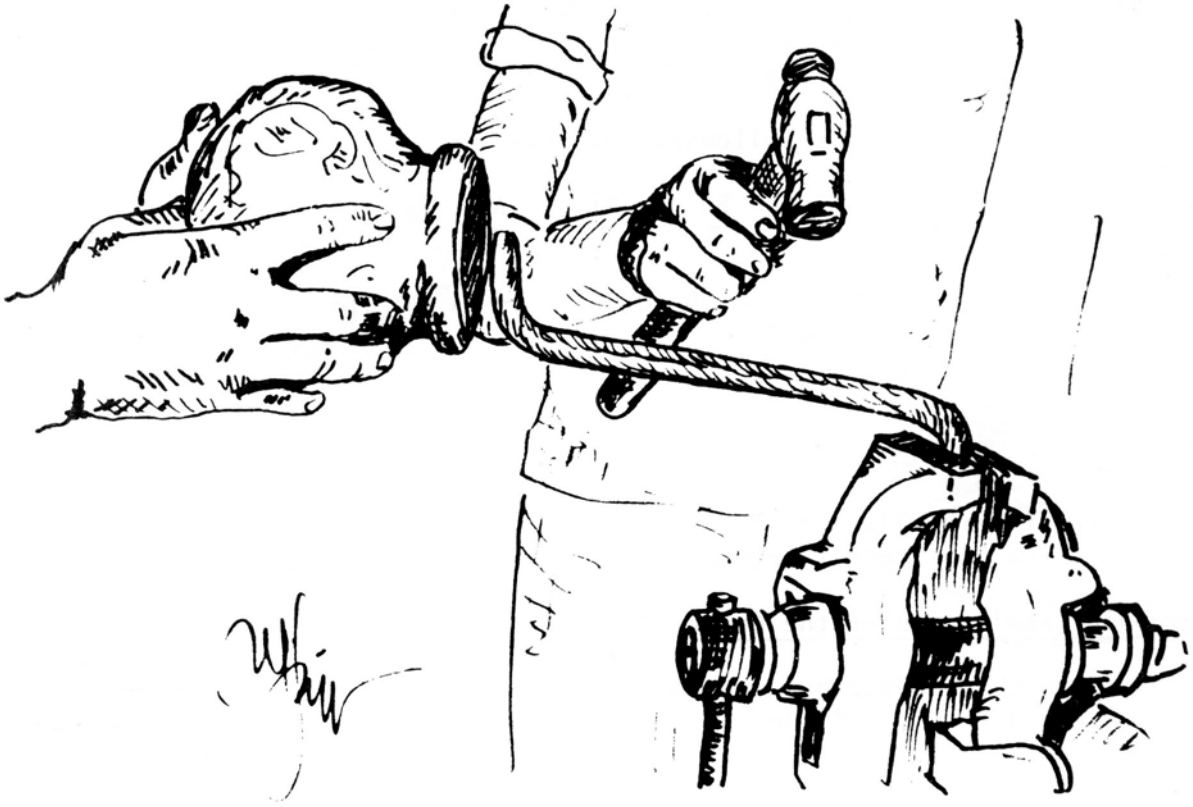


Figure 14
Preliminary embossing

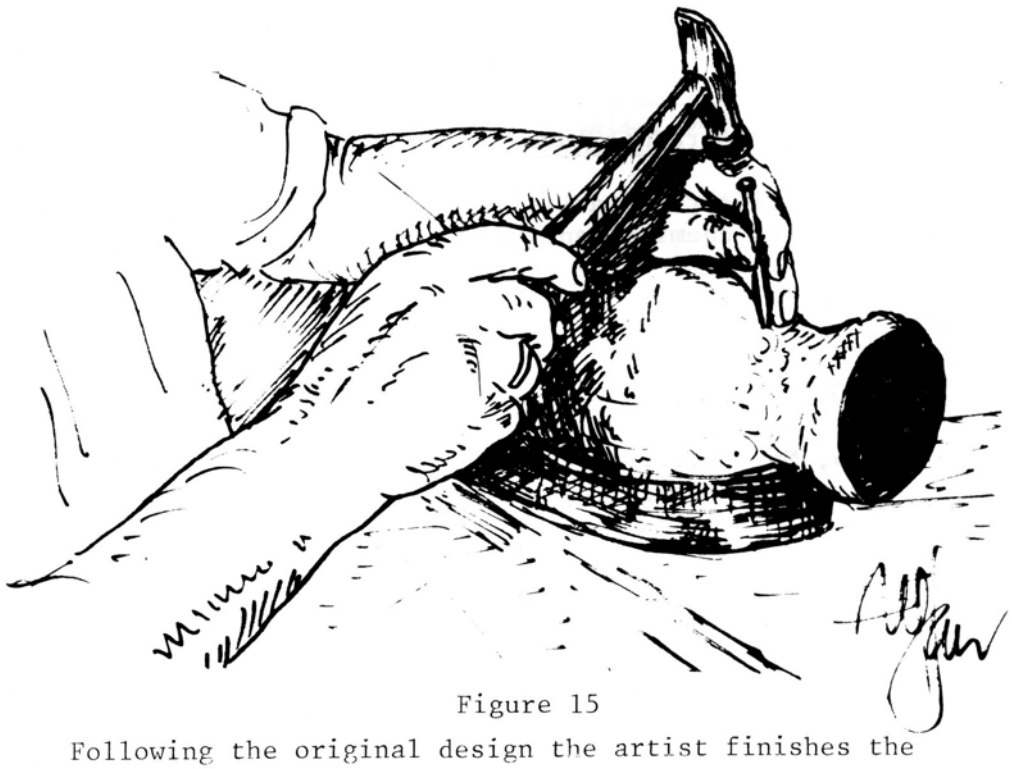


Figure 15
Following the original design the artist finishes the relief decoration on the tar-filled vase

Chemical Analysis of Sleeping Satyr

Chemical analysis showed the following composition :

Sn	Cu	Zn	Fe	As	Cd
%	%	%	%	%	%
13.75	85.50	0.16	0.16	0.34	0.093

Pb, Ni, Au, Ag, Sb, Mn, Co, Zn.....nil.

The above analysis is very similar to that of the rest of the crater, in particular as far as its high tin content is concerned.

Comparing small polished surface areas of the other three statuettes with a set of polished standard bronze samples of known composition we can assess that they have roughly the same analysis. I applied this comparative method because it was not possible to take more samples; I believe it works well far qualitative purposes. I suggest this method to those studying ancient bronze who face the same sampling difficulties.

As mentioned before all statuettes were solid cast, having an approximate weight of 1.5 kg each. Careful examination of the Sleeping Satyr revealed two casting defects; one on the knee, and a minor one near the ankle. Corrosion damage caused both of them to become visible, especially the addition to the knee plate, whose dimensions are 20 x 10mm; those of the ankle are 6 x 5mm.

Apart from these minor defects, all four statuettes and the rich ornamented handles show high standard of technique in metal casting, very remarkable for the 4th century B.C. Relief representations, and the use of the lathe in metal fabrication and finishing, are also among the great achievements of this period. Many small and medium size bronze and silver vases indicate, as mentioned above, signs of spinning at the bottom. Besides, we must not forget the 4th century Eleusis stele, which refers to the use of lathe for the shaping of bronze into cylindrical poloi - a kind of dowel, which with bronze cubical blocks, known as empolia, were set between the column drums to ensure safe and accurate assembly.

Conclusions

The present report refers to the study of the large Derveni crater of the 4th century B.C. which is preserved at the archaeological museum of Thessaloniki. Chemical analysis proved that its golden appearance was due to a high content of tin, and not to any gold plating as was originally supposed.

Metallographic investigation showed the base of the crater, handles and statuettes were cast, while the perforated lid and the main body with its rich and fine relief representations were hammered hot. Comparison of their microstructure with that of laboratory samples determined roughly their final fabrication and heating temperatures. A description of the probable fabrication process followed by ancient metalworkers to produce the crater and the magnificent embossing is also given in this paper.

X-ray examinations showed that the crater was made (up to the middle of the neck) out of one single bronze sheet or disc, and not of several pieces, as one might suppose. X-ray investigations of the four statuettes proved that they were solid and not hollow.

Although there were many obscure gaps to be filled the author hopes to have contributed in opening a small gate, which will lead to the study of metallurgical achievements in Greece in the 4th century B.C. It was a century during which art and technology reached a climax of perfection.

Acknowledgements

Thanks are due to a number of people for help in this study: Mrs E Youris for her valuable suggestion on archaeological and historical matters, and her effective cooperation; Mr Ch Makaronas for his kind assistance; Miss Aikaterini Romiopoulou, Keeper of the Thessaloniki Museum, and its staff for their understanding and help; Mr M Comninos and Mr D Constantacopoulos for their excellent job in taking X-ray radiographs; Mr G Louskos who kindly exhibited his great skill in shaping a hard brass sheet into a simple vase form; Mr M Boutsicos and Mr N Violetis for their valuable contribution in the present study; Mr M Armaos who very kindly allowed me to visit his silver handicrafts shop to study present techniques and take very interesting pictures.

Finally, I wish to thank Mr Morris Pearl, of the Metals Society, London for his kindness in reading my manuscript and giving me most helpful advice.

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Addendum

Since the above was written Dr Ulrich Gehrig has very kindly sent me analytical details of another crater belonging to the Staatliche Museen Preussischer Kulturbesitz in Berlin. This crater (which is in fragments) dates from the first decade of the 4th century B.C. and is somewhat earlier than the Crater of Derveni, which dates from the end of the century. The composition of the crater in Berlin is as follows:

	Cu %	Sn %	Pb %	Zn %	Fe %	Ni %	Ag %	Sb %	As %
Handle	86.78	12.74	0.27	0.01	0.06	0.10	0.04	-	-
Main Body	86.87	12.81	0.16	0.01	0.07	0.01	0.05	0.02	-

These results show that the ancient metalworkers had already acquired significant experience in shaping and working hard bronzes in relief even at the beginning of the 4th century B.C. The same applies in the case of bronze mirrors as far as decoration in relief is concerned. In fact, embossing appears to be a characteristic achievement of this century, and it is very interesting to follow its development throughout this period. For example, the relief decoration on the Berlin crater, and that on the first mirrors decorated by this technique, is not so well developed as that on the Derveni crater and mirrors of the same date. On the other hand the bronze used to produce the Berlin Crater is somewhat softer. Nevertheless, the development in metalworking and embossing during the relatively short period between the two craters is amazing.

BLACKSMITHS' TOOLS FROM WALTHAM ABBEY, ESSEX

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In 1967 two workmen digging gravel in a pit on the Town Mead at Waltham Abbey, Essex, saw a number of iron tools in the bucket of their digger and found that there were more on the conveyor belt. Fortunately they realised the importance of their find with the result that not only was the hoard recovered, but a full account of the circumstances of its discovery was given to the Waltham Abbey Historical Society (1). The hoard was subsequently sent to Mr Norman Cook of the Guildhall Museum, who in turn drew it to the attention of Mr Kenneth Painter of the British Museum. It has now been placed on permanent loan in the British Museum by the Urban District Council of Waltham Holy Cross.

In comparison with some of the better known hoards of ancient metalwork it is of medium size, consisting of twenty-three pieces, of which eleven are blacksmith's tools, six or seven carpenter's tools, and the remainder a mixture of cart fittings and miscellaneous tools, together with a sword. Of these a large number are unique, apparently unparalleled elsewhere either in Britain or on the Continent.

Waltham Abbey lies in the Lea Valley on the north-eastern edge of London. In the Town Mead, where the tools were found, the gravel is covered by some five feet of peat and clay. Being close to the river, the water table is high and the hoard had lain below it, hence its remarkably fine preservation. A few pieces of timber, two or three inches in thickness, were found with the ironwork, but they were too fragile for the workmen to recover. Whether they had formed part of a box originally containing the hoard, or had some other explanation we cannot say, but the workmen were certain that all the objects had originally lain together as one group. Only one piece, the hammer, was found separately when digging began in an adjacent area, but, as we shall see, there is no doubt that it too had formed part of the original group. Presumably the hoard had been in a bag or box which had been dropped into the shallow water at the river's edge. The workmen were positive in denying that there was any sign of disturbance in the topsoil such as should have resulted from a pit being dug.

Any estimate of the date of deposition of the hoard must, of necessity, depend on the date of the pieces within it. Seen as a group there can be no doubt that they originated either in the Iron Age or early in the Roman period; and this would accord with the fact that they had been placed in water, for there are a number of hoards dating from that period which were deposited under generally similar conditions. The most celebrated is the Llyn Cerrig Bach hoard found in an Anglesey peat bog, but others are known from Appleford, Berkshire; Blackburn Mill, Berwicks.; Carlingwark Loch, Kirkcudbrights.; and Eckford, Roxburghs.; and there are several more which are less firmly associated with water (2). In most cases they appear to be votive deposits, offered as part of a water cult of the type which was widespread in Celtic Europe. The fact that so many of the pieces in the Waltham Abbey hoard had been deliberately damaged before deposition may confirm the ritual nature of the group, for such intentional breaking is common in objects which have been dedicated in this way.

If we attempt to refine this period still further we find, unfortunately, that only the linch pin and the sword are of types which can be given a fairly precise date. The linch pin is one of a variety with a loop-head and pierced, curving stem (Fig. 1a). Although a large part of the head was broken off before deposition, the type is sufficiently well known for it to be reconstructed with complete certainty. Similar pieces are known from the Llyn Cerrig Bach and Bigbury (Kent) hoards, and from a Belgic site at Worthy Down (Hants.) (3). All of these groups date from the very end of the English Iron Age, at least in their cultural contexts,

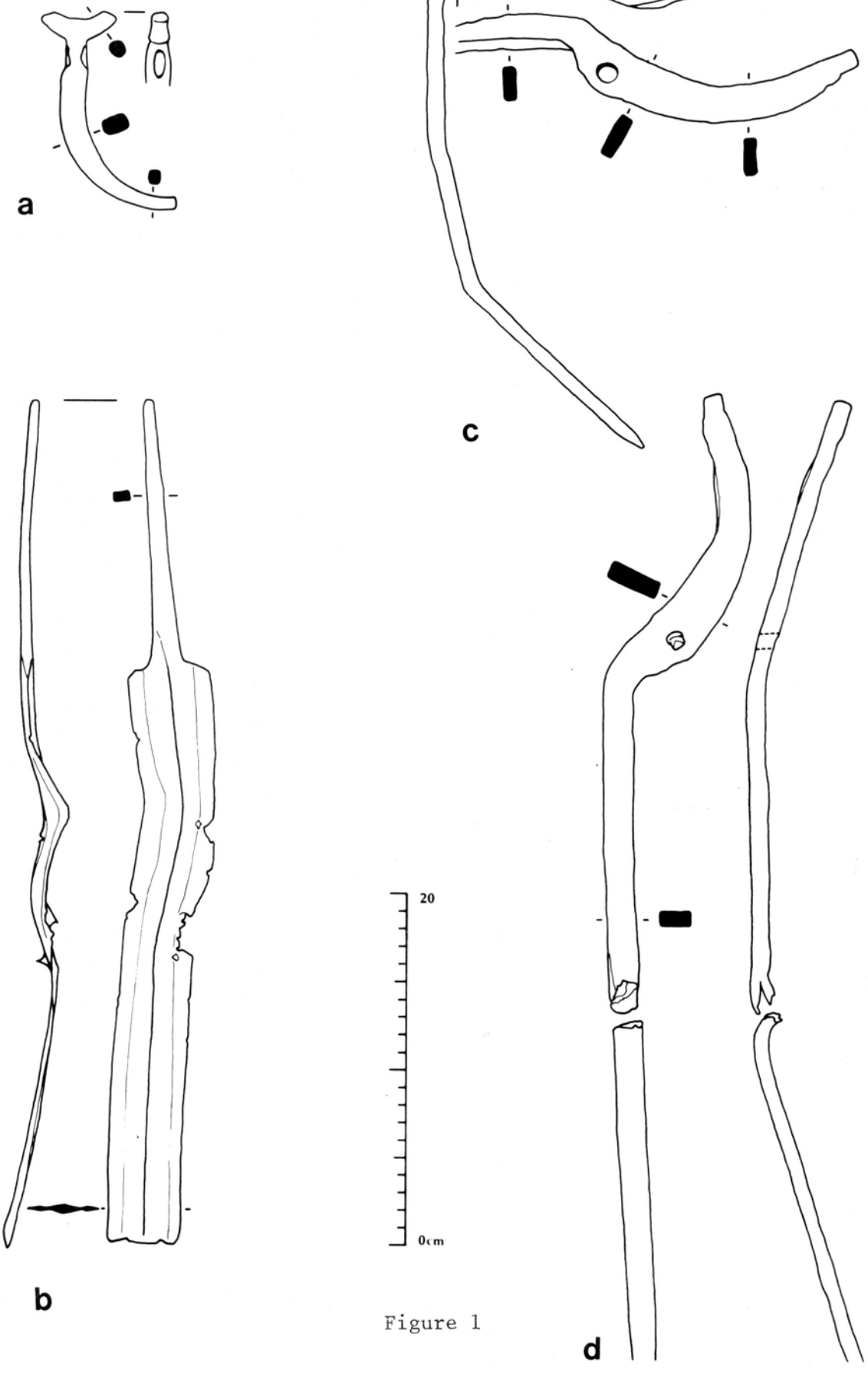

Figure 1

although in the case of the Bigbury hoard a date of deposition after the Roman conquest of A.D. 43 has been suggested (4). The second piece is the sword with its unusually corrugated blade (Fig. 1b). Dr Mansel Spratling, who has examined it writes: 'The fragment of sword-blade is of a type which is extremely rare in Britain, but fairly widely distributed on the European mainland where it is dated by associated finds and by the designs of the scabbards in which such swords are sometimes found, to the first century B.C. An example of the same general type from Aldwincle, near Thrapston, Northants. has recently been published by J.V.S. Megaw. The weapon would originally have been about 90 to 100cm long, and have had a rounded, square or V-shaped tip. Some of the most finely preserved examples of this type of blade were recovered in the nineteenth century during the First Correction of the Jura Waters between Lakes Neuchâtel and Bienne in northern Switzerland' (5). The most likely date for the deposition of the hoard would thus seem to be either late in the first century B.C. or in the first half of the first century A.D.

As well as the smith's tools, and the two pieces just discussed, the hoard contains a fragment of a cart tire, a broken socketed hook; a billhook, and the carpenter's tools: a socketed gouge, a spoon bit, a large bit or reamer, and a group of unusual pieces which are probably to be identified as a second gouge, a very large reamer, and a scraper. There is also an adze or hoe; a form which cannot be assigned with safety to either type, but which in the company of so many carpenter's tools is perhaps more likely to be an adze. The smith's tools, which are the subject of this paper, consist of five pairs of tongs or large fragments of tongs, three anvils, one a block anvil and two with tangs, what at first sight appears to be a sledge hammer of unusual form, a file, and a poker probably for the smithy fire. Of these the tongs offer no problems (Fig. 1c&d; 2 a-3). They form the largest single group of their date so far found in Britain, and may have formed a complete set. If so they raise some points of interest, for although they vary somewhat in size, the jaws, in the four cases where they survive, are all of the same form, bowed with slightly extended gripping faces; probably the most basic of all jaw forms. Normally one would have expected a set of four pairs of tongs to show some variation in jaw design, and their uniform simplicity must raise the question of how widely other jaw forms were used in the Late Iron Age. Unfortunately we have too few tongs of that date from Britain for a negative conclusion to be entirely valid. The large tongs from Llyn Cerrig Bach are of the same type as ours, as basically are the earlier ones from Garton Slack, for which we have a radiocarbon date of 180 $\pm$ 70 bc. The jaws of the tongs from Santon Downham, Norfolk, which are probably of much the same date as ours, are unfortunately damaged (6). A similar situation appears to exist on the Continent and is shown most strikingly in the material from Manching, Bavaria. Here no fewer than twelve pairs of tongs have been found, either complete or in fragments, all of which have their jaws either bowed and merely touching at their tips or with the tips extended as gripping faces (7). This type continued to be the form most commonly used in Roman Britain, probably because of its versatility, but a pair from a late first century A.D. deposit at the Roman fort of Newstead in southern Scotland (8), shows that at least one variant had been introduced by then, quite probably by the Roman army. Certainly variant jaw forms are fairly common in Roman forts in Germany, more so than they appear to be in Britain on the existing evidence. The difference in the length of the handles of the most complete of the Waltham Abbey tongs is quite normal in ancient as in more recent tongs, and is seen again in both the Santon Downham and Llyn Cerrig Bach examples.

The file (Fig. 3 a) is of a type already known in the Late Iron Age in Britain from a group found in Glastonbury Lake Village (9). Our example has 13 cuts per cm; those from Glastonbury varying between 9.5 and 16 cuts per cm. The irregularity of the cuts can be clearly seen. It is perhaps surprising that they are confined to one face for an obvious economy would be to have them on all four faces, as was done with some of the Glastonbury files, and commonly on those of Roman date.

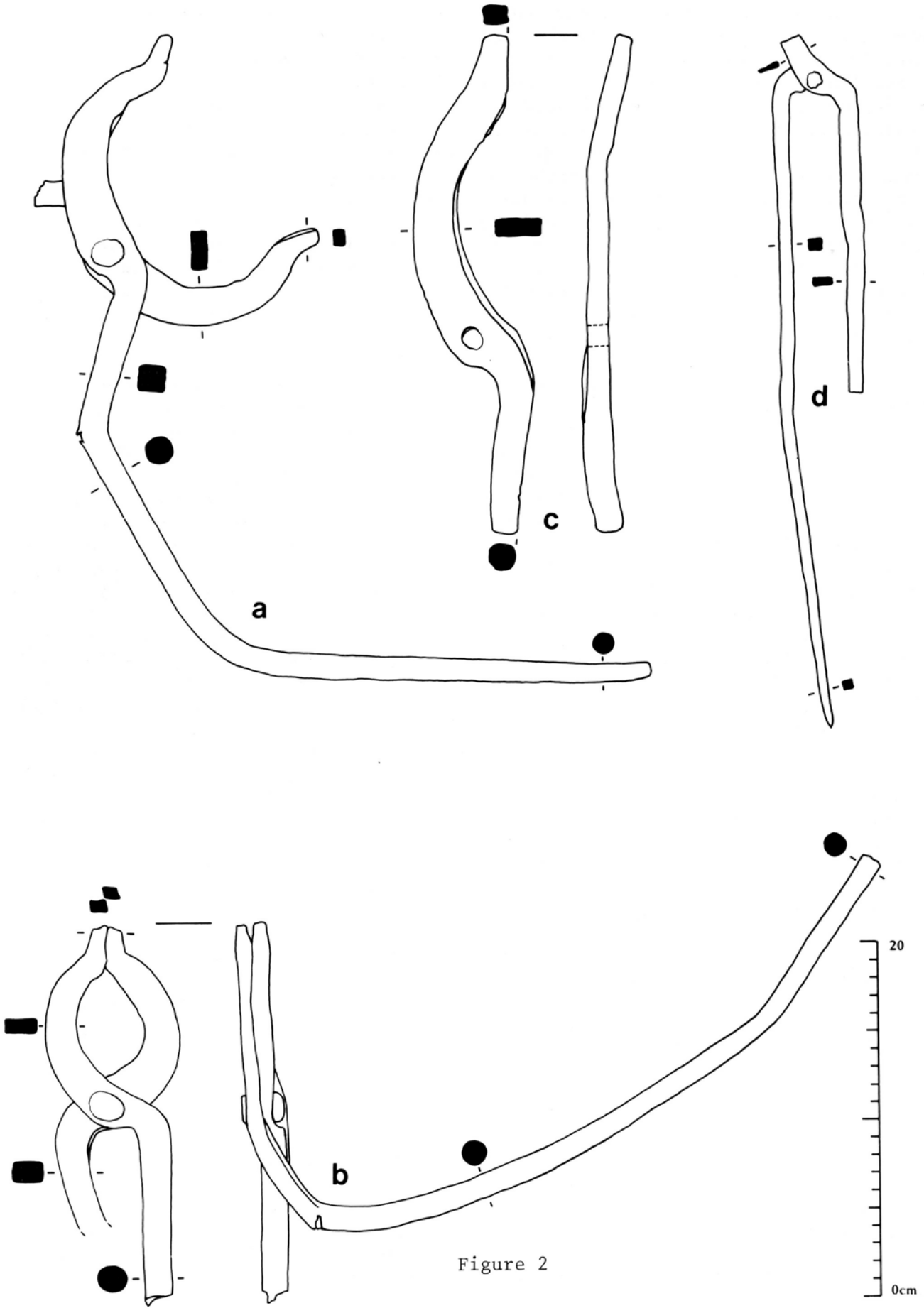

Figure 2

The poker (Fig. 3 b) is an exceedingly simple tool, but one which appears to be surprisingly rare, perhaps in part as a result of the difficulty of identifying them in a fragmentary form. An essentially similar one, but with a knobbed rather than a ring head, comes from an early fourth-century A.D. context at the small Roman farmstead excavated at Whitton Cross Roads in the Vale of Glamorgan by Dr M.G. Jarrett. The type has continued absolutely unchanged to the present day.

The remaining objects, the three anvils and the hammer, are all in their way unique, and are of the greatest interest.

The block anvil (Fig. 3 c) , it is true, bears a marked family resemblance to the normal form of Roman anvil, and, in default of any evidence to the contrary, we must assume it to be the usual anvil of Iron Age Britain. The commonest form of anvil found in the Roman world was a slightly tapering block with a hollowed base which in effect formed four small feet. There are many examples from Pompeii in the Museo Nazionale in Naples, standing c. 18.5cm in height with a working face of c. 11.0 x 11.0cm. The form found in Roman Britain, and which is also known on the Continent (10), differs from this in being more massive and in having a wide stem which fitted into the bench or block on which it stood. Examples can be cited from Sutton Walls, Herefordshire, Stanton Low, Buckinghamshire, Sandy, Bedfordshire, and Great Chesterford, Essex (11). Of these only that from Sutton Walls could be of Iron Age date, although it could equally well be early Roman. Both the Sutton Walls anvil (12), which, with a weight of 111 lb, is exceptionally massive, and the Stanton Low anvil have round punching holes running through from the face to emerge in the undercut side. The function of these holes was to allow the punch to be driven through metal being worked without damaging the face of the anvil or the punch. The Waltham Abbey anvil is a variant on this type; the stem is narrower and the body rather smaller, but the basic similarity is obvious. Where it differs is in having what must be the punching hole running through the stem. The alternative suggestion, that it was intended to secure the anvil in the block in some way, creates a refinement which is made unnecessary by its inherent stability and weight. Experiment has shown that if the anvil is laid on one side it is absolutely firm and could be used in that position, although the presence of the shoulder would obviously limit the work which could be done on it. At first sight this arrangement appears rather eccentric, but a possible reason is not far to seek. Although the sides of the body slope inwards as is normal with such anvils, its face is relatively small and a punching hole running through from the face to emerge in the side would have to be set so close to the edge as to dangerously weaken it. Significantly it was a weakness produced in this way which had caused part of the much larger Sutton Walls anvil to break away (13).

The other two anvils (Fig. 3 d & e) are similar to one another and are apparently unique (14). Both are beaked, with small flat faces, and tapering stems, of rectangular section in one case but rounded in the other. Across the back of the larger one are two U-sectioned grooves set just below the face, while the other has two similar grooves about half way down the stem. In additon the larger anvil has two depressions in one side and a single one in the other. Quite clearly they are intended as multipurpose tools of surprising ingenuity. With their stem set in the bench they would serve as small but adequate anvils, but this was only one of their uses, for both could be reversed with the beak now forming the tang. In this position the original stem would then serve as a mandrel; hence of course, the variation in their sections, for they have clearly been designed to complement rather than duplicate each other. The burred end to the beak of the smaller anvil must have been caused by careless use in this position. Mandrels are otherwise unknown in the British Iron Age, and are extremely rare in the Roman period, although two hand-mandrels are known from the fourth-century hoard discovered at Silchester in 1900. The function of the depressions in the sides of the larger anvil is less obvious. They could have served as punching holes, although they would seem to be unwisely shallow for this. More probably they were for use when metal was embossed rather than pierced or for forming domed or knobbed terminals on rods.

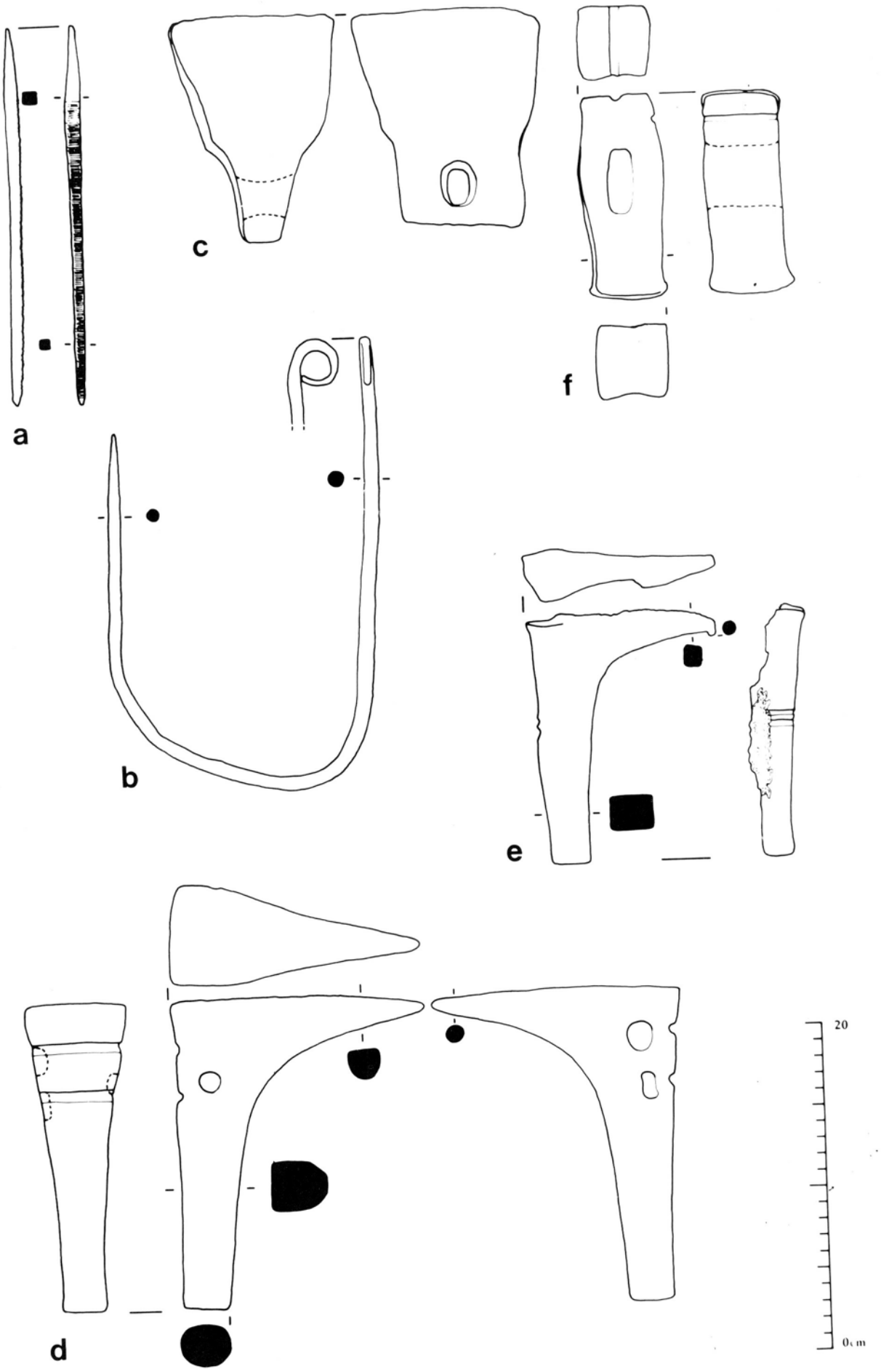

Figure 3

The grooves across the backs of the stems are perhaps the most interesting features of all, for there can be little doubt that they are swages used for rounding metal rods. As such their interest is considerable for swages are otherwise unknown both in the Iron Age and in the Roman period. What we have on the anvils are only the lower halves, the bottom swages, but when we look for the upper swages to complete the sets we find them on the end and side of the so-called sledge hammer (Fig. 3 f) . The groove corresponding to the upper groove on the larger anvil is that on the end face of the hammer; that for the lower groove of the smaller anvil is on the side. In modern usage such a tool would probably serve only as a swage, but the emphasis on the multipurpose function of the anvil-swages is such that we may reasonably suspect it was also intended for use as a sledge hammer, itself a surprisingly rare tool in the Iron Age. It was this hammer, of course, which was found separated from the hoard, and it is because it so clearly forms part of the set that we may confidently restore it to the original group. The fact that we have the upper swage for only one groove on each anvil must indicate that the set originally contained a second swage-hammer (15).

Anvils of Iron Age date are extremely rare on the Continent, but there is some evidence to suggest that both the block and stemmed type existed. Déchelette and Pleiner illustrate two anvils from Szalacska, a La Tène III site in Hungary (16), the first a small block anvil, 12.5cm high, the second a most interesting example of similar size which is basically a block with a basal spike, a beak on one side and a wedge on the other. As Déchelette pointed out this anvil is strikingly similar to those found in the Bronze Age, where among a variety of anvil types we find functionally similar, but much smaller examples (17).

At least three of these bear a distinct family resemblance to our anvil. The first, from Vadsby, near Copenhagen (18), has a square body with two beaks at right angles to one another, and two shallow swage grooves on each of the striking faces. Broholm dates it to Montelius Period III (c. 1200/1100 - 950 B.C.). Another example, which is closer in appearance to the Waltham Abbey anvils, comes from Sutherland in the far north of Scotland (19). It tapers from a flat head to a pointed beak or tang, with the remains of a second beak coming off at right angles at its mid-point. Opposite this are five swage grooves and a small punching hole which runs right through the stem. Analysis has shown it to contain no less than 26.4% tin. However, the closest parallel of all (Fig. 4) comes from a small board of bronze and gold objects found at Fresné la Mère, near Falaise in the Calvados region of France in 1854 (20). It passed into the collection of Sir John Evans whose description of it in his Ancient Bronze Implements can scarcely be bettered: 'It is adapted for being used in two positions, according as one or the other pointed end is driven into the workman's bench. In one position it presents at the end two plane-surfaces, the one broad and the other narrow, inclined to each other at an angle of about 120 degrees, so that their junctions form a ridge. This part of the anvil has seen much service, as there is a thick burr all round it, caused by the expansion of the metal under repeated blows. On the projecting beak there are three slight grooves gradually increasing in size, and apparently intended for swages in which to draw out pins. In the other position the anvil presents no smooth surface on which to hammer but a succession of swages of different forms, some V-shaped and some W-shaped. There are also some oval recesses, as if for the heads of pins.' Its overall length is slightly under 8.0cm, about half that of the smaller of the two Waltham Abbey anvils. In a recent discussion of the type of torc found in this hoard Eogan has suggested that they date from the Bishopsland Phase of the Irish Middle Bronze Age, between the twelfth and tenth centuries B.C. (21).

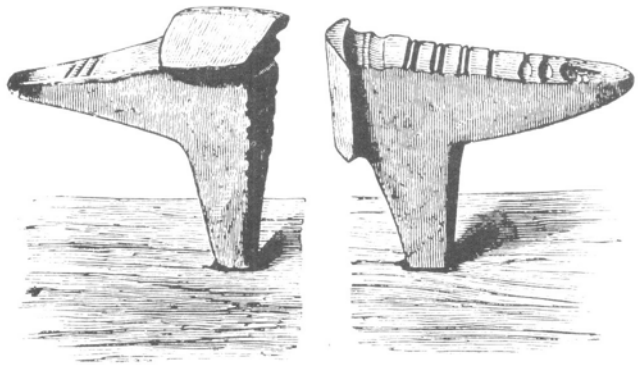

Figure 4: Middle Bronze Age Anvil from Fresné La Mère
(From Evans 1881) 1:2

The basic resemblance of these Middle Bronze Age anvils to the Waltham Abbey examples is so striking as to leave little doubt that there is a link between them. The absence of anvils in the Late Bronze Age and for most of the Iron Age must be more apparent than real, and may perhaps be explained by the fact that they represented a valuable block of metal which could be reutilised once their functional life was ended. As an example of what we may call submerged continuity, they are striking, and must inevitably reinforce our doubts on the validity of much negative evidence, based on the absence rather than the presence of types.

One final possibility remains to be mentioned, namely that the modern form of anvil may have developed from this type rather than from the more common block anvil of the Roman period. Beaked anvils are rare in the Roman world, but they do exist. More massive than the Waltham Abbey anvils, they resemble them in having a stem and beak, but unlike them the working face is enlarged by means of an overhanging wedge behind the stem. Inevitably the increase in weight and size reduces their versatility, and there is little likelihood of their ever having been used in any way other than as a normal anvil; certainly there are no swage grooves. Two examples are known from Britain, one from Silchester dateable to the second half of the fourth century A.D. (22), the other from Norfolk (23), a chance find and therefore undated. More recently one has appeared on a fragment of sculpture from London (24); an apparently unique representation of this type of anvil for the form normally seen in sculpture is the block anvil (25). At least one other is known from Roman Germany, in the great Heidenburg Hoard (26).

Footnotes

1. In particular I wish to thank Mrs R.M. Huggins, the Honorary Curator of the Society who supplied all the information on the circumstances of the hoard's discovery. I am much indebted to Mr J. Brailsford, Dr I.H. Longworth and Mr K.S. Painter for their assistance and for providing facilities while I was working on this material. The drawings are by Miss S.J. Thompson, who was also responsible for the typescript, after originals by Mr P. Crompton, to both of whom I am most grateful. The section on the cultural context of the hoard, and some of the parallels cited owe much to my discussion with Mr C. Saunders. I must also acknowledge Dr M.G. Spratling's kindness in providing a note on the sword, and thank Miss M. Ehrenberg for information on Bronze Age anvils.

2. The hoards are discussed in detail in Manning 1972.

3. Fox 1946, 78, No. 43, pl.II B, & XXXVIII, and the references cited there. The parallel from Polden Hill which Fox cites is probably a trace hook, cf. J. Brailsford, 'The Polden Hill Hoard, Somerset', P.P.S. 41 (1975), 230.

4. Manning 1972, 230.

5. Aldwincle: Northamptonshire Archaeology 11 (1976), 165-170. O. Tschumi, Die ur- und frühgeschichtliche Fundstelle von Port in Amt Nidau (Kanton Bern) (1940). R. Wyss, 'Belege zur keltischen Schwertschmiedekunst', in E. Schmid, L. Berger and P. Bürgin, (Eds.) Provincialia: Festschrift für Rudolf Laur-Belart (1968), 664-681. This sword was metallurgically examined by Mrs Janet Lang of the British Museum Research Laboratory. cf. J. Lang and A.R. Williams, 'The Hardening of Iron Swords', Journal of Archaeological Science 2 (1975), 202.

6. Llyn Cerrig Bach: Fox 1946, 96, No. 131, pl.VI & XIX. Most of the parallels cited by Fox are of Roman date. Garton Slack: Current Archaeology 5 (No. 4) (1975), 112, 115. Santon Downham: Proc. Camb. Antiq. Soc. 13 (1909), 158, pl. XVII.

7. G. Jacobi, Werkzeug und Gerät aus dem Oppidum von Manching (1974), 8, 270, Taf. 2 & 3.

8. J. Curle, A Roman Frontier Post and Its People: The Fort of Newstead (1911), 286, pl. LXIII.2.

9. A. Bulleid and H. St. G. Gray, The Glastonbury Lake Village II, (1917), 374, 387, fig. 141.

10. E.g. from Le Chatelet, near Saint-Dizier (Haute Marne) (Catalogue illustré du musée des antiquités nationales de St.-Germaine-en-Laye, (1925), 269, fig. 275, No. 49838); Mainz (Mainzer Zeitschrift 6 (1911), 114); Heidenburg, near Kreimbach (Lindenschmit 1881, 256-7, Taf. 46, No. 786).

11. Sutton Walls: Kenyon 1954, 22-23, pl. XVI A, and Trans. Woolhope Nat. Field Club 37 (1961), 56-61 (A metallurgical examination by R.F. Tylecote). Stanton Low: R.F. Tylecote, Metallurgy in Archaeology (1962), 240. Sandy: Manning 1964, 55, fig. 3.11. Great Chesterford: Arch. Journ. 13 (1856), 2, pl. 1.13.

12. Kenyon 1954, 22. It came from Area IV, Pit 3 but it had been moved by a bull-dozer before recovery. Dr Kenyon was of the opinion that it derived from a period II deposit (beginning c. A.D. 25), but in view of the considerable Roman occupation on the site, its marked resemblance to Roman anvils, and its size, which indicates that iron was not in short supply when it was made, a Roman date is more probable.

13. Punching holes can also be used for forming the heads of nails, but in view of the extreme rarity of nails at all periods in the Iron Age this is unlikely to have been the prime function of the hole in the Waltham Abbey anvil.

14. This form of anvil should not be confused with cobbler's lasts of the type known from a number of Romano-British sites, including Caerwent, Silchester (Archaeol. 54 (1894), 142), Sandy (Manning 1964, 55, fig. 3.9), and Chester (Chester Arch. Journ. 27 (1928), 76, pl. VI.2). One is shown in use in a relief from Reims (É. Esperendieu, Recueil Général des Bas-Reliefs, Statues et Bustes de la Gaule Romaine, 5 (1913), 41, No. 3685).

15. The fact that the hammer/swage was found separately from the anvils may be no accident. Many of the other pieces in the group had been ritually damaged probably to place them beyond further human use, but the solidity of the

hammer and anvils made them almost unbreakable. By separating them in this way they were functionally broken since the one half was of no value as a swage without the other.

16. J. Déchelette, Manuel d'Archéologie IV (2nd Ed. 1927), 883, fig. 609, 1 & 2. The block anvil is shown upside down. R. Pleiner, Staré Europské Kovářství (1962), 69, fig. 12, No. 11 & 12.

17. J. Déchelette, Manuel d'Archéologie II (1) (1910), 227. Evans (1881), 182.

18. H.C. Broholm, Danske Oldsager IV (1953), 52, No. 425.

19. Proc. Soc. Antiq. Scot. 16 (1882), 22-25.

20. Originally published by Evans (1881, 182, fig. 217 & 218). More recently the entire hoard has been discussed by G. Eogan (1967, 158, fig. 8).

21. Eogan 1967.

22. Archaeol. 54 (1894), 142, fig. 3.

23. In Norwich Castle Museum. Information from Miss B. Green.

24. Britannia 7 (1976), 347, pl. XXX c.

25. W.H. Manning, Catalogue of Romano-British Ironwork in the Museum of Antiquities, Newcastle-upon-Tyne (1976), pl. III from Corbridge, pl. IV from York, and fig. 4 from Rome.

26. Lindenschmit 1881, 256-7, Taf. 46, No. 787.

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EARLY MEDIEVAL METALWORKING ON HELGÖ IN CENTRAL SWEDEN

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General Background

Because of the total lack of extensive manufacturing sites from the Merovingian period, it has long seemed probable that metalworking underwent a rapid and thorough change once the Romans abandoned the Provinces. From being a highly organized industry in the Roman period, centred on the larger towns and military sites(1), metalworking became an extremely sporadic and disorganized activity mainly practised by independent and itinerant goldsmiths and bronze casters(2). It seems very likely that there were permanent workshops at certain political or religious centres in addition to the itinerants who, judging by the finds so far discovered, seem to have been craftsmen only who did not make their models themselves(3). This theory is supported by the fact that the remains of a large permanent workshop are present in the early medieval nucleated settlement on Helgö, central Sweden(4).

The settlement site on Helgö, a small island in Lake Mälaren due west of Stockholm, was discovered in the middle of the 1950s. The unusual wealth of its finds and the type of society which they reflect have become important points in the discussion about the origin and development of the earliest urban centres in northern Europe. At the same time, its rich workshop finds which date from the end of the 5th century to the 9th century with a concentration in the 6th century, contribute to the question of the organization and development of metalworking during the Merovingian period when there is such a dearth of finds of workshops.

As an early developed nucleated settlement with pronounced trading and manufacturing functions as early as the middle of the 1st millennium A.D., Helgö is so far unique in northern Europe. There are some 8th-century examples of similar sites with trading and manufacturing activities, such as the southern settlement area at Haithabu which precedes both in date and development the characteristic urban occupation within the semi-circular wall(5). A further example in northern Europe is Ribe in southern Jutland, which, like the earliest site at Haithabu, dates from the 8th century. The recent excavations have exposed the earliest industrial quarters of the town where the finds suggest that various procedures such as comb making, amber polishing, glass bead production, smithing and bronze casting had been pursued(6).

There are also demonstrable remains of metalworking from the same period in some of the early Slavic sites, for example, Mikulčice in Mähren(7), Tornow in Niederlausitz(8), and Bosau in Schleswig(9).

The Celtic area around the Irish Sea is one part of Europe which is important for metalworking during the period under discussion. Many sites with significant remains of metalworking have been discovered; for example, Dunadd(10), Mote of Mark(11) and Clatchard Craig(12) in Scotland, Birsay(13) on Orkney, Dinas Powys (14) in Wales, Lagore(15), Garranes(16), Carraig Aille(17), Ballinderry Crannog (18), and other places in Ireland.

The fact that urban settlements began to develop during the Viking period in both the most westerly and the northern and eastern parts of Europe means that evidence of metalworking becomes more abundant, as it is precisely this which is one of the activities which characterize the earliest towns.

Against this background, described very generally above, Helgö stands out as a remarkably rich manufacturing centre - on the periphery of Europe but in the centre of an area which, by the middle of the 1st millennium, had developed its own extremely advanced art styles in metal. At the same time a large number of high quality products found all over Scandinavia indicate the experienced technique of the craftsmen.

But central Sweden or eastern Scandinavia was not the only area where metal products were in demand, and Helgö cannot have been the only industrial centre at this time. The workshops in the larger towns in the Roman provinces, for example Cologne, Trier and Mainz, most probably continued in production even after the Romans had withdrawn(19).

The same conditions must have held good in England where metalworking, close to the Scandinavian type and contemporary with it, developed. The fragments of a mould recently discovered at Mucking could imply that a large central workshop, at least as important as that on Helgö, may have existed there(20).

Pending more unambiguous proof of extensive manufacturing sites from the early medieval period, we must now return to Helgö to see what its finds can tell us about the techniques and standards in the area of metalworking.

The Workshop Material

As at Ribe, many brances of industry can be inferred from the finds - bronze casting, gold smithing, iron smithing and bead making(21). An unfinished central head-stone which was found last summer inside one of the workshop areas may imply, as do some other finds of this type, that stone carving and stone polishing had been practised.

The finds which throw light on metalworking, and in particular bronze casting and goldsmithing, are of interest here but it should be mentioned that iron working was a particularly significant factor in Helgö's economy. Iron was, in fact, the only indigenous metal known at this period and it must have been much more accessible as it did not need such long and difficult transportation as other metals, even though the raw material came not only from central Sweden but from the northern and southern parts of present day Sweden. The extent of the iron-working is clearly shown by the great amount of waste products, including large quantities of slag, scrap-iron and currency bars, the last category represented both by complete examples and pieces cut from them.

Gold and bronze working have also left their traces in the form of complete or cut up bars and rods. The finds generally consist purely of waste products and the very few tools and artefacts which are found were those which were either lost or worn out and therefore no longer useful.

As the material may largely be described as waste, its character is incomplete and fragmentary. Most of it had been scattered about within the workshop areas, some by being used as infill for the construction of terraces. The incomplete nature of the material suggests that a good deal had been taken away and tipped into Lake Mälaren. The recent excavations at the harbour in Birka have shown that manufacturing waste was taken from the workshop sites into the bay(22).

The most outstanding objects in this material are the many fragments of moulds - about 50 kg - and the c. 300 kg of whole and fragmentary crucibles. But casting is also indicated by the finds of raw materials in the form of bars and rods, droplets and scrap metal, as mentioned above. In certain cases the scrap metal had obviously been intended as raw material; for instance, the category of finds comprising thin sheet bronze which was folded up and compressed into small "packets". In another instance it is more doubtful whether the scrap metal was intended for melting down or was merely the remains from casting. The ingot

material, only part of which has so far been analysed, consists in one case of 93.5% Cu, while the rest of the analysed examples consist of various different copper-based alloys of which copper-zinc alloys predominate over copper-tin, copper-tin-lead and copper-zinc-lead alloys. An extended series of analyses would, however, show whether this is a general trend within the ingots, and may perhaps also answer the questions about the form in which raw material for bronze casting was imported. The bar with high copper content, mentioned above, may be one such imported ingot. In most cases, however, it must be that the bars and rods were made by melting together old or broken bronze objects; this means that they would consist of very heterogeneous alloys.

There is also some raw material of silver, silver alloys and gold. On the other hand, there are remarkably few objects which either were incompletely cast or incompletely finished off.

A large number of pieces of tempered and partly vitrified clay, probably from ovens or furnaces, form one group of finds discovered in the workshop areas on Helgö which cannot at present be ascribed either to bronze casting or iron smithing. This category of find is common on manufacturing sites and occurs at Haithabu, Ribe and other places. Unfortunately no bases of the original structures are preserved on Helgö but it is possible that they made up a type of feature which is represented, for example, in Lödöse, an 11th-century urban foundation on the west coast of Sweden due north of modern Gothenburg. Remains of furnaces constructed of two or three stones on edge which supported a clay dome were found in Lödöse where they are associated with iron smithing.

Tuyeres form another group of finds which it is also difficult to attribute to any particular branch of metalworking. They consist of flat, heavily tempered pieces of clay of square or rectangular shape with a central hole for the blow-pipe. One side of the tuyere is red-burnt, while the other side which was exposed to very great heat is very heavily vitrified. Similar tuyeres are known from many sites in Europe where they always are connected with iron smelting furnaces. They cannot, however, have served this purpose on Helgö where they may either have been set in the oven walls or used as free-standing collars on blow-pipes associated with open hearths without superstructure. A considerable number of fragments of vitrified, sand-tempered, clay blow-pipes have been discovered on Helgö. They are of the same fabric and colour as the crucibles. Nozzles of various blow-pipes are also known from sites such as Garryduff I(23), Lagore(24), Garranes(25) and Birsay.

A number of small rectangular slabs of pottery-like, tempered clay with remains of slag on their upper surface are associated with finer metalworking. Analyses of the slag showed that it had a high lead and silver content. The slabs may have been used in purifying silver by removing lead. They may be compared with a type of round, fairly shallow and wide crucible with similar deposits from Haithabu and the Viking Age military site of Fyrkat in Jutland. Though I do not know whether any metal analyses have been carried out on these, droplets of silver are clearly visible on some examples from Fyrkat and two of the shallow crucibles from Haithabu contain droplets of gold. A crucible from a goldsmith's grave from Schönebeck in Thuringia dating from the 1st half of the 6th century(26) should also be mentioned here. It also is comparatively wide and shallow with a crust on the bottom containing large quantities of silver and lead.

The Crucibles

As mentioned earlier, a very large number of crucibles were found on Helgö and research on them is not yet finished, although a basic catalogue has been compiled after about three years' work. It will form a basis for further work and the final publication. For the catalogue, every sherd was examined with reference both to details of its construction and the preserved traces of metal. A comparatively small proportion of the material shows remains of metal: only 27 whole and 259

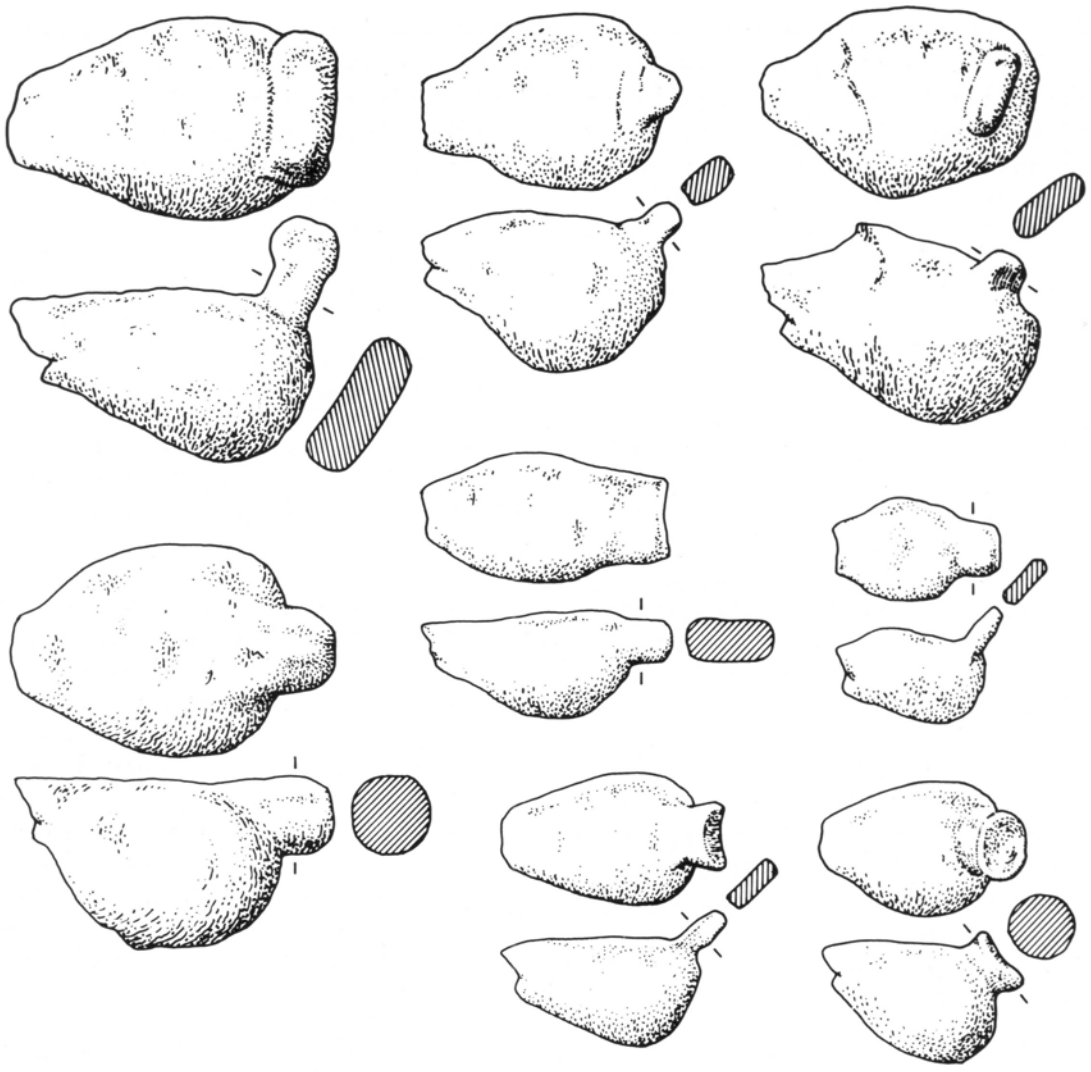

Figure 1 Lidded crucibles

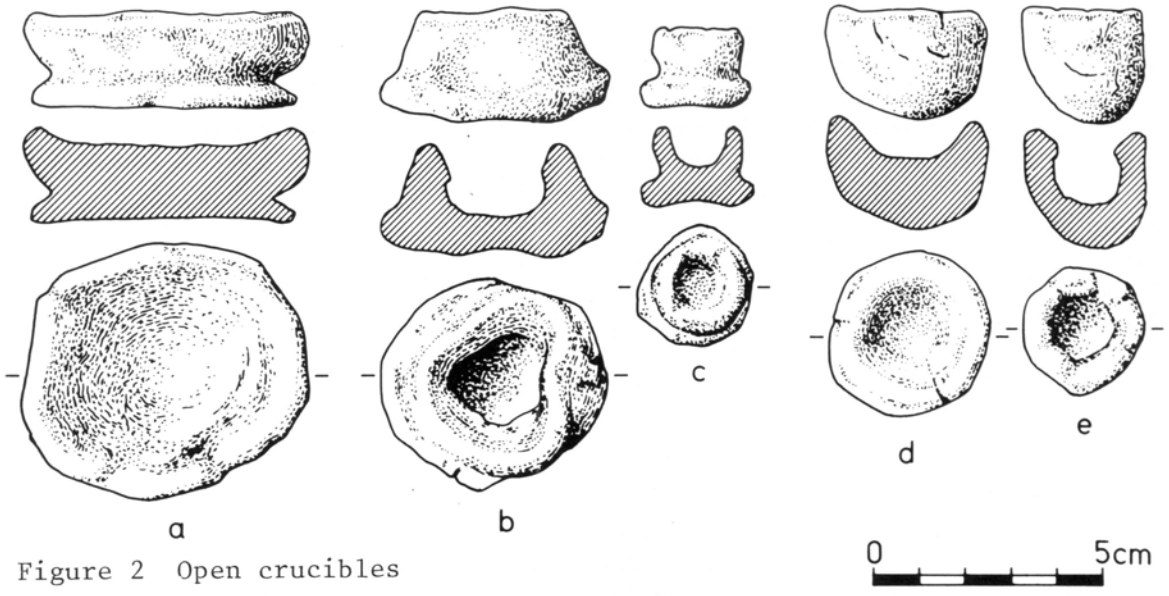

Figure 2 Open crucibles

fragmentary crucibles contain bronze, 10 crucibles and 186 fragments contain gold and 1 complete and 25 fragmentary crucibles contain traces of silver or white metal alloy. This is quite surprising as traces of metal on crucibles from a number of other sites are far from uncommon. Thus, for example, the crucibles from Haithabu and Dinas Powys display a great quantity of metallic remains.

One type of crucible dominates the many finds from Helegö, that is, the integral-lidded crucible with handle and spout which is also known from Dinas Powys(27), Garryduff I(28) and Iona(29). One crucible from Dunadd(30) also belongs to this type, which consists of a crucible bowl - on Helgö most frequently of a pronounced oval shape - one side of which is pinched out into a spout, plus a separate lid. The lid was bent down outside the edge of the bowl and carefully smoothed down and thinned out at its sides. In certain instances the lid covered the whole bowl of the crucible. It is not only the same form of crucible which appears on these widely separated sites, the method of construction is similar, also. The fabric of the crucibles also seem to be very similar, at least on examination by eye.

The lidded type of crucible is not uncommon in Scandinavia and is known from a number of sites in Norway and Sweden in addition to Helgö. As the crucibles have been found on settlements they are difficult to date, but they belong on the whole to the period between the end of the Roman Iron Age - Migration period to the Viking Age when they were replaced by a type of open, cylindrical or bag-shaped crucible entirely new to Scandinavia. This new type of crucible is known from many Viking Age manufacturing sites including Birka which very probably took over Helgö's position as the central manufacturing site in the Mälaren region at the beginning of the Viking Age. The lidded crucible is not known from Birka; the transition to open crucibles may be due to the change to using a new type of oven for bronze melting(31). The lidded crucibles on the whole demanded no ovens, only open hearths, as almost the same result could be achieved in a crucible with limited mouth as in an oven.

It is impossible to say when the lidded type of crucible first began to be used in Scandinavia, as there are no finds of crucibles from the pre-Roman or Roman Iron Age. On the other hand, there are a great many Bronze Age crucibles from various small manufacturing sites throughout Scandinavia(32). The Bronze Age crucibles are all wide and open, having the shape of half a pear with a spout in the narrower end. In shape, therfore, they correspond to the bowls of the lidded crucibles. The addition of a lid meant that bronze could be melted much more easily as the heat loss was not so great and the supply of oxygen less so that less slag was formed.

The lidded crucibles appear at virtually the same time in both the west Celtic and Scandinavian areas. It is at present impossible to say where they developed - perhaps not within these areas at all. The type may be an improvement of the Bronze Age crucible or it may have developed within the Roman provinces. It is very reminiscent of the crucible type known on the Continent as "Schmelzbomben". One thing, however, is certain - this type of crucible cannot have emerged contemporaneously and independently in two such widely separated areas.

The few examples from Dinas Powys, Dunadd and Garryduff I where the position of the handle on the lidded crucible could be established showed it to be on the top of the lid. Some examples of this arrangement are also known from Helgö but it is more common for the handle to be at the back of the crucible, either horizontally or at an angle to its back edge. As in the material from Dinas Powys, that from Helgö shows great variation in the type of handle - pointed, rounded, circular, oval and rectangular (Fig. 1). There are many examples of asymmetrically placed handle including ones twisted to right and left, and impressions of tongs can often be seen on them. The different arrangements suggest that the crucibles were made by different craftsmen. In the case of Helgö this is not surprising as bronze working is believed to have been carried on there for many centuries.

All of this group of lidded crucibles are characterized by having handles, although there are many crucibles with handles which do not have lids such as a group of completely open cylindrical crucibles with handles and a group with their mouths reduced in size by part of the upper edge being pinched together. None of these groups is found on Helgö where all the crucibles with handles also have lids. Crucibles from Dunadd(33), St. Gobnet's house(34), Carraig Aille(35), and Ribe are characteristic of the first group of crucibles and at least the Ribe crucibles are attributed to the 8th century(36). Crucibles are also known from the Slavic area, such as Kiev(37) and Grodno(38) in the Soviet Union, where they can be attributed to the 11th century and later. As far as I know, no definite examples of the second group of handled crucibles are known from the Soviet Union although there are crucibles with handles and two mouths in medieval layers at Novgorod(39), Belaja Veža(40) and elsewhere. Further west in the Slavic area there are, however, several examples of the second group of crucibles with handles - those with mouths partly pinched together - one 8th century example from the Slavic fortress of Bosau in Schleswig-Holstein and one from a grave in Cauerwitz in East Germany, deposited c. 800(41). Some handled crucibles from an early fortress with 9th century layers, Novotroiskoje outside Kiev, may be attributed to the second group(42). About the same date and obviously belonging to this group are the crucibles from Ballinderry II(43) and Birsay, possibly also some of the crucibles from Dunadd.

The above examples must only be regarded as a preliminary attempt at grouping the crucibles with handles. No definite boundaries can be drawn, as there is every variation from the totally open crucible to the crucible with much reduced mouth. It is also completely impossible in many instances to establish the original shape and method of manufacture of the crucibles as they are frequently heavily vitrified or fragmentary. In addition, it is extremely risky to draw definite conclusions from illustrations, particularly in Soviet literature, details of which are not always very obvious.

All these discrepancies in the appearance of crucibles with handles should, however, be regarded merely as minor variations on the same theme - they all belong to the same main type, probably with a common origin. The distribution over three different, culturally distinct areas may indicate either that craftsmen at that period formed an extremely international body, or that knowledge of metalworking was spread, in one way or another, over much more extensive areas than previously believed(44).

As this group of material is so small it is impossible to say definitely whether the crucibles with handles appeared as early in eastern Europe as they did in Scandinavia and the west Celtic areas. On the other hand, they clearly lasted longer there than they did in the west.

It is an open question whether this type of crucible was also widely distributed throughout the other parts of the Continent during the Merovingian period. The few crucibles which are known from that period, for example those from the smiths' graves in Brno(45) and Heddesdorf(46), are open thimble-shaped crucibles.

In addition to the great number of lidded crucibles which are known from Helgö, there are also a few open crucibles without handles; 8 complete ones and 75 fragments in all. None of them belongs to the open Viking Age type and here we are dealing with a completely different type of crucible, probably designed for special purposes, which do not form a homogeneous group in shape or size. Two shapes can, however, be roughly distinguished; one is extremely shallow and wide and has a thickened, flat bottom (Fig 2a), while the other type is rather deeper (one of these crucibles is, however, no more than 5 mm deep) but very narrow with a diameter of 10-20 mm. The latter group comprises both crucibles with a rather thickened flat bottom (Fig 2b-c), and some with rounded bottom (Fig. 2d-e)

Small, open crucibles like these from Helgö are very rare. I know of no direct comparisons for the wide, flat-bottomed type, althogh a flat-bottomed crucible from Bondåkra in Halland on the west coast of Sweden is reminiscent of those from Helgö because of its wide bowl(47), but it is not as shallow. The crucible from Bondåkra is very heavily vitrified on the inside and upper edge, implying that it was heated from above. A large number of small grains of gold remain on the glazed surface.

Flat-bottomed crucibles are also known from some of the Irish workshop sites (48). The material from Garranes also includes round-bottomed crucibles corresponding in shape to some from Helgö(49) although they are considerably larger than the Helgö examples and, with one exception, are made of stone, whereas the Helgö crucibles are made of sand-tempered clay. The crucibles from Garranes are thought to have been used for glass or enamel(50). One open, round-bottomed crucible scarcely 20 mm high is also known from Birka. Oldeberg suggests that it was used in goldsmithing(51).

It is most likely that the small, open crucibles from Helgö served a purpose different from that of the lidded ones. The latter are heavily vitrified on the base, so they must have been placed on top of the hearth. The open crucibles, on the other hand, were heated from above, probably by means of a blow-pipe, in the same way as O'Kelly suggests for some of the crucibles from Garryduff(52). In this connection it should be mentioned that a fairly small iron blow-pipe has been discovered in one of the workshop areas at Helgö.

In addition, traces of gold are preserved on 4 whole and 7 fragments of open crucibles at Helgö; this is a large number in proportion to the total. As traces of gold are also found in many of the lidded crucibles it is probable that they were used in casting gold, while the open crucibles, which held only a limited quantity of metal, must have had a different purpose, such as for use in gilding. Not all the open crucibles from Helgö were used by goldsmiths, though, as at least one of the fragments displays a large globule of bronze. On the wide, shallow crucibles in particular, there are also large, red, glaze-like spots, analysis of which has shown them to have a higher copper oxide (Cu_2O) content that other parts of the vitrified surface(53). Black spots are also common. Red spots also occur on the open crucibles with traces of gold, and red, black and green spots occur quite frequently on the lidded crucibles.

The Moulds

As mentioned above, the moulds form a very large group of finds which, once all the material has been worked on, will give us a great deal of information on casting technique, working methods, technical standards and professional skill within the Helgö workshops. As with the crucibles, the systematization and classification alone is enormously time-consuming. Although the quantity of crucibles is greater in volume, the moulds provide many more recording data. As we are still in the middle of the recording work there is no possibility of presenting anything more here than a preliminary survey of the problems(54).

It must first be emphasised that only fragments and incomplete moulds have been found at Helgö, for all the moulds had been used and then broken apart after casting to extract the object. Moreover, it is probable that they were also broken later as they are quite fragile and would merely have been thrown away after use. In certain instances some fragments can be shown to have been moved around within the area; for example, two fragments which fit together were discovered 25 m apart. A large number of moulds, particularly those for square-headed brooches, were also thrown away outside the gable end of one of the buildings within the largest workshop area but almost as many moulds of the same type were left inside the building.

The moulds represent a relatively wide range of jewellery and dress accessories, primarily 6th century in date. Moulds from later centuries are also present but not in the same quantities.

Square-headed (relief) brooches are the best represented group of objects among the moulds; 29 different variants have so far been distinguished. Work on the square-headed brooch moulds was published in Excavations at Helgö IV where 635 fragments of this brooch type are recorded. Volume IV deals only with the fragments of the front portions of the moulds, that is, the part of the mould which formed the front of the brooch. In addition there are almost the same number of fragments of back portions plus fragments of front portions which have been discovered in the workshop area during excavations since the publication of Excavations at Helgö IV.

Moulds of many other types of brooches are represented, as are those of dress-pins, buckles, strap mounts, decorated buttons from sleeve-clasps etc., all belonging to types of objects which are commonly distributed throughout the east Scandinavian area.

Sword pommels were made in addition to the jewellery and dress accessories; they are decorated with chip-carved spirals and belong to a type which is known from the chieftain's grave in Högom in north Sweden(55) and grave 3 in Orsy by the Rhine(56). Böhner has described the latter as nordic(57) (Fig. 3c).

Even though the moulds have not all yet been identified, it is evident that many different types of objects were manufactured in the Helgö workshops. Square-headed brooches do, however, seem to have been their speciality. The extent and variety of the production suggests that the workshops at Helgö were of a quite different character from those in Ribe where the manufacture, with a few exceptions, consisted only of one particular type of oval brooch - the so-called Berdal type(58), and where it did not seem to have continued for a long time. In the case of Helgö there are certain difficulties in deciding the duration of production as early medieval chronology, at least for central Sweden, is still comparatively obscure. Broadly speaking, however, production must have gone on through the 6th, 7th and 8th centuries. It is, of course, difficult to establish whether it continued uninterrupted during the whole of this period, but it is quite obvious that the large numner of square-headed brooch moulds are not remains of the work of a single bronzesmith. This view is supported partly by stylistic reasons and partly by the differences of manufacturing technique which are shown by the square-headed brooch moulds.

Gussage All Saints may be cited alongside Ribe as an example of a workshop site of a more limited nature, both in time and extent. Evidently only one or two bronzesmiths carried on the very specialized production of chariot equipment and horse harness(59).

The continuity of various workshop sites, the extent of production and the number of active craftsmen are crucial questions but difficult to answer as they are associated with the problem of the earliest formation of nucleated settlements. Which sites with workshop material can truly be described as centralized workshops with continuous production where the manufacture was one of the main sources of livelihood and where it was mainly directed towards commerical ends? And which housed a more temporary production with an itinerant craftsman working for a short period, where the manufacture might then be described more as a domestic activity and where agriculture formed the basis of the economy?

And by which criteria should one really judge the social functions of the different workshop sites? Is it the amount of finds, or the quality of the products or perhaps the size of the workshop site, which is definitive? In the case of Helgö, both the large quantity of workshop finds and their quality show that the manufacture of certain of the Style I jewellery was of a high standard. There

are also clear signs of goldsmithing on the site. Finally, concerning the size of the workshop sites, there are three such sites at Helgö, the largest of which has an area of no less than 5,000 m^2. This workshop alone is more than twice as large as the whole intramural area at Mote of Mark, also an important site, and more than five times larger than the entire occupation area of Dinas Powys.

If one looks more closely at the number of moulds from important workshop sites in Ireland and Scotland, many of which are known to have been royal or aristocratic centres, or monasteries, comparisons with Helgö also fall short. About 1 000 mould fragments have been found at Mote of Mark(60) as opposed to many times that number at Helgö. The number of mould fragments from Mote of Mark clearly exceeds the totals from the three royal sites of Dunadd with 100 fragments (61), Garranes with 30(62) and Lagore with 7(63). Garranes has the largest number of crucibles and crucible fragments of any Irish workshop site, a good 2 500, compared with 263 from Lagore. Other workshop sites in Ireland have fewer still, for example Carraig Aille(64) and Ballinderry Crannog No. 2(65), with respectively 53 and 43 whole and fragmentary crucibles. At Dinas Powys which has been interpreted as the residence of a princely household only about 150 crucible fragments and a few insignificant mould fragments were discovered(66). Stock-breeding seems to have been the main source of livelihood and the basis of the economy of Dinas Powys(67).

The almost total lack of moulds from Dinas Powys, where at least one bronzesmith was active, shows clearly that it is quite simply impossible to estimate the importance or extent of a workshop from the number of mould fragments discovered. One way of making such an estimate more feasible is to use stylistic and technical differences in manufacture to decide whether many bronzesmiths or goldsmiths worked on the site, whether the work was carried on for long periods and whether other branches of industrial activity were also pursued on the site.

Although the contrast between Helgö's c. 10,000 mould fragments and, for example, the eight fragments for buckles from the Migration period workshop at Glauberg (Oberhessen)(68) probably does not reflect the true proportions of the extent of production on these two sites, I still maintain that the large number of mould fragments from Helgö must indicate a quite considerable manufacture. A totally different interpretation has recently been advanced based on the large number of fragments and the fact that no complete moulds were discovered. This is taken to show that the bronzesmiths were not masters of the bronze casting technique, and that the moulds cracked when the hot metal was poured in(69). A further argument used to support this theory is that the moulds from Helgö represent at least 211 different square-headed brooches, while only c. 50 such brooches have so far been discovered in Sweden. The many mould fragments for each variant of square-headed brooch could then be explained more acceptably, than by thinking that large numbers of square-headed brooches were produced at Helgö.

Even if the theory put forward by Arrhenius explains the large number of mould fragments, it certainly does not explain why so many different types of objects and so many variants of one and the same type of brooch are represented. If the bronzesmiths made mistakes as often as this it is difficult to understand why they perpetually changed models within one and the same brooch variant, as they obviously used many different models for each variant. The illustrations and tables published in Excavations at Helgö IV have already shown that small variations in both dimensions and ornamental details occur in the moulds of the different variants. A more precise answer to the question of how many models were used for a single variant or if certain ornaments were stamped directly into the clay of the mould(70) will be given when the photogrammetric measurements, which have been begun on some mould variants, are completed(71). This method enables measurements to be taken as objectively as possible, both in the vertical and horizontal plane, for small elements which are difficult to measure.

According to Arrhenius, the Migration period bronzesmiths in Scandinavia were not only ignorant of how to make moulds which were strong enough to hold the casting, they did not know the art of alloying copper with, for example, zinc, tin or lead, in order to lower the melting temperature and reduce the strain on the moulds(72). Arrhenius here relies on the analyses of 31 brooches from Öland, some of which consisted of 90% copper, and even more in some cases; this entails a melting temperature of a good 1000°C. The analyses of copper-based alloys from Helgö are, admittedly, few in number, but none has shown such a high copper content. Instead, it lies between 60% and 76%(73). There is, however, no reason to doubt that the Germanic bronzesmiths were capable of combining different metals with each other, as this was a skill which must have been acquired as early as the Bronze Age.

Moreover, during the practical experiments carried out by the Helgö Research Unit, in which moulds and crucibles as similar as possible to the originals were made, we never found that the moulds split in casting, despite the fact that our experience in such work must have been considerably less than that of our forebears.(74) On the contrary, the moulds and crucibles showed themselves to be remarkably resistant to high temperatures. For example, the crucibles did not crack until c. 1600°C.

As a proof that the formation of cracks in the moulds was a serious problem for Migration period bronzesmiths, Arrhenius states that brooches from this period show frequent signs of fractures in the metal(75). It should, however, be noted that cracks in a cast product cannot results from cracks in the mould as such as crack would become a ridge on the cast object; this could easily be filed smooth. That there was very little problem with the formation of cracks in the moulds is supported by the fact that there are hardly any cracks in the Helgö moulds.

The technical difficulties which the Migration period bronzesmiths at Helgö had to contend with, have also been attributed to the fact that they did not have the skill to temper the clay with dung, a method with which the bronzesmiths in both provincial Roman workshops and Viking age workshops at Birka were very familiar(76).

But the analyses of moulds and crucibles from Helgö, which have been carried out by two different institutes, have clearly shown that the difficulties mentioned above hardly existed(77). On the contrary, they showed that the technical standards were high and that there was wide appreciation of the qualities of different materials.

The most recent analyses, which consisted of thin sectioning three fragments of square-headed brooch moulds and three crucible fragments, have shown that the moulds were tempered with chamotte (ie sherd-tempered), a temper which was also included in two mould fragments from Birka which were analysed earlier(78). The addition of prefired ceramic material brought many advantages with it: the fabric could withstand higher temperatures, it was more porous and the effect of shrinking was diminished. In other words, it was very important that the fabric of the moulds should be sufficiently porous to allow for the passage of air and gases so that the mould should not crack with the pressure formed within it when the molten metal was poured in. The fabric of two of the analysed moulds had been made even more porous by the addition of charcoal and ash. Also, the fabric's firmness was increased by addition of organic material. These two mould sherds were identical, while the third had a different combination of temper. This showed that the square-headed brooches at Helgö were produced by at least two different craftsmen.

On the other hand, chamotte had not been used in the crucibles, which need to be even more heat resistant and to tolerate temperatures over 1000°C. The clay which was used is of a type frequently found in the Mälaren valley and which characteristically has a relatively low heat resistance. The maximum quantity of natural sand and crushed quartz was added to counteract this. As the amount of sand which was added was enough to make the clay difficult to hold together, charcoal and ash were added as a binder. The outer layer of certain crucibles was provided with more crushed quartz to increase the heat resistance still more.

These ceramic investigations make it clear that at least this technical procedure was of a high standard and not so very different from that of the Viking period.

The question is whether these technical accomplishments were founded on inherited local traditions alone or whether they were also partly new skills which originally stemmed from Late Roman casting techniques. As Late Roman motifs were important in the development of Germanic animal ornament(79) it seems reasonable that innovations from the same milieu should have taken place in the technical field, as the same craftsmen united stylistic and technical skills.

Because the Helgö moulds, provincial Roman moulds(80) and the moulds from Mucking and the western Celtic sites are so very similar, an independent development of the casting technique in Scandinavia is not very likely. A ceramic analysis of a mould fragment from Mote of Mark(81) has shown that it consisted of the same type of clay as that used at Helgö. In both instances it is a case of a material being deliberately chosen for a special purpose. It can hardly be a coincidence that the craftsmen at Mote of Mark and Helgö possessed the same sort of skill in obtaining the best possible qualities in the moulds; both must have built on traditions from a common source. It is highly probable that the knowledge was also spread over wide areas, because the craftsmen themselves were very mobile(82). In connection with this the earlier discussion of the distribution of handled crucibles throughout northern Europe should not be forgotten.

The only method of casting which can be instanced at Helgö is casting in piece-moulds, and the moulds from Haithabu, Ribe and Birka(83) suggest that this technique was also dominant there. The finds from the west Celtic bronze working sites(84), from Feddersen Wierde(85), Runden Berg(86) and Glauberg(87) in Germany, Batta à Huy in Belgium(88) plus those from the provincial Roman workshops(89) imply that casting in piece-moulds was the prevalent casting method throughout the 1st millennium A.D. As this method was preferred to the lost-wax method, the craftsmen must also have preferred working with permanent metal, wooden, horn or bone models, rather than wax models. If the models used were made of a material such as wax or even lead which could easily be melted out of the mould, there would really be no reason to use a piece mould. We do not know what sort of models were used at Helgö, as no models have been discovered there, but there is no reason to doubt that primary models could have been prepared in a workshop with Helgö's capacity. This cannot be proved at present, but neither can the assertion that the craftsmen at Helgö worked with imported metal prototypes and copied various brooches from different parts of Europe(90). The method of procedure described by Vierck whereby, starting with a bronze model of Poysdorf type, a second model of lead was cast in a piece-mould and then, after partly altering the decoration on it, the final bronze or silver object was cast by the lost-wax method, can hardly have been practised at Helgö. If it were the case, all the moulds at Helgö would result from manufacturing models, and Vierck himself thinks this unlikely(91). It does appear, however, less probable that a special technique was employed at Helgö which was different from that used in the rest of Europe.

The mould fragments from Helgö belong for the most part to two-piece moulds. The problem of casting objects with under-cuts, which previously was thought possible only by the lost-wax method(92), was solved in a simple and elegant way - by dividing the mould up into many pieces. The moulds of clasp-buttons (Fig. 3e)

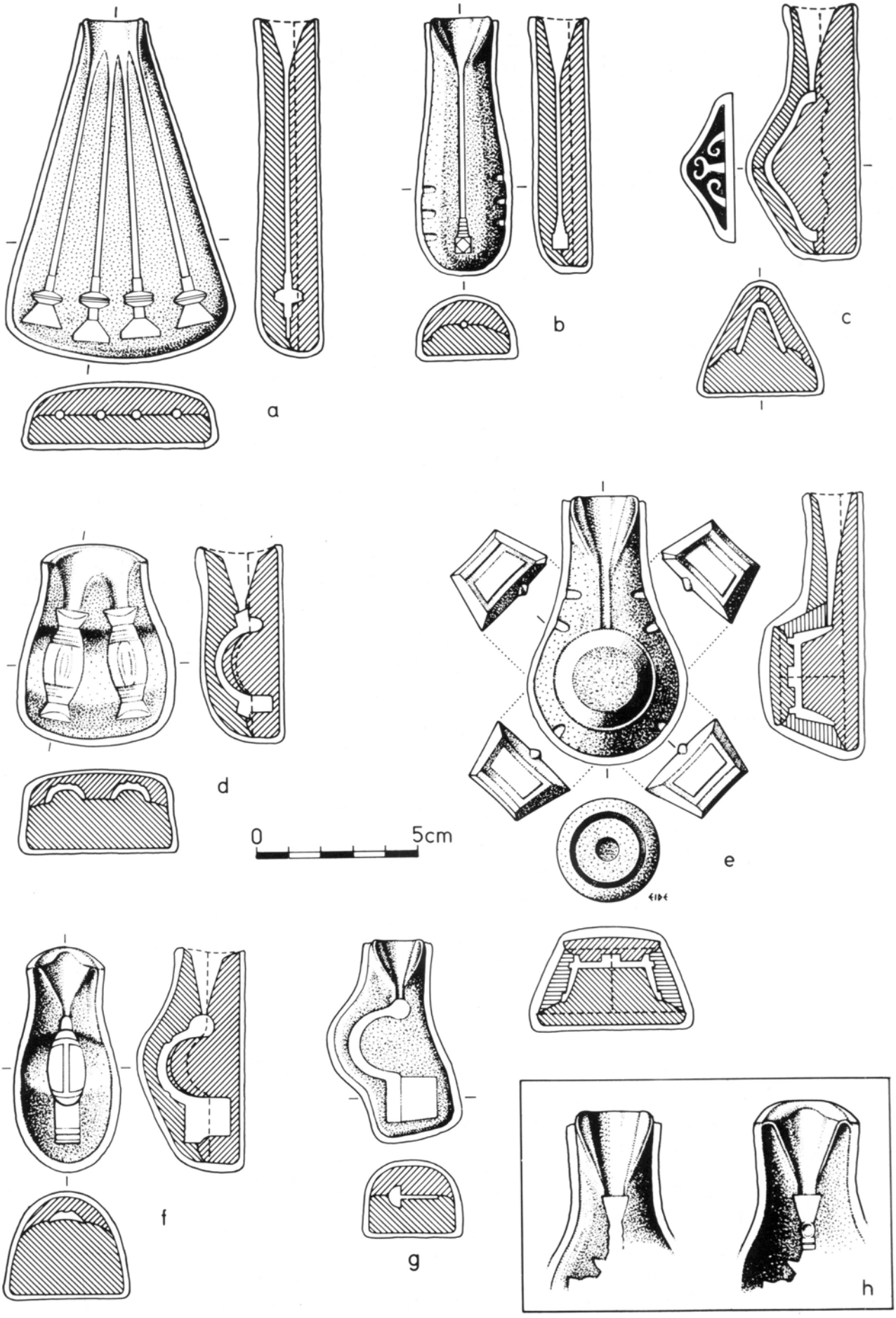

Figure 3: Reconstructions of moulds for different objects and detail of runner

are an example of such multi-partite moulds. The different parts of the mould - this is true also for two-part moulds - are held together by an outer layer of clay; in principle, therefore, they are of the same construction as the lidded crucibles. This method of holding together the parts of the moulds was an unusual practise in the provincial Roman workshops(93).

Two different methods of joining the parts of the moulds together were used at Helgö. One method, which occurs only on one type of crossbow brooch, was to place the halves of the mould together so that they met along the central axis of the bow (Fig. 3g). This method was also used frequently in provincial Roman workshops(94) and also in Scandinavia at an earlier date, as the pre-Roman Iron Age find from Jättened, Västergötland, with its cast but not finally finished brooches clearly shows(95).

The second method of making piece-moulds for casting the brooches was with one half forming the front and the other half the back of the brooch. This method is the only feasible one for casting the wide, flat, square-headed brooches in piece moulds (Fig. 4). The same method was also used for other brooches (Fig. 3d), even those of cross-bow construction (Fig. 3f). The change to dividing up the piece-mould in this way and not along the central axis of the bow is probably connected with the start of casting square-headed brooches.

The decoration of square-headed brooches covers the whole of the front and for all parts was fully developed in the mould. This does not mean, though, that casting always made the chip-carving as sharp as necessary. Small defects were easily modified when the decoration was burnished with various gravers during the final working of the object. A clasp-button discovered at the Helgö workshop which was miscast because the mould was no more than half filled is a good example of how indistinct chip-carving could become through casting. Another clasp-button from Helgö is a similarly good example of how the decoration could be burnished by means of different sorts of gravers(96). When the final working was virtually finished, the metal had unfortunately been cut through at one point so the object was then thrown away.

On both square-headed brooches and clasp-buttons with Style I ornament, the decoration is divided up into small fields surrounded by mouldings. The moulding on the clasp-buttons had served as joins between the different parts of the mould, as it was easier to rub off the casting seams from a plain moulding than from a profiled surface. It is also possible that the mouldings on the square-headed brooches served as boundaries for different parts of the models(97). The main purpose of the moulding, however, was to enable the metal to spread quickly over the whole surface of the object. Figure 4 (where the decoration is not shown) illustrates how the moulding partly followed the contoures of the brooch and partly served as an extension of the runner down towards the headplate of the brooch.

Figures 3 and 4 show that the back portions of the moulds are always flat because they were made while lying on a working surface. The front portions were then formed by hand, and so became slightly rounded. One characteristic of the Helgö moulds is that they are seldom provided with dowels and holes for registration, in contrast, for example, to the moulds from Birsay. On the moulds of the small square-headed brooches the curvature which was formed under the bow of the brooch was sufficient to prevent the halves of the mould from slipping apart. The moulds of the larger brooches do show some dowels around the head plate and outside the terminals of the foot-plate. When the model was pressed down into the clay mould a ridge of clay was formed around it. The front portion, which was built up on the back portion with the model lying in it, acquired the same curvature as the back portion. On the back portions there are also cavities for the pin attachment and catch-plate.

Dowels and holes are also missing from the moulds of one type of dress pin, whereas they are well represented on moulds of another type of pin (Figs. 3a and 3b).

The runner was also designed so that there was the best possible join between the two halves of the mould. For this, the back portions were provided with out-drawn flaps and the front portions had corresponding depressions (Fig. 3h).

Another distinguishing characteristic of the moulds is that they very often lack air vents although sometimes, particularly on moulds of larger brooches, an extremely narrow vent leading from the cavity to the outer layer of the mould can be traced. However, the moulds were porous enough for air vents to be very seldom necessary. Another instance of the good porosity of the clay is that the runner is always placed in the end of the mould where the cavity is narrowest; this must have enatiled certain stress on the mould when the air was forced out. The moulds where three or four dress-pins were cast together attest the skill of the bronzesmiths, for there the runner is placed in connection to the narrowest parts of the pin-shafts. In the trial castings which were done by the Helgö Research unit it was very difficult to make the moulds fill up, but obviously our predecessors had no problems on this point as this type of pin appears commonly in a number of east Scandinavian finds.

Finally, there is a further detail which may be of interest here, as there is a connection with the newly discovered mould fragments from Mucking: the presence of textile impressions on certain moulds.

In Scandinavia impressions of cloth have long been noticed, mainly on the backs of Viking Age oval brooches, but also on some earlier objects. Avar bronzes also show textile impressions on their backs and this has perplexed a good many scholars(98). In Scandinavian literature a number of different interpretations have been suggested, from their having a purely aesthetic function(99) to more practical explanations. Zachrisson has put forward an interpretation which rests on practical experiments. She suggests that after the first half of the mould was made with the model, the cavity was filled in with clay pressed out into a thin layer with the help of a piece of cloth(100). This method would produce a very thin casting, characteristic of Viking Age brooches. Recent measurements of the thickness of Migration period and Viking Age objects also show that the latter are considerably thinner(101). The method of filling the cavity with clay or wax, which has also been suggested(102), is a possible explanation both of how such thin castings could be obtained and of the textile impressions.

The change to making thinner castings has also been attributed to thinner objects making less strain on the moulds and consequently the Viking Age bronzesmiths did not make so many mistakes as their Migration period predecessors(103). But there might also be another explanation and that is that the bronzesmiths were forced to make thinner castings because raw material became more difficult to obtain. Also, considerably more bronze jewellery must have been produced in Scandinavia during the Viking period than in the Migration period as the size of the population and therefore also the demand for these products were clearly greater during the Viking period. For example, the population in the Mälaren Valley is thought to have multiplied during the last half of the 1st millennium A.D. from c. 400-500 settlement units at the beginning of the Migration period to almost 4 000 by the end of the Viking Age(104).

So the presence of cloth has previously been believed to be connected with the desire to make a thinner casting, and that the method must have been introduced some centuries before the beginning of the Viking Age for it to have become quite widely distributed during that period. The fact is complicated, however, by a fragment of a 6th-century square-headed brooch mould with textile impression being found at Helgö. In this case the purpose of the cloth cannot have been to achieve a thinner casting as the fragment was no different from other moulds for square-headed brooches with deep cavities. Furthermore, this is the earliest example so far known in Scandinavia of the use of cloth in casting. It is at present impossible to explain its purpose. The presence of textile impression on a good many crucible fragments from Helgö, as also on some crucible fragments from

Sigtuna(105), is still more perplexing. The only explanation that I can suggest at the moment is that excess water could be mopped up by the cloth, but this may not be a very plausible interpretation of textile impressions on the fragments of moulds.

Translated by Helen Clarke.

Illustrations by Anders Eide

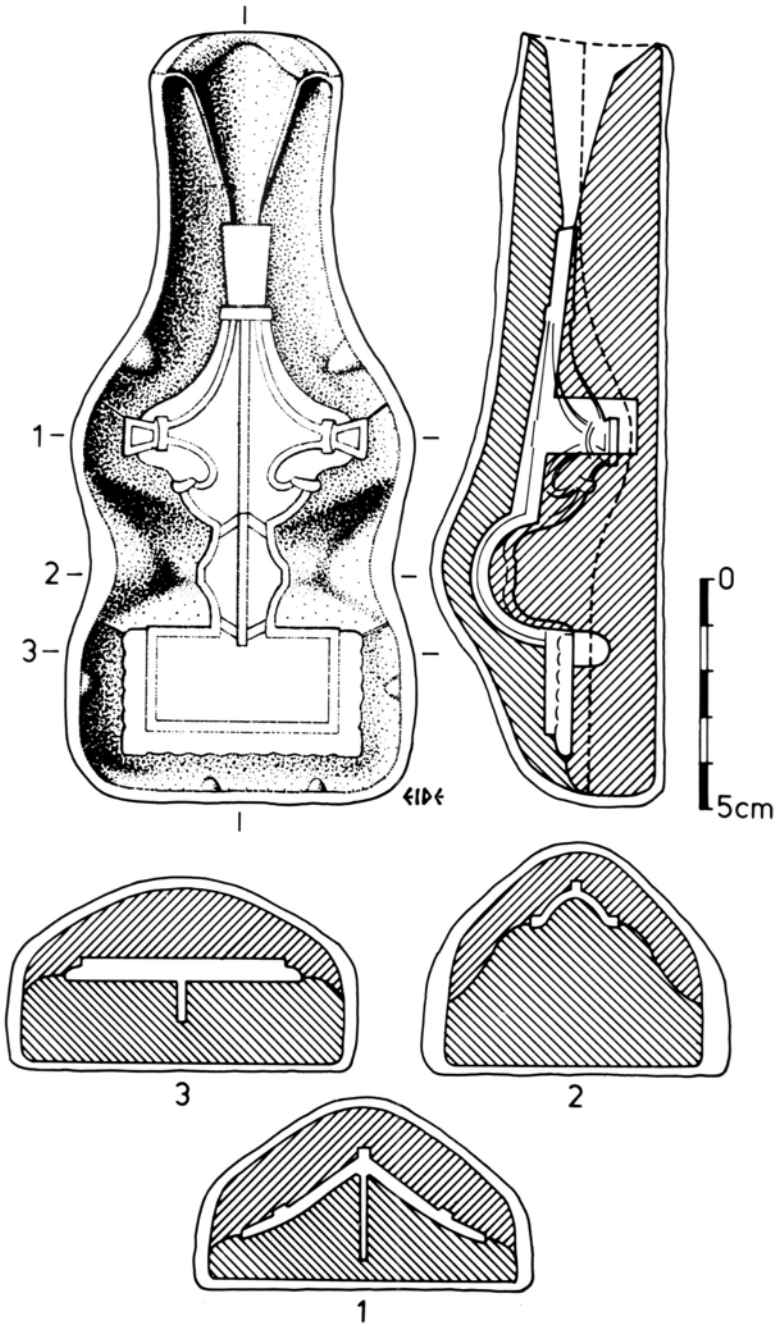

Figure 4: Reconstruction of mould for square-headed brooch

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METALLURGICAL FINDS FROM A MULTI-PERIOD SETTLEMENT AT MUCKING, ESSEX

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Although about a dozen hectares of multi-period (Neolithic to Medieval) settlement traces have - since 1965 - been investigated at Mucking, Essex (1-4), in advance of their destruction by quarrying, finds and features relating to metal-working are few. The location of Mucking on the 100' gravel terrace at the head of the Thames estuary means that there is no local source of ore, though it is well placed for water transport.

Metal artefacts range from the late Bronze Age to the end of the Migration period - perhaps to the mid-8th century A.D. Doubtless the Roman villa had an estate smithy, but this would have been sited near the buildings, whereas the excavation area lies in the fields, with their wells, pottery kilns and cemeteries. Most metal artefacts have come from the very large early Saxon settlement, largely because of the pagan custom of furnishing graves in the two cemeteries, while the Saxon habit of building smaller dwellings with the floor sunk into the ground has also ensured the survival of much contemporary rubbish. Metalwork includes weapons such as swords, shield bosses and spearheads; costume jewellery such as iron brooches, sometimes inlaid with silver, copper and brass; cast bronze buckles and broockes, sometimes gilt, tinned or inlaid with silver; and everyday articles such as knives, pins, shears, strike-a-lights and sheep-bell clappers. Two clay piece-mould fragments, similar to those described above by Dr. Lamm, came from a hut fill. (See Fig. 1).

Because most of the thousands of features are shallow as well as separate, dating must often depend on settlement pattern and on the commonest dating agent - pottery. In some instances, indeed, metallurgical evidence might provide the only means of dating, so Cleere's reference to slag analysis (5) is hopeful reading for a field archaeologist. Since final processing of the finds is not yet under way the following account is provisional.

Slags - presumably of iron - are common finds in late Iron Age, Romano-British and Saxon features, mostly as rubbish in ditches and hut fills. Pieces range from droplets, found with charcoal on the surviving few inches of what may be round smithing hearths, up to slag blocks of which the largest weighs about 20 Kg. This was rescued from an apparent intrusive feature cut into the late fill of an Iron Age ditch, and cannot be more exactly dated archaeologically, though comparable ditches which could be excavated have had late Saxon fills. The block is considered by Tylecote (6) to belong to the Saxon settlement. It seems to resemble the slag blocks illustrated by Bielenin from Poland (7). A Saxon date is archaeologically more certain for slag block fragments found in one case in a pit with 'grass'-tempered pottery, and also in the fills of Saxon huts. No local ore source is known; however Cleere's map (8) suggests it would have been feasible to transport ore by water from Kent. Because of the probable military origin of Saxon Mucking, a related iron industry, perhaps to ensure self-sufficiency in weapons, is an attractive idea.

Copper working evidence is scanty. Pieces of plano-convex ingots came from the late fill of a hillfort ditch; an almost complete triangular crucible from a small pit in an Iron Age area (Fig. 2), and several crucible sherds from Iron Age to Saxon contexts. Slags resembling the greenish cinder adhering to crucibles are also found; and one piece of copper slag has been identified. However, some slaggy-looking fragments seem to be vitrified sand.

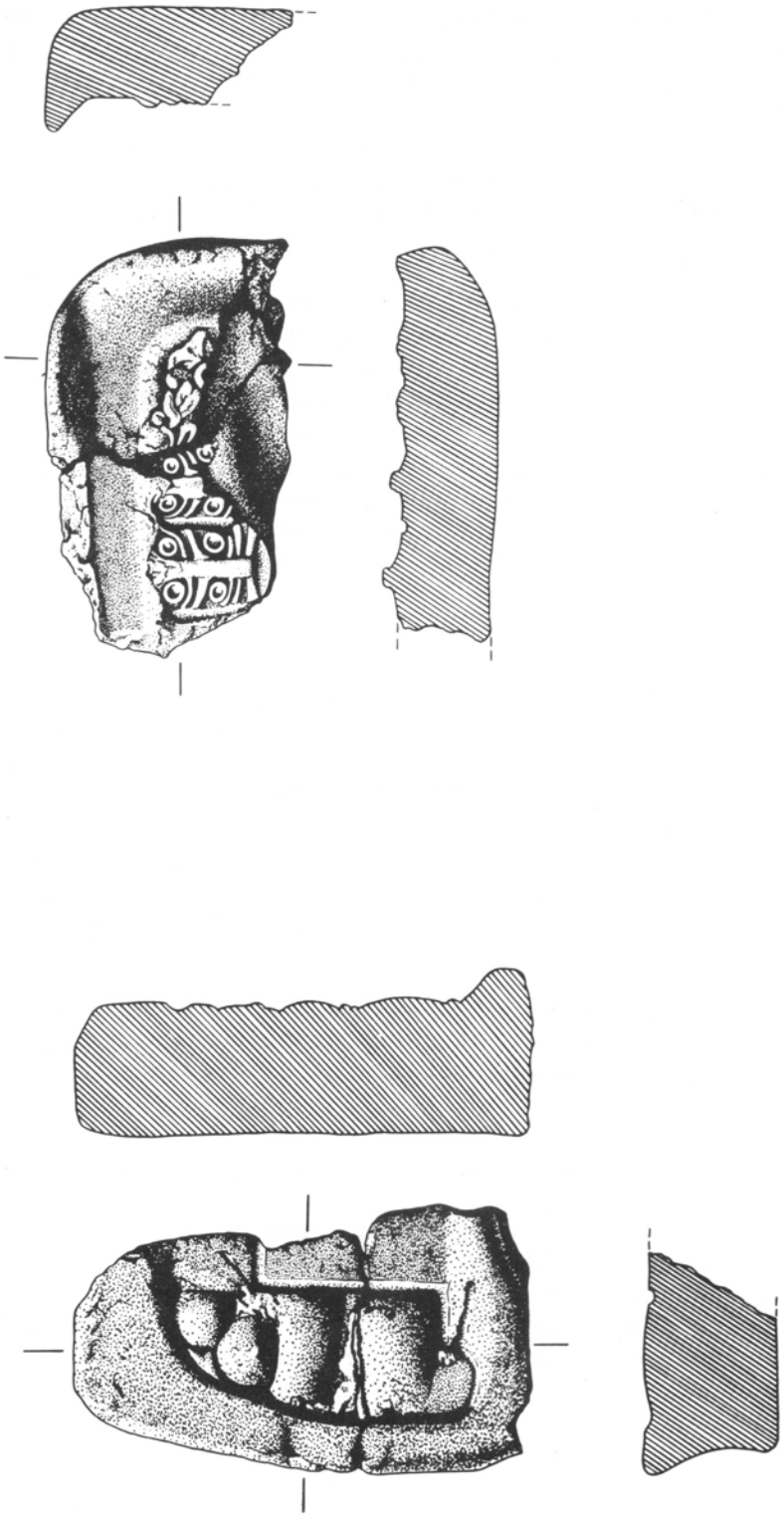

Figure 1

Two fragments of the same mould for a great square-headed Anglo-Saxon brooch. (Scale 1:1)

Lead is a particularly interesting metal at Mucking. A possibly unique vessel of lead (possibly turned) came from a Saxon grave; while lead rings and perforated discs (interpreted as loom-weights) have come from Saxon huts. One hut floor contained clear evidence, in the form of a mass of molten lead close to two lead rings, that lead objects were cast by the Saxons. There remains the problem of its origin. The most likely source is plumbing taken from the Roman villa. Since this must have taken place at or soon after its abandonment which presumably coincided with the Saxon takeover, analysis to try to establish a Roman origin might provide critical evidence.

Finally, we come to the two clay piece mould fragments found as rubbish in the fill of a Saxon hut (9). (A piece apparently of Roman tile from another Saxon hut bearing the impression of what may be a Roman brooch is a mystery) (10). The piece mould fragments were recognised as similar to those from Helgö (11) and were then identified (12) as matching parts of the front and back components for a great square headed Anglo-Saxon brooch with free standing human masks surrounding the headplate. (Fig. 1) Only fragments of two square-headed brooches have so far been found at Mucking, of which one was of the same type as the mould, though not identical.

The method of use of these moulds has been fully described by Lamm (13). Pieces of fired clay with variable sand content are frequent finds of all periods at Mucking, so more mould fragments which have not retained clear surface evidence of their function might still be confirmed. However, the quantity would still be quite insufficient to postulate for Saxon Mucking even a small workshop of Helgö type; though in this connection might be mentioned the distinctly home-made character of several brooches.

Two questions arise from the discovery of the Mucking mould - the first of its date to have been found in England:

i) Should one think of an itinerant bronze-smith making comparatively few pieces at each stop, whether from his own patterns or copying from brooches already in use, which could, of course, have been heirlooms?

ii) Has the metallurgist (by demonstrating the ease with which copies can be made) weakened the main archaeological dating tool for the Migration period - the style history of its fine metalwork?

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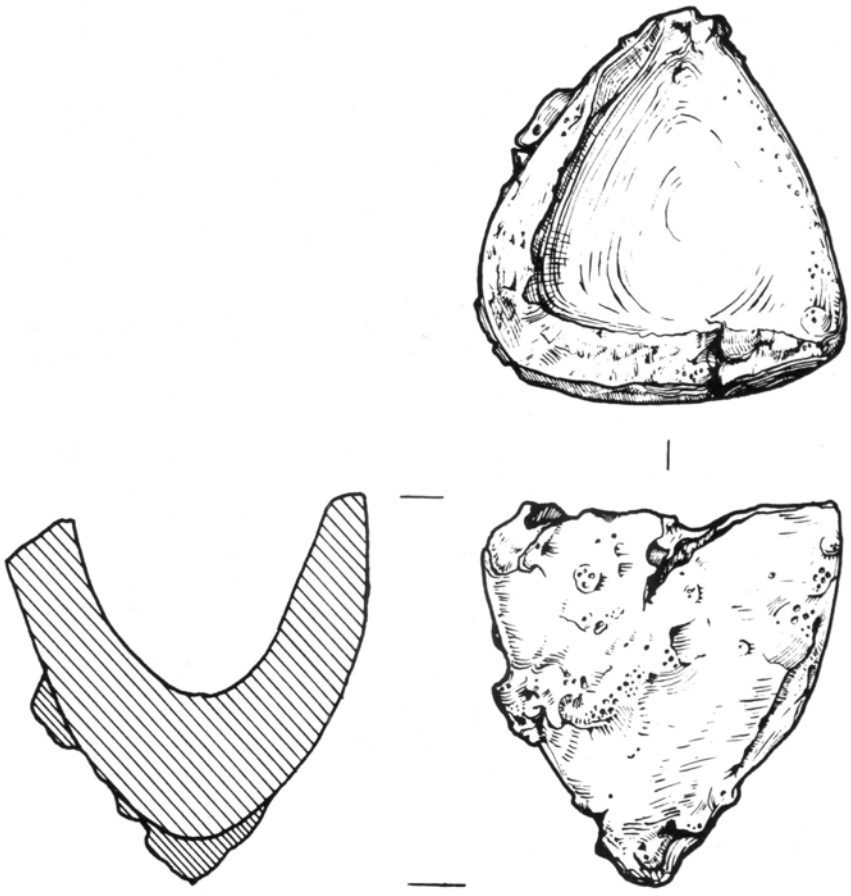

Figure 2

Triangular crucible from a small pit in an Iron-Age area. Scale 1:1

METALWORKING AT THE MOTE OF MARK, KIRKCUDBRIGHT IN THE 6th-7th CENTURIES AD

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Introduction

The Mote of Mark is a rocky outcrop on the Urr estuary at Rockcliffe, Dalbeattie. It was first excavated by Dr Alexander Curle in 1914 (Curle 1914) and was re-excavated in 1973 by Laing. Several interim discussions of the site have appeared in print (Laing 1973; Laing 1975; Graham-Campbell 1976; Close-Brooks 1976; Laing 1976).

The excavations indicate that the summit of the rock, which extends to about an acre, was defended early in the post-Roman period by a timber-laced rampart with a timber gateway. Inside this defence extensive metalworking was carried out of iron and copper alloys, the most important finds being a series of clay moulds for the casting of decorated bronzes and other non-ferrous objects such as penannular brooches, pins, studs and mounts. This phase of metalworking was associated with the importing to the site of Mediterranean pottery of Classes D, E and possibly F (for the classification, Laing 1975, 272-4) and glass of Germanic origin, the latest analysis of which (by Mr John Hunter of Bradford University) indicates a date of manufacture in the sixth century, with a few pieces slightly later. The evidence of the imported pottery and glass would seem to indicate that the metalworking belongs in the main to the sixth century, continuing perhaps into the seventh. This agrees with the radiocarbon date from the timbers of the gateway of 1491 $\pm$ 42 BP (SR 321), i.e. AD 459 $\pm$ 42. Recalibrated, this might suggest an actual date for the construction of the rampart in the sixth century (for recalibration, McKerrell 1971, 78). At some stage when the metalworking was still in progress the rampart was fired, causing it to vitrify, the gateway was blocked, apparently hurriedly, then the rampart demolished. Anglian finds, including two runic inscriptions, indicate possible Northumbrian presence on the site in the later seventh century. There is no evidence for occupation on the site later than the seventh century though late occupation, up to the ninth century, has been claimed by some commentators. Whether the evidence for destruction and the appearance of Anglian material on the site can be associated and perhaps related to an Anglian take-over, as was at first suggested following the 1973 excavations (Laing 1965, 101), or whether from the early seventh century onwards there was a hybrid Anglo-British community on the site as now seems more probable, does not affect the dating or the affinities of the metalworking.

The absence of most of the normal types of occupational debris found on settlement sites of the period and the intensive metalworking might suggest this was mainly an industrial site, perhaps to be compared with the later Kiondroghad on the Isle of Man (Gelling 1973). It could also have been a noble's citadel.

The Metallurgical Investigations

The aims of the investigation were to try to establish, by internal examination of the finds, the technological capability of the inhabitants of the site and possibly their links with other societies both by trade and by cultural heritage. The techniques available for this purpose were: optical microscopy of polished and etched sections combined with electron probe micro-analysis of features in these sections and the identification of elements in slags, ores and crucible fragments by x-ray fluorescence spectroscopy. This last technique is suited to this type of rough irregular material. It was used for element identification and not for quantitative analysis, which was not possible in the circumstances of the investigation.

Electron probe microanalysis can be considered as an extension of optical metallography in that x-ray spectroscopy can be used to identify the elements present in features which can be seen on the scale of the optical microscope (i.e. greater than 2-5μm). The concentrations of the elements can also be determined but, as with the x-ray fluoroscopy, that was not done in this case.

Thus, unfortunately, quantitative analyses of the finds are not yet available. The results therefore represent a general study of the material in order to establish a framework of information about the finds and to point the way to situations where detailed quantitative analysis would be valuable. The metallographic examinations are considered to have yielded the most information and quantitative analysis would require supporting data from the ores used in order to make it more useful. Since these are not known, except for the iron, the lack of analyses of features in the metals is not a serious omission when the other metallographic evidence is so useful.

Ores, Slags and Crucibles

Several pieces of unmelted iron ore were found in both the 1913 excavation and in 1973. The pieces of ore were distinguished from the pieces of slag and cinder by conventional specific gravity measurements which fell into well defined groups of values. The pieces of ore were of two kinds: black, rounded pebbles and the typical "kidney" shaped lumps. Both types were shown to be haematite by using Debye-Scherrer X-ray powder diffraction analysis.

Both types of haematite appear to be plentiful in the locality and in the region. The black pebbles are still found on the beach nearby and in the 19th Century there was a mine at Auckenleck, 5 miles east of Dalbeattie, where the haematite occurs as a vein of the kidney type in the Dalbeattie granite.

There is therefore little or no specific information to be gained from studies of the iron ore, beyond the observation that both types of haematite were apparently recognised and used.

Iron Slags

Three samples of iron slag were examined after selection by eye as typical in appearance from the large number of pieces available. The results are not therefore representative of the whole collection of slag pieces. Rather, they demonstrate the variety of results which would probably be obtained by studying the whole. One confusing result of these examinations was finding copper, zinc and, in one case, lead, as well as the expected elements like silicon and aluminium in the pieces of iron slag.

No extensive furnace structure was found in either 1913 or 1973 so it is presumed that the bowl type was used. A furnace bottom, typical of this type of furnace was found in the 1973 excavation but was stolen from the site before it could be properly examined. The non-ferrous metals were melted and smelted in crucibles and the iron slag could represent the result of scraping off the non-ferrous slags from the crucibles into the fuel bed where it would fuse with the pieces of iron slag.

X-ray spectroscopic methods in this case have shown the existence of unexpected elements which do not appear in the lists of analysis results carried out by normal chemical methods. The analysis of slags by chemical methods is usually directed towards measuring elements expected to be present and so this admixture of 'tramp' elements may be more widespread than in this one situation.

Crucibles

Numerous pieces of crucibles were found in both excavations. Curle described them very well as being made of a fine clay "of a greyish hue". There appear to have been two sizes in use. A longer type of triangular shape which was perhaps associated with the smelting operation and a small type, similar in size to a hen's egg, which may have been used for remelting for casting. Several of the smaller crucibles from the 1973 excavation had a thick outer layer of bubbly material. On one example this outer layer bore the impression of what appears to be the serrated face of a pair of tweezers at an angle such as would be used for lifting the crucible from a hearth.

The impression on the crucible was that of a thin light section. A pair of tweezers was found in the 1973 excavation which fits the impression. However their size and spread were more akin to modern toiletry tweezers and they would be inadequate for spanning the outer diameter of the crucible. They could have gripped the crucible by holding one part of the rim but were probably too short for use near a hot fire. The thickness of the rim of the uncoated crucibles was approximately 3mm.

In the general category of objects made of clay the 1973 excavation produced two large lumps of baked clay with a coating of slag on one side of each of them. The two pieces, discovered separately, were found to fit together to form part of a complex curved surface. Spectroscopy of the slag showed it to contain mainly iron but with some copper. We have deduced that a possible explanation for this object is that it is part of a protective end for a bellows tube (tuyere) and appears to be very similar to the objects found by O'Kelly at Garryduff (O'Kelly 1962). If this is so then the furnace may have been of the same general construction in the form of a bowl shaped hearth in the ground.

Non-Ferrous Ores and Crucible Residues

The results of investigations under this heading have to be considered with the results from the examination of the copper alloys in the next section.

Only one piece of slag-like material from the 1973 excavation could be definitely identified by eye as being non-ferrous. This was a roughly disk-shaped piece with a green surface colour. X-ray fluorescence spectroscopy showed that it was predominantly copper but with tin as the next most concentrated element. The lump also contained lead, zinc, silver and iron. Three pieces of crucible were examined which had residues on a sufficiently flat surface to be analysed. In each case copper was the most concentrated element. In two crucibles zinc was present with tin either absent or only present in a small concentration. In the other, tin was present with zinc only in a small concentration. Iron, lead, aluminium and calcium were also present in varying amounts.

Carbonate and sulphide ores of copper are found at several places along the coast of Kirkudbrightshire, particularly around Gatehouse of Fleet (Wilson 1921). These ores also contain iron, zinc and lead which may account for the iron in the crucible residues and the zinc and lead in the lump. The presence of tin in the lump suggests it represents an unsuccessful attempt at smelting a tin bronze.

The presence of the zinc raises the crucial question about the manufacture of brass. None of the fragments of metal found were brass but the evidence from the crucibles appears to be quite clear that copper alloys with zinc were made and since copper alloys without zinc were definitely made this suggests that the use of zinc as an alloying element was intentional. The significance of this is that the use of zinc is a continuation of Roman technology and is found later in Medieval material (Tylecote 1962, 57). Crucible residues from Lough Rea, Galway, contained zinc (Moss 1927).

The metal find to be described in the next section included a simple tin bronze and a leaded tin bronze but modern records contain no mention of tin in the locality and so if these are a reliable guide to earlier conditions the tin must have been imported.

Copper Alloys

Three finds made from copper alloys were examined: one was a pair of small tapering pieces of very similar size (approximately 45 x 7 x 5 mm) and the second was a strip of four stud shaped pieces fastened together at their flat heads by a flash of metal, presumably from a joint in the mould. A similar find was reported by Curle who also found the moulds which produced them so these studs must represent a production item. The third find was a fragment of strip, approximately 40 mm long by 3 mm wide by 0.2 mm thick.

The metallographic structure of the first two was completely different although both were tin bronzes. The studs had a structure characteristic of a casting, as one would expect from their outward appearance, whereas the tapered pieces were wrought. A more significant difference was that the cast objects contained lead in contrast to the wrought objects which did not.

The fragment of strip was broken to reveal a cross section which could be examined with an electron probe and energy dispersive x-ray spectroscopy. The material was a low tin bronze with inclusions of lead and of calcium rich slag and small amounts of aluminium, silicon and phosphorus but no sulphur. This suggests that carbonate ores had been the source of the copper.

The use of lead as an addition in copper alloys is known from the early Iron Age. The amount of lead in wrought alloys was reduced in Roman times (Tylecote 1962, 58) and that also seemed to be the practice at the Mote of Mark where there was obviously a very clear understanding of the relationship between the composition and the eventual method of fabrication into an object. The lead in the wrought strip is therefore a problem. The influence of lead in forging could be detrimental and cause cracking but hot working may avoid that to some extent. The absence of lead in the wrought pieces suggests that it was deliberately avoided for that method of fabrication. In modern practice lead is added to brasses to make the swarf, removed by cutting tools, break up into small pieces. This in turn suggests that the stud like objects were not intended to be hammered cold as rivets would be.

The evidence from examining these finds suggests that the Mote of Mark community was conversant with the main stream of metal fabrication technology.

Iron Objects

The three largest of the iron objects were chosen for investigation because they were likely to reveal the most general information. One was an iron bar with an irregular shape due to corrosion, which was approximately 30 cms long. One end appeared to have been shaped into a curve. The second was a thinner bar, approximately 20 cms long, which seemed to be pointed at both ends. The third was a wedge-shaped lump weighing approximately 600 gms. The lump was 5 cms wide and 3.5 cms thick at one end tapering over 10 cms to 1 cm thick at the narrow end. The wedge was rounded at the thick end and straight and flat along the sides. The thin end was irregular.

Sections from the first and larger of the two bars showed that it was wrought iron, partially carburised in an irregular manner down its length, as shown by regions of pearlite extending in from what had been the surface. Some sections showed cracks and folds which ran along the length of the bar and in the vicinity of the crack the pearlite penetration into the section was greater than in the

uncracked portions. The oxidation of the bar had produced an almost square section (approximately 1 cm square) in parts, but the polished cross section showed the existence of layers in the oxide scale. They appeared to have developed from an edge running along the length of the bar. The original cross section would then have been triangular in some parts. The penetration of the pearlite was irregular presumably because of inefficient contact with the carburising medium and on one section extended to approximately 2.5 mm. The time needed to diffuse carbon to this concentration at this depth would be approximately 100 hours at 950°C. This represents a low extimate because the loss of metal to the oxide layer has been ingnored.

Some sections of the bar showed extra large grains of ferrite suggestive of a critical amount of strain being introduced by cold work (hammering) and grain growth caused by the annealing which introduced the carbon for the pearlite. In other sections the ferrite grain size was uniformly smaller. Other investigators of iron objects, notably Coghlan (1956), have used microhardness measurements to indicate the general nature of the material. For this bar the hardness results varied from 90 D.P.N. in the coarse grained ferrite to 130 D.P.N. in the fine grained regions. These values are consistent with values published by Coghlan for soft iron with low phosphorus and sulphur concentrations.

The thinner bar was quite different. Its metallographic structure was ferrite and fine spherodised cementite. The bar had been made by welding two fully carburised bars together because a decarburised zone with some entrapped oxide ran down the middle of the bar to the pointed end. The outer edges were decarburised due to the subsequent forging but in the central region of each half the carbon distribution was fairly uniform. The maximum concentration, estimated by quantitative metallography, was 0.3% carbon. The very fine division of the cementite suggests repeated annealing below 700°C and forging to break up the ferrite grains. The maximum microhardness in the regions with the most cementite was 135 D.P.N.

The slag in this bar was in smaller pieces and more elongated along the bar than in the first bar. This is consistent with the greater amount of working which the second bar received. In both bars the slag was a two phase mixture of what appeared to be iron oxide and fayalite. The silicon-rich phase contained calcium, potassium manganese and aluminium as trace elements and was similar in both bars, suggesting a common origin for the ores.

This second bar appears to be a finished article whereas the first bar may represent some stage in the manufacture of a fully carburised bar. The evidence is that the first bar had received some forging treatment but that its last heat treatment had been a slow cooling from 900°C or more. The excessive amount of cracking may have been the cause for its rejection at a stage when it had been carburised for at least 100 hours. The associated forging suggests that this treatment was deliberate and not incidental such as would occur if it were a support in the hearth, for example. The evidence from the second bar and the similarity between the slags and the microhardness of the iron suggests that both bars were made on the site since the first would not bave been imported.

Hence the findings from these two bars indicate the use of carburising and "piling" to produce fully carburised sections in finished tools. The thinner bar may have been an awl. Its mechanical properties would be those of a medium carbon tough and malleable steel.

The third and largest piece was thought to be a wedge or a hammer head from its external appearance but its significance was revealed by sectioning it along its length with a diamond slitting wheel. At its thicker end it contained large inclusions of slag and charcoal forming a very porous iron mass. At the thinner end the inclusions were smaller and their elongated form and the ferrite grains showed signs of forging. In this object the slag was not a two phase mixture as in the other two; the silicon content was lower and there was much more silicon in the iron. In the porous

region, where charcoal was associated with some of the inclusions, some pearlite was observed around the rim of the inclusions.

This object therefore seems to be a billet which was improperly smelted. The inclusions of charcoal and the lack of partitioning of silicon from the metal into the slag suggest that the temperature was too high. The high silicon content in the iron would make it brittle for forging, as appears to be confirmed by the broken end.

When considering what it was intended for it can be noted that the width is very similar to swords of the same period. The evidence from the other bars is that very pure soft iron with good slags could be made on the site and that fully carburised material was produced by repeated carburisation and forging of small sections. The rejection of this larger section by the smith suggests that a soft iron was expected and that he intended to forge a fairly long flat strip from the starting ingot. However it is possible that this width of material was intended for carburisation as a thin strip for use as a core to be built up into a sword. The first bar examined, with its suggestion of a triangular section, could have been intended for a cutting edge.

Conclusions

It is obviously unwise to attempt far-reaching deductions about metallurgy in the Early Christian period in Scotland on the basis of the study of the finds from the Mote of Mark, but a number of features are worth noting. The first is the range of technological skills shown by the smiths. Considerable competence was shown in both the ferrous and non-ferrous metalworking. Although the only direct evidence for non-ferrous metallurgy related to copper alloys, nevertheless the presence of gold and lead among the finds might indicate that these metals were also worked, since lead at any rate was being used in producing copper alloys.

One important question posed by the Mote of Mark technology is the extent to which the techniques known to the smiths were those already known to metalworkers in the pre-Roman iron age, and to what extent the technology reflects innovations of the Roman period. There is a very limited amount of evidence for the carburisation of iron during the pre-Roman Iron Age, the main evidence for it depending on the chariot tyre from Llyn Carrig Bach in Anglesey, which was produced by welding strips of fully carburised wrought iron together (Fox 1946, 12 and 75-75) in a process apparently similar to that employed in the production of one of the bars from the Mote of Mark. The Llyn Carrig Bach tyre, however, is seemingly unique in pre-Roman Britain, and where other analyses have been carried out the rare instances of carburisation recognized have been interpreted as accidental (Tylecote 1962, 202-3; Cunliffe 1974, 272). It should be borne in mind however that the Llyn Carrig Bach deposit, although containing earlier objects, contained objects which could be as late as the mid-first century. AD, and the influence of Roman technology on native craftsmanship cannot be entirely ruled out in spite of the absence of Roman objects from the hoard. Whether of native Iron Age origin or not, the technique does not seem to have become common until the Roman period. The production of steel by the welding together of surface carburised iron strips in this fashion was certainly known in the Roman world by the late first century AD (Tylecote 1962, 249), and can be seen in the second century at Huckhoe, Northumberland, (Jobey 1959). This evidence for deliberate carburization at the Mote of Mark might suggest a Romano-British survival.

The other technique which might suggest a possible survival of Romano-British technology is the production of a copper-zinc alloy. To what extent the zinc was already present in the ore, or to what extent it may have been deliberately added, is difficult to ascertain. The lump of ore, and the record of up to 10% zinc in local copper ores, might suggest it was native to the ore used. Except in a bronze from the late Bronze Age hoard from Taunton, Somerset, and in a pair of Iron Age armlets from Aboyne, Aberdeenshire (Tylecote 1962, 51), zinc is apparently absent

from pre-Roman copper alloys, and in these cases it may have been the result of its native occurence in the ores, as at the Mote of Mark. Zinc-copper alloys were however being deliberately produced in the Roman period by the addition of calamine during smelting (Tylecote 1962, 53), and the taste for copper-zinc alloys, if not the use of calamine, may represent a Romano-British survival at the Mote of Mark. It is noteable that in the Early Christian period in Ireland both tin bronzes and tin-zinc-copper alloys were being produced. A crucible from Lough Rea (Moss 1924-7) contained a residue with tin and zinc, while one from Lough Faughan, C. Down contained a copper-tin alloy (Colling 1955, 74). It seems very likely that the tin used at the Mote of Mark came from Ireland, which would be in keeping with the other affinities of the site.

The deliberate selection of the most suitable type of copper alloy for the intended end-product suggests an advance on Iron Age technology. Alcock, in discussing the crucibles from Dinas Powys, has drawn attention to the great diversity of crucible forms found in the Early Christian period, which he has seen as a reflection on the technological experiments of the time (Alcock 1963, 48). He has also suggested that the crucible forms developed in Britain in the fourth to fifth centuries AD were diffused by peripatetic craftsmen (Alcock, loc. cit.). The evidence from the Mote of Mark would seem to support such an interpretation. The technology of the period seems to have been undergoing the same rapid experimentation and innovation, that can be seen in other aspects of Celtic life.

In connection with the Dinas Powys ironworking, Alcock pointed out that the absence of tapped slag there argued for primitive techniques of smelting, and drew attention to bowl-like depressions on the site with ash or charcoal which might have been bowl-furnaces, though the absence of slag suggested otherwise to him (Alcock 1963, 45). He also found a hollow, in and around which was a quantity of slag and pieces of highly fired clay - it measured 48.5 cm by 33 cm by up to 11.5 cm deep (Alcock 1963, 45). At the Mote of Mark a similar ash-filled hollow was excavated in 1973, but again lacked the slag that might be expected from a bowl-furnace. It measured 45 cm by 30 cm by 10 cm deep and was situated in the main area of metalworking adjacent to moulds and crucible fragments. A hearth investigated by Curle in 1913, and described by him as being of clay, burnt red to a depth of about 10.5 cm and with a diameter of 107 cm, may have been a bowl furnace (Curle 1914, 138). The evidence however is by no means conclusive proof of the type of furnace used on the site.

Acknowledgments

Some of the experimental work in this investigation was executed by Messrs P. Woods, I. Watts and K. Shepherd as part of their Honours Degree course at the University of Liverpool and we are grateful for their assistance.

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GILDING AND TINNING IN ANGLO-SAXON ENGLAND

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Introduction

Gilding and tinning were both well established methods of decorating other metals by the time that the Anglo-Saxons and their contemporaries employed them and gilding, as a method of decorating baser metal, can be traced back to at least the middle of the third millennium B.C., where it occurs on silver objects from Ur(1). From then onwards it has a more or less continuous use in the old world to decorate bronze or silver, although the techniques of application of the gold to the baser metal surface did develop and change.

By the Anglo-Saxon period the universal method of gilding silver and bronze was the mercury-gilding process, and until recently the earliest use of this technique, which was supported by scientific evidence, was in China in the third century B.C.(1). However, it has now been shown that the method was in use to gild bronze finger rings and bangles in the Classical World as far back as the fifth century B.C.(2). Nevertheless, it is clear from large numbers of analyses recently carried out in the British Museum Research Laboratory that the majority of gilded objects in the Greek and early Roman periods were not gilded with the aid of mercury(3). It is only in the third century A.D. that the mercury-gilding technique becomes widespread, coinciding with the period at which it seems to have become universal in the Sasanian Empire for gilding silver.

Tinning on the other hand is not so ancient. It became popular for decorating bronze in the La Tène and Roman periods, and Pliny(4) and Dioscorides(5) knew of the importance of tinning bronze cooking vessels to prevent contamination of the contents by the copper. There does not seem to have been a systematic documentation of pre-Roman occurrences of tinning, coupled with scientific examination, though there are scattered references in the archaeological literature, some of which have been noted by Lins(6) and Jope(7), and Savory lists various tinned Iron-Age objects in his recent catalogue from the National Museum of Wales(8). Savory has, in fact, discussed the origins of tinning and indicated that it was practised as early as in Hallstatt times(9), though whether it then occurs continuously throughout the La Tène period is not yet proved to everybody's satisfaction.

Tinned bronze was the poor man's silver, and as such we find a widespread use of the technique on personal items and all types of decorative metalwork from the Roman period onwards. It is hardly surprising, therefore, to find tinned bronze commonly used to make brooches in the economically poorer Anglo-Saxon kingdoms north of the Thames during the fifth and sixth centuries A.D. at the same time as gilded silver, or even gold, was in use in Kent and those areas of the South East which were in closer touch with the richer Merovingian kingdom in Gaul.

The Technique of Tinning

The usual method of tinning a copper alloy is first to cover the surface with a flux and then either to dip the object briefly into a bath of molten tin and, after removal from the bath, to wipe away excess tin with a suitable piece of rag or leather, or to wipe the surface with a stick of tin while heating in a reducing flame, such as a charcoal fire, which causes the tin to run over the surface. The temperature required is not very high as tin melts as 232°C. It is, however, not easy to tin selected areas of a surface as the flow of the molten metal over the surface cannot normally be controlled. This process survived relatively unchanged into recent times among the tinkers who used to travel around the country

re-tinning copper cooking vessels by the roadside(10). The flux which was used may have been rosin, a natural resin which is obtained from pine trees.

Thouvenin, however, has postulated that tinning in the Roman and Merovingian periods was often carried out by a chemical process in which the object to be tinned is boiled for several days in a solution of potassium bitartrate containing granules of metallic tin(11). The potassium bitartrate was readily available from wine making operations where it settles out as off-white crystals during the fermentation and subsequent clearing stages of the process. The crude crystals are known as argol and are purified by recrystallisation to give cream of tartar (potassium bitartrate)(12). During the sixteenth century the burning of potassium bitartrate was an important source of pure potassium oxide in the ceramic industry(13).

Tinning by this chemical process was certainly known in the eighteenth century where it is described in the technical encyclopaedia of Diderot and d'Alembert for tinning brass pins. Certainly copper alloys can be given a thin, smooth coating with an even thickness by this method, which is less likely to contain flaws than one applied with molten tin. However, the process is slow and boiling for several days is required in order to deposit a durable thickness of tin on the surface.

Nevertheless, Thouvenin has suggested that this method of tinning extends back to the Roman period(11), the arguments relying on the following observations: (i) the extreme thinness of the coatings on tinned Merovingian bronze brooches in which the tinning has in no way filled the engraved design, (ii) the similar thinness of the white metal coating on some late third century Roman coins, and (iii) the fact that these coins were produced in vast quantities, which must have involved some type of "bulk plating" process, as coating individual flans with molten metal would be economically impossible.

Unfortunately Thouvenin cites no authority for assuming that this metal coating on the late third century Roman coins is tin, and although it has been reported as tin in the past(14), it has more recently been convincingly demonstrated that the coating is silver(15).

The evidence for chemical tinning in a bath of potassium bitartrate in Merovingian times is thus reduced to a consideration of the thickness, or really thinness, of the existing layers. Experiments on tinning with molten tin have shown that very thin and even layers can be produced by this technique, and the survival of this process among tinkers into modern times may, perhaps, be used as additional evidence that tinning with molten metal is the traditional technique which stretches back, probably little changed, to the late pre-Roman Iron-Age.

There is some negative evidence to suggest that tinning with potassium bitartrate was not known in medieval times and that is the absence of a description of the technique from the well known technical treatises of Theophilus (dating from the early twelfth century A.D.) and the anonymous Mappae Clavicula (dating from the early ninth century A.D.). Both these documents mention the use of argol derived from wine, calling it "wine-stone" and using it in a recipe for a flux for soldering silver (Theophilus, Book III, ch. 31 (16) and Mappae Clavicula, Recipe 263-A(17)). These two technical treatises are so extensive that, had the chemical tinning process been known, they would almost certainly have described it.

One other technique should be considered and that is coating the bronze object with a slurry of cassiterite (tin oxide) and heating in a charcoal fire. It is possible that this method was used in the Bronze-Age period, when the evidence for the knowledge of tin as a metal is meagre, and Charles has suggested that the addition of tin to copper to make bronze may have been made directly from the tin ore(18). In fact Craddock has suggested the use of tin oxide as the likely

technique for the tinning of an early Bronze-Age flat axe from Barton Stacey (Hampshire) which he has recently examined(19). Nevertheless, by Roman times tin as a metal was common, and there is no reason to postulate any technique, other than use of the molten metal, for most tinning operations from then until modern times.

The Technique of Gilding

Almost without known exception, the technique used to gild silver and copper alloys during the Anglo-Saxon period was that of mercury-or fire-gilding. There are two methods of carrying out the process, but the end products look the same and are usually indistinguishable by scientific methods. In the first of these methods the base metal object is thoroughly cleaned and then a gold amalgam (an alloy of gold and mercury) is applied to the surface. The gold amalgam is made by dropping gold leaf or gold fillings into boiling mercury, and when the amalgam has cooled it is rubbed onto the cleaned surface.

The medieval author Eraclius gives one part of gold to seven of mercury as the correct proportions for the amalgam(20). Although the Eraclius manuscript is known in various versions, scholars are generally agreed that it is a workshop manual which was continually being added to over a long period of time. However, the oldest parts seem to be tenth or eleventh century and so ante-date Theophilus (21). It is quite likely that the proportions of gold to mercury quoted by Eraclius represent a working norm of some considerable antiquity, although, surprisingly, the Mappae Clavicula does not give any proportions in its description of fire-gilding.

Once the amalgam has been applied to the surface the object is heated, causing the mercury to evaporate and leaving a firmly bonded layer of gold on the surface which is ready for burnishing.

In the second method the same end result is obtained by first amalgamating the surface of the base metal object by rubbing clean mercury over it. This process is not easy to carry out, and the surface is more easily amalgamated by dipping the object into a solution of a soluble mercury salt (e.g. mercuric nitrate), but the actual date of origin of this modification of the technique is uncertain. Once the surface is amalgamated gold leaf is laid on top. The gold leaf at once dissolves in the mercury and several layers should be added, each being pressed onto the surface with a piece of smooth leather, until no more will readily dissolve. The object is then heated as before.

One great advantage of fire-gilding as a technique is that it can be used to gild selected areas of a surface, and the technique can usually be identified analytically by checking for the presence of mercury, traces of which always remain in the gold after heating. (This test is not an infallible indication of mercury gilding as the mercury may be present for other reasons. See ref. 1.) By a combination of microscopic examination and either emission spectroscopic analysis or X-ray fluorescence analysis, fire-gilding has been positively identified as the technique used on a dozen silver brooches from the Anglo-Saxon cemeteries at Howletts and Chessel Down(22) and on various items from the Sutton Hoo Ship Burial(23), as well as on several other miscellaneous brooches and objects from the same period.

Gilding and Tinning on the Sutton Hoo Shield and Helmet

One of the unusual technical features of the finds from Sutton Hoo is the fact that on the helmet, and especially on various metal fittings on the shield, both gilding and tinning occur as adjacent surface decoration on the same piece of bronze. The largest area of tinning appears on the foot of the bird plaque, where the foot and talons are tinned and the leg is gilded, but the flying dragon plaque and the various parts of the handgrip assembly on the back of the shield

are decorated with ribbons of tinned surface which wind their way over an area which is otherwise gilded. Figure 1 illustrates the flying dragon from the shield and the ribbon of tinned decoration is picked out in a heavy stipple. (This illustration is not an exact representation of the decoration on the surface, but it shows the relationship of the gilded and tinned areas to one another.)

The close association of the tinned and gilded areas at once raises the problem of which layer was applied first, and how the second was then applied without damaging the first. This problem arises because of the very similar temperatures at which tinning and fire-gilding are carried out. Tin melts at 232°C and mercury boils at 357°C, so the two processes must be carried out slightly above these respective temperatures. Laboratory experiments have shown that attempts to tin on top of mercury-gilding result in a destruction of adjacent parts of the gold layer, and as heating a tinned layer to much above 232°C causes the tin to diffuse into the copper substrate, the existence of the two techniques together seems to be technologically impossible.

Nevertheless, emission spectrographic analysis proved that the techniques ARE tinning and fire-gilding. However, it also showed that the tinned surface layer contains some copper, and so this layer was examined by X-ray diffraction analysis in order to attempt a characterisation of the actual metallic phases present. Analysis of eight samples from tinned areas of the bronze components on the Sutton Hoo shield showed that the so-called "tinning" is, in all cases, a copper/tin alloy in which the ratio of tin : copper varied between approximately 2:1 and 1:4. Now copper/tin alloys of these compositions (i.e. tin in the approximate range 30% to 80%) are hard and white and have melting points in the range 530°C to 750°C.

The high melting points of the alloys found in the tinning layer is the clue to the appearance of the tinning and gilding side by side, because once a bronze has been tinned using a high tin/copper alloy with a melting point greater than about 500°C it becomes possible to carry out fire-gilding on adjacent areas without destroying the tinning. The question remains as to how the tin/copper alloy was applied, and the answer is that it was made in situ.

Although Jope has reported the existence of iron objects which are thought to have been fusion plated with bronze, and claims that the process is simple to carry out(7), the high melting point of a normal bronze (about 1020°C for a 10% tin bronze) would make the process very difficult compared with tinning by the same technique. Even bronzes with much higher amounts of tin, such as those found on the Sutton Hoo shield, would not be easy to use for fusion plating, although laboratory experiments have shown that addition of lead will lower the melting point so that fusion plating becomes possible. However, lead is not present in the tinning on the tinned and gilded items from the Sutton Hoo shield.

In a discussion of the manufacturing technique of Etruscan mirrors, Panseri and Leoni suggested that during the tinning process the rapid interdiffusion of tin with the bronze of the mirror would result in the formation of a tin/copper alloy on the surface, rather than just a layer of pure tin(24). To some extent this is true, but experiments have shown that the tin layer becomes much harder by prolonging the heating at a temperature below the melting point of tin. This should be done in the absence of oxygen (for instance by heating under charcoal) when further interdiffusion of the tin and copper takes place so that the effective melting point of the white alloy layer on the surface gradually rises to well in excess of 500°C. It is important not to overheat the tinned object, otherwise the diffusion of the tin becomes so rapid that the white surface layer is lost completely by absorption into the bronze.

As far as the finds from Sutton Hoo are concerned, we can postulate that the bronze ornaments on the shield must have been tinned first, then subjected to a heating process (probably for several days) and finally gilded in selected areas.

Careful examination of the objects shows that the final cleaning up operation was so thorough that the junctions between the gilding and tinning are virtually perfect. However, the craftsman overlooked one small area on an animal snout on the hand-grip. Here the gilding can clearly be seen to overly the tinning in a very small area where the gold, which was deposited in the wrong place, has not been cleaned off.

Ever since the Sutton Hoo royal grave was first excavated in 1939 the technological achievements of the jewellers and craftsmen who created the personal ornaments of the king have excited the admiration of scholars, and this examination has added yet one more to the list of subtle techniques with which the Anglo-Saxon craftsman was familiar.

Acknowledgements

I am grateful to several of my colleagues for stimulating discussions, but especially to Miss M. Bimson and Mr M.R. Cowell for their analytical contribution.

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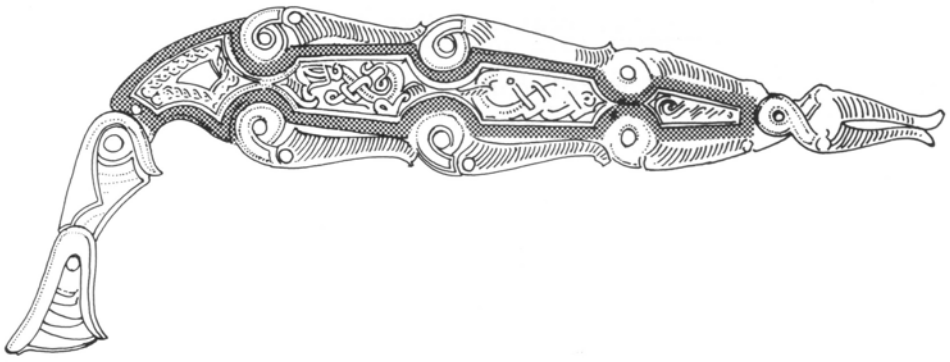

Figure 1

The 'flying dragon' plaque from the Sutton Hoo shield. Scale 1:2 The ribbon of tinning is shown in a heavy stipple. The rest of the surface of the bronze is mercury-gilded.

GOLD AND SILVER IN THE ROMAN WORLD

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This paper is divided into the following sections:

1. Gold

Gold became known in the Aegean during the early Bronze Age. As in modern times, gold supplies were obtained either from the alluvial detritus of gold-bearing rocks, known as placer gold, or from the mining of auriferous rocks, known as reef gold. The methods of obtaining gold from placers are simple; the earth has to be sifted and washed away until only the gold is left. Reef gold must first be broken up and then sifted to free the gold. Native gold is not pure; it is usually an alloy of gold and silver with some copper and iron; the proportions of the alloy vary considerably (1).

Several methods of refining native gold were known to the ancients; but the history of their use is not clearly established. Cupellation was used to get rid of the base metals by oxidation processes, and improved methods, known as liquation and amalgamation, which requires the use of mercury, were introduced in Roman times. The next step - the separation of gold and silver - was carried out by two processes, the salt process and the sulphur process; in both of these the sulphur or salt are used to react with the silver leaving behind refined gold. After refining, the alloy could be tested by use of the touchstone, and assay by

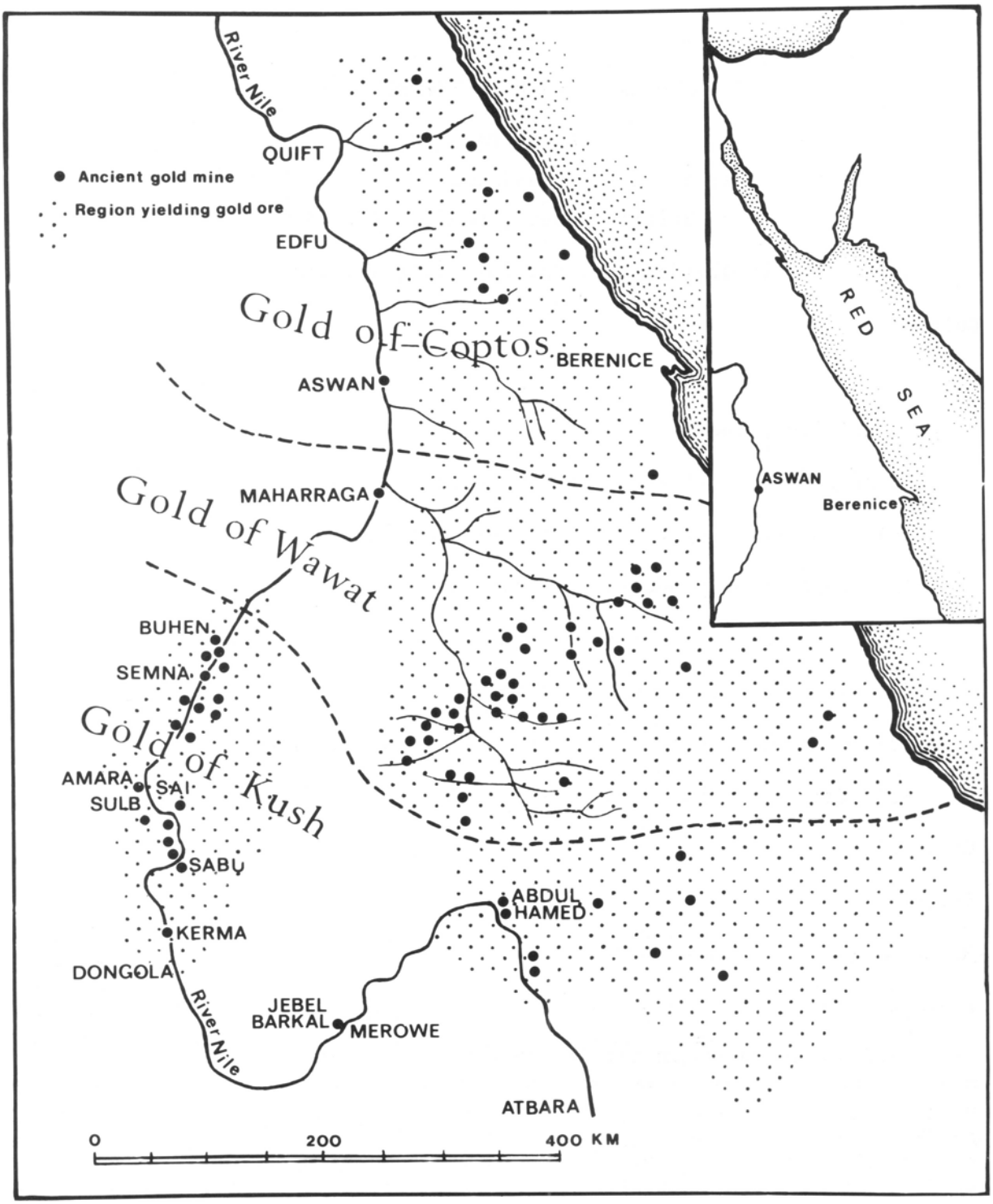


Figure 1. Gold sources and ancient workings in Egypt

cupellation may also have been practised. By classical Greek times certainly, the refining of gold had been brought to a high pitch of skill (2).

In the Bronze Age local sources of gold in Greece and the Aegean islands were probably being exploited; but gold from Egypt, where the main deposits are on the Red Sea coast and in the Nubian desert, was almost certainly imported (Fig. 1). In archaic and classical times a few of the Aegean islands, especially Siphnos and Thasos, and the coastal regions of Thrace and Macedonia were the principal local sources of gold for the Greek world and these sources were much coveted by rival

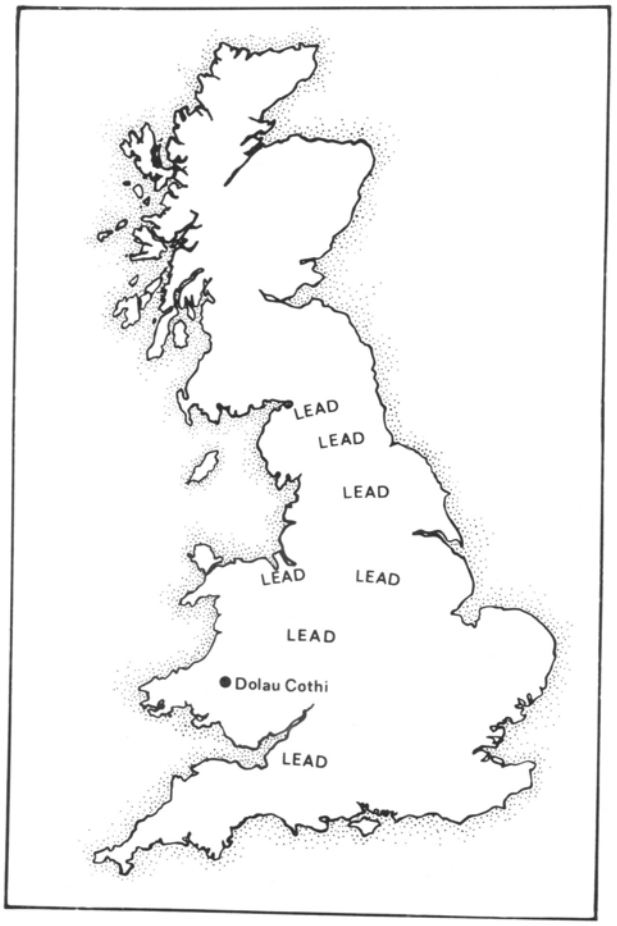


Figure 2. Ancient gold mines and sources of silver bearing lead in Britain

powers. The classical Greeks also seem to have obtained some gold from Asia Minor, and gold from the Altai mines probably came to them indirectly via the south Russian colonies. In Hellenistic times the widening of Greek horizons brought with it direct knowledge of the gold of Afghanistan, Turkestan and India. Nubian gold became a monopoly of the Ptolemies, and the riches of the Seleucids depended largely on eastern sources of gold and silver (3).

The Romans were able to exploit most of the same sources while developing new mines in Spain, the Danube provinces and even in Britain (Figs. 2 and 3). The gold of Dacian mines which flowed into Rome at all times came briefly under Roman control as a result of Trajan's campaigns (4). The Nubian mines were worked under a state monopoly; some late Roman ingots with assay stamps in the British Museum include two of the late third century A.D. from Aboukir (BMCJ, nos. 3148-9) (5). From the fourth century there was a great increase in the quantity of gold in circulation, particularly in the form of coinage; but nothing is known of the exploitation of any new mining areas or of the specially profitable secondary working of old ones. The increase was probably due, in Constantine's time, to the impounding of treasures in precious metal that had been stored in numberless pagan temples, and, in his successors' time, to the increasing insistence of the imperial government on the payment of taxes and other dues in the form of gold (6). The Roman-controlled output of gold perhaps did not exceed that of the Graeco-Persian period, and it might even have fallen short of it; but the addition of Roman to pre-Roman stocks must have resulted in a most formidable accumulation. The steady drain of gold from the Empire to the east and north, while it certainly diminished the amount in Roman hands, did not, for a long time, reduce the stocks to a really dangerous level.

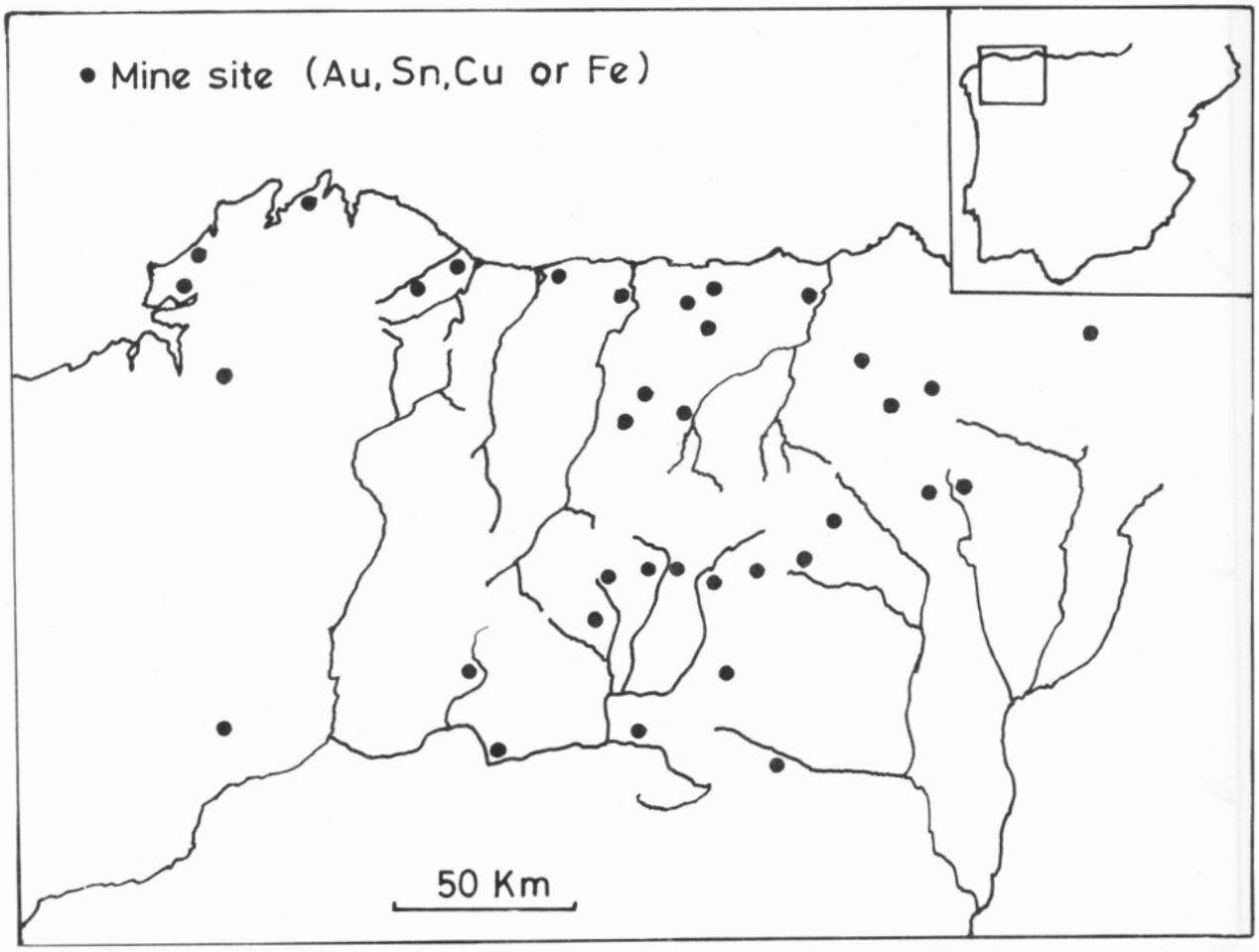


Figure 3. Roman gold mines in the north west of Spain
(after Lewis and Jones, 1970)

From about AD 500 to 700 there are good reasons for supposing that the supply of newly mined gold in Western Europe fell considerably, but there was sufficient gold in general circulation to allow the continuation of gold currencies in France and Spain and to encourage the brief revival of similar gold currency in Britain, and to give scope for the still quite varied and often highly skilled activities of jewellers and goldsmiths (7). Gold for these purposes would have been secured from existing stocks of currency in the west, from the melting down of older treasure of different sorts, from the importation of some quantity at least of gold from the eastern Mediterranean, whether in the form of Byzantine coins or as bullion direct from Egypt or Arabia via Syria, and to some extent from the continued washing of western rivers, especially in Spain, France and the western Alps. There were already signs, however, that the gold supply could not keep pace in Western Europe with the expanding economies of the new powers now consolidated there. In the mid-seventh century, for example, the Merovingian coinage of France became debased from gold into silver, and there was clearly not enough gold available generally either to furnish or to guarantee an economy based on gold coins. Thus the supply of gold in the west had reached a point of scarcity at which gold currency became impossible, and even jewellery became very rare. This western lack of gold was in fact to continue more or less acutely for five centuries from about A.D. 700 (8).

A major cause of the decline of the gold supply in the west was that the Empire in the East, unshaken by the collapse of the western half of the Roman world, had embarked on a period of commercial prosperity as a result of which Constantinople

rapidly became the centre to which a large and constant importation of luxuries became attracted. These luxuries had to be paid for in gold. It was natural, therefore, that the maintenance of a large and pure gold currency should be the basis of Byzantine stability; and the gold coined at Constantinople was famous for its extraordinarily high purity from the time of the collapse of the Western Empire in the fifth century right down to the eleventh (9). The many costly imports during this period suggest that Byzantine gold must to some extent have been obtained on very favourable terms from areas where its price was comparatively cheap. Two such areas could be exploited. The first could be tapped easily and directly, for Constantinople was well placed to receive whatever could be attracted from the perennially great resources of the Caucasus, via Colchis and Trebizond, and Central Asia, via the steppes down to Crimea; thus, for goods or services, as when Byzantine craftsmen were employed to build and fortify a Khazar town on the Sea of Azov, gold from the Urals could be released in return, while the gold of the Caucasus was open to entrepreneurs from Trebizond itself. The second area lay in Africa, and consisted of Nubia and Ethiopia. Here the trade in gold lay in the hands of Egyptians, who brought it northward down the Nile valley. The gold of Africa, being brought from more remote sources, was naturally the more precarious supply of the two, and even in the north the menace of nomad invasion from the steppes was never far removed.

Nevertheless, even though much of the African gold probably never got much farther than Egypt and Syria - centres, at this time, of notable luxury and the greatest manufacturing activity - Constantinople and its empire were certainly assured of very large supplies by one means or another, as is shown by her long record of great prosperity and the paramount fineness of her gold coinage, so much of which was minted only to disappear for ever into Persian or Arab possession in the Levant hinterland. The reserves did vary and even fluctuate seriously, as when African sources were interrupted; but even after the Arabs had overrun Egypt in the middle of the seventh century, the gold coinage of Constantinople continued equally pure, however much its volume might tend to alter. Indeed, it is likely that the Arabs, enriched by Syrian and Egyptian gold booty, and thus bringing it westward in their swift passage along the north coast of Africa into Spain, actively benefited Byzantium, for the gold thus introduced into Western Europe enabled Western courts to trade it back to Constantinople for the Byzantine luxuries which they required.

The evidence of the currency is confirmed by the knowledge of the immense wealth in gold which could be accumulated by the Byzantine emperors themselves and even by their subjects; and the richness and profusion of the work of Byzantine goldsmiths tells the same story. The Emperor Anastasius at his death in AD 518 left a personal treasure of 320,000 lb of gold. When, to figures such as these, there are added private holdings of gold often in the region of 2,000-3,000 lb, together with the great stocks of gold held as church treasure, it is clear enough both that the Byzantine Empire was rich in gold and also that this very richness was itself a cause of the gold famine which spread over Western Europe after about AD 700, for all possible gold was being brought to Constantinople as an element in her trading structure (10). It was, nevertheless, inevitable that a consumer economy so luxuriously unbalanced as that of Byzantium should sooner or later fall into difficulties with the supply of gold. Heavy imports, a remarkable scale of internal luxury, frequent and costly wars, and subsidies to foreign powers seemed for a considerable time to cause no very serious damage; but the elements of ultimate collapse were building up formidably, and serious trouble finally became apparent in the eleventh century when the standard gold coin of the Byzantine Empire, the 'bezant', was alloyed up to an amount of 30% over a period of 40 years (11). The collapse stemmed from the seventh-century Arab conquest of the Middle and Near East, which wholly dislocated the structure on which much of the previous Byzantine prosperity had been based. The Arabs quickly absorbed great accumulations of gold, some of which in other circumstances would normally have been traded back to Constantinople. Their conquest of Persia and Syria in the seventh century AD was

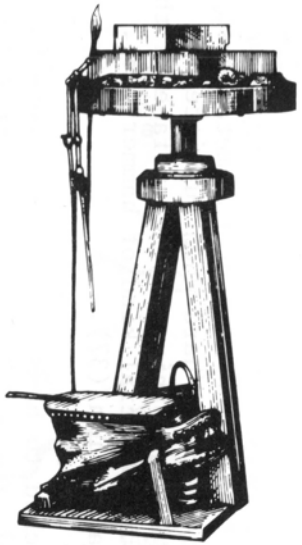
immediately reflected in the establishment of a gold coinage, of great purity- about 97 per cent - and ultimately great profusion, which quickly attained the status of a major international medium, eventually rivalling and even exceeding that of Byzantium in its range and penetration (12). For the Arab invaders the possession of large stocks of captured gold offered either the transition to instant habits of personal luxury or the opportunity of taking from the Byzantine Empire whatever could be taken of her widespread commercial habits. They chose the latter course, and in doing so set themselves up as a trading race of enormous activity and success. This achievement was signalled at the end of the seventh century when the first Arab gold coins appeared under the Caliph 'Abd al-Malik at Damascus, the immensely rich capital of the Umayyad dynasty. At first they imitated contemporary Byzantine types, but almost at once changed to the form in which Arabic dinars were to be famous for hundreds of years to come, not only in the Levant and Africa, but in Europe as well, with all pictorial ornament religiously excluded in favour of quotations from the Koran (13).

2. Silver

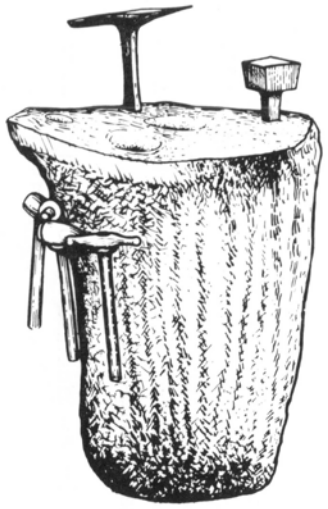
Silver, from the early Bronze Age and throughout ancient times, was obtained almost entirely by smelting lead ores and then separating the silver they contain (14) The commonest of these lead ores is galena (lead sulphide, PbS), which occurs in surface deposits in many parts of the classical world and could also be mined from deeper strata. The most famous of the deeper deposits of galena were the mines of Laurion in Attica, which are said to have had more than 2,000 shafts, some reaching to a depth of 250 ft. After mining the ore, crude lead was obtained by smelting and this was then purified. The lead will contain something between 20 and 200 ounces of silver per ton, the latter being the highest figure estimated for the Laurion mines, and it was desilvered by a process which involved two stages: (a) smelting of the galena to produce lead metal which was tapped off and allowed to cool, and (b) the cupellation of the lead metal, involving oxidation of the lead and other base metals with a blast of air. It is thought that the Romans could desilver lead down to 0.06% (15).

Occasional analyses show that silver was sometimes artificially alloyed in the manufacture of plate, since pure silver is generally considered too soft for making vessels (16). However in Roman times the silver used for plate was surprisingly pure, corresponding perhaps with the alloy of the contemporary coinage (17). Under the early Emperors this was very fine, 95-99 per cent, though Nero alloyed it with 10 per cent copper (18). In later times it dropped much lower, coming down to as low as 80 per cent at certain periods. A high standard of purity is found in the silver plate of the late Roman hoards. Three analyses carried out on the Traprain Law hoard gave 94.08, 96.2 and 95.3%; the Mildenhall and Water Newton hoards of silver plate similarly contain an average of 95-97% silver (19). The consistently high silver content in manufactured plate is explained by the fact that the Romans of the Empire collected plate as a means of hoarding their wealth; in the late Empire, as the hoards of broken silver ('Hacksilber') show, a great deal of plate was reconverted into bullion and it is in this period, the fourth century AD, that there first appear what seem to be assay marks on manufactured plate, which, like the mint marks on gold and silver ingots, were a guarantee of the quality of the alloy in the piece (20).

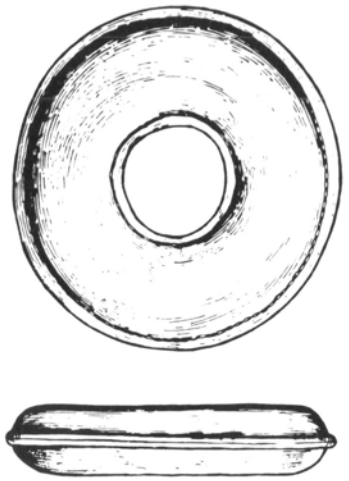
There are very widespread surface deposits of galena in Asia Minor, which is generally thought of as the home of silver production, and which was certainly exporting large quantities of silver from the third millennium onwards (21). In Bronze Age Greece local sources of silver must have been in use; some of the Cyclades - Melos, Paros and Thera - were probably producing silver. It is uncertain whether the mines of Laurion were in use at the time; if so, they went out of use



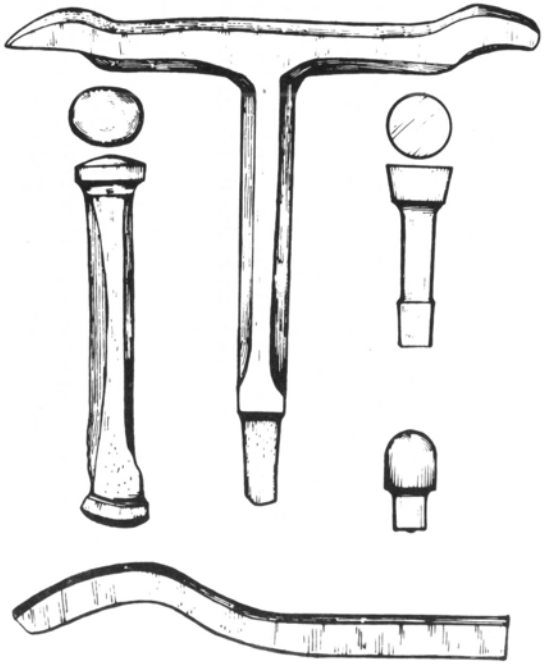
a Modern turntable hearth with bellows and blowpipe



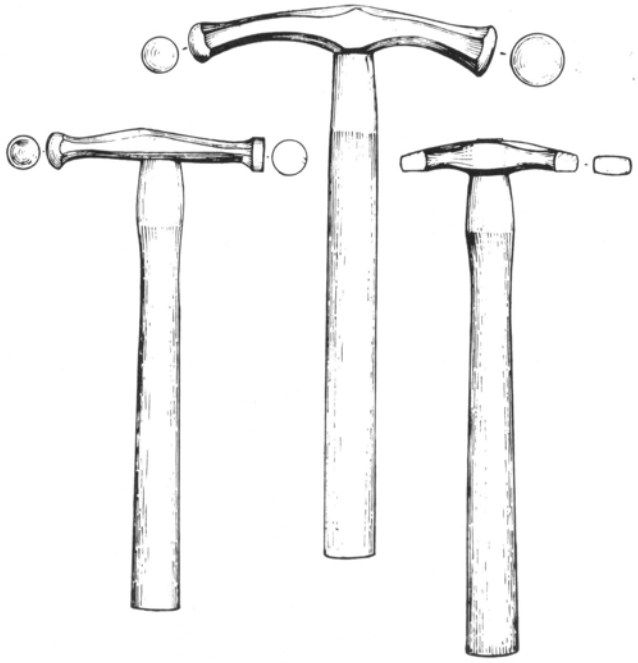
b Steady block with anvils and stakes



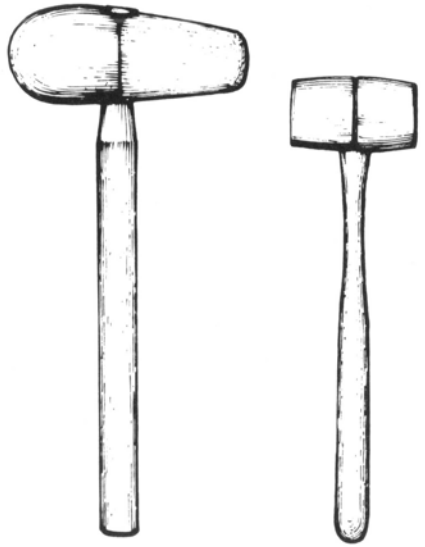
c Leather ring-pad for blocking and raising



d Stakes for raising and planishing



e Hammers for planishing, blocking and raising



f Wooden mallets

Figure 4

again until the sixth century B.C, and the richest seam was not revealed until 483 B.C. The mines of Cyprus were not apparently used in Mycenaean times but were certainly exploited later (22). We have no definite evidence about the Spanish mines before they were worked by the Phoenicians, and the first record of Spanish silver being acquired by Greeks belongs to about 650 B.C. (23). After the collapse of the Mycenaean world the supplies of precious raw materials in the Greek world had evidently been interrupted; but the spread of silver coinage in the eighth and seventh centuries shows that these metals were becoming common again.

As in the case of gold, the conquests of Alexander and the activities of prospectors in his retinue opened up rich new sources of silver, and in Roman times, as Pliny notes, almost every province was producing the metal. Spain was certainly the principal source; the rich mines started by Hannibal were acquired by the Romans after the Second Punic War and remained very productive. Augustus opened up new mines which were either let to contractors or run directly under Imperial control. Of the other provinces, Britain produced a good deal of silver (24). Lead pigs found in the province bear inscriptions stating that they were cast from the residue of the desilverisation process (25). The Danube provinces, Asia Minor and Macedonia continued to be the principal sources for the Roman world (26).

3. Craftsmens' Techniques

There is no contemporary treatise on the techniques used by ancient craftsmen with the one notable exception of the fourth-century Leyden Papyrus X from Egypt (27). We draw our evidence, therefore, from the objects they produced, from contemporary literary sources, of whom the most important is Pliny the Elder, and by analogy with later techniques (28). An important later source is the book of the medieval monk Theophilus of the twelfth century, which describes the work of a medieval craftsman of the day and probably makes use of ancient technical treatises as well. Much of what he says may be taken to apply to Roman times (29).

In the workshop the source of heat was probably an open charcoal fire with some means of making a forced draught to raise the temperature, such as a blow-pipe or bellows (Fig. 4a) (30). The work to be heated was placed in the fire, sometimes in a clay crucible (31). The principal tools were an anvil of metal or stone (Figs. 4 and 5); hammers for beating sheet metal and for driving punches of different shapes and sizes; stamps and cores; moulds for beating and for casting; chisels; engraving-tools of stone or iron; tongs; files; abrasives; burnishing-stones; scales; crucibles of clay; and a bowl of pitch (32). At some point a drawplate for making wire may have been introduced (33).

The basic techniques in ancient times for manufacturing gold and silver vessels are the same as those employed by craftsmen today. The most important is the process of raising (Figs. 4 and 5a-d) which consists of hammering a flat disc of metal supported on a stake into the shape of a vessel by means of a series of concentric hammer blows from the outside (34). During the process the metal must be frequently annealed and allowed to cool, since it becomes hard when submitted to repeated blows and will eventually crack (35). The smoothing of the surface of the vessel is known as planishing, which is done with a special kind of hammer (36). Various fine abrasives are used to give the final polish (37).

The casting of feet and handles to be attached to hammered vessels seems to have been introduced in the archaic Greek period, around 600 B.C. From about the fifth century B.C. onwards the bodies of metal vessels were sometimes cast (38). The method demands the use of a lathe to clean up metal surfaces, and also to produce patterns (eg. on the bases of paterae) and this seems to have been known as early

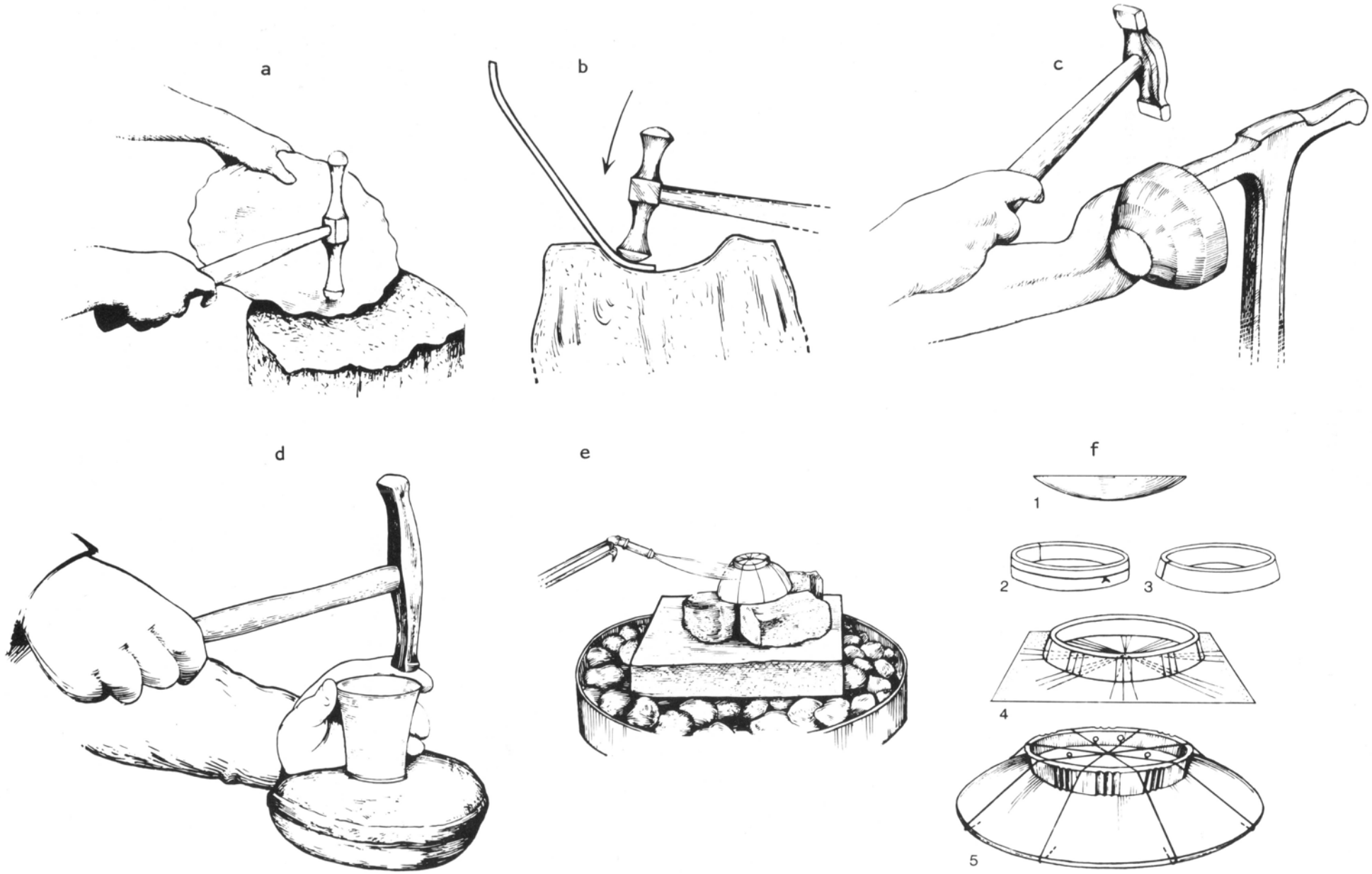


Figure 5

a - d Blocking, raising and thickening the rim of a vessel

e - f Soldering a base-ring to a vessel

as the fifth century BC (Fig. 6a-c) (39). In Roman times casting seems to have been commonly used, not only for decorated vessels but also for plain dishes and bowls (40)

A fast revolving lathe many also have been used for spinning, a process which is in common use among manufacturing silversmiths today (41). In this process sheet metal is forced into the shape of a prepared form set up on a lathe and it would have been especially suitable for the mass-production of little perfume pots and the like. However spinning is a process which needs a great deal of power, which may not have been readily available to silversmiths in antiquity.

The basic components from which ancient jewellery is composed are sheet metal, wire, and - to a lesser extent - castings (42). Most pieces consist of a number of separately made parts. The various parts both of vessels and of jewellery were attached to one another by means of rivets or by the use of solder (Fig. 5d and e). The two types of solder used are known as hard solder and soft solder. Hard silver solder is made by alloying the metal with copper, and gold solder by alloying the gold with copper or copper and silver. Soft solder, which is composed of lead and tin, does not seem to have been used until Hellenistic and Roman times (43).

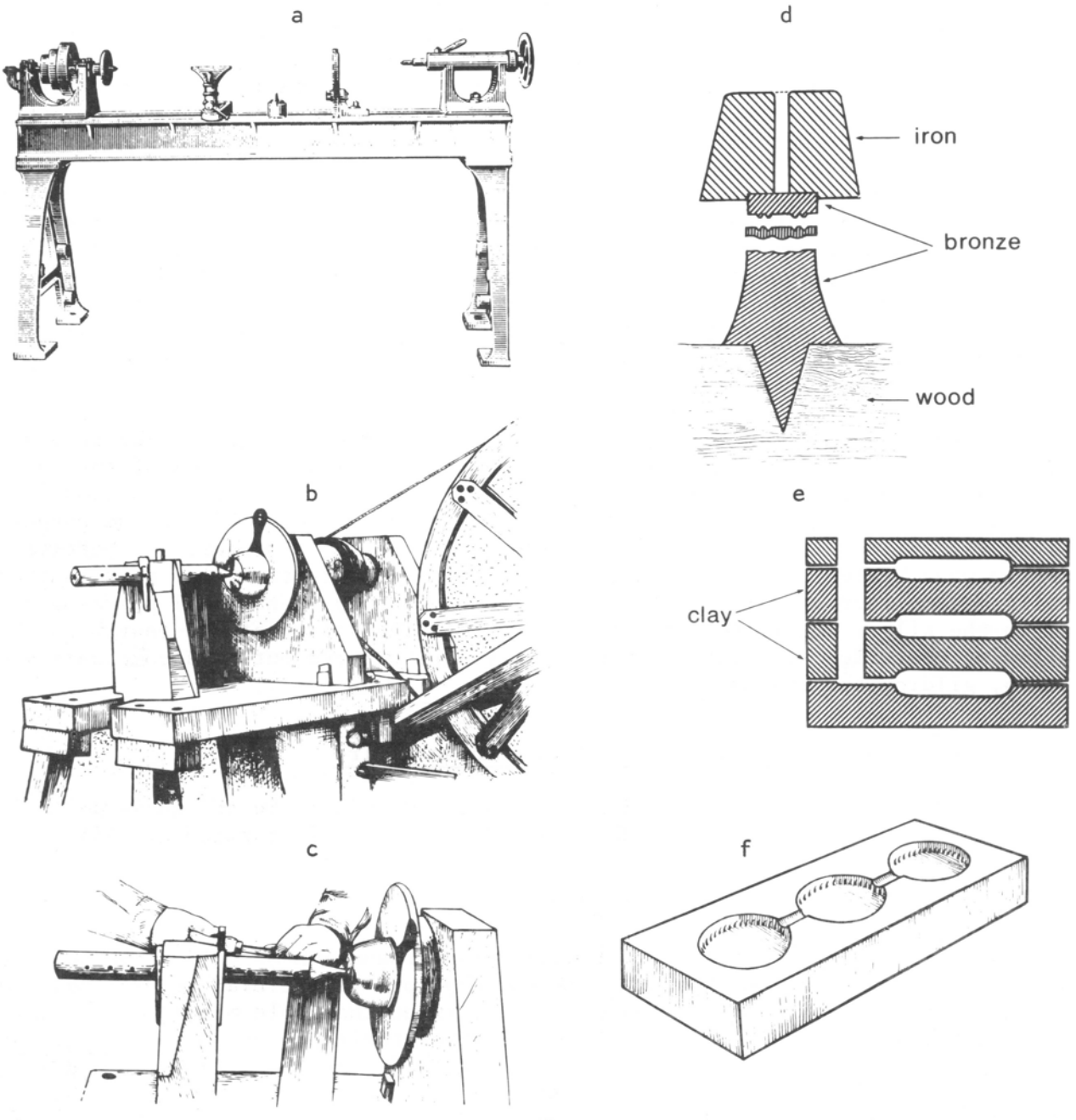
Methods of coin production included both casting and striking (Fig. 6d-f) (44). Some coins were made solely by casting; but in general in the Roman period it is likely that the casting process was confined to the manufacture of blanks (45). The blanks were then struck between a pair of dies. The dies themselves, particularly if they were of bronze, would wear fairly quickly, and the idea that the dies themselves were produced from an iron or steel master is an attractive one; but the majority of dies surviving from the Roman period are fashioned from a high tin bronze (46). A major problem in the manufacture of coins from dies is the maintenance of the relationship of the two faces to each other. This alignment may have been achieved in some cases by leaving a small projection on the dies, or in other cases by hinging together two bars with the dies correctly aligned at the other ends ready to be struck on the blank by the hammer; but even where dies seem to be aligned there is enough variation between the obverse and reverse axes to show that the trussel was more usually detached and positioned by eye (47).

Surface decoration on gold and silver is carried out by means of flat chasing, which is done with the aid of hammers and punches (Fig. 7a and b) (48). In this process, no metal is removed from the vessel, a line being composed of a series of oblique indentations of the punch. The term may be used to cover a variety of different effects, from simple linear patterns and elaborate geometric and floral designs to the achieving of low-relief designs of the surface of the metal. This was the technique apparently applied to heavy metal vessels such as the Oceanus dish from Mildenhall (49). The metal must have been held on a hard unyielding surface, such as a metal anvil, and the design was then drawn out on the front. The background was next driven down, leaving the figures in relief to a maximum height of one-sixteenth inch, and the final details were modelled with chasing tools.

Engraving with various fine pointed tools was used to draw designs on metal from the fifth century BC (Fig. 7d-f) (50). In the process of engraving the metal is actually removed by cutting the line. For this reason it may be grouped together with the process of cold tooling, which involves carving and chasing relief designs in solid metal. This technique was probably used from the first century AD onwards and was especially popular in the workshops of Roman Gaul during the third century AD.

Decoration by repousse relief involves hammering metal from the back to leave the design embossed on the front (51). Repousse ornament, however, was already on the decline in Pliny's day, in the first century AD, and by the third century casting

Figure 6



a Modern lathe

b Use of the lathe for finishing a vessel

c Hypothetical reconstruction of an ancient lathe

d Striking a coin

e & f Moulds for casting coins or blanks

to a convenient basic form was the first process in most cases, even if the vessels were afterwards decorated in relief, whether in repousse or worked from the surface. The technique of solid cast applied figures seems to have been introduced in Corinthian metalwork at the same time as cast handles and bases, about 600 BC. By the fourth century BC, if not before, relief decoration on silver vessels was commonly carried out by casting, and in late Hellenistic and Roman times the methods of thin hollow casting by the lost wax method had been brought to a high pitch of skill. The series of plaster casts from ancient metalwork seem to have been distributed with a view to preparing moulds for casting cups and other vessels. The relief decoration on handles of saucepan-paterae is usually cast; a number of steatite moulds have survived, which must be connected in some way with the mass-production of these handles (52).

Various forms of inlaying and overlaying were used for decoration. It is not known when gilding with the use of mercury was first employed. It has been reported on vessels of the fourth century BC and was probably in use in Hellenistic times; but it was not in universal use until the third century AD. In this process the gold and mercury form an amalgam which is painted on to the surface of the silver. When the mercury is evaporated a thin film of gold remains fused to the silver. In Roman times, when mercury was available on a commercial scale, this was the normal, but not the universal, method of gilding silver (53).

Inlaying of silver with other metals was also practised (54). The recesses of the inlay were prepared either by stamping or cutting and the edges of the recesses were usually bevelled to hold the gold or copper inlay in position. A common form of inlay on silver in the Roman period is a black compound of silver and copper sulphides, called niello, which is inlaid in the form of a powder. It becomes plastic when heated but sets hard on cooling, and is burnished to a final surface. Niello became increasingly popular in the third century when floral patterns were cut in the silver and filled with niello, and in the silver of the fourth and following centuries elaborate figured scenes were carried out in a combination of niello, gilding and engraving.

4. Aspects of Gold and Silver in the Later Roman Empire

The preceding sections have discussed gold and silver in the Roman world in general. What follows refers to the later Roman Empire in particular (55).

4a. Production of Gold and Silver: Mining

An example of the attempts to increase the production of gold is to be found in the actions in the fourth century of the emperors Valentinian and Valens. In 365 these brothers, in a concerted enactment, ruled that gold miners should pay a tax of 8 scruples per annum, and sell the rest of their product to the largitiones, from which they would receive 'an equitable price', presumably in debased denarii. Valentinian hoped that on these terms volunteers would take up the trade, but compulsion was soon required to recall workers who had strayed from the industry into agriculture. In 370 Valens ordered all runaway miners to be combed out throughout his dominions, even from the lands of the res privata, and his brother loyally ordered Petronius Probus to track down and return all Thracian miners who had found refuge in Illyricum and the Macedonian diocese. Similar measures were taken in the west, where for reasons unknown miners attempted to escape to Sardinia: the praetorian prefects of Italy and Gaul were instructed to order the governors of maritime provinces to keep a strict watch on the coast, and masters of ships were to be fined 5 solidi for every miner to who they gave a passage (56).

Figure 7

a & b Tools and technique for chasing

c to f Tools and technique for engraving

The organisation of mining in other respects in the later Roman Empire is similarly obscure. The important gold mining areas in the western Balkans were under the control of the comes metallorum per Illyricum, and under him there were in the provinces of Macedonia, Inland Dacia, Upper Moesia and Dardania procuratores metallorum who collected their dues from the miners: the office was filled by decurions supplied by the city councils. No similar organisation is recorded for the adjacent gold mining areas of the Thracian diocese, or elsewhere. Some gold mining areas (metallica loca) were state property, but they might be acquired by private persons, who were bound to carry on production. Nothing is known of the organisation of the silver mines (57).

4b. Control of Production, Collection and Distribution: the Comes Sacrarum Largitionum

The state thus obtained some of the gold, and probably some of the silver, required for the mints from mines which it owned itself. These mines and the mints were controlled by the comes sacrarum largitionum (58), together with the state factories in which arms and armour were decorated with the precious metals. The same official collected such old money taxes as survived the inflationary period, and other levies in gold and silver which were devised subsequently. He was responsible for paying the periodical donatives in gold and silver which the troops received, and probably also the cash stipendia, so long as they survived, of solidiers and officials. He also handled the collection or production of clothing, and its distribution to the court, the army and the civil service.

This last function seems somewhat incongruous for a department which was otherwise concerned only with revenue and expenditure in coin and with the precious metals. The structure of the officium of the comes sacrarum largitionum is known to us not only from the summary notices in the Notitia Dignitatum, with which we usually have to be content, but also from a detailed schedule attached to a constitution of 384, which is preserved in the Code of Justinian. In the former ten principal departments are named. These include two departments concerned with gold, the scrinium aureae massae or bullion department, and the scrinium auri ad responsum; it perhaps dealt with returns of gold stocks in the diocesan depots. Between these the law of 384 lists groups of technical staff, the aurifices specierum or goldsmiths, the aurifices solidorum who minted the gold coins, and the engravers and other craftsmen (sculptores et ceteri artifices). The scrinia argenti and a miliarensibus presumably handled silver bullion and silver coin respectively. The schedule adds the silversmiths of the court (argentarii comitatenses) and the barbaricarii who ornamented arms and armour.

In addition to this central office, the comes sacrarum largitionum had a large staff in the dioceses and provinces. The sacrae largitiones had a number of depots (thesauri) in the provinces, in which gold, silver and other goods (presumably clothing) were collected and stored and from which they were either issued locally or transmitted to the comitatus. These thesauri were also local audit chambers, where retiring directors of mints, managers of state factories and collectors of revenues had to submit their accounts. In the West the Notitia records three thesauri in Illyricum at Salona, Siscia and Savaria, four in Italy at Rome, Aquileia, Milan and Augusta Vindelicorum, four in Gaul at Treveri, Remi, Lugdunum and Arelate, and one in Britain at Augusta (London); none are mentioned in Spain or Africa, but the omission is presumably accidental. No details are recorded in the East but we happen to know that Caesarius, the brother of Gregory Nazianzen, was praepositus thesaurorum at Nicaea, and that there was a thesaurus at Philippopolia in Thrace.

The largitiones received a number of taxes, some old, some instituted by Constantine, whose common characteristic was that they were levied in gold and silver.

Among the old taxes were the custom duties, which, being ad valorem, had survived the inflation unscathed. Another old tax was the aurum coronarium. This was an offering of gold crowns, in theory voluntary, but long customary, made by the cities of the empire to the emperor on his accession and on the quinquennial celebrations of that event, and also on such festal occasions as triumphs. Closely allied to the aurum coronarium offered by the cities was the aurum oblaticium contributed on the same occasions by the senate. Of the new taxes the collatio glebalis or follis, instituted by Constantine, was levied annually on all senators. Another new tax instituted by Constantine was the collatio lustralis. It was, as its Latin name suggests, levied every five years, on the accession and subsequent quinquennial celebrations of each emperor; by the fifth century it was apparently demanded every four years. As its Greek name shows, it was originally paid in gold and silver, but from the reign of Valentinian and Valens it was normally collected in gold only. It fell upon negotiatores, by which was apparently meant anyone who made his living by buying and selling or by charging fees. Those liable were entered on a list (matricula) in each city and elected from among themselves the mancipes who collected the tax; this procedure is confirmed by a law of 399, which states that it was the general practice in most cities. The only clue that we have to the yield of the tax is that Edessa was paying 140 lb in gold every four years when Anastasius finally abolished the tax. The aurum tironicum, or gold levy in commutation for recruits, was paid to the sacrae largitiones: it was normally at the rate of 25 or 30 solidi per man. So too was the commutation for military remounts. It seems likely that the largitiones also received a money tax on land.

The comes sacrarum largitionum was responsible for clothing the court, the army and the civil service. Part of the clothing was supplied by the state factories under his control, but a proportion was provided by compulsory purchases or levies. By the end of the fourth century the issue of uniforms to the army was already in part commuted for gold. Simultaneously the levy of garments was likewise commuted and by 423 was apparently all collected in gold. Apart from the distribution of uniform or uniform allowances the only regular outgoings of the largitiones were the military stipendium, the donative of 5 solidi and a pound of silver per head made to the troops at the accession of an emperor, and the subsequent quinquennial donatives of 5 solidi per head. The department had also to provide precious metals needed for any public purposes. Symmachus complained in one of his despatches that a state carriage decorated with silver had been ordered at Rome, and, as the largitiones had no silver available at the time, it was provided from two Roman treasuries, the arca quaestoria and the aqueduct fund, and from the stocks of private silversmiths. He asked that the comes sacrarum largitionum should at long last refund the bullion.

4c. Imperial Mints and the Coinage

The imperial mints were managed by procuratores, who had to produce guarantors on entering office, and present accounts on leaving it. The metal was provided by the government from various sources. Some of the gold came from mining and washing, either by the gold levy (auraria praestatio) paid by owners of auriferous land, or by the fixed annual tax (metallicus canon) paid by gold washers and miners in the state-owned goldfields, or by compulsory purchase from miners and washers, who were obliged to sell all their product, over and above the tax, to the largitiones. Gold and silver also came in from confiscated or escheated estates either in the form of plate or of coin. The great bulk of the precious metals used by the mints was undoubtedly provided by the levies and taxes in bullion or gold and silver coin. It had probably always been the practice of the imperial government to melt down and remint coins received in tax: it would hardly have been possible otherwise to maintain the constant stream of new issues. From the time of Valentinian and Valens this became an absolute rule for gold. A constitution of 366-7 enacts that all solidi received in tax were to be melted down in the provinces, and the gold sent up to the

comitatus in bar. This was a precaution against clipped or forged solidi being passed by the collectors, but the frequent reminting which the rule necessitated must have been an important factor in maintaining the purity and weight of the solidus.

The great achievement of the imperial government was to maintain a stable gold coinage. The solidus was never adulterated or reduced in weight from Constantine's time until the middle ages. It was indeed in some ways regarded as a piece of pure gold weighing 4 scruples rather than as a coin. People spoke of the copper coins as money (pecunia) and when they exchanged copper for gold or vice versa said that they were buying or selling solidi. The gold currency increased in volume from Constatine's time onward; the various gold taxes (which might be paid in bullion) no doubt extracted hoards and brought then into circulation. By the fifth century there was apparently an ample stock of solidi current. The government was able to commute levies and payments in kind into gold, and gold was used for all major private transactions: even coloni paid their rent in solidi. Prices in gold seem, so far as we can judge, to have remained stable. No significant change can be detected from the fourth to the sixth century.

4d. Commerce and the Circulation of Gold and Silver

A great deal of precious metal was thus brought into circulation throughout the late Roman Empire. How far did it circulate, however, among the population? The Roman empire in many ways provided conditions favourable to commerce. It formed a vast common market, stretching from Britain to Egypt, and even when it was administratively divided no political barriers were set up against trade. Even when the Western parts were broken up into barbarian kingdoms trade seems to have remained free from political difficulties. In the early seventh century there were still Alexandrian merchants who specialised in the Gallic trade, and at the other end of the route at Marseilles there were still in the late sixth century regular imports of papyrus, which must have come from Egypt, as well as of oil, which probably came from Africa; wines from central Italy and Gaza were also imported into Gaul. The Alexandrian merchants who specialised in the Spanish trade seem still to have continued their activities in the sixth century: we hear of 'Greek' merchants landing at Spanish ports and coming up to Emerita, and the Visigothic kings were liberal to overseas merchants, allowing them to settle their own disputes between themselves according to their own laws, and to employ local men as agents, provided that they did not take them overseas with them. There were also no currency difficulties to hamper large-scale commerce. Imperial coins wherever minted were legal tender throughout the empire. There was an excellent road network, and roads and bridges were maintained by the government at the expense of landowners. Tolls levied were not excessive.

While conditions were in these ways generally favourable to trade, there were on the other hand important factors which restricted private commerce. In the first place the imperial government, the greatest consumer, made virtually no use of the private merchant, supplying the major needs of its hundreds of thousands of employees by levies in kind upon the producers, by manufacturing some parts of its requirements in state factories, and by conveying the goods thus levied or manufactured to their recipients by means of state transport services.

The state, and to a lesser extent great landlords, thus cut a considerable sector out of the market by supplying their own needs directly. In what remained of the market private commerce was hampered by two important factors, the high cost and slowness of transport and the low purchasing power of the mass of the population.

The vast majority of the population of the empire were peasants, whose standard of living was low and whose needs were simple. The working classes in the towns

seem to have been as poor, to judge by the difficulty they had in paying a solidus or two every four or five years for the collatio lustralis. This meant that the global demand for manufactured goods was very low. Trade in manufactured goods was even more restricted, for the mass of the population could afford only the cheapest and simplest articles, and these were locally produced.

4e. Craftsmen and the Use of Gold and Silver

Rather superior to the ordinary run of craftsmen were the workers in certain highly skilled trades. The aristocracy of these craftsmen were the goldsmiths, silversmiths, and jewellers, who from the nature of their trade had to carry some stock of expensive goods. Even they, however, did not need to be wealthy men, for they often worked up customers' materials. A story is told of a pious apprentice in a goldsmith's shop. A wealthy patrician ordered an elaborate gold cross set with jewels, providing the materials, and the apprentice in his pious zeal added some gold out of his own wages. When the cross was weighed in the presence of the customer and found overweight, he was accused of alloying the metal supplied: the story ends happily with the patrician adopting the apprentice as his son. We also hear of a deacon who worked as a silversmith at Jerusalem. His shop was burgled and he lost 100 pounds of silver, which would have been worth the considerable sum of 400 solidi. But his distress was all the greater because much of it was not his own property. It was the ambition of the silversmiths and jewellers of the metropoleis to be enrolled among the cohortales of the provincial officium. This seems a humble enough ambition, but Theodosius II indignantly ordered 'every rank and grade to be purged of such contagion.'

Conclusion

It was not, then, for the craftsmen classes that the objects of gold and silver were made. The lavish luxury, however, of the last century B.C. created the dilemma that the success of an emperor and the prosperity of his subjects were judged, both within and outside the frontiers, by the sumptuous use and display, by emperor and by subjects, of gold and silver in the form of coinage, plate and jewellery. These objects, therefore, are direct evidence of the prosperity or instability of the government and the state. They are not a simple index, and the information they supply must be used critically; but gold and silver were used by all, state or individual, as the medium to display or pretend success, and so all surviving objects in these metals provide the maximum evidence in small compass, for the state of the Roman world and its imitators, and on gold and silver can be found expressed the best available art in support of all the current issues of importance (59).

Footnotes

1. Davies (1935); Sutherland (1959); Forbes (1954); Forbes (1971); James (1972); Notton (1974). No ancient Egyptian records describe the way in which gold was extracted there (except for the papyrus map of 1100 B.C. from Egypt now preserved in the Egyptian Museum, Turin); but Agatharchides, a Greek writer of the second century B.C. whose account is preserved by Diodorus Siculus in his Bibliotheca Historica of about 60 B.C., describes methods used in Egyptian mines in later times.

2. Methods of refining gold: (a) Tylecote (1962); (b) Egypt: there is no evidence that the ancient Egyptians used any technique for refining the gold they acquired from their mines and alluvial deposits - James (1972), p. 40; compare Notton (1974) on the value of Agatharchides' account in attempting to establish when gold refining was invented in ancient Egypt.

3. Nature and distribution of gold deposits: Maclaren (1908); Lewis and Jones (1970). Sources of gold in antiquity: Tylecote (1962); Strong (1966); Sutherland (1959).

4. Sutherland (1959); Spain: Jones and Bird (1972); Lewis and Jones (1970), who include a translation and discussion of Pliny's text as an appendix; Britain: Davies (1935); Smyth (1846); Nelson (1944); Carmarthenshire (1917); Jones (1960); Boon and Williams (1966); Lewis and Jones (1969); Jones and Lewis (1971); Dacia: Davies (1935); Boon and Williams (1966); O. Doppelfeld (ed), Die Römer in Rumänien, Köln, 1969.

5. BMCJ nos. 3148, 3149.

6. Jones (1964).

7. Kent and Painter (1977).

8. The debasement was complete by about A.D. 680. Kent and Painter (1977).

9. The subsidiary mints at Antioch and Alexandria ceased to mint gold in the reigns of Maurice Tiberius and Justin II (or possibly Heraclius) respectively. They were both captured by the Arabs in the mid seventh century. The standard of Constantinople gold, however, remained good throughout the period. In the west things were very different. In Italy the composition fell from about 96% gold in the mid 7th century to zero by the mid 8th century, and in Sicily the standard fell to about 80% gold in the 690's, where it remained until about A.D. 835, after which it fell to zero by about A.D. 865. I owe this information to Mr Andrew Oddy. It is based on his lecture to the Royal Numismatic Society in May 1975, and he has kindly allowed me to use it here in advance of publication.

10. Private holdings of gold, personal treasure of Anastasius: Sutherland (1959); Jones (1964).

11. Grierson (1954 and 1961).

12. Burnett (1977).

13. Miles (1967); Grierson (1960).

14. Tylecote (1962).

15. Desilvering process and desilvering level: Tylecote (1962) and personal communication from M J Hughes.

16. Strong (1966).

17. Kent and Painter (1977).

18. Strong (1966).

19. Traprain: Curle (1923), pp. 92-93; Water Newton: H Barker et al in Painter (1977a); Mildenhall: J R S Lang et al in Painter (1977b).

20. Baratte (1975a); Dodd (1961); Painter (1972).

21. Davies (1935); Strong (1966).

22. Cyprus: Davies (1935); Laurion: Ardaillon (1897); Hopper (1953); Hopper (1968).

23. Spain: Bird (1972); Jones (1976); Jones and Bird (1972); Lewis and Jones (1970); Richardson (1976); Davies (1935), especially pp. 107-110 for desilverised ingots.

24. Britain: Davies (1935); Tylecote (1962); Frere (1967).

25. Tylecote (1962).

26. Davies (1935).

27. Leyden Papyrus X: Hunt (1976); Caley (1926).

28. Ancient sources: (a) the Turin papyrus map (Egyptian Museum,Turin) of about 1100 B.C. shows a gold-bearing region in the Wadi Hammamat in the Eastern Desert of Egypt; (b) Pliny the Elder, Natural History, Book XXXIII; (c) Diodorus Siculus, writing about 60 B.C. quotes Agatharchides' travels in Egypt in the second century B.C. See Notton (1974). Modern manuals: Holden (1954); Cuzner (1962); Untracht (1969). Histories of technology: Forbes (1954); Maryon and Plenderleith (1954); Forbes (1971); Strong (1966); Sherlock (1976); Baratte (1975b).

29. The monk Theophilus wrote in north-west Germany in the first half of the twelfth century, most probably between 1110 and 1140. He was a practising craftsman, and he wrote well on his subject. The original text no longer exists, but can be reconstructed from a number of copies made between the 12th and 14th centuries (one early 13th century German manuscript is in the British Museum). The treatise is divided into three Books, the first dealing with painting, the second with glass-making, and the third and largest with metalwork, including the working of iron, copper, bronze, silver and gold. See Dodwell (1961); Dodwell (1971).

30. Open furnaces - Egypt: James (1972), p. 41.

31. Crucibles: Tylecote (1962), pp. 130ff.; Forbes (1954).

32. Tools: Untracht (1969).

33. Gold wire may have been manufactured in Egypt by the drawn process, although this has not been established for most periods of Egyptian antiquity. In general, wire was probably mostly made from rolling thin strips of gold sheet. See James (1972), p. 42. See also Tylecote (1962), pp. 141, 145, 146; Higgins (1976), pp. 55-56.

34. Holden (1954); Strong (1966); Untracht (1969); Sherlock (1976).

35. Annealing is a term which does not include the cooling process. A metal which has been annealed can be allowed to cool in air or by quenching. The term quenching is used for relatively rapid cooling in a bath containing water, oil or salts. The object can also be left in the furnace to cool down with the furnace when the heat source is removed. Usually silver is quenched in water or an acid bath, in order to remove oxide scale rather than to affect the properties. In steels, by contrast, the rapidity of the quench does affect the properties.

36. Strong (1966); Untracht (1969); Sherlock (1976).

37. Strong (1966); Untracht (1969).

38. Payne (1931), p. 213; Strong (1966).

39. Österreichische Jahreshefte VIII (1905), pp. 51-60.

40. Painter (1977a); Painter (1977b).

41. Lathes: Mutz (1972).

42. Higgins (1961); Hoffmann and Davidson (1965); James (1972); Higgins (1976).

43. Soldering: Roberts (1973); Thouvenin (1973); Strong (1966), p. 9.

44. Tylecote (1962), pp. 157 ff.

45. Sellwood (1976), pp. 63 ff.

46. Sellwood (1976), p. 69.

47. Sellwood (1976), p. 71.

48. Untracht (1969); Strong (1966), pp. 9-10.

49. Maryon (1948); H Barker et al in Painter (1977a) and J R S Lang et al in Painter (1977b).

50. Painter (1977a); Painter (1977b); Strong (1966); Sherlock (1976).

51. Sherlock (1976), pp. 17-19; Strong (1966), p. 10; Baratte (1975b).

52. Ippel (1937); Strong (1966), pp. 10-11. Steatite moulds were probably used for making wax models rather than for direct casting of metal: Österreichische Jahreshefte VII (1904), pp. 180 ff. Plaster casts from Mit Rahinet, Begram, Chersonnesus: Strong (1966), pp. 84, 139.

53. Gilding: James (1972); Vittori and Mestitz (1975); Strong (1966), p. 11; Lins and Oddy (1975). See also the paper by Oddy in this volume.

54. Niello: Moss (1953); Strong (1966). Precious stones: Strong (1966), p. 12.

55. For the section which follows see Jones (1964) and his extensive documentation and bibliography.

56. Jones (1964), p. 148.

57. Jones (1964), p. 838.

58. Section by J P C Kent on the Comes Sacrarum Largitionum in Dodd (1961).

59. I have received help with various aspects of this paper from very many people; but I owe particular and grateful thanks to the following: D W Akehurst; H Barker; P C Compton; M J Hughes; Miss C M Johns; Mrs H P Lane; Mrs J Lang; I M MacIntyre; W A Oddy; and C J Wheatley.

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EARLY METALLURGY IN ITALY

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In the third millenium both metal objects and chamber tombs for communal burial appear on the Italian peninsula, while the pottery forms of the various regional cultures undergo important changes. This paper is devoted to examining the origin and development of metallurgy in prehistoric Italy, especially as it appears in the Remedello, Rinaldone and Gaudo cultures, in the context of current discussions of diffusion vs. autochthony in the archaeology of the Mediterranean. basin.

Introduction

Although extensive work has been done in the archaeology of the Central Mediterranean, and the history of its cultures has long been studied, the history of technology in this area is not yet well understood. In order to form an interpretation of a culture on the basis of the products of its technology, it is important to understand both the technology itself and its place in the context of the culture in which it developed. To make use of such material it is necessary to combine laboratory investigations and compositional analyses with more traditional archaeological methods. An example of an archaeological question requiring a background in both science and archaeology for its solution is the recurrent problem of independent invention vs. diffusion in early metallurgy. The aim here is to examine various aspects of the early phases of alloying in Italy, a subject of importance for the understanding of technological development in general and especially of the history of invention.

Metal tools first appear on Late Neolithic sites in Northern Italy, in the latest phase of the Bocca Quadrata culture in Emilia and the Veneto and further west in the settlements of the Lagozza culture (c. 3500-2800 B.C.). Metal was, however, very scarce until the succeeding phase, called the Eneolithic in Italian terminology, when metal objects become almost as common as stone and flint. These cultures are somewhat difficult to define as they are known almost entirely from their tombs. The principal groups include the Remedello on the Po plain, the Rinaldone in central Italy east of the Apennines and the Gaudo in the South, in the area later called Campania (c. 2800-2200 B.C.)(1).

In the past it was generally agreed that the appearance of metal objects was a clear sign of outside influence. It was believed that the sudden emergence of the Eneolithic cultures of peninsular and northern Italy was probably due to the extension of Aegean maritime trade into the western Mediterranean and the Adriatic toward the end of the third millenium, a time when the demand for tin necessitated extensive trade between the eastern and western Mediterranean. The question of the Aegean origins of Italian metallurgy had important chronological implications. If the search for tin provided the impetus(2), then the Remedello, Rinaldone, Gaudo and related cultures on the Italian peninsula must be contemporary with the Early Minoan III Period, i.e., 2200-2000 B.C. Recently this view has been challenged on stylistic grounds(3) and the case for an independent development of metallurgy has been vigorously presented by C. Renfrew and R. Whitehouse(4).

A second influential view, whose chief proponent is R. Peroni(5), sees as a homogeneous whole an 'antica eta del bronzo' which begins with the appearance of a bell beaker horizon (equated with Polada culture) in the north and percolates through Italy from north to south (allowing for some Aegean influence in the South and Sicily). Differences are seen as geographical not temporal. The latter theory appears now to be untenable in the light of the contributions of recent fieldwork

in terms of chronology, both relative and temporal. The latter theory appears now to be untenable in the light of the contributions of recent fieldwork in terms of chronology, both relative and absolute. The stratigraphic relation of bell beakers to both Remedello and Polada cultures has been clarified by recent excavations at La Romita di Asciano (Pisa) and at Monte Covolo (Brescia). At La Romita di Asciano bell beakers are found in a layer above one with Remedello-Rinaldone ceramics and below a layer containing Early Bronze Age Polada pottery. At Monte Covolo the Lagozza (Late Neolithic) level is stratified directly under the level of Polada and bell beaker pottery(6).

Both of the current theories of the origin and development of Italian metallurgy largely ignore the growing body of analytical data accumulated for this period.

Analytical Data

The great majority of objects analyzed, which span the period from the Late Neolithic to the end of the Bronze Age, are drawn from museum collections and are largely without provenance or clear archaeological context. The analyses summarised in Table 1 are drawn from those published by M. Passerini (1929)(7) of the Museo Archeologico di Firenze; by Otto and Witter (1952)(8) of the Museo Civico di Arezzo, the Museo Civico di Bologna, the Museo di Storia Naturale di Brescia, the Museo Chierici di Reggio Emilia, the Museo Civico di Verona and the Museo Ponti di Varese; by L. Cambi (1958)(9) of the Pigorini in Rome; by the Arbeitsgemeinschaft für Metallurgie des Altertums in Stuttgart (1960 and 1968)(10) of the Museo Civico di Arezzo, the Museo Civico di Bologna, the Museo Archeologico di Firenze, the Museo di Castello di Pavia, the Museo Chierici di Reggio Emilia, the Museo Archeologico di Siena, the Torino Museo di Antichita, the Museo Nazionale di Artigleria (Mercurgo, Varese) and the Museo Almeria Reale, and by E. Slater of the Pigorini in Rome (1971)(11). Included also are the objects from the excavations at Buccino (Salerno)(12) and Monte Covolo (Brescia)(13), both sites of great importance for our understanding of developments during this period.

From the analytical data accumulated to date for the so-called Bronze Age on the Italian peninsula, three main alloys emerge. These are copper (more or less pure), arsenical copper and tin bronze(14). Of primary interest here is the relative use of arsenical copper and tin bronze in the successive phases of the Bronze Age (see Table 1).

Table 1

Early alloying in Italy

Periods Involved

A Copper Age (Lagozza, Remedello, Rinaldone, Gaudo, Beaker)
c. 3000 - 2200 B.C.

B Early Bronze Age (Polada, Protoapennine)
c. 2200 - 1800 B.C.

C Middle - Late Bronze Age (Terramara, Appenine, Subapennine, Protovillanovan)
c. 1800 - 900 B.C.

Arsenical Copper Data

ANALYTICAL TOTALS

Period	A	B	C
Arsenic content			
Above 10%	0	0	0
5 - 10%	7	0	0
1 - 5%	45	20	15
c. 0.5%	11	60	40
Below 0.1%	46	92	73
Totals	109	172	128

PERCENTAGE TOTALS

Period	A	B	C
Arsenic content			
Above 10%	0	0	0
5 - 10%	6	0	0
1 - 5%	42	12	12
c. 0.5%	10	35	31
Below 0.1%	42	53	57
Totals	100	100	100

ALLOYING SUMMARY. ALL ARTEFACTS. PERCENTAGE TOTALS.

Period	A	B	C
Arsenic content			
Above 10%	0	0	0
5 - 10%	6	0	0
1 - 5%	48	12	12
c. 0.5%	58	47	43
Below 0.1%	42	53	57

Tin Bronze Data

ANALYTICAL TOTALS

Period	A	B	C
Tin content			
Above 10%	0	11	11
5 - 10%	3	56	94
1 - 5%	4	59	20
c. 0.5%	3	26	4
Below 0.1%	100	20	7
Totals	110	172	136

PERCENTAGE TOTALS

Period	A	B	C
Tin content			
Above 10%	0	6	9
5 - 10%	3	33	67
1 - 5%	3	34	15
c. 0.5%	3	15	4
Below 0.1%	91	12	5
Totals	100	100	100

ALLOYING SUMMARY. ALL ARTEFACTS. PERCENTAGE TOTALS.

Period	A	B	C
Tin content			
Above 10%	0	6	9
5 - 10%	3	39	76
1 - 5%	6	73	91
c. 0.5%	9	88	95
Below 0.1%	91	12	5

In the first phase of the 'Bronze Age' (designated Copper Age in Table 1) nearly half the objects analysed have a useful level of arsenic. Tin bronze is conspicuously absent. The Early Bronze Age shows a marked decrease in the use of arsenic, especially of the higher levels (> 5%) with a dramatic increase in the use of tin. This trend continues into the later phases of the Bronze Age until

tin has completely replaced arsenic as the preferred alloy. It is thus quite clear that there is a basic division between the Eneolithic Period and the Bronze Age proper on metallurgical grounds. The recognition of arsenical copper as a definite technological stage in the first phase of the Bronze Age is not new(15). However, a recent and comprehensive program at the National Museum of Antiquities of Scotland in Edinburgh combining all past literature on the subject together with 2,000 new analyses of metal objects from the Aegean and the Near East has definitively confirmed that in the earlier period arsenical copper was the most common alloy of early metallurgy in the Mediterranean basin.

In the Early Bronze Age arsenical copper was very widespread throughout the ancient Mediterranean and for certain areas (Syria, northwest Iran, the Cyclades, Crete and Mainland Greece) it accounts for two-thirds of all objects analysed. Tin bronze, in contrast, is absent or scarcely represented in Egypt, Palestine, Crete and Mainland Greece. Only in the Troad was there more use of bronze than arsenical copper in this period. For the Middle Bronze Age, tin bronze in general appears to have been more widely used; the average is about one quarter of the objects from most areas. Significantly, Minoan and Mesopotamian use is about half of their level. Arsenical copper is still the more common alloy, again with the Troad as the only exception. In the Late Bronze Age tin bronze eventually replaces arsenical copper in all areas. The rate of replacement is very variable and is dependent both upon the type of artefact as well as differential access to tin supplies. The pattern of alloy use in the Aegean/Near East is summarised in Table 2. It should be noted that the considerable bulk of EB analyses from Crete, Mainland Greece and the Cyclades relate only to EB2; also there are insufficient MB analyses for the latter two areas to warrant any sensible use of the relevant data. The similarity to the Italian material is indeed striking and it is clear that they are part of a widely shared technology.

Table 2

Changes in the use of tin bronze and arsenical copper from EB to MB

		Tin above 5%			Arsenic in the range 1-5% and greater		
		Proportion of Artefacts		% Increase EB to MB	Proportion of Artefacts		% Increase EB to MB
		EB	MB		EB	MB	
Egypt	Archaic - Old Kingdom 1st-2nd Intermediates	3%	22%	+ 630%	28%	54%	+ 93%
Palestine	EB IE/MB-MB	0%	22%	+2000%	24%	32%	+ 33%
Syria	Amuq G-I/J Amuq I/J-L	13%	30%	+ 130%	61%	23%	- 62%
Mesopotamia	ED1-Akkadian Post-Akkad-Old Babylonian	12%	12%	0%	32%	21%	- 34%
N. & W. Iran	c. 3000-2200 B.C. c. 2200-1600 B.C.	23%	26%	+ 13%	58%	29%	- 50%
C. Anatolia	EB2-3A EB3B-MB	24%	40%	+ 67%	31%	41%	+ 32%
Troad	Troy 1-2 Troy 3-6	37%	25%	- 32%	20%	8%	- 60%
Crete	EM1-2 EM3-MM	2%	14%	+ 600%	75%	55%	- 27%

Arsenic Alloying and 'Silvering'

The advantageous effect of arsenic on the castability and workability of copper has been emphasised by J.A. Charles(16). Arsenic like tin imports important deoxidizing and hardening properties in alloys with copper. Particularly important to our understanding of prehistoric technology is the high level of technical skill involved in the use of arsenical copper, and the care and deliberate control of arsenic levels as a function of artefact use. It is unlikely that alloying in any direct sense was involved, though such use of native arsenic cannot be ruled out in certain areas, e.g. at Massa Marittima and at Monte Amiata in the Rinaldone province(17). It has been demonstrated experimentally that the likeliest method of fabrication was by direct co-smelting of partially roasted copper and arsenic sulphide ores. Experimental co-smelting of almost any arsenic mineral (whether oxidized or sulphidic) with properly roasted copper ores results in an almost complete recovery of the arsenic, provided the atmosphere is kept at least partially reducing. However, if the atmosphere is sufficiently reducing to facilitate such manufacture, any related iron content will transmit partially to the copper alloy, producing a brittle, useless metal, unless roasting has first taken place. Roasting is an essential prerequisite to the smelting of copper sulphide ores, but experiment has shown that a slow, careful roast can leave up to a half of the initial arsenic content(18). As arsenic oxide is extremely poisonous, with a fatal dose being between 0.1 and 0.2 grams, great care must have been taken during this stage.

It would have been uneconomic (in terms of time and fuel), tiresome and indeed quite unnecessary, to have prepared a batch of arsenical copper whenever required by direct co-smelting. A more practical procedure would be to add some already prepared high arsenic metal (up to 15% arsenic) which, if melted with copper under charcoal, would provide just the contents of arsenic we see in the Eneolithic period. Some confirmation of this practice is available from elsewhere in Europe, since it is at least possible that the beads from the Caucasus published by Selimkhanov(19) and the ingots reported by Otto and Witter(20) could have been used for this purpose.

Table 3

Selimkhanov's Caucasian Bead Analysis

% Sn	% As	% Sb	% Ag	% Ni	% Pb
0	14.2	0.05	0.032	0.003	0.008
0.001	16.2	0.004	0.04	0.002	0.003
0.002	21.0	0.03	0.06	0.002	0.005
0.002	24.2	0.03	0.042	0.004	0

Witter's Ingots of Fahlerz Metal

% Cu	% Sn	% Pb	% Ag	% Au	% Ni	% Co	% As	% Sb	% Bi	% Fe	% Zn	% S
44.54	0.34	0.83	0.58	Tr.	15.92	4.50	16.49	12.97	0.04	0.55	Tr.	2.23
33.17	0.16	0.07	0.43	Tr.	19.10	6.65	16.76	13.09	0.04	5.72	Tr.	4.38

Hardness and castability are, however, not the only attractive properties exhibited by arsenical copper, encouraging its spread. A high arsenic content imports to copper a bright silver colour, a 'silver' which indeed tarnishes less readily than silver per se. On casting even a realtively low arsenic content in the copper exhibits the phenomenon of inverse segregation. In this phenomenon, a small quantity of high arsenic content copper (c. 15-20% As) is forced to the surface to form a complete outer 'skin' of silvery metal.

The skill of the early metal workers, especially in dealing with the highest level of arsenic, is illustrated in Table 4.

Table 4

Relationship of various types of metal artefacts to their arsenic contents. Figures are expressed as a percentage within each artefact and chronological period.

Period	Copper Age				Early Bronze Age				Middle-Late Bronze Age			
Arsenic Level (% As)	0.1 c	0.5	1-5	>5	0.1 c	0.5	1-5	>5	0.1 c	0.5	1-5	>5
Axes	73	21	16	0	64	25	11	0	65	32	3	0
Awls	0	0	50	50	50	50	0	0	-	-	-	-
Blades	9	0	73	18	57	26	17	0	72	24	4	0
Pins	-	-	-	-	100	0	0	0	0	0	0	100
Non utilitarian	67	33	0	0	100	0	0	0	20	58	22	0

Relationship of various types of metal artefacts to their tin contents. Figures are expressed as a percentage within each artefact and chronological period.

Period	Copper Age				Early Bronze Age				Middle-Late Bronze Age			
Tin Level (% Sn)	0.1 c	0.5	1-5	>5	0.1 c	0.5	1-5	>5	0.1 c	0.5	1-5	>5
Axes	83	5	5	7	19	5	47	35	9	5	12	74
Awls	100	0	0	0	50	0	0	50	-	-	-	-
Blades	93	2	5	0	29	0	31	40	5	2	19	74
Pins	-	-	-	-	0	0	0	100	0	0	0	100
Non utilitarian	100	0	0	0	0	0	0	100	0	0	14	86

Particularly striking is the high level of arsenic exhibited by the blades in the Eneolithic Period, not only for the greater hardness possible (with appropriate cold working) but also for a silvery surface. Indeed in some cases the arsenic content is so high as to preclude cold working (though not hot working) because of increased brittleness (over 7% As). As these blades are grave goods, the choice of a high arsenic level may reflect their ritual character. Axes in contrast show a low content of arsenic, for these tools are subject to severe blows.

In the Aegean and the Near East many examples of arsenic 'silvered' surfaces are known, from the Caucasus, Anatolia, Egypt and the Cyclades(21). These examples, like the bronze bull from Horoztepe(22) now in the Fine Arts Museum in Boston, appear to have been deliberately coated with a silver coloured high arsenic alloy. One simple way to produce such a coating is to paint a thin paste of arsenic oxide on the areas to be coloured, then to cover the object in charcoal powder, and heat briefly until bright red. The silver colour emerges clearly after cleaning and

polishing. Moreover, many halbards from Scotland, Central Europe (Diskau hoard) and the Iberian El Argar culture have been shown to have been silver coloured in their original condition. These, like the Italian Eneolithic blades, exhibit the effect of inverse segregation in casting.

It seems possible that it was this silvering effect that led to the discovery of the advantages of the use of arsenical copper as an alloy. Although at present this practice of silvering copper with arsenic is demonstrated only for the latter half of the third millenium B.C., it is probable that it developed much earlier from experimentation with pigments (which would include the brightly coloured sulphides of arsenic) and with cementation (as evidenced by the invention of faience). This cannot, of course, be proved, but it is difficult to see how arsenical copper could have been developed in a search for a harder material when the only other metals known (gold and silver) were relatively soft and brightly coloured.

The change to tin

In the succeeding period, the true Bronze Age, tin gradually but completely replaces arsenic as the preferred alloy. In view of the demonstrated safety of manufacture(20), this phenomenon is difficult to understand. Presumably the greater ease of manufacture and especially of control of alloy level gave tin bronze the lead as the demand for metal objects grew.

Conclusion

The intentional use of copper arsenic alloying (from Iran to Italy, Iberia to Britain) as well as the phenomenon of 'silvering' objects with arsenic - all in the third millenium - is a clear indication of the value of technology rather than typology alone in the study of the dissemination of ideas. This is not to deny the essential autonomy of the Italian Copper Age. Each local region had its own culture, which we recognise today chiefly by the indestructability of its pots. The concentration of tanged daggers on Remedello sites, of round heeled blades in the Rinaldone province, the distinctive 'cut outs' of Gaudo show that there was some regionalism even in metallurgy. What impresses us most in our incomplete knowledge of this period is the speed of the spread and practice of metallurgy. Despite far flung contacts, after an initial impetus Italy developed in its own way with its own metal types.

The demand for Cretan prospectors looking for tin arises because of our own inability to think of trade and contacts except in terms of the activity of a real class of traders exchanging goods and materials for financial gain. Surely this is true of the real Bronze Age, and one of its distinguishing characteristics. But this economy is partly the result of the impact of metallurgy itself. The adoption of metallurgy was a gradual process but once adopted it profoundly transformed both society and itself.

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JOINING TECHNIQUES

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Introduction

Any but the most primitive metal-using society joins one piece of metal to another. There are a number of different techniques which can be used to do this: making simple linkages by folding, use of pins, rivets or twisted components, and making a join by applying heat to metal, as in welding, casting on, sintering, brazing and soldering. The last two methods, involving the application of heat, also require the use of a filler metal: brazing, or hard soldering as it is often called, takes place at a higher temperature than soldering, and this temperature can be near to the melting point of the body metal. In contrast soldering (e.g. soft soldering) uses a lower melting point alloy and takes place at a much lower temperature than the melting point of the body metal.

Recent work

Modern investigations of ancient silver joining are not common. We have some as yet unpublished results in the Research Laboratory for material from earlier periods. These show that hard solder was used for soldering gold lugs to a silver bowl from the Royal Graves at Ur (2500 BC) and two small silver jewellery objects of the 5th and 6th centuries BC from the Greek and Roman department have also been hard soldered. Some work was done on the material from the Traprain hoard (Curle 1923) but we have not been able to find much else reported in the literature. There is, however, recently published work on gold (Roberts 1973) and bronzes (Lechtman 1970). Wolters, in his review "On the history of soldering" (Wolters 1975), states that the Romans used silver-gold, gold-copper, and silver-copper hard solders for silversmithing, and says "to judge by the Hildesheim silver hoard, recently connected with the defeat of Varus in 9 AD, on the one hand hard soldering was used for mounting and repair work, while on the other hand even such parts as handles, which required to be mechanically strong, were soft soldered". Wolters cites many examples of the use of hard and soft solder at various periods, but the lack of adequate references considerably reduces the usefulness of his review.

The authors of the present paper, in their study of Roman silver undertaken in connection with the Wealth of the Roman World Exhibition (British Museum 1977), were mainly concerned with the joining techniques of Roman gold and silversmiths in the period covered by the Exhibition - AD 300 to 700.

The Ancient Literature

Literary references to the joining techniques used in the Roman world are few. Pliny (AD 79) mentions solders in several places. "The goldsmiths also use a special gold solder of their own for soldering gold, and according to them it is from this that all other substances with a similar green colour take the name. The mixture is made with Cyprian copper verdigris and the urine of a boy who has not yet reached puberty, with the addition of soda; this is ground with a pestle made of Cyprian copper in mortars of the same metal, and the Latin name for the mixture is santerna. It is in this way used in soldering the gold called silvery-gold .... On the other hand 'coppery' gold shrinks in size and becomes dull, and is difficult to solder; for this purpose a solder is made by adding some gold and one seventh as much silver to the materials above specified, and grinding them up together". (Pliny, Book XXXIII, Ch. XXIX).

"While speaking of this it will be well to annex the remaining particulars, so as to occasion all round admiration for Nature. The proper solder for gold is

the one described; for iron, potter' clay; for copper in masses, cadmea; for copper in sheets, alum;..... Black lead however is joined by means of white lead and white lead to white lead by using oil; stagnum likewise with copper filings and silver with stagnum ...." (Pliny, Book XXXIII, Ch. XXX).

The first method mentioned by Pliny for gold soldering is very similar to the technique described by Littledale (Maryon 1948) for joining granules of gold to gold sheet. A powdered copper-bearing ore (eg. malachite) is heated with a flux under reducing conditions to provide very finely divided copper which makes the join. This method can be used for silver as well as gold, but is less easy to effect with silver. The second method described by Pliny is a form of hard soldering or brazing but what constituted "silvery gold" and "copper gold" is not clear.

Stagnum is apparently an alloy of lead and silver, and would not in fact be very useful for soldering silver. Hard soldering or brazing of silver is not mentioned elsewhere in Pliny as far as can be discovered, although Maryon says that "The Roman craftsmen ... were perfectly familiar with the process of hard soldering; for 3000 years metal workers had freely employed it. Pliny described it as it was practised by the Roman craftsmen of his day". Here Maryon was referring to Pliny while discussing the soldered footrings on Roman silver dishes such as those found in the Mildenhall Treasure (Maryon 1948). Pliny also describes "a counterfeit stagnum" which is discussed below in the analytical section, and another, now termed argentarum, made from pale and dark lead in equal amounts. The name tertiarium is similarly given to an alloy of "two parts of dark lead with one of pale .... it is used for soldering pipes". Tertiarium is therefore similar to modern soft solder. Pliny says "Pale lead" (i.e. lead) is naturally dry, while dark lead is pre-eminently moist and pale lead, if unalloyed, is useful for nothing, and silver cannot be soldered with it, since the silver liquifies first. It is stated also, on good authority, that silver is corroded by a silver containing less than the correct proportion of dark lead, with respect to pale. Bailey (1929) in his notes on this paragraph refers to Digest 41.1.27 which is a law which says that "if you solder a leaden cup with someone else's lead, the entire cup is yours, but that if you repair a silver article with someone else's silver the article is not entirely yours". Whether repairing in this case means soldering with silver alone, or simply making a mechanical joint is not clear.

Other than Pliny there are few contemporary ancient sources. Vitrivius (33 BC) mentions chrysocolla (i.e. malachite) for use in soldering and the Leyden Paprus X (Hunt 1976 and Caley 1926), which dates from about 325 AD, gives two recipes for gold solder, the first contains 4 parts of copper, two parts of asem (which has not been identified) and one part of gold. The second recipe gives two parts of gold and one of copper, with a little silver which is a good composition for soldering. Theophilus, (Dodwell 1961) and also the Mappae Clavicula, (Smith and Hawthorne 1974) contain similar recipes at somewhat later dates (9th to 12th centuries AD).

Foot Rings

Work on the Neptune dish from Mildenhall, published in the new Mildenhall handbook (British Museum 1977), suggested that the footring on which the dish rests was not soldered or brazed on, as Maryon had suggested (Maryon 1948), but perhaps had been part of the original casting, using the method suggested by Curle (Curle 1929) for some of the Traprain dishes. He wrote "In all these cases (beaded rimmed bowls) the bowl has in the first instance been cast in a mould approximating in form to the desired shape of the body, including a foot-rim beneath". The ring was appropriately shaped during subsequent raising operations.

In the present study a number of dishes with footrings from the Esquiline and Mildenhall Treasures were examined optically and using x-ray fluorescence analysis

(details of the latter are given later). None of these showed any clear sign that their footrings had been soldered on; no soldered joins or other discontinuity was visible and there was no significant difference in composition between the footrings and the dishes. At the same time a number of Sasanian dishes from Persia, made during the same period, were also examined (Table I) and it was found that hard solder had been used to attach the footings in all cases. Akehurst (private communication), in a study of all the silver Sasanian dishes in the British Museum, had similarly come to the conclusion that without exception the footrings had been obviously soldered on. The Sasanian bowls generally showed a significant difference in composition between the metal of the dish and the footring. It appears therefore that different techniques were used in the West and East. It is possible that in the Western area extremely fine brazing was carried out either using a granulation technique (this is difficult to perform on silver) or a brazing alloy with a composition very close to that of the body metal. The Romans were quite capable of soldering large objects, such as the large bronze statues described by Lechtman (see above) so this would not have presented a problem. However in view of the similarity of the composition of the dishes and footrings it seems, on the evidence at present available, most likely that raising was a preferred technique amongst craftsmen working in the Western part of the Empire. The silver content was high, conferring superior malleability on their silver objects compared with those of the Sasanians, who clearly preferred the use of soldering, a technique long known and practised with skill in the Eastern Mediterranean area.

Beading and Rims

Remaining with bowls and dishes for the moment, thickened rims are frequently produced by tapping around the edge during each raising process, but one example of what might be described as welding was found. The fluted bowl, from Mildenhall, showed folding and welding at the rim; the rim had been somewhat thickened by folding down the thinned metal at the edge produced by raising, and then hammer-welding it. Some of the dishes examined had decorated rims. Beading, as on the Neptune dish, was a common form, and there was the possibility that the decoration had been made separately and then applied. However we did not find any evidence to suggest that the rim of the Neptune dish was in fact soldered on. Although there were breaks at the rim which appeared to have been soft soldered in order to repair them. Analysis showed only the presence of silver. It is possible that a small quantity of silver had been cast on to make a repair, as implied in Digest 41.1.27, so this may have been a regular technique.

Other beaded bowls were examined and, with one exception, showed beading which has an integral part of the bowl, made by punching metal around the rim into a die. However, in the case of a fragment of "hacksilver" from a dish with a beaded rim from the Coleraine hoard, the beaded section is apparently soldered or brazed onto the dish. At the broken edge the overlap of the two pieces of metal is obvious, and analysis indicates that they have different compositions.

Decoration

Surface decoration was produced mainly by chasing, repousse, gilding, inlay and so on, with no need for the employment of any joining technique. However there are one or two instances where metal is joined to metal to enhance the decorative effect, or where a functional join is turned into a decorative feature.

The Sasanians made use of a kind of applique to increase the relief on some of their designs. A channel was cut around the edge of the figure in the base metal, probably with a chisel, and a suitably shaped piece of metal was pressed into the channel. In most cases the join was burnished over, but in one instance the extra metal was soldered into position.

In some composite objects rivets were used to join pieces of the object together, and the head of the rivet was made decorative in some way. For example, the goblet or chalice from the Water Newton find has a conical base with a cup-shaped upper section, the two being joined by a bead through which a shaft passes from the underside of the cup to the underside of the cone-shaped base. The ends of this shaft have been carefully hammered, not only to fix it in position, but also to make a good decorative effect. The same idea was used in the goblets from Mildenhall, but in a more complex form. Here the shaft is of cast metal, split into four segments and decoratively carved. By compressing it lengthwise, the segments were moved apart sufficiently for the spindle to be inserted, compressed a little more, and the spindle (which was already decorated by turning) was secured. The ends of the shaft were inserted through the plate which forms the base of the goblet, and through the bowl, and finally hammered to make a decorative feature.

Handles and Constructional Joins

Rivet heads in the shape of small balls were used on the strainer from Water Newton. The bowl of the strainer and part of the handle were made from one piece of metal, which was then joined to the rest of the handle by a lap joint. This was probably originally soldered, and finally secured by three ball-headed pins, which were cut off on the underside, and the cut ends hammered to secure them in position.

In the Mildenhall Treasure there is a set of small ladles. The handles of these have been secured to the bowl by soldering but without any decoration. Where they have been detached, scratch marks are clearly visible on the bowls to provide a key for the solder. A Roman silver skillet, reputed to have come from Wales, has a flat, decorated handle. This was originally soldered on and subsequently repaired. There is also a repair on the handle which has been made by applying a piece of silver and the composition of this is akin to sterling silver. This appears to be a modern repair.

Several other objects with handles have been examined for traces of solder. The handles of the fluted bowl from Mildenhall are hollow and have been filled with lead, presumably to economise on silver. On the bowl itself there are traces of a tin-lead solder at the point of attachment. Curle (1929) reported that the escutcheons on one of the Traprain dishes were filled with a mixture of 85% tin and 15% lead, which was used to join them to the dish. The use of rivets particularly to join several components together had already been mentioned in considering decoration. We found one instance of the use of solder in the construction of an object. This was a ewer from the Esquiline Treasure. It is facetted and has a spout, handle and inset base. The spout and inset base are both soldered into position.

Gold

Some gold jewellery from New Grange (Ireland) has also been examined with respect to joining techniques. This material is interesting in that it consists of a number of objects on which various joining techniques have been employed. There is a chain with lapped joints, fused by pressure and possibly heat (although this is not necessary). There are several rings which are decorated with beaded (or swaged) wire and little gold balls. Analysis of the wire and balls shows them to be made of very pure gold with no detectable silver (i.e. less than $\frac{1}{2}$%, if any) and only a small amount of copper. The fused areas joining the wire and balls have a slightly higher copper content which suggests the use of solder or granulation type jointing. Tiny globules of metal, apparently incompletly fused, were visible in this joining region. The same phenomenon was observed in two bracelets made with twisted wire. Partial fusion had taken place between the strands of wire, separate globules again being distinguished. It was possible to examine three of them *in situ* in the SEM and the analysis showed that one of the globules

contained nickel with gold, while the other two contained copper with gold. This phenomenon implies the use of small particles of gold in a joining process which may have been simple melting, although some kind of granulation process might have been used. The bracelets were also decorated with a gold bead at either end of the clasp which had been brazed on. One bead had been incompletely soldered on. The other showed a good joint in which a cast dendritic structure of gold with copper and silver was visible. This contrasted with the wire and bead itself which were almost pure gold with only a trace of copper and no silver. These qualitative analyses show clearly that the bead had definitely been soldered (brazed) on.

In this group of objects three different joining techniques have therefore beem employed; welding, brazing (or soldering) and melting together.

Quantitative x-ray fluorescence analysis

The aim of the analytical study of joining techniques was to obtain some analyses to indicate the types of soldering materials in use, particularly as regards Roman silver, and to provide some analyses of composite silver objects to see how various alloys were used within a single object. Technical details of the equipment used for the analyses are given in an Appendix together with a note on the limitations of this type of surface analysis for providing quantitative analyses of ancient solders. In particular the curved shape of the surface of the hard solders which were analysed placed some limits on the accuracy obtainable and the soft solders analysed were all corroded so that some change in composition had taken place. The elements which were measured were silver, tin, copper, zinc, gold and lead, being the only elements, apart from small amounts of iron and possibly nickel, which produced measureable XRF peaks within a reasonable length of time.

With the factors dealt with in the Appendix in mind, the results obtained are presented in Tables 1 and 2 for hard and soft solders respectively. The hard solders occurred exclusively on Sasanian silver dishes which have attached foot-rings and the analyses of all three components of each dish, namely the bowl, footring and solder, are given in Table 1. In only one of the dishes is it very clear that the bowl and footring are of the same metal composition (No. 124091). On the other hand it is clear that in dish 124093 the bowl and footring are of very different compositions, but for the other three dishes the copper content (which is the most important factor in assessing difference in composition) differs by between 10 and 15% of the copper percentage and so it is likely that the bowl and footrings in these cases are of different metal.

Considering first the hard solders, the minor elements gold and lead are not important constituents and are present in about the same concentrations in the body metal as in the solder. The range of copper percentages is interesting, though, with two as high as 30%. As explained above, the accuracy of individual analyses is often poor because the solder forms a thin junction with awkward geometry for XRF analysis. It would, therefore, be safest to assume that the solders with the higher values of copper, say 20-30% copper, represent the type of solder composition in use, while the two lower copper concentrations (10-15%) probably represent the analysis of an area on the objects which consisted of a thin line of solder plus some of the surface of the body metal, that is, there has been an effective 'dilution' of the solder as seen by the XRF instrument. An alternative explanation of these two lower figures is that fusion of the solder with the metal has caused partial melting of the latter and inter-mixing in the area of the soldered joint. The only way it would be possible to differentiate between these two possibilities would be to cut proper cross-sections of the relevant joints of analysis, and this is quite clearly an unacceptable course of action.

The hard solders are therefore simple silver-copper alloys containing about 20-30% copper and these are used to join silver metal pieces which contain only

Table 1

Analyses of Sasanian silver dishes: body, footring and hard solder

LRGS No.	BM Reg. No.	Part of dish	Ag	Cu	Au	Pb
011	133033	body	91.7	7.56	0.12	0.57
013		foot ring	90.4	8.40	0.36	0.78
014		solder	66.0	31.7	0.83	1.36
015	124091	body	94.3	4.57	0.70	0.40
016		foot ring	94.3	4.41	0.67	0.48
019		solder	75.1	23.0	1.52	0.33
020	124092	body	94.2	4.72	0.70	0.32
068		foot ring	94.9	4.05	0.59	0.46
069		solder	87.6	11.8	0.34	0.16
168	124093	body	94.0	4.41	0.82	0.64
169		foot ring	96.9	1.61	0.92	0.44
170		solder 1	83.8	15.1	0.72	0.33
170		solder 2	68.5	30.7	0.70	0.03
070	124095	body	92.0	6.90	0.44	0.63
071		foot ring	93.4	5.48	0.52	0.60
072		solder	75.9	22.1	1.02	0.37

5 to 8% copper. A point of importance for the solders is their melting point relative to that of the metals which they are being used to join. The silver objects themselves, will have melting points in the range 890-900°C, while for the solders, the most fusible alloy (i.e. lowest melting point) has a composition of 72% silver and 28% copper and melts at 778°C. Some of the hard solders (see Table 1) have compositions which approach this value, while the others with lower copper content will have melting temperatures intermediate between the eutectic and that of the silver objects themselves.

For the reasons given above, considerable variation is found in the analytical results for the soft solders (Table 2). In every case except LRGS 180, silver is the predominant element simply because the solder being analysed consists of corrosion products which are thin, and therefore the underlying silver metal is also contributing to the analysis. However, since the soft solder does not contain any silver itself, one can ignore the silver figure and look at the other five elements in terms of their concentrations relative to each other. What stands out from the results is that both tin and/or lead are the major elements where the silver is excluded. This fact alone confirms that these are indeed soft solders. Even with the four analyses which show the presence of large precentages of tin (LRGS nos. 179, 181, 188 and 193) the amount of lead which accompanies the tin is very variable, the maximum being 13.9% in 188. For tin-rich samples, re-calculating the results to exclude the silver, the tin: lead percentages range from about 80% tin: 20% lead down to small percentages of lead. For the lead-rich samples (eg. 180) exactly the reverse occurs, the tin: lead percentages range from 20% tin: 80% lead, to samples such as no. 103 which seem to contain only lead. Since we know that solders usually have tin: lead ratios of 2:1, 1:1 or 1:2, one could conclude that these sort of compositions are represented in Table 2 in a much corroded form, with the possibility that no. 188 (tin: lead of 4:1) is not too far from the value for the original metal. One minor-metal which occurs only on the ewer from the

Table 2

Analysis of ancient soft solders

*Number in Kent & Painter	Object with Solder	Date	B.M. Reg. No.	Ag	Sn	Cu	Zn	Au	Pb
106	Skillet	4-5c AD	1942,1-7,1(1)	53.2	-	0.91	0.38	0.35	45.1
			(2)	73.4	-	16.5	0.57	3.7	5.8
-	Ewer base	4c AD	66,12-29,5(1)	70.4	-	21.1	3.24	2.15	3.1
			(2)	90.8	-	3.4	2.27	2.55	0.97
-	Ewer spout	4c AD	66,12-29,5	95.9	-	1.69	0.38	1.31	0.72
35	Strainer	Water Newton	1975,10-2,9(1)	57.3	36.1	1.65	0.26	3.50	1.10
			(2)	48.4	46.6	1.48	0	2.39	1.04
66	Fluted bowl	Mildenhall	1946,10-7,15	31.3	11.7	1.00	0.38	0.02	55.5
70	Ladle	Mildenhall	1946,10-7,22	52.5	42.1	2.68	0.17	0.67	1.79
-	Jug	Chaourse	89,10-19,17	28.9	52.2	4.31	0.28	0.29	13.9

*J.P.C. Kent and K.S. Painter (eds) Wealth of the Roman World, British Museum, London 1977

Esquiline treasure is zinc. Zinc has not been detected in other than quite small amounts in any of either the solders or the silver objects themselves which have so far been analysed in this project. Its presence in 2-3% in the soldered areas on the ewer may merely point to its inclusion as a minor element occasionally added to Roman soft solders. However a point of some interest is the statement by Pliny (Book XXXIV, Ch. 160) that "at the present day a counterfeit stagnum is made by adding one part of white copper (i.e. brass) to two parts of white lead (i.e. tin)". Since this alloy contains brass, zinc would be present in amounts possibly ranging up to 10%, but certainly of a few percent. There is a possibility therefore that the ewer represents the use of soft solder somewhat of the type mentioned by Pliny. The validity of this hypothesis is strengthened by the fact that one of the analytical results for this object (LRGS 140 (1)) shows the presence of 21% copper whereas the base itself contains only 4% copper and the body even less.

Conclusion

A limited number of silver objects from the late Roman World, with a few gold objects from its periphery, were examined in order to see what the preferred methods of joining were. Sasanian objects which were examined revealed the use of hard solder: on the other hand, objects from the Western Empire did not provide any examples of hard solder used on silver. Soft solder had been used to attach handles and for repairs, and a possible example of the stagnum described by Pliny was found. Other favoured techniques included hammer-welding and riveting, in which decorative use was often made of the rivet heads.

Appendix

X-ray fluorescence analysis: technique and limitations

The equipment used for the analyses consisted of a Link Systems energy-dispersive x-ray fluorescence spectrometer consisting of a Kevex Si (Li) detector and a computer-based multi-channel analyser. The source for excitation of the XRF is either a minature x-ray tube or an Am^{241} isotope source: the unit is virtually the same as that described by Hall et al (1973) and is known as the 'Isoprobe'. For the

analysis described here, excitation was by x-ray tube only, run at 25KV and 0.4 MA. Calibration was by means of multi-element metal standards and object compositions were calculated using a computer program, MC9, based upon a program written in the University of Bradford for isotope-induced XRF (Brinklow, 1975).

Prior to analysis, a small area on each object was cleaned down to bright metal using a triangular bladed silversmiths' knife and the process repeated (usually 2-3 times were necessary) until consistent analyses were obtained. The elements which were measured were silver, tin, copper, zinc, gold and lead, being the only elements, apart from small amounts of iron and probably nickel, which produced measureable XRF peaks within a reasonable time. The counting period was set at 200 seconds since together with cleaning and re-analysing, this seemed to offer the best compromise between time per sample and detection limits for the elements.

The technique provides surface analyses rather than results from the interior of objects being examined, and therefore when surface areas on an object being examined contain corrosion products, the results have to be treated with caution. It is important to bear this in mind in considering the solders which were analysed for this paper. In the case of the soft solders, the area analysed with the XRF almost invariably consisted of corrosion products, the original metal solder having corroded right through. Hence two factors contribute to the final analysis result obtained: if the corrosion products are thin, the exciting x-ray beam produces fluorescence from the underlying metal (silver in almost all the present work) which is seen by the detector as well as that from the solder; secondly in the corrosion of soft solder, there will probably be preferential loss of lead as compared to tin, which remains as the relatively stable and insoluble tin oxide. Thus the analyses for the soft solders must be treated with caution, and the variability in the results obtained bears this out. In practice the XRF technique for corroded soft solders seems to be useful for identifying the presence of tin and lead, and possibly other elements such as zinc, which are not present to an appreciable amount in the underlying metals to which the solder was applied, but does not provide quantitative data on the composition of the solder. In contrast, the hard solders are less severely corroded than the soft solders, therefore the analytical results for hard solders are more satisfactory. However one technical point does arise in the case of hard solders, namely that in terms of the preferred sample geometry for XRF analysis, the nearer the surface for analysis approaches a plane surface the better. Deviations from a plane surface up to about 10^{o} either way have little effect on the quantitative results, but the hard solders studied in this paper were used exclusively for joining a foot ring to a dish and therefore, being at the right angle junction between the ring and the dish, had sharply curved surfaces. The results for the hard solders are therefore less accurate than those for the objects themselves.

Acknowledgements

The authors would particularly like to thank Mr P. M. Roberts and Mr B. M. Allen for help and advice, and also their colleagues Michael Cowell and Nigel Meeks for analyses and Christopher Wheatley for technical advice.

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Note added 7 November 1979

Since writing the above, a rare published analysis of an ancient hard solder has come to our notice, Lefferts (1970). This technical study of a Proto-Elamite silver animal figurine (ca. 3000 BC) includes analyses by thermal neutron activation (by Dr. P. Meyers) of the solder which joined the head to the body and solder on the left side of the vase which the animal holds. There were several analyses made of the body metal of the figurine, indicating the presence of 0.6 - 1.7% copper, 0.006 - 0.04% gold, the balance to 100% being silver. The body metal is therefore of quite pure silver. The solder at the neck contained 4.6% copper and 0.1% gold, while that on the vase contained 13.3% copper and 0.004% gold. While the neck solder is a relatively high melting-point solder, the solder on the vase corresponds in composition more with that on the Sasanian silver dishes analysed above (Table 1).

The analyses quoted in the main text above now appear in a paper (Hughes and Hall, 1979) listing some 200 analyses of Roman and Sassanian silver, obtained by x-ray fluoresence analysis.

Hughes, M.J. and Hall, J.A. 1979, X-ray fluorescence analysis of Late Roman and Sassanian silver plate, J. Archaeol. Science, 6, 321-344.

Lefferts, Kate C., 1970, Technical examination (of a Proto-Elamite silver figurine in the Metropolitan Museum of Art), Metropolitan Museum Journal, 3, 15-24.

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WEIGHING OF GOLD IN PREHISTORIC EUROPE

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It has recently been demonstrated that the origins of weighing in prehistoric Europe are to be placed at least as early as 4000 BC, by which time a system of units of weight, that lasted well into historic times, had come into being in the Lower Danube basin (Spratling in preparation). From study of the weights of axeheads of the semi-precious stone jadeite from Britain and Ireland, it seems likely (though it is not yet certain) that the system spread repidly across Europe during the fourth to third millennia BC. Certainly by the late second millennium it was in use thoughout Europe for the measurement of the weight of metals. The use of the system has been demonstrated from the measurement of the weights of gold and gold-alloy artefacts from prehistoric Europe, and of the weights of the hoards in which such artefacts are often found. Gold was first used in Europe, in the south-east, during the fifth millennium BC; from the outset it appears to have been measured by weight.

The precision with which gold-alloy artefacts were made to exact weights may be demonstrated from a hoard, dated to about 1200 BC, from Féregyháza, Hungary (Table 1; Mozolics 1973, 194, pls. 78-80). Two identical elaborately ornamented armrings (nos. 2a, b) each weigh (211.45 grammes, and another pair (nos. 5-6) each weigh 55.21 g; a fifth armring (no. 3) weighs 331.25 g, a sixth (no. 1) 53.64 g, and a penannular loop of metal (no.15) 6.31 g (Mozsolics 1973, 194, pls. 78-80). Now , 55.21 x 6 = 331.26, 331.25÷52.5 = 6.31, 211.45÷33.5 = 6.31, and 53.64÷8.5 = 6.31. These correlations can hardly be coincidental; similar ones can be found in many hoards of precious metals in prehistoric Europe. Moreover, it is possible that the objects from Féregyháza were weighed to an even greater accuracy than to 0.01 g, for this was only the limit of accuracy of the modern balance on which they were weighed a few years ago. The degree of accuracy of weighing exhibited by this hoard is thus effective to about (or at least) 30 p.p.m., that is, ten milligrammes per 331.25 grammes.

Table 1

Weights of the gold objects in a hoard from Féregyhàza, Hungary

Object no.	Weight (g.)	Correlations
1	53.64	÷ 8.5 = 6.31 (no. 15)
2a	211.45	÷33.5 = 6.31 (no. 15)
2b	211.45	
3	331.25	÷6 = 55.21 (no. 5; no. 6) / ÷ 52.5 = 6.31 (no. 15)
4	51	
5	55.21	x 6 = 331.26 (no. 3) / ÷ 8.75 = 6.31 (no. 15)
6	55.21	
7	30.02	
8	17.12	
9	54.80	
10	50.10	
11	34.09	
12	35.76	
13	53.94	
14	39.49	
15	6.31	x 8.5 = 53.64 (no. 1) / x 8.75 = 55.21 (no. 5)
		x 33.5 = 211.38 (no. 2a) / x 52.5 = 311.27 (no. 3)

Table 2

Comparison of the total weights of five gold hoards of the late second and early first millennia BC from Europe

Name of hoard	Date (BC)	Weight (g.)	Correlations
Downpatrick, Ireland	c. 700	1038.0	x 2.5 = 2595
Bodrogkeresztur, Hungary	c. 1200	1036.2	x 2.5 = 2590.5
Bexley, England	c. 700	691.5	x 1.5 = 1037.25 x 2.25 = 1555.88 x 3.75 = 2593.13
Bodonal de la Sierra, Spain	c. 1000	1555.85	x 2/3 = 1037.23
Eberswalde, Germany	c. 800	2594.5	x 0.4 = 1037.8

An even higher order of precision in weighing is indicated by the correlations in the total weights of certain hoards of gold (-alloy) artefacts of the late second and early first millennia BC. Table 2 lists five such hoards, widely dispersed around Europe but correlating with one another to a quite extraordinary degree of accuracy. Thus, those from Bexley and Bodonal de la Sierra correlate at the level of about 25 milligrammes in over 1.5 kg., or to about 2.5 p.p.m. Such accuracy is not unknown in the ancient world, for sixty years ago Petrie showed that certain Islamic glass coin-weights of the year AD 780, weighing 32.662, 32.665 and 32.667 grains respectively, differ from each other by no more than one two-hundredth of a grain or one-third of a milligramme (Petrie 1918, 115-6). It is of major technological importance to discover that prehistoric goldsmiths in Europe had at their disposal balances and standards of weight of a sensitivity and order of accuracy hitherto not thought to have been attained in Europe until the development of precision scientific instruments in the last two or three centuries (cf. Stock 1969), and that artefacts were manufactured, and hoards of artefacts made up, to units of weight of such a high order of precision. A whole new dimension is thus added to the study of prehistoric European workmanship and social organisation -viz. the maintenance of accurate standards in societies that are normally considered to have been at a quite primitive stage of technical and social development.

The total weights of hoards (here used in the narrow sense of the word, that is, excluding tool-kits, etc. which are often characterised as hoards by archaeologists) are frequently of great significance, as the following correlations indicate clearly. Another gold hoard of about 1200 BC from Hungary, Bodrogkeresztúr (Mozsolics 1973, 191, pls. 86-7), weighs in its entirely 1036.2 grammes, while one of about 700 BC from Downpatrick, Ireland (Proudfoot 1955), weights 1038.0 g. A gold hoard of about 800 BC from Eberswalde, East Germany (Schuchhardt 1914), weighs 2594.5 g, which is 2.5 times 1037.8. A fourth gold hoard, of about 700 BC, from Wansunt near Bexley, Kent (Hawkes and Clarke 1963, 231, 234, 235), weighs 691.5 g which is two-thirds of 1037.25; a fifth, of early first millennium BC date, from Bodonal de la Sierra, Spain (Almagro Gorbea 1976), weights 1555.85 g which is 1.5 times 1037.23 (Table 2). It is clear from these figures (and others can be cited, see below) that hoards of metal were often made up to precisely calculated units of weight, and they are not just more or less random collections of complete or

incomplete artefacts, scraps, billets, ingots, and so on. A further set of correlations may be cited (Table 3), since it will lead us directly onto a brief discussion of the actual units employed.

Table 3

Comparison of the weights of certain gold finds from Europe.

Name of find	Date (BC)	Weight (g.)	Correlations
Tisza-Sűlős, Hungary	late IVth Millennium	462.15	
Vatin, Yugoslavia	c. 1300	460.28	
Vinča, Yugoslavia	c. 1300	107.5	x 4.3 = 462.25
Jászdózsa, Hungary	c. 1300	36.25	x 12.75 = 462.19
Nyíracsád, Hungary	c. 1200	307.5	x 1.5 = 461.25
Morvah, England	c. 700	461.6	
Ipswich 1968, England	first century	4617.7	÷ 10 = 461.77
Glascote, England	first century	463.5	

The hoard of gold-alloy torcs (neckrings) of the late Iron Age found at Ipswich in 1968 (Brailsford and Stapley 1972) weighs 4617.7 g; a hoard of gold bracelets of about 700 BC from Morvah, Cornwall (Hencken 1932, 92-3 fig. 26), weighs 461.6 g; another hoard of gold bracelets, of about 1200 BC, from Nyíracsád, Hungary (Mozsolics 1973, 201), weighs 307.5 g which is two-thirds of 461.25; a late fourth millennium BC gold hoard from Tisza-Sűlős, Hungary (Milojčić 1953; revised data from F.E. Barth, Naturhistorisches Museum, Vienna), weighs 462.15 g; a gold hoard of about 1400-1300 BC from Vatin, Yugoslavia (Mozsolics 1968, 56, pl. 26), weighs 460.28 g; the first century BC gold-alloy torc from Glascote, Staffordshire (Painter 1971; revised weight from Miss J. Peirson-Jones, Birmingham City Museums & art Gallery), weighs 463.5 g; and a silver mirror from the Boscoreale treasure, on the slopes of Mt Vesuvius (Héron de Villefosse 1899, 88-90, pl. XIX) weighs 461.5 g. Now, this last objects bears an inscription which reads "1½ pounds", giving a value of 307.7 for the pound. Two-thirds of the weight of the Glascote torc is 309.0 g, which is the same as a bronze billet from Ringstead (309.04 g) and of a bronze balance-weight, marked with the numeral I, in the mid-first century AD smith's hoard from Seven Sisters, Glamorgan (Davies and Spratling 1976, no. 11), which weighs 309.5 g. Now, the Eberswalde gold hoard noted above (2594.5 g) weighs 8.4 times 309.9; and so on.

Calculations of this kind show that the system of weighing in early Europe was as follows: A - B = C. C is much more constant than A and B, being about 331g (which, it may be noted, is the weight of one of the armrings from the Féregyháza hoard discussed above). A can be calculated at 637, with a maximum range of deviations held constant throughout the life of the system of ± 3 g (or about 0.5%). Unit B is about 308g (with a similar range of constant deviation). At Gussage All Saints, the billet from pit 209 (63.45 g) is one-tenth of unit A, and the iron balance-weight from the site (1144.66 g) is 1.8 times 635.92 g (Wainwright, et al., 1979).

The formula A - B = C is a natural one for use with an equal-armed balance, the instrument invariably used for weighing in western Eurasia until the advent of the unequal-armed steelyard with travelling weight in Europe at the close of the first millennium BC. If a weight of unit A is placed on one pan, and one of unit B the other, then the difference (C) is easily calibrated. Such a system has distinct advantages, for it obviates the use of very tiny weights - pieces which could easily get lost, or which, more importantly, would get abraded and thus lose weight far mor quickly than weights of large size. For example, if A = 110 and B = 50, then one-fifth of A would be 22 , and one-half of B would be 25; the difference is only 3.

If is of more than passing interest that the confusion which surrounds the calculation of the units of weight used in the Roman Empire (ie the early centuries AD) coincides with the fact that in about the first century BC the steelyard (or unequal-armed balance) was invented and widely disseminated. Now, on the steelyard only one standard of measurement can be used at a time (ie either A or B or C, for example), but there is no doubt that A and B in addition to C (the so-called 'Roman pound of 327.45g') continued to be used alongside each other for the measurement of precisely the same kinds of objects, and not, as it were, A for gold, B for silver, and C for bronze - as was so often the case in Medieval and post-Medieval Europe until the adoption of the metric-decimal system for all goods and materials. Now, for precise calibration of weight (as in that of gold and silver ingots, billets and coins), equal-armed balances continued to be used in the Roman Empire, so it is not, therefore, at all surprising that the values for units of weight that can be calculated for those objects which bear official inscriptions recording their weight, cluster significantly around the values for A and B noted above (cf. the silver billets studied by Painter 1972). It may be noted too that the six tin and pewter from the River Thames at Battersea, studied by Hughes (this volume, pp. 44-50) correspond to the values of A and B (Table 11), and that the total weight of tin and lead in the six ingots is in the exact ratio of 2:1 (66.73% Sn), or 33 pounds of tin and 16½ pounds of lead at a value for the pound of 319.47 g.

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METALWORKING AT GUSSAGE ALL SAINTS, DORSET : A REVIEW OF RECENT WORK.

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The debris of metalworking from Gussage All Saints, Dorset, was discovered in 1972 during the excavation of the pre-Roman Iron Age settlement (Wainwright 1979). The debris, consisting of crucible and cire-perdue mould fragments, hearth material and tuyeres, slag, and waste bronze and iron, has been extensively analysed by Dr. M. Spratling (1979), while further work on the mould fragments has recently been undertaken by the author (Foster 1980). Most of the debris came from a single pit (209) dated to c. 390 BC - AD 50 on calibrated radiocarbon dates. Other fragments, possibly derived from the same deposit, though some may represent earlier phases of metalworking, were scattered in several other features.

The Moulds

A major component of the assemblage consisted of cire-perdue mould fragments (Foster 1980). The broken clay fragments, which totalled 7380 pieces, came mainly from pit 209 with only 84 of them from other features (Foster 1980, Appendix C). Most of the moulds were of hard-fired refractory clay with the addition of varying amounts of quartz, although a few were of a different fabric (Howard 1980). They were modelled by hand around the wax originals, and only one 'gate' was provided for each mould. Internal markings, and the uniformity of the objects which would have come from the moulds, suggest that master moulds were used to produce the wax models.

The mould fragments represent the debris from a fairly short period of bronze casting during which an estimated 50 sets of equipment for chariots were produced (Spratling 1979, 140). The group divides into moulds for terrets, bridle bits, linchpins, strap unions and button-and-loop fasteners. Represented among the 1091 terret fragments are fourteen decorative varieties of terrets, of which six are otherwise unknown in the archaeological record. The decoration, as on the bridle bits, was impressed directly onto the wax original before the clay was invested (Foster 1980, plate 13). This has important implications for the study of decoration on Iron Age metalwork of all types, as much decoration hitherto thought of as cold working probably took place prior to casting. It has been possible to identify some terret gates, showing that terrets were cast upside down with the bar to the top.

The three-link bridle bits, for which there were 1878 mould fragments, were cast in three stages: first the two side links were cast in separate moulds; then the centre link was cast around the two bronze side links; finally the stop-knobs for the rein-rings (Spratling 1979, 138) were cast, four to a mould. This completed the casting work, since the bronze bits produced at Gussage probably had iron rein-rings coated with sheet bronze. Possibly some of the forged iron in pit 209 (see below) was intended for the production of the rein-rings. It is fortunate that some of the moulds for the centre link casting showed the position of the side links during casting (Foster 1980, fig.11). In order to separate the side links from the wax centre link during the production of the latter, the craftsmen appear to have used fabric (see Foster 1980, Section III, 2). Some of the wax used in the formation of the centre link sometimes flowed onto the two side links and as the fabric was removed before the investment of the mould, on a few moulds the clay took up the impression left in the wax. The fibres appear as positive impressions on these moulds.

The other bronze objects produced at Gussage were also connected with chariotry. Moulds for the bronze heads and feet of iron linchpins occurred in small quantities. The feet were cast onto the wrought iron pin, but the heads were separate so that the linchpin could be passed through the axle of the wheel. There were also a few moulds for strap unions which were intended as decorative additions to the harness and served the same function as modern horse brasses. Three button-and-loop fastener moulds were also identified.

In all, the moulds reveal metalworking to produce one specific group of objects, that is chariot fittings. The distribution of the mould fragments within the layers of the pit (Foster 1980, fig. 20), suggests that the debris was deposited in a very short space of time. From the technological point of view, the remains indicated a high level of craftsmanship; there were very few wasters or failed castings (Spratling 1979, 134) and the craftsmen were capable of casting complicated items, such as a three-link bridle bit, and of joining a bronze linchpin foot onto an iron shank.

The crucibles

The mould fragments from Gussage were complemented by the crucibles, a total of 588 fragments being recovered. It has been possible to reconstruct 13 crucibles almost completely, of which 11 came from pit 209. Pieces of a very similar crucible came from Layers 1,3 and 6 of pit 857 and another large fragment from Ditch section 1M. The latter contrasts in shape with the rest of the assemblage and possibly represents an earlier phase of metalworking. The fragments from other unreconstructed crucibles from pit 209 possibly represent at least another 19 vessels.

All the crucibles are triangular in plan with rounded pouring corners and slightly curving bases. They are very uniform in size, with sides of c. 72-88 mm, and a depth of between 20 and 35 mm. Spratling has calculated the capacity of two crucibles as 20 and 47 ml (1979, 130), ideally suited for the objects cast at Gussage. Most of the vessels are now cracked and brittle, with a glassy vesicular inner surface which often retains drips or pieces of bronze. The crucible fabrics (Howard, this volume) seem, on the whole, to be of a different texture from the moulds, although there are a few mould fragments which were made in a "crucible" type of fabric (Howard 1980).

Other finds: Bronze, iron and furnace waste

Also included in the pit were numerous fragments of iron and bronze waste, including bronze droplets; bronze sheet and wire fragments; lumps of bronze and iron; and iron artifacts (rods, ?chisels, nails etc.). Some of the bronze and iron objects were submitted to Professor R.F. Tylecote for metallurgical analysis, and were divided into three groups: copper-based bronze alloys; irons and steels; and composite artifacts. Two interesting objects were a tin-bronze billet (Spratling 1979, 130), presumably discarded in the pit by mistake, and a bronze-plated steel link from a three-link bridle bit (ibid. fig. 97). The link was of quenched steel, as were two other iron-based artifacts. It had been bronze plated by dipping in molten bronze: analyses have shown that the bronze would have to be heated to c. 1000° C and the iron preheated in reducing conditions (Tylecote 1975). The remainder of the iron objects examined by Tylecote were of bloomery iron (wrought iron), consisting mainly of ferrite and slag. Some pieces had been folded over and welded. The analyses also revealed other techniques used in the production of the artifacts. Many of the bronze objects, eg. bronze rivets, had been subjected to cold working.

Among the layers of ash and charcoal in pit 209 were also the remnants of hearth material, coarsely made of local clay (Howard 1980), and fragments of rectangular block tuyeres, again made of lightly fired local clay, were found in large numbers. Pieces of slag were examined by Tylecote who concluded that production of iron took place on the site. One drop of iron forge slag was possibly dripped from a piece of iron as it was taken from the smelting hearth prior to forging (Tylecote 1975).

Conclusion

The discovery of this deposit has greatly augmented our knowledge of Iron Age bronze casting and should facilitate the identification of similar debris among the finds from earlier excavations. The fabric analyses of the refractory clays by Howard (below and Howard 1980) have already answered some of the questions posed by the Gussage assemblage, and it is to be hoped that this work will be extended to other metalworking debris. Other questions prompted by this deposit relate to the production of prehistoric bronzes by the cire-perdue method, particularly the decoration of bronzes prior to casting and the use of master moulds for the production of wax blanks. In the light of the high quality of the work, it would be interesting to be able to relate the evidence for metalworking to the life of the settlement. Metalworking may have been a regular feature in the settlement's economy, as suggested by Spratling (1979, 141). Alternatively, the short period of production may indicate that the workshop was set up by an itinerant craftsman for the purpose of completing a specific order (Foster 1980, p.37). Theories concerning the social and economic implications of this group of material will no doubt reverberate in archaeological circles for some years to come.

Acknowledgements

I should like to thank Dr. M. Spratling for his help and advice in my work on the material from Gussage All Saints.

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PRELIMINARY PETROLOGICAL REPORT ON THE GUSSAGE ALL SAINTS CRUCIBLES

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1. Introduction

During recent years considerable attention has been focussed on the scientific analysis of ancient pottery fabrics to investigate sources of raw materials and methods of manufacture. Until now, however, this type of research has extended hardly at all to other branches of the ceramic industry, and refractory bodies found in archaeological contexts have received but a cursory glance. The published chemical examinations of prehistoric crucibles have been undertaken by metallurgists interested exclusively in residual slag (see, for example, Moss 1927; Liversage 1967, Appendix 7; Bachmann 1976; Tylecote 1976, Table 13), the fabrics themselves being generally ignored. An important exception is Clement Reid's visual examination of the Glastonbury Lake Village crucibles (Bullied and Gray 1911, 301). Reid suggested that the source of raw material might be the fire-clay seams and gannister beds of the Bristol coal fields, but this is unsupported to date by scientific analysis. This lacuna is surprising, considering the light which studies of refractory bodies might shed on the organisation of early metalworking, and the amount of information concerning the development of pyrotechnology which detailed analyses might provide. The present short report is intended to draw attention to the potential of crucible-fabric studies.

2. Procedure and results

Scientific examination of the Gussage All Saints crucible assemblage was undertaken by the writer with two aims in view. Firstly, it was hoped to ascertain whether the manufacturers were fully aware of the refractory requirements of bronze-melting vessels, and secondly, to suggest the possibility of seeing crucible production as a specialist activity, whether undertaken by the metalworkers themselves, the potters, or a separate class of manufacturers of hearth-furniture.

A random sample of 100 crucible fragments was drawn from the total assemblage from pit 209 at Gussage All Saints (Wainwright 1979), and these were examined macroscopically (together with 4 fragments from the 'working hollow' - feature 2, and nearby pits 437 and 857) under a x10 binocular microscope. On the basis of this inspection, it was possible to recognise two main fabric-groups distinguished by texture and by size and quantity of quartz sand inclusions. From the total of 104 sherds, 26 appeared to fall outside these two groups, and were themselves insufficiently similar to form a separate homogeneous cluster. Work on these sherds is continuing, and the present report is confined to groups 1 and 2.

All samples examined showed evidence of high temperature firing, with partial and often complete vitrification visible around the upper edges, particularly the pouring lip. Colour observations suggested that the same white-firing clay source had been exploited for the manufacture of the entire assemblage. Grey to black reduction zones refired to white at 1200°C in an oxidising atmosphere.

Group 1 fabric is characterised by an exceedingly crumbly texture resulting from a fairly high density of large-sized angular and sub-angular quartz grains, a sparse matrix, and high porosity. Fabric 2 contains an extremely high tenor of very fine quartz sand and, although still friable, appears altogether denser and less porous. Whereas fabric 2 may be described a 'rough', fabric 1 is positively harsh to the touch.

To test the validity of the initial macroscopic division, 11 sherds were selected for petrological analysis. The crumbly nature of the fabrics rendered impregnation necessary prior to thin-sectioning, and Lakeside 70 was found to be the most effective medium for the Gussage crucibles. It is to be noted, however, that whilst impregnation with Lakeside 70 is fast and efficient, high cost prohibits its general use. Thin sections (0.03mm) of the 11 impregnated sherds were cut and examined under the potrological microscope. All were found to contain a high density of moderately to well-sorted grains of angular and sub-angular quartz set in a sparse, optically anisotropic fine clay matrix. 'Virtually all the larger grains (0.25mm upwards) showed evidence of extensive cracking resulting from stresses set up in the crystal structure during heating to 1083°C (the melting temperature of copper) and subsequent rapid cooling (for a concise explanation, see Singer and Singer 1963, 99). In addition to quartz, sparsely scattered fragments of iron oxide were visible in all sections.

As expected, the fabrics were divisible only by the size range of the sand inclusions, and particle size analysis (cf. Peacock 1971) was performed to determine this range. 150 grains were randomly selected from each of six of the prepared sections, and their long axes measured. The data thus derived were used to construct cumulative frequency curves enabling mean grain size, standard deviation, skewness (a measure designed to show whether the bulk of the inclusions were coarser or finer than the mean) and Kurtosis (the 'peakedness' of the distribution curve) to be statistically ascertained (Folk and Ward 1957). The results of this analysis are given in Table 1.

Table 1 (see key at end)

Section No.	Mz Ø	σ_I	SK_I	K_G	V	
267	2.793	1.412	0.140	0.682	50.54	Fabric I
237	2.756	1.460	0.099	0.780	52.98	
5071	2.710	1.558	0.187	0.539	57.45	
229	2.763	1.098	0.034	1.102	39.73	
466	3.320	0.900	-1.491	0.8106	27.12	Fabric 2
5B	3.440	1.119	-0.147	3.708	32.52	

Fabric group 1 would thus seem to be clearly defined with fine sand grains (mean size: Ø2.75 = 0.14mm) predominating, and with a 'tail' of very fine grains indicated by the positive skewness measure. The small sample of group 2 sherds subjected to size analysis does not yet permit any valid conclusions to be drawn, but detailed work on this group is proceeding and it is hoped to include the results in a broader study of prehistoric crucible fabrics.

The results of fabric 1 analyses suggest that all sherds visually assigned to this group (52/105) emanate from a single source. The heavy mineral residue of a single group 1 sample was examined in an attempt to obtain information concerning this source, and was found to consist predominantly of tourmaline (63.23%) with accessory amounts of zircon, rutile, kyanite, and a single grain of andalusite. This heavy mineral suite tends to indicate the tertiary sands of the Wareham-Poole area as the most likely origin of raw material supply (Williams 1977). These sands occur within the Bagshot beds in close association with good quality pipe-clay

(Reid 1899); as this is the closest source of fine, white-firing clay to the Iron Age settlement at Gussage All Saints, it seems likely that both the crucible matrix material and the filler were obtained from the south Dorset coastal region. Unfortunately, as no group 2 sherds of adequate size (a minimum of 20 gms. is required) have yet been made available for heavy mineral analysis, it is not yet possible to predict a source for this fabric type. The writer hopes to continue with work of this nature after the completion of the conservation and reconstruction programme.

3. Conclusions

In accordance with the stated aims of the project, two conclusions may be drawn from the preliminary results presented here: firstly, that specific raw materials were selected - this selection depending on functional requirements - and, secondly, that either raw materials or finished crucibles were transported. The major requirements for modern metal-melting crucibles include adequate refractoriness to withstand any temperature to which they may be subjected; adequate density to prevent absorption loss of contents; and thermal shock resistance. In fulfilling these requirements many present-day clay crucible types contain a high tenor of quartz sand: Cornish crucibles consist of 50% ball clay and 50% sand, while Hessian crucibles are made from two parts clay and 4 - 5 parts sand (Singer and Singer 1963, 1277). The average proportion of sand to matrix in group 1 Gussage All Saints fabrics was 79.18% sand to 20.82% clay and voids, and both the group 2 samples produced similar readings. This exceptionally high proportion of quartz sand may have resulted in the failure of some of the crucibles; it may be noted that several badly warped and cracked examples were recovered from pit 209. Excessive quartz can be deleterious because of volume changes accompanying the α-β transformation at 573°C and its corresponding inversion during the cooling process (Kingery, Bowen and Uhlmann 1960, 543). The writer is presently conducting tests on a variety of clay bodies with different percentages and sizes of inclusions, to investigate this problem and its relation to rate of temperature change.

Despite such problems it is evident from the results of analyses of the Gussage All Saints crucible fabrics that their manufacturers were equipped with the technical knowledge necessary to produce adequate refractory vessels and were aware of a suitable source of raw materials. Although this technical expertise suggests a specialist class of manufacturers, just who these specialists were, and exactly where the production centre was located, must remain problems pending further research on both the Gussage All Saints material and on similar metal-working debris from other sites.

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Key to table 1:

Mz is mean grain size in Ø units, where Ø = $\log_2$ diameter (mm)

σ_I is the standard deviation of the grain size

SK_I is the skewness

K_G is the Kurtosis

V is the coefficient of variation of the mean grain size and the standard deviation.

These terms are explained in Folk and Ward (1957).