Sonderdruck aus / offprint from:

Ü. Yalçın (Hrsg.), Anatolian Metal III,
Der Anschnitt, Beiheft 18,
2005 Bochum

Paul T. Craddock, Michael R. Cowell & Maria-Filomena Guerra

Controlling the Composition of Gold and the Invention of Gold Refining in Lydian Anatolia

Introduction

The recent publication of the excavation and scientific study of King Croesus gold refinery at Sardis (Cowell et al. 1998; Craddock et al. 1998; Meeks et al. 1996; Ramage & Craddock 2000; Geçkinli et al. 2001) has given a unique insight into one of the more important metallurgical processes of antiquity and one that was vital for the development of moneyed economies. The relatively complete survival at Sardis of the parting furnaces and cupellation hollows, associated with gold refining, accompanied by sherds of the parting vessels, gold foils in all stages of refinement etc, have enabled many aspects of the ancient process to be described. Inevitably there were some outstanding questions.

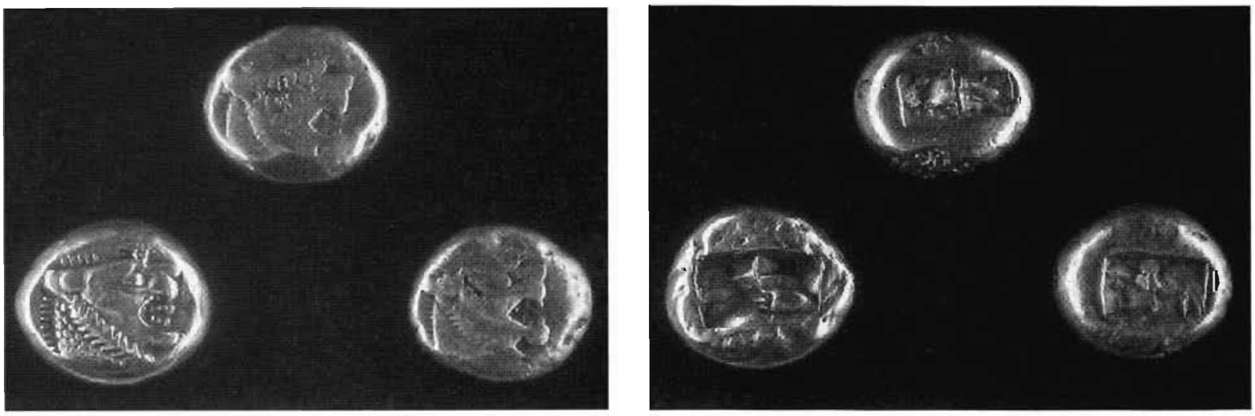
Not least of these was problem of how the Lydians had attained a reasonably constant composition for the very first coins, the so-called Electrum Series (following the nomenclature used in the previous reports we shall refer to the unchanged and unrefined natural gold as natural or alluvial gold and the gold-silver alloy in the coins as being of electrum). New, more sensitive analyses of the coins by ion beam activation analysis reported here (Table 4) have enabled these questions to be tackled. In this paper we will describe the method by which the electrum alloy for the first coinage was most likely prepared, followed by a more general description of the refining process used and its broader significance.

The First Coins

It is generally accepted that the concept of coinage as a means of exchange was first introduced in the West by the Lydians sometime in the late 7th – early 6th centuries BC. Coins were small round or oval pieces of precious metal, bearing recognisable designs and stamps that guaranteed their weight and composition (Plate 1). Although this definition has been generally accepted, it seems that little attention was given as to how the control of the composition was achieved. It seems to have been assumed, without much thought or analysis, that the coins of the Electrum Series had been made of native alluvial gold without control or modification of the composition (a very few coins on analysis do seem to be of unmodified native gold, see Nicolet-Pierre & Barrandon 1997, Table 2, for example, but the majority are of a deliberate artificial alloy).

The source of the gold is believed to have been principally from the river Pactolus, although the differences in the trace element composition, discussed below, may reflect a different source for the pure gold coins which followed the Electrum Series. Natural gold, whether from the primary rock deposits or the secondary alluvial sands and gravels, almost always contains quite substantial amounts of silver, typically between about 5 and 40 %, although higher and lower silver contents are known (Antweiler & Sutton 1970). The natural gold also has small quantities of copper, typically under a percent.

Plate 1: Electrum Series coins analysed for this paper, from the Cabinet de Médailles, Bibliothèque nationale de France. Nos. 22,24 & 25 from left to right., 1a obverse, 1b reverse (Photo:. A. Gondonneau & M.-F. Guerra).



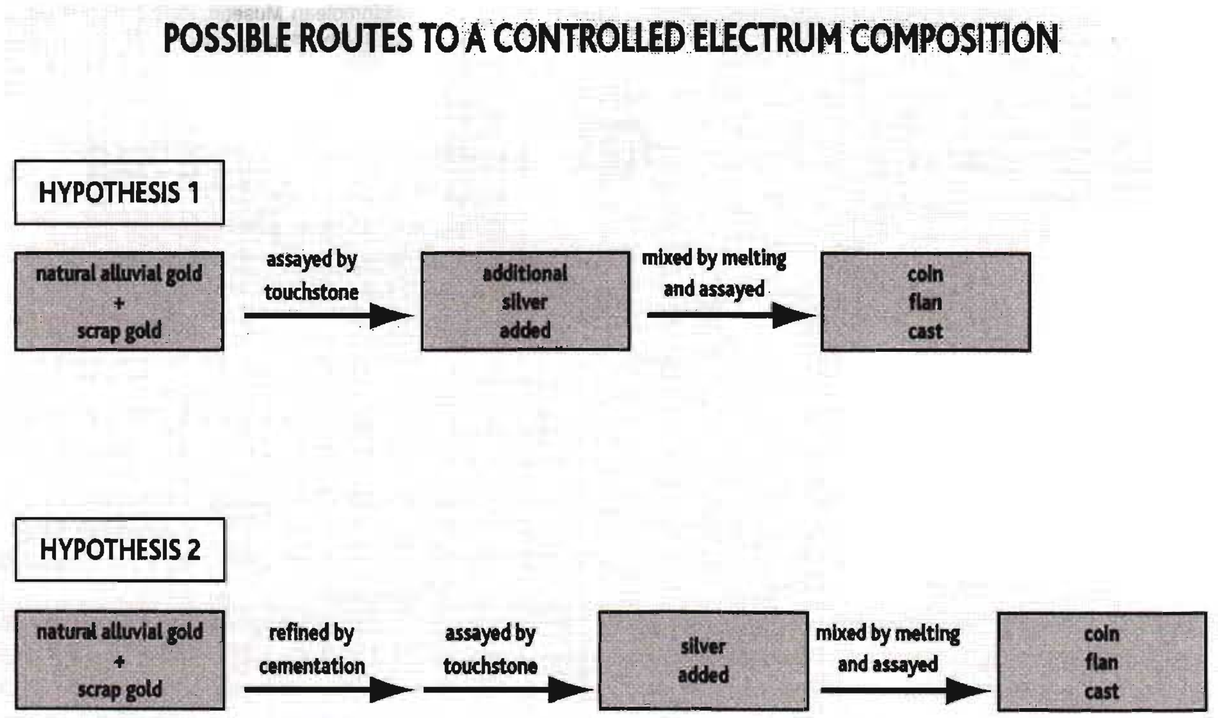


Figure 1: Diagrammatic representation of the two paths to the composition of the Electrum Series coins (created by A. Simpson).

More specifically, two grains of alluvial gold excavated from the Sardis refinery (sample 30A, Meeks 2000: 148), and analysed by X-ray fluorescence microanalysis in the scanning electron microscope were found to contain 16 % and 30 % of silver, and 0.6 % and 0.5 % of copper respectively. Furthermore, the analysis of seven of a series of alluvial gold flakes adhering to the surface of a parting vessel sherd, Lab sample no. 44401Z (Meeks 2000: 104, table 5.1), showed them to contain between 1.5 % and 40 % of silver, but copper could only be detected in one of the seven flakes analysed (the detection limit for copper was 0.15 %). Clearly the gold used at Sardis had a very variable natural silver content, but not much copper. Lead could not be detected in any of the samples, but the detection limit of the analytical system at the British Museum was about 2000 ppm.

The few analyses of Lydian electrum coins published before the work on the Sardis refinery showed that the silver content was very high, approximately equal amounts of gold and silver and a little copper (Kraay 1958; Visamara 1993; Pászthory 1980; Nicolet-Pierre & Barrandon 1997). A small number of the coins analysed by Nicolet-Pierre and Barrandon had lower, more variable silver, lead, tin and copper contents, which suggested to them that these coins were of the unrefined natural gold-silver alloy.

As part of the Sardis project some Lydian coins of electrum, refined gold and silver from the collections of the British Museum were analysed by X-ray fluorescence. These were published together with the analyses of some other Lydian coins from the Ashmolean Museum, Oxford, that had been analysed many years previously by Adon Gordus, but not published, using the technique of neutron activation (Cowell & Hyne 2000; Cowell et al. 1998: tables 1-2). These were still quite small groups but did show that the electrum coins were of a reasonably consistent alloy containing about 54 % of gold, 45 % of silver and about 1 % of copper. Clearly the Lydians were able to produce coinage of a regular controlled composition, but how was this achieved?

There were two very different hypotheses (Figure 1):

Hypothesis 1

It is possible that the refining of gold was already known and that from the outset the Lydians could have refined the natural gold and then debased this by the controlled addition of the silver and a little copper.

Hypothesis 2

The other possibility is that the very concept of gold refining was unknown at the outset of coin production. Thus the regular composition of the first electrum coins was achieved by the addition of small amounts of additional silver to the alluvial gold, which still contained its natural silver, to produce a consistent alloy.

It had been previously argued that the high silver content of the coins represented nothing more than the debase-

Table 1: Gordus Neutron Activation analysis of Lydian Electrum Series coins from the Ashmolean Museum, Oxford and a selection of the Sardis gold foils. Note sample 20 is almost certainly a foil made from an old Electrum Series coin ready for reprocessing (from Cowell & Hyne 2000: table 7.1).

Sample	Reference	Coin type	Denom.	Wt (g)	Au%	Ag%	Cu%
E-295/6	E.S.G. Robinson gift 1964	BMC Lydia 2/5	⅓ unit	4.70	51	46	3.4
E-297/8	E.S.G. Robinson gift 1962 (ex M&M sale 25, no. 469)	BMC Lydia 3/16	⅙ unit	2.38	52	46	2.2
E-337/8	E.S.G. Robinson gift 1969 (ex Bank Leu)	inscribed Alyattes	⅙ unit	2.37	60	38	1.9
E-339/40	E.S.G. Robinson gift 1968 (ex Bank Leu)	MN12, pl. I, 1	⅙ unit	2.36	51	46	3.6
E-341/2	E.S.G. Robinson gift 1964 (ex M&M 1955)	cf. Traite, pl. II, 3	1 unit	13.93	55*	42*	2.9
E-345/6	J.G. Milne gift 1924, O'Hagan sale no. 578	BMC Lydia 2/2	⅓ unit	4.65	54	44	2.1
E-347/8	Greville J. Chester gift 1892	BMC Lydia 2/2	⅓ unit	4.74	53	45	2.5
E-349/50	F.P. Weber gift 1906	BMC Lydia 2/2	⅓ unit	4.44	51	46	3.1
E-351/2	Keble College, Oxford	BMC Lydia 2/2	⅓ unit	4.72	51	46	3.1
E-355/6	Balliol College, Oxford	BMC Lydia 2/2	⅓ unit	4.74	53	44	2.2
E-357/8	Bodley miscellaneous	BMC Lydia 2/2	1⁄12 unit	1.17	55	43	2.1
24	light foil				64	33	3.1
19	light foil				86	11	2.6
26	light foil				89	10	0.7
20	light foil				57	42	1.2
21	cut lump				84	15	1.0

The gold, silver and copper figures are the mean of two measurements, precision typically ±1% absolute.

* Comparisons with XRF analyses of this coin suggest that the NAA figures for gold and silver were transposed in the original data table supplied. The figures shown here are the likely correct NAA analyses.

Table 2: Combined XRF and SEM analyses of Lydian Electrum Series and gold coins in the British Museum (from Cowell & Hyne 2000: table 7.4).

Sample	Registration	Type	Denom.	Wt (g)	SG meas.	Au%	Ag%	Cu%	Pb%	Fe%
46852	BMC14	royal	⅓ stater	4.66	13.42	53	45	1.6	<0.04	0.04
46854	1964, 13-3, 13	royal	⅓ stater	4.69	13.51	55	44	1.3	0.11	<0.04
46855	BMC7	royal	⅓ stater	4.73	13.51	53	45	1.6	<0.07	0.04
46856	BMC6	royal	⅓ stater	4.71	13.34	54	44	1.8	<0.04	<0.04
46857	1928, 4–4, 1	royal	stater	14.24	13.77	57	42	1.0	<0.04	0.09
47049	BMC2	royal	⅓ stater	4.72	13.76	55	43	2.0	0.13	0.12
47050	BMC9	royal	⅓ stater	4.73	13.48	52	46	2.3	0.12	0.11
47051	BMC11	royal	⅓ stater	4.70	13.61	54	44	1.7	<0.05	0.14
46863	BMC30	geometric	stater	10.65	19.04	99	0.7	0.2	<0.06	<0.04
46864	BMC31	geometric	stater	8.04	19.09	99	0.7	0.2	<0.06	<0.04
46865	BMC34	geometric	stater	8.06	19.09	99	0.6	0.2	<0.06	<0.04
46866	BMC35	geometric	stater	4.11	19.03	99	0.9	0.2	<0.06	<0.04

Precision: major components (over 10%) ±1%; minor components (1-10%) ±10%; trace components (<1%) ±20-50%.

ment of the coins by the Lydian authorities seeking increase their profit margins. However, if they lacked the technology to remove the natural silver content from the alluvial gold then the only way that they could have achieved an alloy of regular composition was by debasement to below the lowest gold figure ever encountered in the natural gold, that is to below about 60 % of gold. This would necessarily have been a complicated process, having to assay each batch of natural gold, and then calculate the amount of silver that would have to be added, but maybe the Lydians had no choice.

It had already been suggested by Cowell et al. (1998) and Cowell & Hyne (2000) that the lead content of the electrum coins could reveal which hypothesis was likely to be correct. Put briefly, the lead content of the natural gold is variable but generally very low, usually no more than about 100 ppm at most (Antweiler & Sutton Jr. 1970), although Nicolet-Pierre & Barrandon (1997) found rather more in three early gold-silver coins that they believed were made of unrefined natural gold. In contrast the silver used by the Lydians typically contained several thousand ppm of lead. This is because silver ores are almost always associated with lead, and certainly by the first millennium BC the main source of silver in Anatolia will have been from argentiferous lead ores. The few so-called "dry ores" that were relatively free of lead will have had lead added to them in the course of the smelting process in order to concentrate the silver (Craddock 1995: 221-232). The silver will have been released from the argentiferous lead by the process of cupellation (such as was carried out at the Sardis refinery to recover the silver salts, see below, p.00). The resulting

Table 3: Combined analyses of Lydian silver coins from the British Museum. Note the high lead contents typical of silver prepared by cupellation (from Cowell & Hyne 2000: 171, table 7.5).

Sample	**Registration**	**Denom.**	**Ag%**	**Au%**	**Cu%**	**Pb%**	**Bi%**
46869	BMC37	stater	99	0.92	0.68	<0.03	0.23
46870	BMC40	stater	100	0.07	0.28	<0.03	0.11
46871	1987, 6–49, 436	stater	99	0.33	0.09	0.30	0.18
46872	1948, 7–12, 10	½ stater	99	0.47	0.11	0.32	<0.01
46873	1948, 7–12, 11	½ stater	97	0.52	1.5	0.32	0.14
46874	BMC49	½ stater	99	0.44	0.36	0.19	0.12
46875	BMC50	½ stater	99	0.45	0.29	0.20	0.09
46876	BMC51	½ stater	99	0.61	0.39	0.23	0.09

Precision: major components (over 10%) ±1%; minor components (1-10%) ±10%; trace components (<1%) ±20–50%.

Table 4: Proton Activation analyses of a selection of Lydian Electrum Series and Croeseid coins now in the Cabinet de Médailles, Bibliothèque Nationale de France (As, Cr, Fe, Hg, Pb, Pd, Pt, Ru, Sb, Sn, Ti and Zn are in ppm).

Electrum issues

BNF Ref.	%Au	%Ag	%Cu	As	Cr	Fe	Hg	Pb	Pd	Pt	Ru	Sb	Sn	Ti	Zn
22	51.0	46.2	2.4	15	<1	377	<1	1106	9	41	<1	12	1860	6	11
23	55.6	42.1	2.0	16	<1	600	86	1139	9	255	<1	10	529	3	16
24	57.0	40.9	1.9	8	<1	324	<1	1202	6	43	<1	10	203	19	26
25	77.1	19.9	1.1	26	<1	829	<1	2042	34	1860	12933	6	1009	12	1
26	55.8	42.3	1.8	9	9	428	9	675	<1	84	<1	5	269	7	9
Croesids															
526	99.3	0.3	<0.03	1	2	327	<1	66	62	2592	292	0.2	<1	4	15
527	98.0	1.6	0.03	3	5	247	<1	156	55	2858	562	1	23	5	78
528	99.2	0.5	0.04	<1	<1	460	<1	104	<1	204	802	<1	65	13	26
529	98.1	1.0	0.10	4	16	261	<1	49	36	2865	4499	<1	25	5	16
532	99.4	0.3	0.20	<1	<1	287	18	27	<1	446	38	3	65	7	11
533	99.2	0.5	0.30	6	3	123	<1	157	<0.4	<1	<1	1	18	3	13
537	98.3	1.2	0.20	<1	<1	255	<1	74	<1	1229	1148	<1	37	6	47

silver metal will usually contain substantial traces of lead, the eight Lydian silver coins analysed by Cowell et al. (1998) and Cowell & Hyne (2000) for example, contained between less than 300 ppm and 3000 pm of lead (Table 3), with an average of approximately 2000 ppm, that is very much higher than found in the natural gold.

Thus the lead content of the electrum coins should provide a good indication of whether the metal had been refined prior to alloying with silver. Unfortunately none of the previous analyses were really capable of quantifying the traces of lead with any precision, with the exception of Pászthory's (1980) destructive gravimetric analyses necessarily carried out on only two coins. They apparently contained 2400 and 4300 ppm of lead, which seems very high compared to the other analyses reported more recently with the exception of those of Nicolet-Pierre & Barrandon (1997). The neutron activation analyses of Gordus could not determine lead, and the X-ray fluorescence analyses of Kraay (1958) and Visamara (1993) could not detect lead, or at least did not report it. Cowell and his co-workers sought lead in the coins but unfortunately the lead content in five of the eight electrum coins analysed lay below the detection limit of about 400 ppm, and the other three were close to it, such that no confidence could be placed in the results, and averages etc. would have been meaningless (Table 2). However, overall they suggested the lead figures lay in the region of less than 400 ppm to1300 ppm, higher than would be expected for natural gold, but lower than if all the silver had been added. Thus the rather low lead content suggested that the alloy used for the coins was likely to have been made by relatively small additions of silver to the unrefined metal. More recently further analyses of Lydian coins of electrum (Plate 1) and of gold have been undertaken using the more sensitive ion beam activation method of analysis (Table 4).

Analyses

The bombardment of an object with an incident beam issued from an accelerator produces X and gamma rays, the energy of which is diagnostic of the elements present. The analysis of gold coins by gamma ray spectrometry using the higher energy beams from a cyclotron was first developed by Pieter Meyers (Meyers 1969). A similar setup but using a 12 MeV proton beam was developed by J. Poirier in the 1980's (Poirier 1983) and was used to analyse the coins minted in Sardis.

In general, for 12 MeV only (p,n) nuclear reactions are produced in gold which minimises the interferences and improves the limits of detection. A lead sheet interposed between the detector and the sample allows the measurement of low half-life isotopes. The path of a 12 MeV proton in gold is of about 240 µm but most of the information comes from the first 50 µm, in general enough to avoid most of the surface heterogeneity. Major, minor and some trace elements can be measured in gold with limits of detection down to 1 ppm (Guerra & Barrandon 1998).

The new analyses presented here which have much better detection limits and precision for the lead contents, suggest that the previous estimate of the lead content was too low (Table 4). The analyses of the five early electrum coins have lead contents between 675 ppm and 2042 ppm, which average at approximately 1200 ppm. Because of the much greater sensitivity of the method it was also possible to quantify the lead content in a selection of the succeeding Croeseid coins of almost pure refined gold. The five coins analysed contained between 66 ppm and 157 ppm of lead with an average of about 100 ppm (Gondonneau & Guerra 2000).

With these figures it is possible to make a much better judgement of the likely alloying route (Figure 1):

Hypothesis 1
If the gold had been refined this should produce metal that contained about 100 ppm of lead, to which would have been added silver with about 2000-3000 ppm of lead. Thus the total in an alloy of very approximately 50 / 50 gold and silver would be about 50 + 1000 to 1500 ppm, that is between about 1000 and 1500 ppm lead, which corresponds well with the lead content of the coins reported here.

Hypothesis 2
If additional silver was added to the natural alluvial gold that typically contained around 15 % to 30 % of silver, then between 15 % and 30 % additional silver would have had to be added to make up the alloy to about 45 % silver. The natural alluvial gold should have contained less than 200 ppm of lead and with the additional silver, typically containing about 2000 to 3000 ppm of lead, would represent between about 500 and 1100 ppm of lead in the total electrum alloy. This is below the lead figure in four of the five coins analysed and well below the average and range of lead found in the coins. This strongly suggests that the first electrum coins were in fact made from refined pure gold that had then been debased with regular additions of silver.

The sensitivity of the ion beam method also enables a wider range of elements to be detected and quantified. Of particular interest to this study were the tin, the iron and some of the platinum group metals.

At a first cursory glance the tin and platinum group metal contents are extremely disquieting, apparently giving contradictory evidence for refining. The several hundred ppm of tin in the Electrum Series are matched by tin contents of well under 100 ppm in the Croeseids; the generally low platinum and ruthenium in the Electrum Series are matched by several thousand ppm in the Croeseids. This could be interpreted as the inherent natural tin content of the alluvial gold, present in the Electrum Series coins of unrefined gold, but being removed by the parting process for the gold of the Croeseids. Similarly, the platinum group element (PGE hereafter) inclusions in the natural gold remain intact in the unrefined Electrum Series gold (the analysis of coin 25 seems to have actually included such an inclusion), but have been broken down and dispersed into the gold in the Croeseids. That is, the Electrum Series apparently were of unrefined gold, contradicting the lead evidence. However, closer consideration of the evidence leads to a different conclusion.

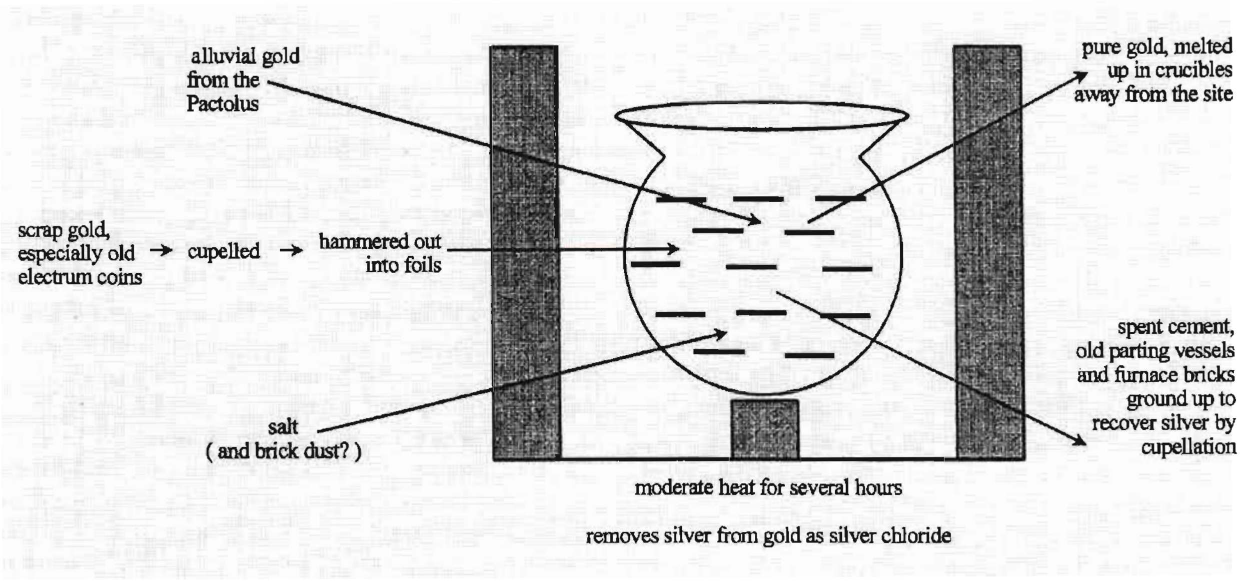
Whether the Electrum Series coins were of refined gold or not their copper content is too high to be other than a deliberate addition. The copper content of native gold should generally be below a percent, and as mentioned above, specifically the two granules of untreated alluvial gold found at the Sardis refinery contained 0.6 % and 0.5 % copper, and copper could only be detected in one of the seven alluvial gold flakes on the Sardis parting sherd (see p.00). Thus the gold should contain no more than about 0.5 % copper overall, and the added silver should contain no more than about 0.4 % copper (the average in the contemporary silver coins in Table 3). The copper content of the Electrum Series coins averages around 2 %, and thus something of the order of 1.5 % copper must represent an addition, whether the gold was refined or not. If this is the case then it is entirely possible that some of the copper was actually in the form of bronze. If we assume that the parting process removed any natural tin from the gold then the average present tin content of around 500 ppm could result from, say, the addition of one part of a 10 % tin bronze to two parts copper. This is not to suggest that there was any fixed formula, but that the additions could unconsciously include scrap bronze leading to the variable tin compositions found in the coins. Some support is lent to the hypothesis that the tin originated in the copper additions by the coin with the highest copper content (2.4 %) which also has the highest tin content (0.186 %). This composition could have arisen, for example, by the addition of a bronze containing about 7 % tin, or a mixture of two parts of a 10 % tin bronze and one part copper.

The iron contents are also interesting, being relatively consistent at several 100 ppm in all of the coins analysed. By contrast the iron content of natural gold is very variable, some gold have several percent of iron (Antweiler & Sutton 1970), and refining should remove the majority of it as the volatile ferric chloride, $FeCl_3$. It was postulated in the main study (Craddock 2000a: 180-181, and see below p.00) that one of the main reactive agents in the parting process would have been ferric chloride, generated in the furnace initially by the reaction between iron oxides from the clay walls etc, the salt and water vapour. The ferric chloride vapour would attack the silver in the gold directly or decompose to ferric oxide, releasing chlorine and then react with more salt or hydrogen chloride to reconstitute the ferric chloride. Thus ferric oxide and chloride vapour would have been present in the parting vessel and permeating the gold alomg the grain boundaries (see below) until almost the end of the process when depletion of the salt would have stopped the regeneration of ferric chloride, leaving the ferric oxide as a stable and involatile solid. Thus this ferric oxide would be deposited in and on the gold at the end of the process. The overall similarity and consistency of the iron contents in the Electrum Series coins and in the Croeseids suggests that they have been through a common parting process.

The platinum and ruthenium contents of the coins are also revealing. Previous examinations of the PGE inclusions in both the Electrum Series coins and in the Croeseids show that they comprise principally osmium, iridium and ruthenium, with rather more ruthenium in the Croeseids (Meeks & Tite 1980; Cowell & Hyne 2000: 173; Craddock 2000b). The analyses in Table 3 include the Electrum Series coin 25, which, as noted above, apparently included an inclusion and thus enable an estimate of the composition of a typical inclusion to be made. The platinum to ruthenium ratio is approximately 1 to 8, which is in line with the analyses of the inclusions themselves by Meeks & Tite (1980). Thus platinum was a minor component in the Electrum Series PGE inclusions, but the Croeseid gold has variable but quite high platinum contents. It is just not possible to derive the thousands of ppm of platinum in the Croeseid gold from a putative breaking down of the PGE inclusions in the parting process, especially as intact PGE inclusions are also regularly found in the refined Croeseids. The ruthenium content is even more erratic in the Croeseids, varying from below the 2 ppm detection limit to an astonishing 0.45 % in coin 529 (it is possible that an inclusion has been included in the area analysed). The greater variability is not surprising, as in contrast to platinum, ruthenium is insoluble in gold and in addition would be prone to oxidise and evaporate at the putative temperatures of the Sardis parting process.

The major differences in the platinum and ruthenium contents of the coins can only really be explained by postulating different sources of gold for the Electrum Series and later Croeseid coins. This raises the possibility that the deposits in the Pactolus may already have been largely worked out by the time that the Croeseids were minted, inviting comparison with the deposits found in 1849 in California. There the gold was in very rich 'bonanza' placer deposits that were soon exhausted. Certainly, already by the time that Herodotus wrote in the 5th century BC, gold production at Sardis was no more than a memory. Just one association with gold production and refining lived on

Figure 2: Flow diagram of the gold refining process at Sardis (from Ramage & Craddock 2000: 202, fig.10.2).



through to the end of classical antiquity, and that was the touchstone. Both Theophrastus (*On Stones* 45-47; Caley & Richards 1956: 54-55, 150-159) and Pliny (*Natural History* 33.126; Rackham 1952: 95) specifically mention pebbles from the streams, including the Pactolus, flowing down the slopes of Mt. Tmolos above Sardis, as making the best touchstones for the assay of gold (Craddock 2000e).

The Technology of Gold Refining at the Sardis Gold Refinery (Figure 2)

Before the discovery of the gold refinery at Sardis and its excavation by the Harvard-Cornell Archaeological Exploration of Sardis, and the subsequent scientific study of the material from those excavations, knowledge of the solid state or cementation parting process in Classical antiquity was limited to literary sources (Halleux 1974; 1985; Healy 1978: 155; Nicolini 1990, although the best account of traditional salt cementation parting remains that of John Percy, published in 1880). The best surviving account from classical antiquity is that of Agarthacides, summarised by Diodorus Siculus in the first century BC (Burstein 1989), together with a rather confused description by Strabo (*Geography* 3.2.8; Jones 1923: 24) and some sparse comments by Pliny in the *Natural History* (NH 33.60, 33.69, 33.84, 35.183; Rackham 1952: 49, 54-55, 65-67, 397), each discussed at length in Craddock (2000c: 32-37). These ancient accounts were reinforced by the much more detailed accounts of the cementation parting process in Renaissance Europe, in works such as the *Probierbuchlein*, and metallurgical treatises by Biringuccio, Agricola and Ercker (Craddock 2000d: 55-69). Some work of experimental replication of the salt parting process has been undertaken, notably by John Notton (1974). The excavations and scientific study and further replication experiments (Geçkinli et al. 2000; 2001) have been fully reported in Ramage & Craddock (2000). The account which follows is based on the more detailed reconstruction of the process given in Craddock (2000f).

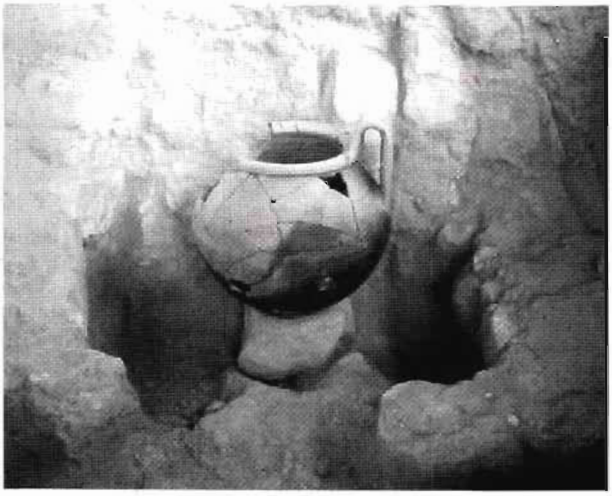


Plate 2: A typical Lydian earthenware cooking pot similar to the type that would have been used for the gold cementation set on the central plinth of one of the parting furnaces at Sardis (from Ramage & Craddock 2000: 132, fig. 5.3).

Plate 3: The bases of two typical brick-built parting furnaces with openings and central plinths. Note the similarity to that depicted in Figure 5, some 2,000 years later (Photo: P.T. Craddock).

The refinery dates to the sixth century BC, very likely to the reign of King Croesus, the last ruler of independent Lydia, just before he unwisely took on Cyrus and the might of the Persian Empire in 547 BC.

The primary source of Lydia's wealth lay quite literally in the bed of the presently rather insignificant little stream that runs through the centre of Sardis, a few metres from the refinery. This was the river Pactolus, one of the most famous gold sources of antiquity, producing gold on a prodigious scale for a few generations around the mid first millennium BC. As with all natural gold, the Pactolus gold contained substantial quantities of silver which were separated at the refinery.

From around the furnaces a number of thin foils of partially refined gold were found, but in addition some of the sherds of the parting vessels had tiny flakes of natural gold attached. Thus it seems likely that the natural alluvial gold was treated directly in the parting furnaces without recourse to any pre-treatments or even to being melted and turned into foils, and the foils are likely to come from scrap gold that was being recycled. The scrap gold, including the old Electrum Series coins, would have first been cupelled to remove any base metals such as copper, and then hammered into the foils to expose the maximum surface area to the astringent vapours of the parting process.

The gold would have been treated with the parting cement. None of this survives but it seems most likely that it was just common salt, sodium chloride, although the classical accounts suggest that a little alum, aluminium potassium iron sulphates, may also have been present.

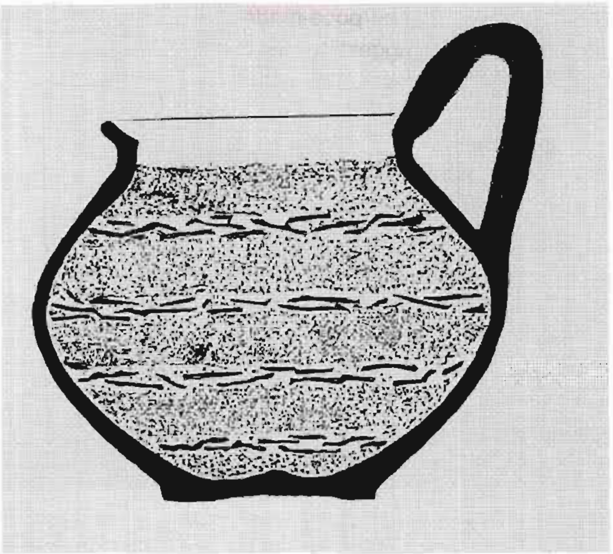


Figure 3: Section through a typical Lydian earthenware cooking pot used as a parting vessel with layers of gold and the salt parting cement (from Ramage & Craddock 2000: 89, fig. 4.31).

Later cements usually contained an inert carrier such as brick dust but there is no evidence for this at Sardis or in any of the ancient descriptions. Agatharcides stated quite specifically that at the cessation of the process there was nothing left in the parting vessel except the refined gold.

The parting vessels used at the Sardis refinery seem to have been based on the contemporary Lydian earthenware cooking pots (Plate 2). Alternate layers of cement and impure gold would have been laid in the pot which was then probably lightly sealed with clay (Figure 3). The pot was placed in the parting furnace. The lower parts of several of these furnaces survive at Sardis (Plate 3, Figure 4). They are square in plan and have a single opening in one side of the base. They were probably under a metre in height and may be compared with the 16th century furnace illustrated in Figure 5. The floor has a clay lining and in the centre there is a mortared brick plinth upon which the parting vessel would have stood surrounded by a fire of burning wood that provided the heat energy for the cementation process. Petrological and SEM study of the furnace bricks suggested that the maximum temperature to which they had been exposed did not exceed 800° C, and other evidence, such as the survival of the PGE inclusions in the refined gold, suggest the temperature was probably in the region of 600 to 800° C.

At temperatures over 500° C in the oxidising and rather moist atmosphere prevailing inside the earthenware parting vessels, vapours of hydrogen chloride, chlorine and ferric chloride would have formed, of which the chlorine and especially the ferric chloride would have been active in attacking the silver in the impure gold. The vapours rapidly penetrated into the metal along the grain boundaries, converting the silver into silver chloride, which be-

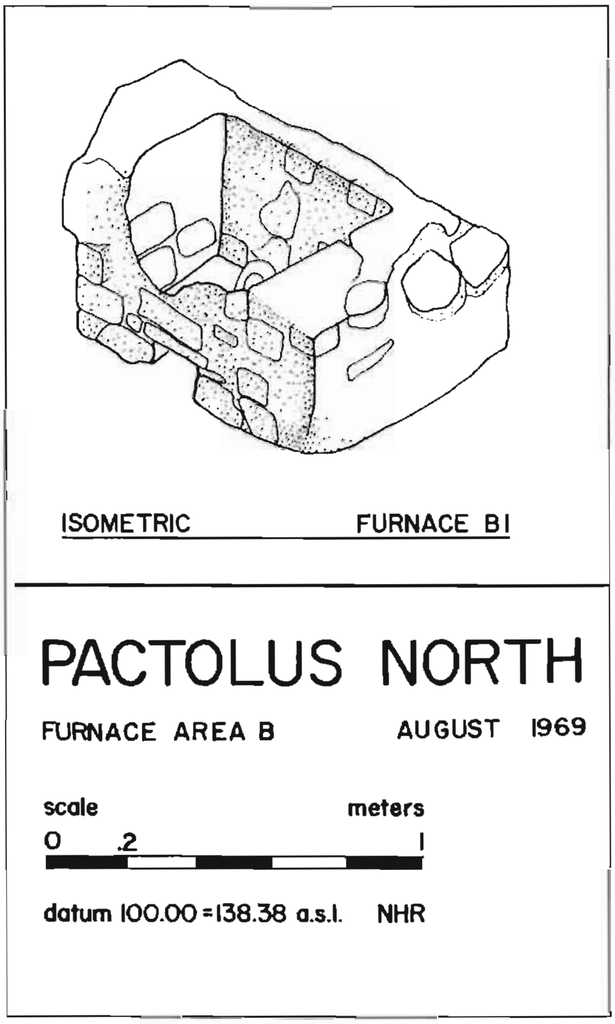


Figure 4: Isometric drawing of a parting furnace at the PN refinery at Sardis (from Ramage & Craddock 2000: 87, fig. 4.27).

Figure 5: 16th century parting furnace, from Agricola's De re Metallica of 1556, note the similarity to the furnace depicted in Plate 4 (from Hoover & Hoover 1912: 455).

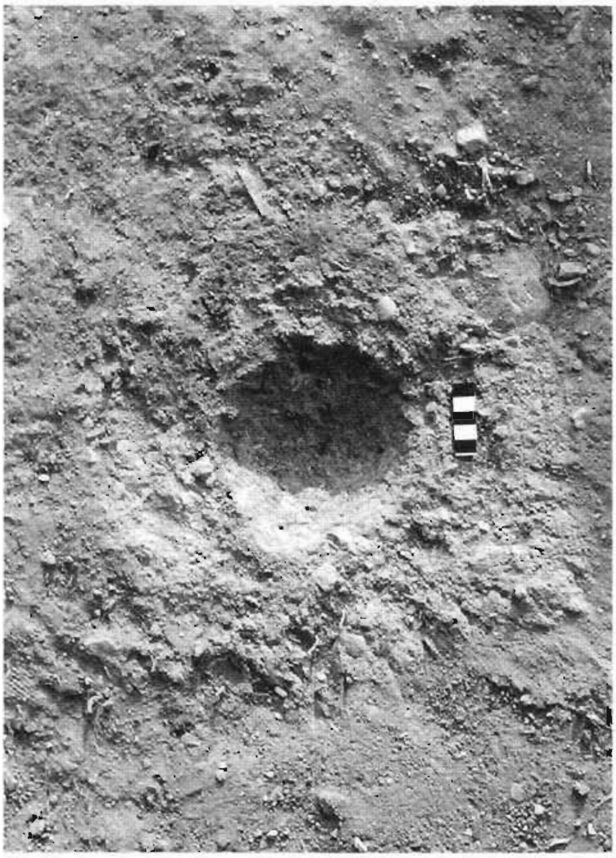


Plate 4: Cupellation hollow, one of many such lead-rich hollows in the ground near to the furnaces where it is believed the silver was recovered by cupellation (Photo: P.T. Craddock).

ing itself volatile left the gold as a vapour. Much of the silver chloride escaped through the walls of the parting vessel, which together with the furnace walls are permeated with silver, one furnace brick contains no less than 3 % by weight of silver.

As already noted, the foils found near the furnaces were in every stage of refinement, and were accompanied by a series of earthenware pot sherds that had clearly been re-used as melting trays or crucibles at temperatures of around 1100° C for short periods and contained globules of gold or of silver in their vitrified surfaces. It is suggested that samples of the gold were removed periodically from the parting vessels for assay to judge the progress of the parting process. The samples would have been melted on the sherds and almost certainly analysed by touchstone (Craddock 2000e). Similarly, the silver recovered from the operation by cupellation (see below) was also being tested by fire assay (Craddock 2000e). The parting process is very temperature dependent, and at the very low temperatures postulated here the process could have taken times in the region of the five days stipulated by Agatharcides. At the conclusion of the process the gold must have been removed from the parting vessels and melted in a crucible to produce a single piece. Not a single sherd of a real purpose-made crucible was found on the site, strongly suggesting that the gold, probably still in the parting vessel, was taken elsewhere for the next stages of goldworking or coining.

Periodically the furnace bricks and old parting vessels etc, were smelted to recover the considerable quantities of silver that they contained, although much must have been lost to the atmosphere and surroundings. Near to the furnaces are a series of small, burnt hollows dug into the ground (Plate 4). These are rich in lead and it is suggested that this was where the silver would have been recovered by cupellation. It is envisaged that the silver-rich refractory ceramics and bricks would first have been smelted with lead in small shaft furnaces (from which a few fragments of furnace wall were recovered). The lead would absorb the silver into itself, in much the same way as in the contemporary smelting of argentiferous lead ores the lead absorbed the silver (Craddock 1995: 216-228). The resulting argentiferous lead would then have been placed in one of the hollows beneath a charcoal fire and subjected to a strong blast of air from bellows. In these hot oxidising conditions, in excess of 1100° C, the lead oxidised to litharge, lead oxide, PbO, but the silver was unaffected and floated on the molten litharge "like oil on water" in Pliny's apt phrase (NH 33.95, Rackham 1952: 72-75).

In the vicinity of the hollows there was a heap of litharge cakes which fitted perfectly into the hollows (Plates 5 - 6). There were also a number of fragmentary ceramic tuyeres and tiles that had clearly been exposed in part to great heat and lead salts as they were now partially vitrified and heavily lead glazed. It is probable that the tiles were used to make a small hearth over the hollows to contain the burning charcoal. The tuyeres are rather distinc-

Plate 5: Cake of litharge from a dump where it was awaiting recycling. Note the impression in the top where the molten silver originally sat "like oil on water" (from Ramage & Craddock 2000: 90, fig. 4.35).

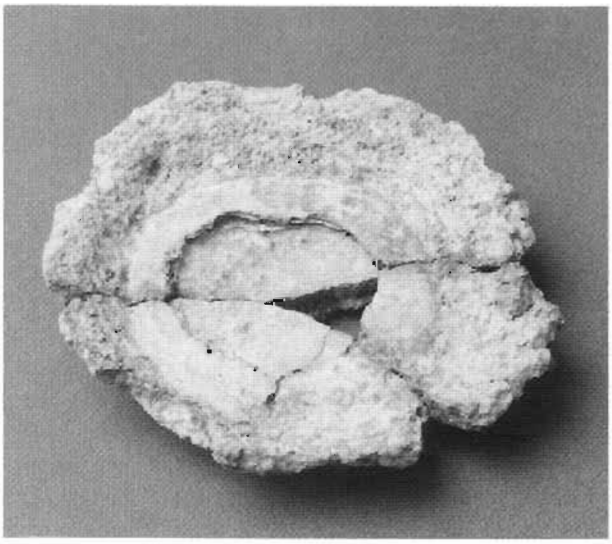


Plate 6: Reconstruction. A square-section tuyere placed by a cupellation hollow in which one of the fragments of litharge has been sat. Such tuyeres were ideal for sitting on the ground and directing the air blast from the bellows onto the molten argentiferous lead at white heat in the hollows (from Ramage & Craddock 2000: 208, fig. 10.3).

tive (Plate 6), being of a square external section, suitable for lying on the ground, some with an angled nozzle and thus being ideal to direct the air from the bellows down into the hollows.

Overview of the Origins of the Gold Refining Process

In Ramage and Craddock (2000) and in the earlier publications listed in the first paragraph of this paper, it was argued that although the surface enhancement of gold had been known, probably almost from the inception of goldworking, gold refining to separate the silver from the body of the natural gold was likely to have commenced much later, probably stimulated by the concept of coins of fixed purity.

Part of the evidence for this was the apparent absence of gold refining technology for the first Electrum Series coins. The more accurate analyses published here show that the gold is likely to have been refined from the very beginning of coin production at Sardis. However, it is still probable that gold refining began with coin production.

The most direct evidence is the general absence of any consistent high purity gold, equivalent to that found in the Croeseids, in artefacts before the introduction of coinage. Furthermore references to white gold as distinct from refined gold occur no earlier than Herodotus' descriptions of the gold deposited by King Croesus at Delphi (Herodotus I 14, 50; Godley 1920: 57; Craddock 2000c). It must also be stressed that in the ancient world there was no concept of elements with constant inviolate properties. On the contrary, metals especially gold, were believed to have intrinsic properties that were specific to the environment from which they came. Thus refining would have been a strange idea without the concept of the existence of some standard to aim for. Experiments trying to control the composition of the natural gold for the first coinage would have shown that there really was an ultimate weigh loss and colour change beyond which it was impossible to refine the gold any further, and also that the original natural gold could be recreated quite easily by adding silver. It is probable that with this information came the realisation that the differences in the various natural golds were largely due to the silver content.

Thus although the new analytical results presented here suggest that gold refining was practised from the inception of coin production, overall the evidence still suggests it was not practised earlier. The impetus is likely to have been the problems of controlling the composition. The installation excavated at Sardis is thus likely to have been amongst the first, if not the first, gold refinery and already had features that were to persist until the end of gold parting by cementation over 2000 years later.

Bibliography

ANTWEILER, J.C. & SUTTON, JR., A.L.:
1970 *Spectrochemical analyses of native gold samples*, US Geological Survey Report. (USGS-GD-70-003). Washington DC.

BURSTEIN, S.M.:
1989 *Agatharcides of Cnidus: On the Erythraean Sea*, *The Hakylut Society*, London.

CALEY, E.R. & RICHARDS, J.F.C., (TRANS.):
1956 *Theophrastus on Stones*. Ohio State University Press, Columbus, Ohio.

COWELL, M.R., HYNE, K., MEEKS, N.D. & CRADDOCK, P.T.:
1998 Analyses of the Lydian electrum, gold and silver coins. In: W.A. Oddy & M.R. Cowell (eds.), *Metallurgy in Numismatics* 4. Royal Numismatic Society, London, 526-538.

COWELL, M.R. & HYNE, K.:
2000 Scientific Examination of the Lydian Precious Metal Coinages. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold*, BMP, London, 167-174.

CRADDOCK, P.T.:
1995 *Early Metal Mining and Production*. Edinburgh University Press, Edinburgh.
2000a Replication Experiments and the Chemistry of Gold Refining. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold,* BMP, London, 175-183.
2000b The Platinum Group Element Inclusions. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold*, BMP, London, 238-244.
2000c Historical Survey of Gold Refining (1): Surface treatments and refining world wide and in Europe prior to AD 1500. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold,* BMP, London, 27-53.
2000d Historical Survey of Gold Refining (2): Post Medieval Europe. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold,* BMP, London, 54-71.
2000e Assaying in Antiquity. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold*, BMP, London, 245-250.
2000f Reconstruction of the Salt Cementation Process at the Sardis Refinery. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold*, BMP, London, 200-221.

CRADDOCK, P.T., MEEKS, N.D., COWELL, M.R., GEÇKINLI, A.E., HOOK, D.R., MIDDLETON, A.P. & RAMAGE, A.:
1998 The refining of gold in the Classical world. In: D. Williams (ed.), *The Art of the Greek Goldsmith*. BMP, London,111-121.

GEÇKINLI, A.E., ŎZBAL, H., MEEKS, N.D. & CRADDOCK, P.T.:
2000 Examination of the Sardis Gold and the Replication Experiments. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold,* BMP, London, 175-184.

GEÇKINLI, A.E., MEEKS, N.D. & CRADDOCK, P.T.:
2001 The examination of the gold samples from Pactolus North at Sardis, Turkey. *Archaeometallurgy in The Central Europe III. Acta Metallurgica Slovaca* 7, 20-26.

GODLEY, A.D.:
1920 *Herodotus*, Vol 1. Loeb Classical Library, Heinemann, London.

GONDONNEAU, A. & GUERRA, M.F.:
2000 L'or perse à travers l'analyse de monnayages antiques et médiévaux, *Revue d'Archéometrie* 24, 27-38.

GUERRA, M.F. & BARRANDON, J.N.:
1998 Ion beam activation analysis with a cyclotron. In: A. Oddy & M. Cowell (eds.), *Metallurgy in Numismatics* 4, Royal Numismatic Society Special Publication 30, London, 15-34.

HALLEUX, R.:
1974 L'affinage de l'or de Crésus aux premiers alchimistes. *Janus* 78, 79-102.

HALLEUX, R.:
1985 Méthodes d'essai et d'affinage des alliages aurifères dans l'antiquité et au moyen âge. In: C. Morrisson, C. Brenot, J-N Barrandon, J-P. Callu, J. Poirier & R. Halleux (eds.), *L'or monnayé I: Purification et altération de Rome à Byzance*. Cahiers Ernst-Babelon 2. CNRS, Paris, 39-77.

HEALY, J.F.:
1978 *Mining and Metallurgy in the Greek and Roman World.* Thames and Hudson, London.

HOOVER, H.C. & HOOVER, L.H.:
1912 *Georgius Agricola*: *De Re Metallica. The Mining Magazine*, London.

JONES, H.L.:
1923 *The Geography of Strabo*, Vol. 2. The Loeb Edition, Heinemann, London.

KRAAY, C.M.:
1958 The composition of electrum coinag. *Archaeometry* 1, 21-23.

MEEKS, N.D.:
2000 Scanning Electron Microscopy of the Refractory Remains and the Gold. In: A. Ramage & P.T. Craddock (eds.), *King Croesus Gold*, BMP, London, 99-156.

MEEKS, N.D. & TITE, M.S.:
1980 The analysis of platinum-group element inclusions in gold antiquities. *Journal of Archaeological Science* 7, 3, 267-275.

MEEKS, N.D., CRADDOCK, P.T., GEÇKINLI, A.E., HOOK, D.R., MIDDLETON, A.P. & RAMAGE, A.:
1996 The scientific study of the refractory remains and the gold particles from the Lydian gold refinery at Sardis. In: S. Domirci. A.M. Özer & G.D. Summers (eds.), *Archaeometry* 94, Türbitak, Ankara, 461-482.

MEYERS, P.:
1969 Non-destructive activation analysis of ancient coins using charged particles and fast neutrons. *Archaeometry* 11, 1, 67-84.

NICOLET-PIERRE, H. & BARRANDON, J-N.:
1997 Monnaies d'électrum archaïques. Le trésor de Samos de 1894 (IGCH 1158), conserve á Paris. *Revue de Numismatique* 152, 121-138.

NICOLINI, G.:
1990 *Techniques des ors: la bijouterie ibérique du VII au IVe siècle*, Vol 1. Paris.

NOTTON, J.F.H..
1974 Ancient Egyptian Gold Refining. *Gold Bulletin* 7, 2, 50-56.

PÁSZTHORY, E.:
1980 Investigations of the early electrum coins of the Alyattes type. In: W.A. Oddy & D.M. Metcalf (eds.), *Metallurgy in Numismatics* 1. Royal Numismatic Society, London, 151-156.

PERCY, J.:
1880 *The Metallurgy of Silver and Gold.* Vol 1, John Murray, London.

POIRIER, J.:
1983 Contribution à l'analyse de l'or antique. Application aux monnayages du monde méditerranéen du IIe au XVIe siècles, PhD thesis, University of Orléans, France.

RACKHAM, H., (TRANS.):
1952 *Pliny: The Natural History.* Loeb Classical Library 9, Heinemann, London.

RAMAGE, A. & CRADDOCK, P.T:
2000 *King Croesus Gold.* BMP, London.

VISAMARA, N..
1993 Proposte per un nuovo ordinamento della monetazione arcaica della Lydia. In: J. Borchardt & G. Dobesch (eds.), *Akten des III Internatinal Lykien-Symposios*, Vienna, 191-201