Metallurgy in Numismatics 6

Mines, Metals, and Money
Ancient World Studies in Science, Archaeology and History

EDITED BY

KENNETH A. SHEEDY
and GILLAN DAVIS

AUSTRALIAN CENTRE FOR ANCIENT NUMISMATIC STUDIES

MACQUARIE UNIVERSITY

THE ROYAL NUMISMATIC SOCIETY
SPECIAL PUBLICATION NO. 56

LONDON

2020

ROYAL NUMISMATIC SOCIETY SPECIAL PUBLICATIONS
GENERAL EDITOR: ROGER BLAND

To our daughters:
Lucy Clare Sheedy, Rebecca Allen and Tamara Davis

The Royal Numismatic Society Special Publication No. 56

ISBN 0–901405–37–X

British Library Cataloguing in Publication data
A CIP catalogue record is available from the British Library

Set by New Leaf Design, Malton, North Yorkshire
Printed by Gutenberg Press Ltd, Tarxien, Malta

CONTENTS

PART 2

ANALYSIS

8. THE MINTING/MINING NEXUS: NEW UNDERSTANDINGS OF ARCHAIC GREEK SILVER COINAGE FROM LEAD ISOTOPE ANALYSIS

Zofia Anna Stos-Gale and Gillan Davis

ABSTRACT

This paper presents fresh interpretations of 160 lead isotope analyses of Archaic Greek coins on the OXALID database based on new data for ore sources in Spain, Sardinia, Bulgaria, Romania, Greece, Turkey and Iran. It demonstrates that the earliest minters used far more diverse metal sources than the literary evidence suggests, and engaged in what could be described as opportunistic minting. Some currently held views on the importance of Siphnian silver, Peisistratid access to Thracian silver, the sources of Aiginetan, Thasian and Chian silver, the use of gold and tin as tracers for Siphnian and Lavrion silver, and the mixing of silver are challenged. Thoughts are offered on how archaic minting drove intensification of mining.

INTRODUCTION

The first large research project to use lead isotope and chemical analyses for the identification of ore sources of Archaic silver coins was begun in 1978 by Wolfgang Gentner, Otto Müller and Günther Wagner from the Max Planck Institute for Nuclear Physics in Heidelberg, in collaboration with Noel Gale from the Department of Geology, University of Oxford.[1] The main group of coins for analysis came from a large hoard discovered in 1969 in Asyut, southern Egypt, comprising 900 or so coins minted by many of the Archaic Greek cities from Sicily to Cyprus. The publishers of the Asyut Hoard suggested it was buried around 475 BC (Price and Waggoner 1975) which provides a useful *terminus ante quem* for silver sources and minting practices at the end of the Late Archaic Period.

The Stiftung Wolkswagenwerk purchased 120 severely damaged coins of low numismatic value for analysis, and a further 45 Aeginetan coins from the same hoard were contributed by Dr Leslie Beer. Altogether 99 coins and one silver ingot from the Asyut Hoard were analysed for their lead isotopes, and 89 of these also for their elemental compositions. The results were published in 1978 (Gentner *et al.* 1978) and in 1980 (Gale *et al.* 1980). They concluded that many coins were consistent with origins in the mines of Lavrion and Siphnos, but they had some doubts over interpretation of the data, mainly due to the lack of a database of lead isotope compositions from other ore deposits.

Over the next 20 years, two other research projects in the Isotrace Laboratory at the University of Oxford provided more lead isotope and chemical analyses of Archaic silver coins from Thasos (Gale *et al.* 1988) and Chios (Hardwick *et al.* 1998), summarised in Table 1. Since then, a great deal more lead isotope data and archaeometallurgical information have been published for ore sources in Spain, Sardinia, Bulgaria, Romania, Greece, Turkey and Iran.[2]

In this paper, the lead isotope data are re-evaluated in a numismatic context, endeavouring to understand the operations of the earliest Archaic Greek mints, and especially their sources of silver.

METHODOLOGY OF METAL PROVENANCE STUDIES

The lead isotope provenance method is based chiefly on comparisons of lead isotope and elemental compositions of ores and slags from known ore deposits and ancient artefacts. In the 1980s, the database of European and Middle-Eastern deposits of lead-silver and copper ores included only a few hundred lead isotope ratios. The current database used for interpretation of lead isotope data published on the Oxford Archaeological Lead Isotope Database (OXALID) and by other researchers

[1] We thank Professor Jack Kroll for reading and commenting on this paper as well as the anonymous reviewers.

[2] A preliminary re-evaluation of the possible origin of these coins was discussed at the RITaK Graduate seminar held in the Mining Museum Bochum in November 2014 (published in Stos-Gale 2017).

consists of over 6,000 lead isotope ratios for lead, silver and copper ores from the majority of important deposits in Europe, and some from the Middle East (Turkey, Israel, Jordan, Iran and Saudi Arabia), as well as several thousand data for prehistoric metals from the same regions. Furthermore, the methodology of comparing the data has been vastly improved due to advances in computer software over the last 30 years.

An ancient artefact is regarded as being fully consistent with originating from a given ore deposit if its three independent lead isotope ratios are identical (within ±0.1% analytical error for each ratio) with the lead isotope ratios obtained for the ores from this deposit. Finding the matching ore samples for each artefact is done using the TestEuclid procedure (Stos 2009). This three-step process involves first searching the database covering all ore data. Second, the lead isotope ratios of the artefacts are plotted on at least two lead isotope diagrams that include all three independent ratios, together with the data for all ore deposits that appear to show matching lead isotope ratios. In the third step of the interpretative process, a broader picture of the possible origin of metals is considered including:

i. Rejection of ore deposits that on geochemical or chronological ground could not have supplied silver or copper for these artefacts.
ii. Comparisons with lead isotope and elemental data for the artefact from various related archaeological sites.

It is important to stress that identical lead isotope characteristics of a group of metals do not guarantee that their elemental characteristics will also form a group and *vice versa* (Rychner and Stos-Gale 1998; Pernicka 1999). It is assumed that silver artefacts usually do not contain added lead since it is in most ores being cupellated, but only traces of lead remain after processing. Small amounts of copper that might have been added to silver do not usually contribute enough lead to change the lead isotope compositions of the original silver.

It is also necessary to consider the possibility that an artefact was made from melting together silver from different sources. The effect of this activity on lead isotope provenance studies has been discussed at length (summarised in Stos-Gale 2001; Ling *et al.* 2014). The problem of mixing can be assessed by examining the distribution of the data points on the lead isotope plots; each metal obtained from mixing two (or more) other sources will plot on a straight line between the data points representing these other sources. On lead isotope plots the 'mixing lines' run diagonally following the general trend of the radioactive decay lines.

POSSIBLE SOURCES OF SILVER FOR ARCHAIC GREEK COINS AND EVIDENCE OF THEIR EXPLOITATION

Silver was available in the Aegean from the Bronze Age (Gale and Stos-Gale 1981a and b; Pernicka *et al.* 1985; for dating cf. Wagner *et al.* 1986). Archaeometallurgical research has provided evidence that silver ores were mainly exploited on the Cycladic island of Siphnos in the Early Bronze Age (third Millennium BC) and in the first Millennium BC (Wagner and Weisgerber 1985), and more or less continuously in Lavrion, Attica, from the Early Bronze Age until the Roman period and later (Conophagos 1980; Gale *et al.* 2008).

Other main sources in the Archaic Period were in northern Greece in the Chalkidiki peninsula, the island of Thasos, and the Rhodope Mountains including Mt. Pangaion.[3] For Chalkidiki there seems to be no evidence of silver exploitation in the Bronze Age but quite possibly it was mined from the first millennium BC (Wagner *et al.* 1986).

[3] For the vexed question of the location the Mt Pangaion mines, see Wagner and Weisberger 1988.

Further afield to the east were the silver-bearing ores in the Troad Peninsula (Wagner *et al.* 1985), Taurus Mountains in southern Turkey (Yener *et al.* 1991) and Iran (Pernicka *et al.* 2011) where silver was exploited since the Early Bronze Age. The Phoenicians traded to the Western Mediterranean in the Archaic Period and eagerly sought Spanish silver which was exploited from the Argaric period in the third-second millennium BC (Kassianidou 1992; Rothenberg and Blanco Freijeiro 1981; Renzi *et al.* 2009 and 2012). There was also mining in Roman times in the south of France in Massif Central (Baron *et al.* 2006; Davis 1935), and on Sardinia (Valera *et al.* 2005), with some possibility they were exploited earlier in the Late Bronze Age.

A further potential source is to the north of Greece in present day Romania where there are rich mineral deposits. The Romans established a province of Dacia there at the beginning of the second century CE, and exploited gold and silver ores in the Apuseni Mountains in the south-east Carpathians (also known as the Transylvanian Metalliferous Mountains).[4] Some distance north in the Baia Mare part of the Eastern Carpathians there are also gold and silver ores (Kouzmanov *et al.* 2005b: Marcoux *et al.* 2002). It is quite possible these rich gold, silver and copper deposits were exploited before the Roman period by Thracian tribes back to the Bronze Age (Stos-Gale 2014).[5]

RE-EVALUATION OF THE RESULTS OF EARLIER LEAD ISOTOPE AND CHEMICAL ANALYSES OF ARCHAIC GREEK COINS

The OXALID database contains lead isotope data for 160 Archaic Greek coins analysed in Oxford and securely dated to sixth-fifth centuries BC (Table 1).[6]

Athens

A keen debate surrounds the source(s) of silver for the earliest Athenian coinage known as the *Wappenmünzen*, begun under the Peisistratids in the second half of the sixth century BC. [Aristotle] *Ath. Pol*. 15.2 claimed Peisistratos derived the *chrēmata* (literally 'resources' but usually understood in this context to mean 'money' in the form of bullion) to pay mercenaries to seize his tyranny of Athens from "the neighbourhood of Pangaion", though Herodotus said the inland mines were controlled by the local tribes (7.112). [Aristotle] *Ath. Pol*. 22.7 (cf. Hdt. 7.144) claimed the major strike of rich silver ore in Lavrion was in 483 BC, but the common scholarly opinion assumes the mines had been exploited somewhat earlier, spurred on by the loss of access to Thracian silver when Darius conquered the region in 512 BC (Hdt. 5.11; 5.23).[7] The expectation from literary evidence is thus that the *Wappenmünzen* were minted from Northern Greek silver, succeeded by Lavrion silver for the massive minting of 'owls' (Hdt. 1.64.1; cf. summary of evidence and arguments in Davis 2014a). Against this, there is clear evidence of Lavrion silver from lead isotope analyses of seventh century *Hacksilber* from Tel Miqne-Ekron in Southern Israel (Stos-Gale 2001 and OXALID).

Gale *et al.* (1980) analysed seven *Wappenmünzen* dating to the end of the sixth century BC from the British Museum and Ashmolean Museum (Oxford) collections (Fig. 1). Six of them show very varied lead isotope compositions which definitively exclude Lavrion, and reflect widely different origins of silver unknown to Gale *et al.* (1980, 30). Only one, a 'wheel' obol is fully consistent with Lavrion silver, supporting the independently derived conclusion

[4] This area covers about 900 km^2 and even today contains large quantities of epithermal Au-Ag, and porphyry Cu-Au ores (Neubauer *et al.* 2005; Kouzmanov *et al.* 2005a; Baron *et al.* 2011).
[5] The silver deposits in the Apuseni Mountains and Rosia Montana (to a lesser extend) are significant. Even in the second half of the 20[th] century over 30 tonnes a year of silver were extracted in Romania (Dunning *et al.* 1982, p. 287).
[6] The data are freely available at: http://oxalid.arch.ox.ac.uk. This includes information on where samples were collected.
[7] In fact, there are problems with this as Professor Kroll pointed out in correspondence. The Persians were not maritime traders, and collection of tribute did not amount to monopolisation. Trade in Aegean silver must have continued for Thracian coinage to show up in Egyptian and Levantine hoards.

Table 1. Lead isotope data for the 160 analysed coins from the OXALID database

Mint	*Chronology*	*Number of analysed coins*	*Reference*	*Lead isotope based possible origin of silver*
Acanthus	Before 475 BCE	3	Gale *et al.* 1980	2 Chalkidiki, 1 Pangeon
Aegina	6th-5th c. BCE	44	Gale *et al.* 1980	8 Chalkidiki, 8 Lavrion, 5 Pangeon, 10 Rhodope, 2 Romania, 6 Siphnos, 1 Thasos, 1 Troad, 1 South Spain, 2 unknown (1 South France, 1 Taurus Mts.)
Athens, 'Wappenmünzen'	6th c. BCE	7	Gale *et al.* 1980	1 Lavrion, 3 south Spain, 2 Rhodope, 1 Iran (Nakhlak)
Athens, 'Owls'	5th c. BCE	21	Gale *et al.* 1980	1 Chalkidiki or Thasos, 19 Lavrion, 1 Romania (Baia Mare)
Chios	6th-5th c. BCE	14	Hardwick *et al.* 1998	2 Chalkidiki or Thasos, 7 Lavrion, 2 Rhodope, 1 Romania (Rosia Montana), 2 south Spain
Corinth	Before 475 BCE	8	Gale *et al.* 1980	1 Chalkidiki, 5 Lavrion, 1 Siphnos, 1 Rhodope
Lesbos	Before 475 BCE	1	Gale *et al.* 1980	1 Chalkidiki or Thasos
Lycia	Before 475 BCE	2	Gale *et al.* 1980	2 Troad, Canakkale
Mallus or Caria	Before 475 BCE	5	Gale *et al.* 1980	3 Lavrion, 1 Iran (Pasar), 1 Rhodope or Thasos,
Messana, Sicily	Before 475 BCE	1	Gale *et al.* 1980	1 Lavrion
Orescii	Before 475 BCE	6	Gale *et al.* 1980	6 Chalkidiki
Persia	Before 475 BCE	3	Gale *et al.* 1980	1 Iran (Pasar), 2 Lavrion
Salamis, Cyprus	Before 475 BCE	1	Gale *et al.* 1980	1 Lavrion
Samos	Before 475 BCE	5	Gale *et al.* 1980	4 Lavrion, 1 Siphnos
Thasos	5th c. BCE	36	Gale *et al.* 1980 and Gale *et al.* 1988	9 Chalkidiki, 4 Lavrion, 1 Pangeon, 10 Rhodope, 2 Romania (Apuseni), 2 Siphnos, 5 Thasos, 1 south Spain, 2 unknown
Zankle, Sicily	Before 475 BCE	3	Gale *et al.* 1980	1 Lavrion, 1 Romania (Rosia Montana), 1 Thasos
		160		

that the wheel fractions do not belong with the early *Wappenmünzen* and date to the end of the sixth/beginning of the fifth century BC (Davis 2014b). A comparison of the previously unknown lead isotope ratios with the current database indicates that two of the analysed *Wappenmünzen* (BMC3 'amphora' and BMC 18 'gorgoneion') are indeed consistent with lead isotope ratios of ores from northern Greece (the southern Rhodope - Macedonia or Thrace). However, one (BMC 1[H] Histiaea) matches samples of ores from a silver mine at Nakhlak in Iran, and the three remaining coins have lead isotope compositions consistent with silver mines in Spain: BMC 17 with ores from Mazarrón in eastern Spain near Murcia, and BMC 1(D) (Diadus) and 9 with ores from Jaén in south-west Spain.

Gale *et al.* (1980, 28, Table 6) published analyses of fourteen Athenian unwreathed 'owl' tetradrachms dated to the early years of the fifth century BC and concluded that they all are consistent with an origin in the silver mines of Lavrion.[8] Another eight such coins have subsequently been analysed (from the Bibliothèque nationale de france and the Leslie Beer

[8] A fifteenth coin listed in their Table 6 as Athenian is in fact an Oresci coin - Price and Waggoner No. 65 = MPI 69.

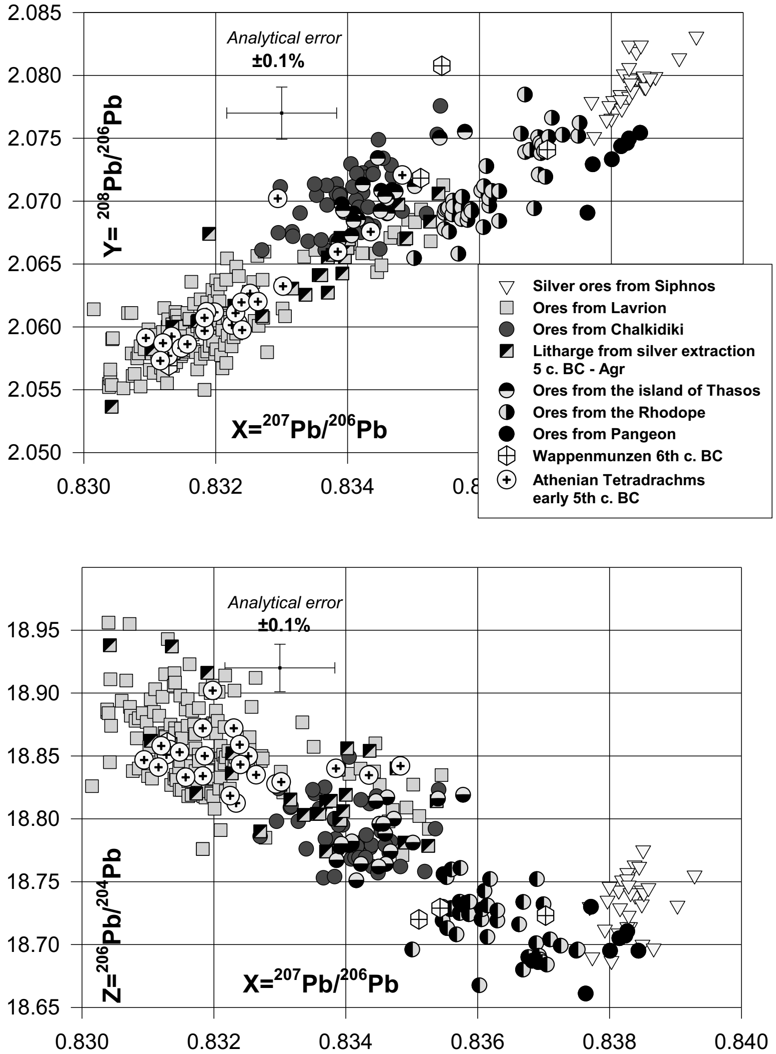

Figure 1. Lead isotope analysis of 7 Athenian *Wappenmünzen* and 12 early unwreathed 'owl' tetradrachms

collection) of which six are consistent with Lavrion. More specifically, two fit the lead isotope ratios of the litharge from the fifth century BC silver extraction site in Agrileza in Lavrion (Paris 289 and Paris 9; cf. Ellis Jones 1988) and the others are identical isotopically to the ores from the Lavrion mines of Kamareza, Plaka and Esperanza. One of the two non-Lavrion tetradrachms seems to be consistent with the ores from Chalkidiki or Thasos (MPI 38 (PW 407-417),[9] and the other with ores from Baia Mare in Romania (MPI X).

These data suggest the sixth century BC *Wappenmünzen* were minted from any silver that was to hand from Spain to Iran, and the early fifth century owls and wheel fractions from Lavrion silver with some admixture from silver coming into the system. For whatever reasons, silver mining at Lavrion must have (virtually) ceased in the sixth century BC only restarting towards the end of it (see discussion in Davis 2012; Davis 2014a).

Aegina

Aegina was one of the first Greek states to mint silver coinage, but the island does not have silver deposits. Lavrion might seem an unlikely direct source due to the political and com-

[9] These two sources cannot be distinguished on the grounds of lead isotope compositions of analysed ores.

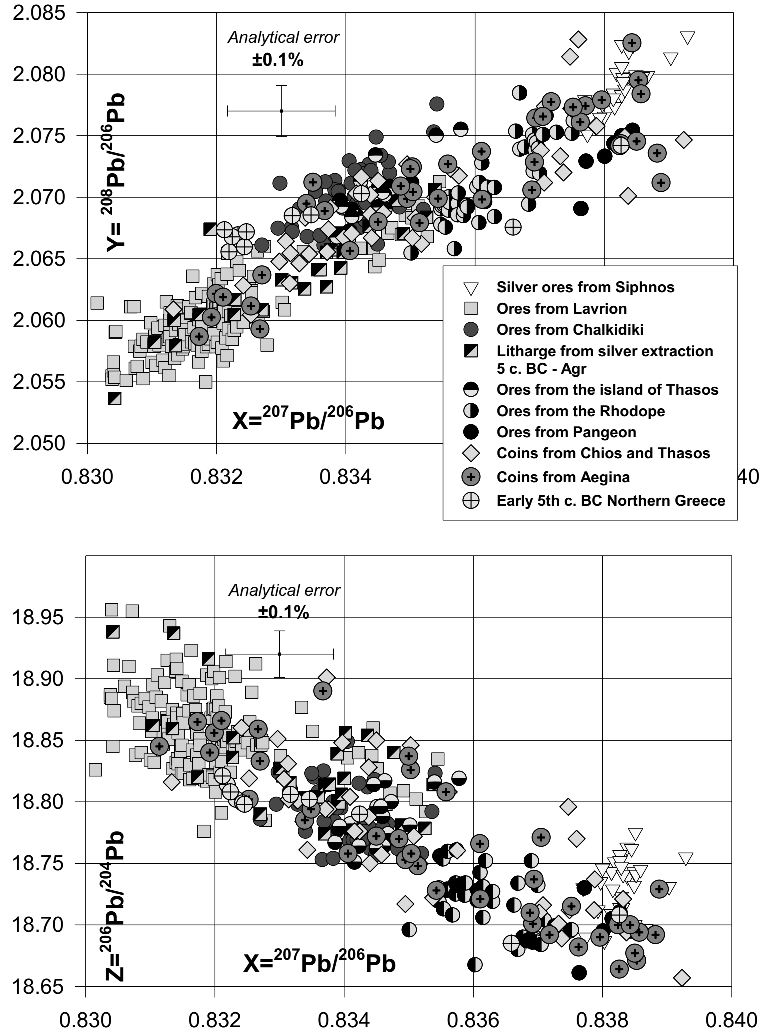

Figure 2. Lead isotope analysis of coins from Aegina, Chios, Thasos and other early fifth century coins from Northern Greece

mercial rivalry between Aegina and Athens dating back to the beginning of the sixth century BC (Hdt. 5.79-89; 6.49-51, 73, 85-94). The alternative is that silver was acquired through trade in which Aegina was a leader. The first attempt to find the origin of the silver was undertaken by Kraay and Emeleus (1962) using neutron activation for chemical analysis. They analysed 37 Aeginetan 'turtles' which provided them with good data on Ag, Au and Cu. In an oft-quoted finding, they concluded that the relatively high gold content of Aeginetan coins distinguished them clearly from Athenian 'owls' which they had analysed in parallel. Furthermore, they proposed that Aegina probably obtained its silver from Siphnos which Herodotus (3.57) stated had gold as well as silver mines.

Gale *et al.* (1980) analysed 44 coins from Aegina from the Asyut Hoard for their lead isotope compositions.[10] They concluded that nine were likely to be from Lavrion, and from their chemical testing they noted that eight had a low gold content which they contended indicated silver from Lavrion (p. 36). The ratios of the ninth coin (No. 540), and the chemical composition with high gold and low lead contents, were not completely consistent with Lavrion ores. Rechecking the data using the TestEuclid procedure confirms these eight coins

[10] Gale *et al.* (1980), Table 7 has 45 coins, but the last one is a fourth century BC coin from the Wells Hoard (LBT Ox) and thus not included here. This late coin has composition of ores from Romania.

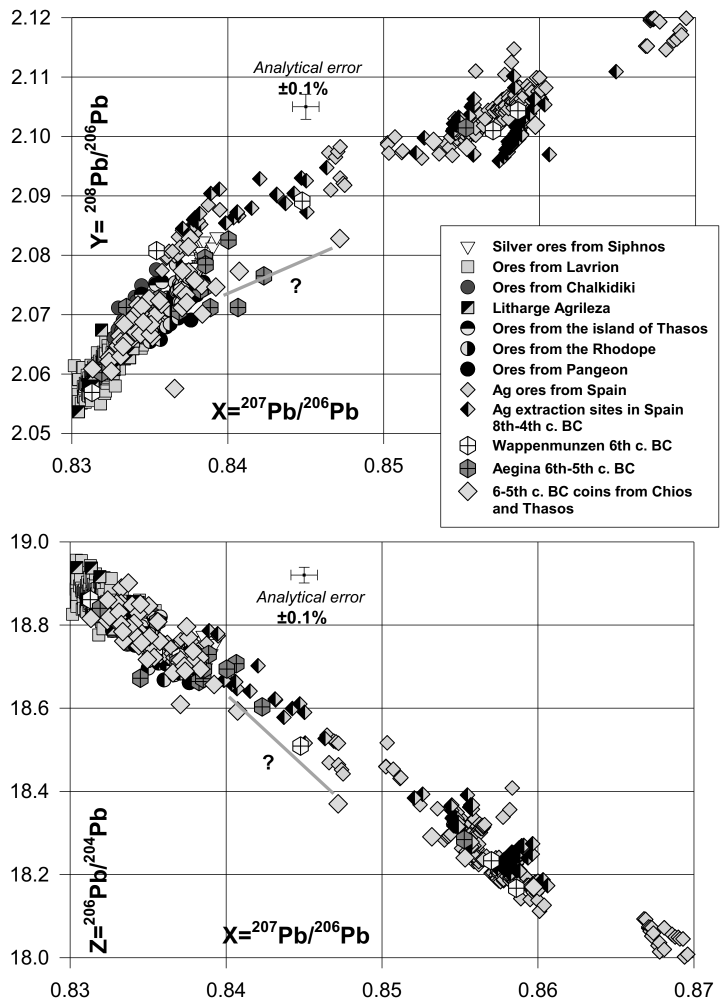

Figure 3. Lead isotope analysis showing diverse ore sources of Aeginetan coins

are fully consistent with Lavrion lead isotope compositions (Fig. 2). Their range of lead isotope ratios is nearly identical with the main group of *Hacksilber* from Tel Miqne-Ekron, indicating that the silver was from the same Lavrion mines used in the seventh century BC. However, only one of the eight coins is of the earlier type dated by Price and Waggoner to the end of the sixth century BC; the others are of the type dated to 495-485 BC. The ninth coin (No. 540) is slightly later still dated to 485/480 BC. It is fully consistent with the lead isotope ratios of the ores from northern Greek mines in Madem Lakkos and Olympias in the Chalkidiki.

Gale *et al.* claimed that 10 of the coins they analysed originated from Siphnos (1980, 36). In their discussion they combined the results of chemical and lead isotope analyses (1980, 33-43). They claimed that elemental compositions, in particular gold and tin content, are the main elements that can distinguish Siphnian ores on the bases that tin is often associated with gold ores, and, as mentioned previously, gold was mined on Siphnos. However, this is not convincing since the range of trace elements is quite varied. One difficulty is that Siphnos herself minted few coins and few of these have yet been subject to lead isotope analyses (cf. Sheedy *et al.* this volume). X-Ray Fluorescence spectrometry analyses of Siphnian coins (reproduced in Gale *et al.* (1980, 41, Table 12) show considerable differences in gold content. Using the much greater number of lead isotope analyses of Aegean lead/silver ores plotted on Figure 2, it seems that only six are fully consistent with lead isotope ratios of Siphnian ores and litharge (PW 514, PW 534, PW 542, PW 550, PW 435 and PW 436).[11] Unfortunately, Gale *et al.* (1980) did not identify all the coins which they interpreted as deriving from Siphnos, One (PW 512), perhaps originated from ores in the Apuseni Mountains in Romania (Rosia Montana: Baron *et al.* 2011), while another from Aegina has an isotopic composition more consistent with Transylvanian ores (PW 479 Windmill IVa). Crucially, five coins which it seems were identified as being from Siphnos, are tentatively consistent with the lead isotope compositions of the Pangaion region, noting that few samples have been analysed (PW 432, PW 433, PW 446, PW 471, PW 549; the data for the ores is also on the OXALID; cf. Vaxevanopoulos this volume).

However, there is a large group of Aeginetan coins for which the lead isotope compositions fall between the values for Lavrion and Siphnos, and which Gale *et al.* (1980, 42) suggested might have derived from Macedonian silver. Their hypothesis seems to be correct based on the currently available data for Greek silver/lead ores. Figure 2 shows a large group of coins which are fully consistent with lead isotope data for the ores from the Chalkidiki, Thasos and various ores from the southern Rhodope Mountains. An interesting detail given by Gale *et al.* (1980) concerns three coins from the same obverse die (511, 512, 513); two of them have lead isotope ratios consistent with Lavrion, and one is quite different, possibly from the Romanian mines in Rosia Montana (not Siphnos, as previously published).

Three of the Aeginetan coins have lead isotope compositions not consistent with any of the Aegean ore deposits (Fig. 3).[12] One coin (PW 444), has a lead isotope composition fully consistent with the mines of Jaén and the debris from the Phoenician site of La Fonteta near Alicante (Renzi *et al.* 2009) in southern Spain (as distinct from Rio Tinto). Another coin (PW 477) is consistent with the silver from the Massif Central in Southern France (Baron *et al.* 2006), and one is possibly from ores in the Taurus Mountains in southern Turkey. It is not known at present if these ores were exploited in the mid-first millennium BC, but they were mined in earlier periods (Yener *et al.* 1991).

Gale *et al.* (1980, 43) contemplated that Aegina derived silver for its coins from three main sources: Lavrion, Siphnos '*…and a third as yet unlocated source, perhaps in Macedonia, Lydia or even Euboea*' on the plausible basis that "silver was probably a normal item of export in exchange for goods" (p.34). This re-evaluation of the lead isotope data finds a different emphasis. Only eight of the 44 Aeginetan coins are consistent with Lavrion and six with Siphnos, while 24 are consistent with the northern Greek mines in Chalkidiki, Pangaion, southern Rhodope, and possibly Thasos. Single coins came from further away with origins in the east, west and north Aegean. This pattern suggests the main supply of silver was coming to Aegina from northern Greece, followed by Lavrion and Siphnos, the former especially in the fifth century, with a small trickle from various other places, possibly re-using existing bullion.

Thasos

36 Thasian coins are listed on the OXALID database, mostly also with elemental compositions (Figs. 2 and 3). This is a major advance on the four coins from the Asyut Hoard analysed solely for their lead isotope compositions by Gale *et al.* (1980). These additional analyses were performed on coins from the Ashmolean Museum in Oxford and from the Bibliothèque nationale de france in the Isotrace Laboratory (Gale *et al.* 1988). They published the results

[11] The seventh one (PW 537) seems to have the ratio of $^{206}Pb/^{204}Pb$ which is too high for Siphnos, but since there are no other silver ores that would have such sets of ratios it is most likely that the TIMS run of this coin was very poor and the ratios to ^{204}Pb were not accurately measured, such problems with TIMS measurements were not uncommon when lead extracted from samples was too low to run strong isotopic ion beams, and therefore it can be presumed that the silver in this coin is indeed of Siphnian origin.

[12] On Figure 3 these two coins are indicated with a '?'.

of 31 of these coins, (p.218) and concluded that 15 of them have lead isotope compositions consistent with Thasian silver ores, and three with Lavrion (1985, 1993 and J9). However, there are a maximum of five coins consistent with lead/silver ores from Thasos.

A major problem is that modern (mostly zinc) mining in Thasos has reprocessed the ancient galena slags making sampling difficult. As a result, there are currently only 22 lead isotope analyses of ores and slags. An added difficulty is that several groups of ores in the northern Aegean have a very similar range of lead isotope ratios; the data for ores from Chalkidiki and part of Thasos are isotopically indistinguishable (Fig. 2). However, on the present evidence it seems that there are many more coins consistent with lead isotope compositions from Chalkidiki and from several deposits in the Rhodope Mountains (Kirki, Virini, Madjarovo in Bulgaria, Iasmos and Farasinon in Thrace) than from Thasos. Overall, the data suggest the prolific mines of Thasos were those it controlled on the mainland, not the island itself, confirming Herodotus (6.46.2-3; cf. Gale *et al.* 1988, 221).[13]

Gale *et al.* (1988, 219) also concluded that five coins are consistent with a Siphnian origin. This again cannot be confirmed. Two coins (MPI 84 PW 123 and MPI 86 PW107) have lead isotope ratios within the analytical error of the group of the analysed Siphnian ores,[14] and do not fit with any other known silver ores, so they might be of Siphnian origin, but there are no other Thasian coins isotopically consistent with ores from Siphnos.

Chios

Chios like Aegina was an important minter with no local deposits of silver on the island. 19 coins from Chios (including two from its colony of Maronea) dating to the fifth century BC were analysed for their lead isotope and elemental compositions (Hardwick *et al.* 1998). The lead isotope ratios of the main group of coins from Chios are plotted on Figure 2. Three coins fall outside the range of lead isotope ratios on this diagram. Of these, number 1949-4-11.809 c. 510 BC is identified in Hardwick *et al.* (1998, 380) as of uncertain origin, but the reanalysis shows its lead isotope ratios to be fully consistent with the new data from the Rosia Montana in Romania. Another coin (BM 1841.3030) identified previously as from Balya is also consistent with the lead isotope ratios of the ores from this region (Baia Mare). Additionally, two coins are consistent with silver originating from the Iberian Peninsula, and in particular with the silver extraction site in Monte Romero in Huelva (Kassianidou 1992 and OXALID).

Others

The other small groups of coins analysed in the project published by Gale *et al.* (1980) were not mentioned in their paper but they seem to follow the same patterns of silver sources. The coins from other northern mints (Acanthus, Lesbos and Orescii) are mainly consistent with Chalkidiki (or Thasos) and Pangaion. Five of the eight coins from Corinth are consistent with Lavrion, while the other three are from the ores of Chalkidiki, Rhodope and (uncertain) Siphnos or Romania. Four of the five Samian coins are consistent with Lavrion ores, and the fifth with Siphnos. The two coins from Lycia are consistent with the Balya mines in the Çanakkale Peninsula (Wagner *et al.* 1985). The five coins from the Asyut Hoard described as ‘Mallus or Caria’ are partly from Aegean silver (3 Lavrion, 1 Rhodope) and one of them (PW 672) might be consistent with silver from Iran (Pasar). One of the Persian sigloi (PW 716) seems to be of the same origin, while the other three are consistent with Lavrion silver,

[13] Two coins (T2005 G16 and MPI83 PW82) are consistent with an origin in the Apuseni Mountains in Romania, and one (3664 J10) has lead isotope ratios of the silver mines in southern Spain. There are also two Thasian coins (T1999 and T777) which have lead isotope ratios not isotopically consistent with any known silver ore deposits. On Figure 3 they plot in the group marked with ‘?’.

[14] Two data points on Fig. 2 are above the value of 2.08 on the upper plot.

as is one coin from the Cypriot mint of Salamis. The four analysed coins from the Sicilian mints of Messana and Zankle represent silver from Lavrion (2), Thasos (1) and Romania, Rosia Montana (1).

The lead isotope data for the ores from Romania became available only in recent years (Baron *et al.* 2011; Marcoux *et al.* 2002) and therefore the possible origin of metals from there has not been raised in discussions about the prehistoric sources of metal in the Aegean. Out of 160 analysed Archaic Greek silver coins dated to the sixth-fifth centuries BC, seven have lead isotope compositions consistent with the ores from Rosia Montana (5) and Baia Mare (2) from several different mints: Athens (1), Aegina (2), Thasos (2), Chios (1), and Zankle (1).[15] These results suggest that a small quantity of silver from Transylvania circulated in the south of Europe in the first millennium BC, and possibly a small amount of silver may have been exploited at that time in the Massif Central in the south of France.[16]

COMMENTS ON THE ELEMENTAL ANALYSES OF THE ARCHAIC COINS

Out of the 160 coins dated to the sixth-fifth centuries BC discussed in this paper, 129 coins from the Asyut Hoard and Thasos have published analyses of Au, Cu and Pb with good accuracy and detection limits for the minor elements in silver. These published data show that the silver in these coins is very pure; nearly half of the analysed coins have silver content above 98%. The highest copper content was found in the coins from Thasos, with the average of 2.9%, highest of 11%, and for fourteen coins Cu is above 2%. The Cu values for coins from Aegina and Athens are much lower averaging at 1.1% and 0.65% respectively. The lead contents for Athens and Thasos coinage are just over 1%, while the Aeginetan coinage is quite low in lead at 0.47% average. For all the other early coins the contents of copper and lead are low, usually not exceeding 2% each. The chemically most interesting group of coins are the six Orescii coins from the Asyut Hoard. They are nearly identical isotopically, consistent with the ores from Chalkidiki, with very low gold contents (<0.01%), copper below 0.05% and lead around 2%. It seems that all these six coins were minted from the same batch of silver, most likely extracted from galena by cupellation that left around 2% of lead in silver.

As mentioned above, gold is one of the elements that during silver extraction is not separated from silver and therefore it has been often suggested that the Au/Ag values can be characteristic for the original silver ores. On Figure 4 the upper plot gives the values for contents of all three minor elements Au, Cu and Pb in the *Wappenmünzen* showing the variation of their content in relation to the origin of silver. The silver in the obol from the Ashmolean collection contains all three impurities below 0.1%. Two *Wappenmünzen* ('amphora' and 'gorgoneion') which have lead isotope compositions consistent with the ores from the Rhodope Mountains have very low Au content (0.04% and 0.17%), and copper and lead below 0.5%. It is interesting to note that apart from the coin consistent with an origin from Lavrion ores, all the other *Wappenmünzen* have lead contents close to 0.5%, indicating perhaps the common level of lead remaining from cupellation in experienced silver extraction regions.

The lower plot on Figure 4 shows the Au/Ag ratios for all coins with possible silver sources marked by different symbols. This plot demonstrates that even in Lavrion not all silver ore

[15] Also an ingot C with turtle stamp from the Selinus hoard found on Sicily (Beer-Tobey *et al.* 1998) has its lead isotope composition consistent with these ores.

[16] The information about the exploitation of the ores in this region is very fragmentary. The lead isotope ratios used in this paper for comparisons come from geological literature and the data from a paper about Mediaeval silver extraction in this area (Baron *et al.* 2006), but so far there is no scientific information about the production of silver in the south France in the first millennium BC, so the hypothesis of the origin of silver from this mines for the Archaic coins proposed here is very tentative. Davis in his book on Roman mining in Europe (1935, 77-78 and 81-83) mentions many ancient silver mines in southern Gaul, but much more information and lead isotope data is needed to confirm this hypothesis.

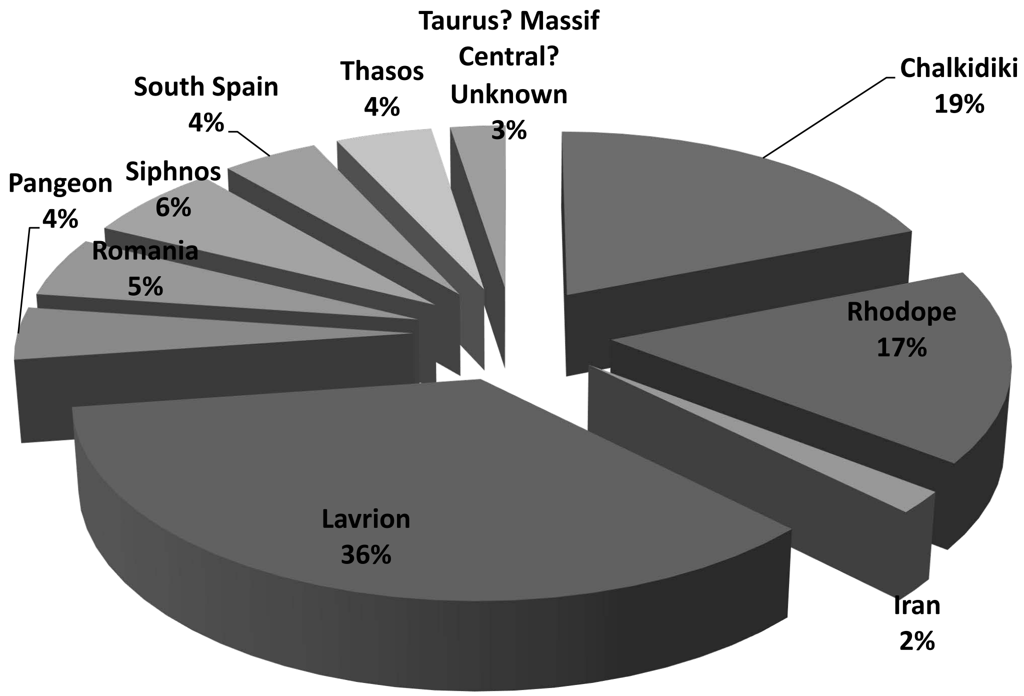

Figure 4. Pie chart representing fractions of silver from various sources

had the same low gold contents. In particular the coins consistent with the cupellation debris from Agrileza have generally higher gold content. On the other hand, the group of the Orescii coins while showing lead isotope ratios consistent with ores from Chalkidiki, have very low gold contents. Silver from Chalkidiki, Pangeon and Rhodope and Iran have a wide range of gold contents.

CONCLUSIONS

The lead isotope compositions of the analysed coins indicate that the majority of the silver used by the Archaic Greek mints was from Lavrion (36%), Chalkidiki (19%) and the deposits in the Rhodope Mountains (21% including 4% from Pangaion). Small quantities of silver seem to have originated in the West Mediterranean and perhaps the Carpathians. The fractions of silver from various sources are represented in Figure 4.

A key finding is that the percentages of silver in Archaic Greek coins originating in Siphnos (6%) and Thasos (4%) are considerably less than earlier evaluations would suggest. Further analyses of the earliest coins from different mints are required to confirm this hypothesis given the majority of coins analysed so far are from the Asyut Hoard and the north Aegean islands of Thasos and Chios.[17] Also, the interpretation of lead isotope data presented here relies on few analyses of ores from the mining regions of Pangaion, Thrace and Macedonia, which are known from the writings of Herodotus and other sources. More extensive archaeometallurgical research is required both in northern Greece and Bulgaria (northern Rhodope) where there are also large quantities of lead slags and known silver mines.

Having said this, the data are sufficient to challenge a number of current scholarly assumptions. Firstly, the Peisistratids did not derive the silver for the *Wappenmünzen* coinage principally from northern Greece, and thus probably did not control mines in the region.

[17] The predominance of silver from northern Greece can be related to the proximity of the islands to these mines.

Secondly, the Aeginetans did not derive more than a small proportion of their silver from Siphnos, but did make extensive use of Lavrion silver in the early fifth century BC. Thirdly, the Thasians derived substantially more silver from their control of mines on the mainland than from the island itself, which helps explain their later conflict with Athens. Fourthly, and perhaps surprisingly, there is little or no evidence for mixing of silver. It seems the mints struck silver from discrete sources, and more attention should be paid to the technical processes of producing coins in the light of this. The earliest mints were simple operations with low outputs. Silver is a relatively soft metal, and maybe it was easier to overstrike, trim, or fold to achieve the desired weight than to re-melt and create new flans.[18] Fifthly, gold and tin contents are not adequate chemical tracers by themselves for provenancing the ore sources of coins to either Siphnos or Lavrion.

Thought also needs to be given to the nexus between minting and mining. The data demonstrate that for all the early Archaic Period minters, minting was opportunistic. They minted when they had a supply of silver, and that supply could come from anywhere from Spain to Iran. With incipient monetisation of economies, as silver became money in the full sense of the word, and profit accrued to the state from minting, this lack of a secure supply would have been unsatisfactory. The demand drew in silver from further afield, and was the catalyst for an enormous expansion in mining. Any state lucky enough to possess silver mines could use it as an export commodity with no regard for the end user, which is why Aegina could apparently reliably access Lavrion silver despite their rivalry with Athens. In turn, minting practices changed, especially for export coinages such as Athens with the introduction of the new owl type and use of multiple dies.

REFERENCES

Baron, S., Carignan, J., Laurent, S. and Ploquin, A. 2006. 'Medieval lead making on Mont-Lozere Massif (Cevennes-France): Tracing ore sources using Pb isotopes', *Applied Geochemistry* 21, 241-252.

Baron, S. Tămaş, C.G., Cauuet, B. and Munoz, M. 2011. 'Lead isotope analyses of gold-silver ores from Roşia Montană (Romania). A first step of metal provenance study of Roman mining activity in Alburnus Maior (Roman Dacia)', *Journal of Archaeological Science* 38, 1090–1100.

Beer-Tobey, L., Gale, N.H., Kim, H. and Stos-Gale, Z.A. 1998. 'Lead isotope analyses of four late archaic silver ingots from the Selinus hoard', in Oddy, A. and Cowell, M. (eds.), *Metallurgy in Numismatics, Vol 4***.** Royal Numismatic Society, Special Publication No. 30. (London), 385-393.

Conophagos, C.E. 1980. *Le Laurium Antique et la technique grecque de la production de l'argent* (Athens).

Davis, G. 2012. 'Dating the drachmas in Solon's laws', *Historia* 61, 1-30.

Davis, G. 2014a. 'Mining money in Late Archaic Athens', *Historia* 63, 257-277.

Davis, G. 2014b. 'Where are all the little owls?', in Matthaiou, A.P. and Pitt, R.K. (eds.), ΑΘΗΝΑΙΩΝ ΕΠΙΣΚΟΠΟΣ: Studies in honour of H. B. Mattingly (Greek Epigraphic Society, Athens), 339-47.

Davis, O. 1935. *Roman Mines in Europe* (Oxford).

Dunning, F.W., Mykura, W. and Slater, D. (eds.) 1982. *Mineral Deposits of Europe, Vol. 2: Southeast Europe.* The Mineralogical Society. The Institution of Mining and Metallurgy (London).

Ellis Jones, J. 1988. 'The Athenian silver mines of Laurion and the British School at Athens excavations at Agrileza', in Ellis Jones, J. (ed.) *Aspects of Ancient Mining and Metallurgy*. Acta of a British School of Athens Centenary Conference at Bangor (Bangor), 11–22.

Fischer-Bossert, W. 2015. 'Kyzikener Falzschrötlinge', *Mitteilungen der* Österreichischen *Numismatischen Gesellschaft* 55, 79-92.

Gale, N.H., Gentner, W. and Wagner, G.A. 1980a. 'Mineralogical and Geographical Silver Sources of Archaic Greek Coinage', in Metcalf, D. M. (ed.), *Royal Numismatic Society Special Publication No.13, Metallurgy in Numismatics,* Vol.1 (London), 3-50.

Gale, N. H. and Stos-Gale, Z. A. 1981. 'Lead and silver in the ancient Aegean', *Scientific American* 244/6, 176–192.

Gale, N. H. and Stos-Gale, Z. A. 1981b. 'Cycladic lead and silver metallurgy', *Annual of the British School at Athens* 76, 169–224.

Gale, N.H., Picard, O. and Barrandon, J.N. 1988. 'The Archaic Thasian silver coinage', in Wagner, G. A. and Weisgerber, G. (eds.), *Antike Edel- und Buntmetallgewinnung auf Thasos. Der Anschnitt*. Beiheft 6, (Bochum), 212-223.

[18] Professor Kroll has recently demonstrated the wide prevalence of folding and restriking coins in Archaic times – see Kroll 2017 for evidence from Athens, Elis, Thebes and Aegina, and an example from Cyzicus in Fischer-Bossert 2015.

Gale, N.H., Kayafa, M. and Stos-Gale, Z.A. 2008. 'Early Helladic Metallurgy at Raphina, Attica, and the Role of Lavrion', in Tzachili, I. (ed.), *Aegean Metallurgy in the Bronze Age*, University of Crete, Rethymnon (Athens), 87-104.

Gentner, W., Müller, O., Wagner, G.A. and Gale, N.H. 1978. 'Silver sources of Archaic Greek coinage', *Naturwissenschaften* 65, 273-284.

Hardwick, N., Stos-Gale, Z.A. and Cowell, M. 1998. 'Lead isotope analyses of Greek coins of Chios from the 6th - 4th centuries B.C', in Oddy, A. and Cowell, M. (eds.), *Metallurgy in Numismatics, Vol 4.* , Royal Numismatic Society, Special Publication No. 30. (London), 367-384.

Kassianidou, V. 1992. 'Monte Romero, a silver producing workshop of the 7th century BC in southwest Spain', *Institute for Archaeometallurgical Studies – IAMS 18*, (London), 7-10.

Kouzmanov, K., Ivăăcanu, P. and O'Connor, G. 2005a. 'Porphyry Cu-Au epithermal Au-Ag deposits in the southern Apuseni Mountains, Romania', in Blundell, D., Arndt, N., Cobbold, P. R. and Heinrich, C. (eds.), *Geodynamics and Ore Deposits Evolution in Europe. Ore Geol. Rev. 27*, 46–47.

Kouzmanov, K., Bailly, L., Tămaă, C. and Ivăăcanu, P. 2005b. 'Epithermal Pb_Zn-Cu (Au) deposits in the Baia Mare district, Eastern Carpathians, Romania', in Blundell, D., Arndt, N., Cobbold, P. R. and Heinrich, C. (eds.), *Geodynamics and Ore Deposits Evolution in Europe. Ore Geol. Rev. 27*, 48–49.

Kraay, C. M. and Emeleus, V.M. 1962. *The Composition of Greek Silver Coins. Analysis by Neutron Activation*, Ashmolean Museum (Oxford).

Kroll, J. H. 2017. 'Striking and Re-striking on Folded Flans: Evidence from Athens, Cyzicus, (?)Sinope, Elis, Thebes, and Aegina', in Caltabiano, M.C. (ed.), *XV International Numismatic Congress Taormina 2015 Proceedings*, Vol.1, 378-82.

Ling, J., Stos-Gale, Z.A., Grandin, L., Billström, K., Hjärthner-Holdar, E. and Persson, P.-O. 2014. 'Moving metals II: provenancing Scandinavian Bronze Age artefacts by lead isotope and elemental analyses', *Journal of Archaeological Science* 41, 106-132.

Marcoux, E, Grancea, L., Lupulescu, M and Milesi, J.-P. 2002. 'Lead isotope signatures of epithermal and porphyry-type ore deposits from Romanian Carpathian Mountains', *Mineralium Deposita* 37, 173−184.

Neubauer, F., Lips, A., Kouzmanov, K., Lexa, J. and Ivăşcanu, P. 2005. 'Subduction, slab detachment and mineralisation: the Neogene in the Apuseni Mountains and Carpathians', *Ore Geology Review* 27, 13–44.

Pernicka, E., Lutz, C., Bachmann, H.-G., Wagner, G. A., Elitsch, V. And Klein, E. 1985. 'Alte Blei-Silber-Verhüttung auf Sifnos', in Wagner, A. and Weisgerber, G. (eds.), *Silber Blei und Gold auf Sifnos*. Anschnitt Beih. 3 (Bochum), 185–199.

Pernicka, E. 1999. 'Trace element fingerprinting of ancient copper: A guide to technology or provenance?', in Young, S. M. M., Pollard, A. M., Budd, P. and Ixer, R. A. (eds.), *Metals in Antiquity*. BAR Internat. Ser. 792 (Oxford), 163–171.

Pernicka, E., Adam, K., Böhme, K., Hezarkhani, M., Nezafati, N., Schreiner, M., Winterholler, B. and Momenzadeh, M. 2011. 'Archaeometallurgical Research on the Western Central Iranian Plateau', in Vatandoust, A., Parzinger, H. and Helwing, B. (eds.), *Early Mining and Metallurgy on the Western Central Iranian Plateau. The first five years of work. Arch. Iran u. Turan 9* (Mainz), 631–688.

Price, M. and Waggoner, N. 1975. *Archaic Greek coinage – the Asyut Hoard* (London).

Renzi, M., Montero-Ruiz, I. and Bode, M. 2009. 'Non-ferrous metallurgy from the Phoenician site of La Fonteta (Alicante, Spain) a study of provenance', *Journal of Archaeological Science* 36, 2584−2596.

Renzi, M., Rovira-Llorens, S. and Montero Ruiz, I. 2012. 'Riflessioni sulla metallurgia fenicia dell'argento nella Penisola Iberica.' *Notizie Archeologiche Bergomensi* 20, 185-194.

Rothenberg, B. and Blanco Freijeiro, A. 1981. *Studies in ancient mining and metallurgy in south-west Spain. Institute for Archaeometallurgical Studies – IAMS,* (London).

Rychner, V. and Stos-Gale, Z. A. 1998. 'Compositions chimiques et isotopes du plomb: la production métallique l'Âge du Bronze moyen et final en Suisse', in Mordant, Cl., Pernot, M. and Rychner, V. (eds.), *L'Atelier du bronzier en Europe du XXe au VIIIe siècle avant notre ère : les analyses de composition du metal: leur apport à l'archéologie de l'Âge du Bronze*, vol I. Colloque int. Bronze (Neuchâtel et Dijon: session de Neuchâtel, 1996), Eds du CTHS, (Paris), 153–174.

Stos, Z.A. 2009. 'Across the wine dark seas. Sailor tinkers and royal cargoes in the Late Bronze Age eastern Mediterranean', in Shortland, A.J., Freestone, I.C. and Rehren, T. (eds.), *From Mine to Microscope – Advances in the Study of Ancient technology'*, Oxbow Books (Oxford), 163-180.

Stos-Gale, Z.A. 2001. 'The impact of the natural sciences on studies of Hacksilber and early silver coinage', in Balmuth, M. (ed.), *Hacksilber to coinage: new insights into the monetary history of the Near East and Greece*. Numismatic Studies No. 24. The American Numismatic Society (New York), 53-76.

Stos-Gale, Z.A. 2014. 'Silver vessels in the Mycenaean Shaft Graves and their origin in the context of the metal supply in the Bronze Age Aegean', in Meller, H., Risch, R. and Pernicka, E. (eds.), *Metalle der Macht- Frühes Gold und Silber. 6. Mitteldeutscher Archäologentag vom 17. Bis 19 Oktober 2013 in Halle (Saale)*. Tagungen des Landesmuseums für Vorgeschichte Halle. Band 11/1, 183-208.

Stos-Gale, Z.A. 2017. 'The sources and supply of silver for Archaic Greek coinage: a re-evaluation of the lead isotope and chemical data', *The RITaK conferences 2013-2014*, (Mining Museum Bochum), Der Anschnitt, Beiheft 34, 201- 217.

Valera, R.G., Valera, P.G. and Rivoldini, A. 2005. 'Sardinian ore deposits and metals in the Bronze Age', in Lo Schiavo, F., Giumlia-Mair, A., Sanna, U. and Valera, R. (eds.), *Archaeometallurgy in Sardinia, from the origin to the Early Iron Age*. Monographies instrumentum 30. Editions Monique mergoil. (Montagnac), 43-88.

Wagner, G. A., Pernicka, E., Seeliger, T., Öztunali, Ö., Baranyi, I., Begemann, F. and Schmitt-Strecker, S. 1985. 'Geologische Untersuchungen zur frühen Metallurgie in NW-Anatolien', *Bulletin of the Mineral Research and Exploration Institute of Turkey* 101/102, 45–81; 100–101.

Wagner, G.A., Pernicka, E., Vavelidis, M., Baranyi, I. and Basiakos, I. 1986. *Archäeometallurgische Untersuchungen auf Chalkidiki*. Anschnitt 38, (Bochum), 166–186.

Wagner, G.A. and Weisgerber, G. (eds.). 1985. *Silber, Blei und Gold auf Siphnos, prähistorische und antike metallproduktion. Der Anschnitt*, Beiheft 3. Deutsches Bergbau Museum, (Bochum).

Wagner, G.A. and Weisgerber, G. (eds.). 1988. *Antike Edel- und Buntmetallgewinnung auf Thasos*. *Der Anschnitt*, Beiheft 6. Deutsches Bergbau Museum, (Bochum).

Yener, K.A., Sayre, E.V., Özbal, H., Joel, E.C., Barnes, I.L. and Brill, R.H. 1991. 'Stable lead isotope studies of central Taurus ore sources and related artefacts from eastern Mediterranean Chalcolithic and Bronze age sites', *Journal of Archaeological Science* 18, 541–577.