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The sources and supply of silver for Archaic Greek coinage:

A re-evaluation of the lead isotope and chemical data

ABSTRACT: *Over the centuries, numismatists have refined the study of types, legends, weights and minting techniques, but the possibility of chemical and lead isotope analyses of the coins allowed a new insight into the economy of the ancient coinage. The earliest Greek coins are of particular interest in this respect, since there are several theories as to the rise of the silver currency in the first millennium BC in the Eastern Mediterranean and to the sources of silver that provided reliable supplies of this metal to the Greek city states. In particular, it has been suggested that the Phoenicians were supplying silver from Spain to the Eastern Mediterranean. Several analytical projects were conducted in the 1980ies and 1990ies to identify the sources of Archaic Greek coinage on the grounds of their chemical and lead isotope compositions. With the vastly increased database of the European ore deposits it seems timely to re-evaluate the data obtained in these projects, and in particular to test how much silver from the Western Mediterranean was used in the Aegean in this period.*

KEYWORDS: ARCHAIC SILVER GREEK COINAGE, LEAD ISOTOPE AND ELEMENTAL ANALYSES, SILVER MINES IN SOUTHERN EUROPE IN 1ST MILLENNIUM BC

Introduction: The beginnings of coinage

There is no certainty when pieces of metal of exact weight started to be used for payments, but it is not impossible that this practice started in the Eastern Mediterranean in the Late Bronze Age. It has been suggested by archaeologists in the past that the copper 'oxhide' ingots were used as currency. The great majority of these ingots found across the Mediterranean, from Sardinia to Turkey, were made of copper from Cypriot deposits that guaranteed very high purity of copper (Stos-Gale, et al., 1997, Hauptmann, et al., 2002). The excavations of Late Bronze Age sites in the Mediterranean often contain hoards of pieces of 'oxhide' ingots of different weights, as can be seen on Fig. 1.

Early in the first millennium BC, the Phoenician trade in the Mediterranean gave rise to the use of small bags of pieces of silver as pre-coinage currency (Balmuth, 2001). The Near Eastern hoards of so-called 'Hacksilber' show that silver became widely available in this period. The use of Hacksilber was followed by the electrum and later silver coins. The first coins were made in Ionia, what is now Aegean Turkey, not of silver but of electrum in the 7th century BC (Price and Waggoner, 1975, pp.122-123). The source of electrum was almost certainly an alluvial natural alloy from the neighbourhood of Sardis in Lydia. The introduction of silver coins in this region was probably about 560 BC, slightly before the introduction of silver coins at Aegina, Athens and Corinth which occurred not earlier than 550 BC (Price and Waggoner, 1975, p.122). Coins of this type in both gold and silver continued to be struck by Persians after Cyrus' conquest of Lydia (547 BC). The Persians soon saw the advantage of producing their own coinage in a part of their empire where coinage was indigenous and introduced their own gold 'darics' and

Fig. 1. Fragments of oxhide ingots from the Late Helladic 'Poros Wall Hoard' found in Mycenae (photographed in the National Archaeological Museum at Athens in 1987 by Z.A. Stos-Gale).

silver ‘sigloi’, which circulated only in Western Anatolia between 516 and 500 BC (Kraay, 1976, p.32).

One of the earliest coins in the Greek part of the Aegean were minted on the island of Aegina (Fig. 2), a barren rocky island with little good agricultural land, therefore, its inhabitants were driven to make living by seafaring and trading, for which they were famous in the ancient world as noted by Herodotus (II, 178). Apart from their merchant seafaring the Aeginetans were also a considerable naval power before their conquest by Athens in 457 BC; their influence was exerted in the Cyclades as a whole and also on Crete, where they forcibly established a colony at Cydonia about 520 BC. The trading of the Aeginetans was largely a matter of transporting and selling at a profit the goods and raw materials produced by others. Greece was in many parts short of grain but produced a surplus of ceramics, whilst the Black Sea region and Egypt often had a surplus of corn. Amongst other products the Aeginetans were also no doubt trading in marble, perfumes, unguents, wine and olive oil. Their profit would have been taken partly in the form of food supplies for Aegina itself, but the success of their trading ventures created surplus wealth which could only partly be used in building ships and temples, so there is little doubt that their trading over much of the ancient world will have allowed them to acquire stocks of silver by barter, and that much of their surplus wealth would be stored as silver bullion before the beginning of their coinage in c. 550 BC (Price and Waggoner, 1975, p.122). The early adoption of coinage increased their importance in the ancient world, alone amongst the states of central Greece they were represented in the Greek trading community at Naucratis at the mouth of the Nile in Egypt. There are no known sources of silver on Aegina itself, so it is very likely that they amassed silver from several sources extensively used in this period. The known sources of silver nearest to Aegina are on the island of Siphnos and in Lavrion in Attica. It has been suggested therefore that one of the sources of the earliest Aeginetan silver was Siphnos. Lavrion mines are thought to be a less likely source for this coinage because of a known animosity between the Aegina and Athens at that time.

For most of the 6th century, the only really substantial coinage of central Greece was the Aeginetan; the early coinage of Athens and Corinth which started not much later were comparatively insignificant in volume. A different picture is presented by the group of coinage of the northern Aegean where there were silver mines in the Pangeon, Thasos and Chalkidiki. Starting about the middle of the 6th century BC, they provide a case of export of coined silver as one of the natural products of the region: these Traco-Macedonian coins seem to have had little function locally, because they are mostly found in other regions, far away from their mints. By the end of the 6th century, due to the Persian occupation of Thrace and Macedonia, the mints of this area seem not to have produced much coinage. If the silver mines were still producing much silver it was perhaps distributed into other regions. The Aeginetan coinage became to decline in volume from the early 5th century, too.

Fig. 2. Typical early Archaic silver coin of Aegina (photo courtesy British Museum, London).

Fig. 3. Obverse and reverse of a Wappenmünzen tetradrachm dated to c. 530-520 BC: Obv. Gorgoneion, Rev. Lion’s head in incuse square. Coin in private collection (photo: N.H. Gale, bequest).

The one great coinage of the 5th century was that of Athens. Silver from Lavrion was exploited extensively since the Bronze Age (Stos-Gale and Gale, 1982) and its exploitation intensified in the first millennium BC. It is quite remarkable that the majority of Hacksilber from the 7th century hoards found in one of five Philistine capitals of Tel Miqne-Ekron (Gitin and Golani, 2001) have lead isotope compositions consistent with Lavrion (Stos-Gale, 2001 and OXALID). It seems that in the early years of the 5th century a rich vein of silver was found in Lavrion and until the 413 BC when the mining activities were interrupted by the Spartans, the production of silver there was considerable. Athens insisted on the use of its own coinage by the allies in official transactions and banned the local minting of silver, such was the volume of the Athenian coinage that it attained a status of international currency not only among the Greeks of the Aegean, but also in the west provinces of the Persian empire and to a certain extend in the other parts of the Mediterranean. The earliest coinage of Athens bears no unequivocal marks of its origin, but its attribution is soundly based upon the evidence of types, weights and finds. This coinage is usually known as Wappenmünzen, because their types were once thought to be the heraldic symbols of Athenian noble families (Fig. 3); this idea is no longer accepted and it is thought that the symbols had religious significance. The minting of Wappenmünzen might have started in the second quarter of the 6th century and ended about 520

Figs. 4+5. Athenian tetradrachms with the owl dated to early 5th century BC analysed for their lead isotope compositions at Oxford. Both have lead isotope compositions consistent with the origin from Lavrion (AA and BB on the OXALID). In private collection, (photos: Z.A. Stos-Gale).

BC, when the first 'owl and Athena' coins were struck. These coins were small issues of a local significance only and are rarely found outside Attica. Very different was the Athena and owl coinage which began about 520 BC. Instead of a coinage with changing types and no clear indication of origin, the national types of Athena and her owl became fixed and the source of the coinage was made quite explicit by the addition of the inscription *ΑΘΕ* and the tetradrachm became the standard denomination (Figs. 4+5). This new coinage was soon produced in such huge quantities that the high artistic level of earlier examples could not be maintained and the dies of many later issues are quite crude, but the standards of weight and silver purity were strictly maintained (Kraay, 1975). The circumstances of the emergence of this coinage suggest that they were made from primary silver. Therefore it is of considerable interest to reconstruct the economic development of silver supply in the 6^{th}-5^{th} century BC Aegean.

The silver ore deposits and application of elemental and lead isotope analyses for the provenance of the Archaic silver Greek coins

The accepted method of tracing the sources of metal is based on comparative lead isotope and chemical analysis of ores and metals. This method is based on the fact that lead in different ore deposits has varied isotopic compositions depending on the age of the deposit and the amount of uranium and thorium in the ore forming fluid (Gale and Stos-Gale, 2000). Providing that there is an extensive database of lead isotope and geochemical analyses of ore deposits, by comparing the lead isotope ratios of single coins with these of the ores it is possible to exclude or prove that a deposit could have provided the silver for a coin. This is more complicated if the silver from two or more deposits was melted together to create a secondary material, but even then the lead isotope compositions might provide information as to the possible original source of silver. The lead isotope composition of metal made from a mixture of metals of different origin will lie on straight lines between all three independent lead isotope ratios for the primary ore deposits. Its exact position will depend very strongly on the amount of lead present in each fraction added to the alloy. For example: if pure lead is added in substantial amount to copper or silver, then the lead isotope composition of the resulting alloy will be practically the same as that of the added lead (see example in Stos-Gale, 2001). The lead content in the silver Archaic coins is mostly below 2 %, which is within the usual range of lead in silver resulting in extraction of silver from galena, so it is most likely that no lead was deliberately added to their metal. In 454 BC, Athens seized the silver bullion collected from all members of the Delian League from the treasury on Delos and in 449 BC the Coinage Decree issued by Athens curtailed minting of the member-state coinage and demanded that all silver will be transported to Athens and used for minting the Athenian 'owls'. Therefore, the later Athenian coins might indeed show lead isotope compositions of re-melted silver.

The search for the sources of silver used for the Archaic Greek coins needs to be based on a database of lead isotope and chemical characteristics of silver ore deposits that were exploited in this period in the regions that are known to be connected by trade with the Aegean. Silver ores are not very common in the Old World and the location of the major deposits, rich enough to be exploited in ancient times, is reasonably well-known. The earliest silver, lead and copper metallurgy has been developed in the Middle East and Anatolia. There are several significant silver deposits in Turkey, in particular, the silver seems to have been exploited in the Taurus Mountains in southern Turkey since the early Bronze Age (Yener et al. 1991). Ryan writes in the chapter on silver mines in Niğde as follows: 'In Çamardi county … on Aladag, there are very old gold-silver-lead workings. The veins are composed mostly of plumbojarosite as at the Bolkardağ mine.' (Ryan 1960, p. 11-12). There are also known ancient silver mines in the south east Turkey at Keban (Wagner, et al., 1986) and in the Troad Peninsula (Çanakkale) in the north-west (Wagner, et al., 1985). Modern Iraq and Syria are not known to have any major silver mines, but to the east of the Babylonian and Assyrian kingdoms, in modern Iran, there are considerable deposits of silver, copper, lead and also some gold. There might be some silver ores in the mountains of Caucasus, but a reliable geological information about the former Soviet Republics is not available at present.

Fig. 6. Exposed by the road 2 m thick lead slag heap in Chalkidiki (University of Oxford and IGME archaeometallurgical survey in 1982, photo: Z.A. Stos-Gale).

Fig. 7. Partly undisturbed lead slag heap in the Rhodope Mountains (University of Oxford and IGME archaeometallurgical surveys in northern Greece, 1979–1981, photo: Z.A. Stos-Gale).

In the Aegean the ancient silver mines in Lavrion, Attica, are well-known (Conophagos, 1980). A prehistoric silver extraction on the island of Siphnos is well documented, too (Wagner and Weisgerber, 1985). The archaeometallurgical surveys of the deposits in Chalkidiki (Wagner, et al., 1986), Thasos (Wagner and Weisgerber, 1988), the Pangeon Mountains and many slag heaps in the Rhodope Mountains prove that these deposits were exploited extensively for many centuries for lead and some of them also for silver (Figs. 6+7).

The Phoenician and earlier trade around the Mediterranean Sea is well documented, so it is also worth considering as sources of silver for these early coins the known silver mines in the Western Mediterranean. Silver ores have been mined in historical and Roman times in the south of France in the Massif Central (Baron, et al., 2006; Brevart, et al., 1982; Davis, 1935), on Sardinia (Valera, et al., 2005) and to a large extend in Spain (for example: Santos Zaldeuegui, et al., 2004; Kassianidou, 1992; Rothenberg and Blanco Freijeiro, 1981; Renzi, et al., 2009). It is also possible that some silver might have come to Greece from the north, where the deposits in the eastern Carpathians might have been used since the Bronze Age (Marcoux, et al., 2002; Baron, et al., 2011; Stos-Gale, 2014).

About 40 years ago, several research projects were started to provide systematic lead isotope characterizations combined with the archaeometallurgical fieldwork in Greece, Turkey, Iran, Sardinia and Spain (for discussion and references see Stos-Gale and Gale, 2009). These projects and many papers aimed at geological research, published during the last decades considerably increased the comparative database that can be used for identification of sources of ancient metals. Currently the database assembled from all these publications used for the interpretation of the lead isotope ratios found in the European ancient metals contains some 7000 sets of data.

The lead isotope analyses of ores and slags, and also ancient remnants of metal extraction like litharge, give three independent lead isotope ratios. To identify the possible origin of an ancient artefact, in this case a silver coin, it is necessary to compare its lead isotope ratios with all available data and then to eliminate those which are not possible sources of silver ore, for example, copper deposits like Cyprus, or lead ores with very low silver contents as, for example, they are on many Cycladic islands. For each analysed artefact, the TestEuclid software calculates the Euclidean distances to all analysed ore samples (Ling, et al., 2014, p.116-117). The second stage of interpretation are two 2 dimensional plots of the data for ores and artefacts. In a graphic representation each ore deposit can be characterised by three numbers, independent ratios of four lead isotopes, which can be presented as points in 3-D space. Since such comparisons are made with several thousands of data on ores, therefore in the first instance it is convenient to calculate the Euclidean distances of the lead isotope ratios of the ancient metal to each of the samples of ores, in order to test which of them have identical lead isotope ratios and then prepare plots only of the ore deposits that have lead isotope and geochemistry consistent with the ancient metal.

The first large research project that used lead isotope and chemical analyses for the identification of the ore sources of the Archaic silver coins was started in 1978 by Wolfgang Gentner, Otto Müller and Günther Wagner from the Max Planck Institute for Nuclear Physics at Heidelberg, in collaboration with Noel Gale from the Department of Geology, University of Oxford. The main group of coins for analyses came from a hoard from Asyut in southern Egypt. The Asyut hoard was discovered in 1969 and consisted of some 900 coins. According to the numismatic research, it was buried around 475 BC and therefore the coins from this hoard guaranteed the common date and Greek origin (Price and Waggoner, 1975). As all coins from the Asyut hoard must have been minted before 475 BC, it also seems probable that most of them were minted from primary silver (Gale, et al., 1980).

The mints represented among these coins ranged from Sicily to Cyprus, and included most of the Archaic

Greek cities. The Stiftung Volkswagenwerk secured for analyses within this project a purchase of 120 severely damaged coins with low numismatic value. The results of this research were published in 1978 (Gentner, et al.) and in 1980 (Gale, et al.). The selection of coins for lead isotope analyses was much extended by the inclusion of a series of coins of Aegina from the same hoard kindly contributed by Dr. Leslie Beer. Altogether, 102 coins from the Asyut hoard were analysed for their lead isotope, but only 50 for the elemental compositions. Unfortunately, the chemical and lead isotope analyses were not performed in all cases on the same coins. The results have shown that many coins were consistent with the origin from the mines in Lavrion and Siphnos but there was a number of doubts as to the interpretation of the data, mainly due to the lack of a database of lead isotope compositions of other ore deposits.

In parallel to the analyses of coins, a large program of archaeometallurgical fieldwork in the Mediterranean was started, funded by the Stiftung Volkswagenwerk for the German team and by the British Science Research Council and the Leverhulme Trust for the Oxford team. These surveys conducted in collaboration with the Greek Institute of Geological and Mineralogical Exploration (IGME) brought much new information about the antiquity of mining, geochemistry and lead isotope compositions of the ore deposits in the Aegean. In the next 20 years three 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), Chios (Hardwick, et al., 1998) and silver Archaic ingots from Sicily (Beer-Tobey, et al., 1998). Since these publications, much more lead isotope data and archaeometallurgical information have been published for ore sources in Spain, Sardinia, Greece and Turkey. It seems that it is a good time now to undertake the task of re-evaluating the extent of data on Greek coins in the light of this new information.

The re-evaluation of the sources of silver used for the Archaic silver coinage based on the lead isotope and chemical analyses

Coins of Aegina

In their publication of the results of analyses of the Archaic coins Gale (et al., 1980, p.34) stated that they analysed 46 Aeginetan coins. However, there are only 45 listed in their table 7 and this is the number that was entered in the OXALID database. According to Price and Waggoner (1975), they are dated to the 6th- 5th century BC, starting about 550 BC. This was the successful coinage which was widely used throughout the Greek world and also penetrated Persia, Taranto and Egypt. Since there are no silver occurrences on the island of Aegina, and Lavrion as a source was precluded due to the difficult relationship between Aegina and Athens, the suggestions made by numismatists as to the sources of silver for these coinage ranged from Siphnos to Spain. The first attempt to find the origin of the silver used for these coins through chemical analyses of their compositions was undertaken by Kraay and Emeleus (1962). The analyses by neutron activation of 37 Aeginetan 'turtles' gave very good data on Ag, Au and Cu contents and led to the conclusion that the varied gold content in the Aeginetan coins distinguished them clearly from the Athenian 'owls', parallely analysed , which were very pure. They concluded that Aegina obtained silver from a different source from that used by Athens and that the Aeginetan source was probably Siphnos. Gale (et al. 1980 p.36) concluded that among the group of Aeginetan coins from the Asyut hoard analysed for their lead isotope compositions 9 were *'falling into the Laurion field'*, while 8 of them had the high purity acceptably suggested for the silver from Lavrion. The questionable ninth coin No. 540 had ratios not quite consistent with the Lavrion ores and additionally somewhat anomalous elemental compositions with rather high gold and low lead contents. We have now many more analyses of the minerals from Lavrion and indeed these 8 coins are fully consistent with their lead isotope compositions as can be seen on Fig. 8. Besides, their range of the lead isotope ratios is nearly identical to the main group of Hacksilber from Miqne, indicating that the same mines in the region of Lavrion might have been used in the 7th and 6th centuries BC. It might be of significance that only one of the coins of the earlier type dated by Price and Waggoner to the 6th century BC is consistent with the origin from Lavrion. All the others are of the type dated to 495-485 BC. The ninth coin No. 540 is also late, dated to 485/480 BC, and on the present evidence seems to be fully consistent with the lead isotope ratios of the ores from mines at Madem Lakkos and Olympias in Chalkidiki.

Ten of the analysed coins from Aegina are said by Gale (et al., 1980, p.36) to have originated from Siphnos. The discussion of the significance of the results of analyses of the Aeginetan coinage in Gale (et al., 1980, p.33-43) combines the results of chemical and lead isotope analyses. The elemental compositions, in particular gold and tin content, are highlighted, as the main elements that can distinguish the Siphnian ores on the principle that tin is often associated with gold ores, and gold has been known to be mined on Siphnos. However, the discussion of the elemental compositions of the said 10 coins is not convincing; their range of trace elements is quite varied. It is noted though that it is rather curious to see that for an island which produced silver there are remarkably few coins known to be minted on Siphnos. Unfortunately, there are no lead isotope analyses of such coins and the coins reproduced in Gale (et al., 1980, p.41, table 12) XRF analyses of some coins from the Siphnian mint show considerable differences in the gold contents amongst them. With many more lead isotope analyses of the Aegean lead/silver ores plotted in Fig. 8, it seems that the

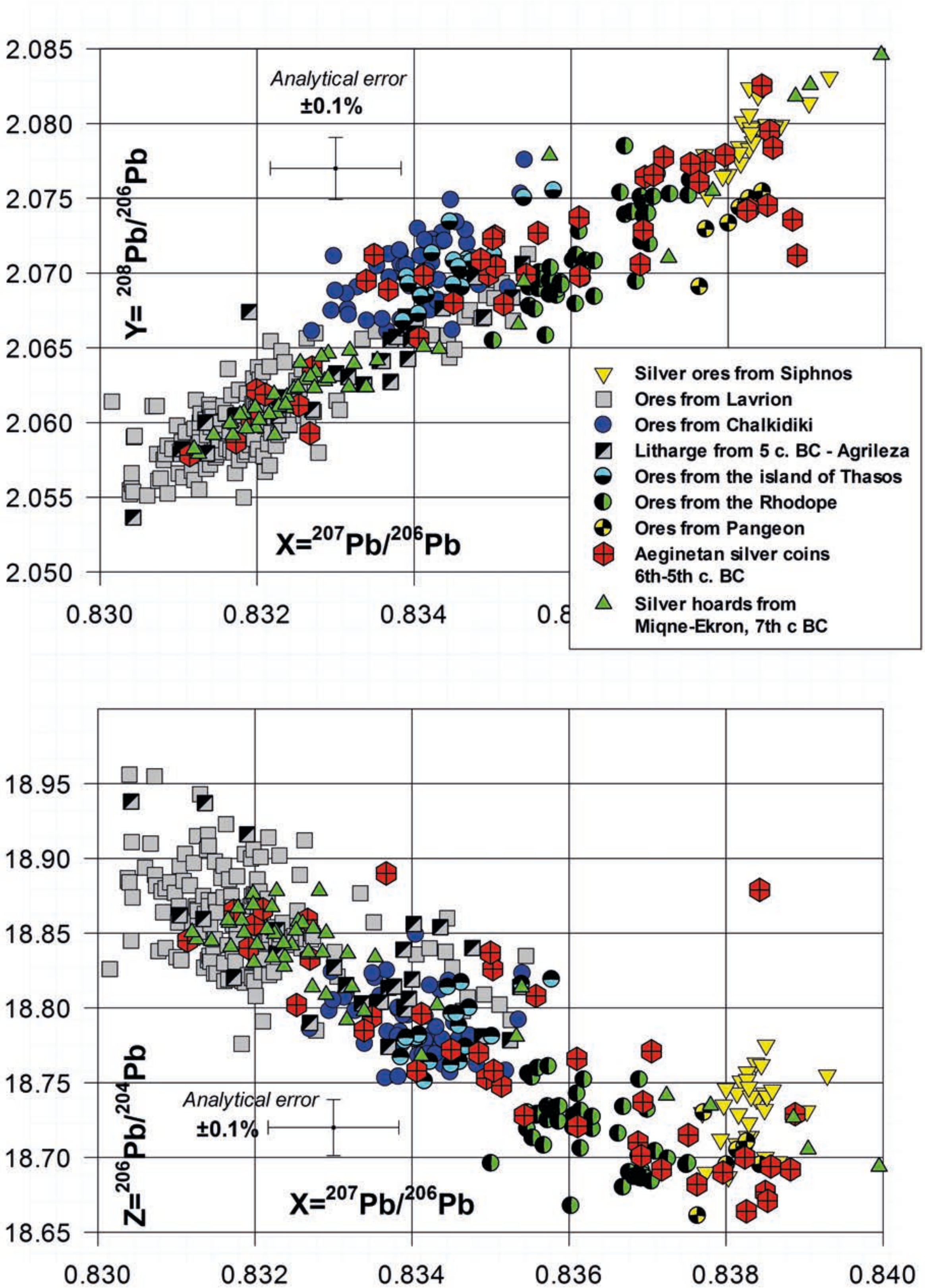

Fig. 8. Lead isotope compositions of the Aegean silver ores and the 6th-5th century coins from Aegina. As a demonstration of the silver production from the mines of Lavrion in the 7th century BC, there are also plotted here the data for the Hacksilber from the hoards found in Miqne-Ekron.

Mint or site	Chronology	Number analysed	Possible origin of silver
Miqne-Ekron	7th-6th c. BC	57	43 Lavrion, Greece; 6 Massif Central (Mt. Lozère) southern France; 1 Rhodope or Pangeon; 3 Siphnos; 1 Thrace; 2 Spain; 1 Rosia Montana, Romania.
Acanthuhs	Before 475 BC	3	2 Chalkidiki; 1 Pangeon
Aegina	6th-5th c. BC	45	8 Lavrion; 5 Pangeon; 10 Rhodope; 1Thasos; 8 Chalkidiki; 2 Romania; 6 Siphnos; 1 southern Spain; 1 Massif Central; 2 unknown (Taurus?), 1 Troad, Balya (n-w Turkey)
Athens, 'Wappenmünzen'	6th c. BC	7	1 Lavrion; 3 southern Spain; 2 Rhodope; 1 Iran, Nakhlak
Athens	5th c. BC	28	26 Lavrion; 1 (uncertain type) Romania, Baia Mare; 1 (ingot) Chalkidiki or Thasos
Chios	5th-4th c. BC	17	9 Lavrion; 2 Chalkidiki or Thasos, 2 Rhodope; 2 Romania; 2 southern Spain
Corinth	Before 475 BC	9	6 Lavrion; 1 Chalkidiki; 1 Siphnos or Romania; 1 Rhodope
Lesbos	Before 475 BC	1	1 Chalkidiki or Thasos
Lycia	Before 475 BC	2	2 Troad, Balya (Çanakkale)
Mallus or Caria	Before 475 BC	5	3 Lavrion; 1 Rhodope; 1 Iran, Pasar or Rhodope
Maronea	385-37 BC	2	1 Lavrion, 1 Rhodope
Messana	Before 475 BC	1	1 Lavrion
Orescii	Before 475 BC	6	6 Chalkidiki
Persia	Before 475 BC	4	3 Lavrion; 1 Iran Pasar or Rhodope
Salamis	Before 475 BC	1	1 Lavrion
Samos	Before 475 BC	5	4 Lavrion; 1 Siphnos
Selinus hoard, Sicily	6th-5th c. BC	5	1 Lavrion; 1 Rhodope; 1 Chalkidiki 1 Massif Central, southern France; 1 Baia Mare, Romania
Thasos	5th c. BC	36	4 Lavrion; 9 Chalkidiki; 5 Thasos; 1 Pangeon; 10 Rhodope; 2 Romania Apuseni; 1 southern Spain; 4 unknown
Zankle, Sicily	Before 475 BC	3	1 Lavrion; 1 Thasos; 1 Rosia Montana, Romania

Tab. 1. The silver pieces from Miqne-Ekron (Gitin and Golani, 2001; Stos-Gale, 2001) and Greek Archaic silver coins analysed for their lead isotope compositions and discussed in this paper. All lead isotope and chemical data can be seen on the OXALID. Other references: Gale, et al., 1980; Gale, et al., 1988 (Thasos) and Hardwick, et al., 1998 (Chios).

number of Aeginetan coins consistent with the ores from Siphnos is much smaller than 10. In fact, only 6 are fully consistent with the lead isotope ratios of Siphnian ores and litharge (PW 514, PW 534, PW 542, PW 550, PW 435 and PW 436), the seventh one (PW 537) seems to have the ratio of $^{206}Pb/^{204}Pb$ 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 of ^{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. Not all coins which were interpreted as of Siphnian origin are identified in Gale (et al., 1980) but one (PW 512) on present evidence seems to be more likely to have originated from the silver ores in the Apuseni Mountains in Romania (Rosia Montana: Baron, et al., 2011), but this is rather uncertain. Another two coins from Aegina have isotopic compositions more securely consistent with the silver ores from Transylvania (PW 479 and LBT Ox). Five coins, which might have been previously identified as from Siphnos, seem to be consistent with the lead isotope compositions of the few ore samples from Pangeon that have been analysed (PW 432, PW 433, PW 446, PW 471, PW 549; the data for the ores is also on the OXALID). The Pangeon Mountains are near the northern coast of Aegean facing the island of Thasos. The Pangeon is mentioned by Herodotus as a mining centre in 510 BC. Davies (1935, pp.234-235) wrote that Pangeon mines were being worked by Thracian or private Greek concessionaries in the later part of the 6th century BC.

A large group of the lead isotope compositions of the Aeginetan coins falls between the values for Lavrion and Siphnos. Gale (et al., 1980, p.42) suggested that these coins might have been made of the silver mined in Macedonia. This hypothesis seems to be fully confirmed by the currently available data for the silver/lead ores from Greece. As can be seen in Fig. 8, a large group of coins is fully consistent with the lead isotope data for the ores from Chalkidiki, Thasos and various ores from the southern Rhodope Mountains (data on the OXALID). The ores from Chalkidiki, Thasos and Balya (silver mine in the Çanakkale region of n-w Turkey) have been formed by very similar ore forming events at nearly the same time and therefore, they are not easy to distinguish isotopically. Nevertheless, it seems rather more likely that the Aeginetans have been procuring quite a large amount of silver from the mines located in northern Greece, and also some silver from Transylvania has found its way to the Aegean. It must be said though, that the isotopic compositions of some of these coins could have been created by melting together silver from Lavrion and Siphnos, but only a few lie on a convincing 'mixing line' between these two deposits. A further detailed consideration of their trace elemental and isotopic compositions might test that possibility, however, at present it is accepted that most of these early Aeginetan coins were minted from primary silver and therefore, in Tab. 1 the ores that show consistency with the lead isotope compositions for specific coins are given as possible origin of silver. An interesting detail given by Gale (et al., 1980) concerns three coins that have been apparently stamped with the same obverse die (511, 512, 513): two of them have lead isotope ratios consistent with Lavrion, one is quite different, possibly from Rosia Montana (not Siphnos, as previously published). This seems to indicate that silver from different mines was weighed for minting in pieces appropriate for the coins. The hypothesis of the use of primary silver for these coins can also be re-enforced by the high purity of these coins (over 98 % Ag in majority): using silver bullion of unknown quality would not guarantee their high value.

Four coins from Aegina have lead isotope compositions not consistent with any of the Aegean ore deposits and out of the range of their lead isotope ratios; therefore, they are not plotted on Fig. 8. One coin, as already indicated by Gale (et al., 1980 p.43) has lead isotope composition fully consistent with the mines in south Spain, but not really the Rio Tinto mines. On present evidence this coin (PW 444) is consistent with the ores from the mines of Jaén and the debris from the Phoenician site of La Fonteta near Alicante (Renzi, et al., 2009). There is also one coin (PW 477) that seems consistent with the silver from the Massif Central in southern France (Baron, et al., 2006) and one possibly consistent with the ores in southern Turkey in the Taurus Mountains. This coin is of high purity containing 99 % Ag. It is not known at present if these ores were exploited in the mid-first millennium BC, but they were used in the earlier periods (Yener, et al., 1991). Unfortunately there are no chemical analyses of the coins that have lead isotope compositions consistent with the origin from the Western Mediterranean and Romania.

This re-evaluation of the lead isotope data for the Aeginetan coins is somewhat different to the conclusions drawn by Gale (et al., 1980, p.43). They concluded that Aegina relied on three main sources of silver for the coins: Lavrion, Sipnos *'…and a third as yet unlocated source, perhaps in Macedonia, Lydia or even Euboea'*. However, out of 45 coins only 8 are consistent with the origin from Lavrion and 6 from Siphnos. More than half of this group of analysed coins (24) is consistent with the northern Greek mines in Chalkidiki, Pangeon, southern Rhodope and possibly Thasos. Small amount of silver might have been also coming from much further, or being re-used from earlier reserves of high quality bullion. Single coins indicate origins in the west, north and east of the Aegean. This pattern shows that perhaps the main supply of silver was coming to Aegina from the Macedonian and Thracian tribes, not from Lavrion or Siphnos, and there was also a small trickle of silver resulting in a wide ranging trade of the Aeginetans. The summary of the possible origin of silver for the Aeginetan coins is listed in Tab. 1.

Athens

The mines in Lavrion, Attica, are located some 50 km south of Athens on the Aegean coast and played most certainly an important role in the production of silver used for the Athenian coins (see for example: Conophagos, 1980). Extensive research into the sources of metals in the Bronze Age Greece has revealed that the mines in Lavrion have been exploited for lead, silver and copper since at least the late 3rd millennium BC (Spitaels, 1984; Gale, et al., 2008; Stos-Gale, 2014). It is known from the writings of Herodotus that the rich silver ores were discovered in Lavrion in 483 BC but it seems from the lead isotope analyses of the earlier silver (for example, the 7th century Hacksilber from Miqne) that the production of silver in Lavrion was quite prolific also earlier. It is therefore quite surprising that the analysed earliest Athenian coins, the seven Wappenmünzen dated to the end of the 6th century BC, are not all made of silver from Lavrion, as can be seen in Fig. 9. Only one of them (a wheel obol from the Ashmolean Museum in Oxford) is fully consistent with the origin from the Lavrion silver, but Gale (et al., 1980) notes that the obols were also minted in the early 5th century BC, so this coin might be later than the others. The other six, all from the British Museum collection, show very varied lead isotope compositions excluding their origin from the Lavrion silver and reflecting widely different origins of silver. Gale (et al., 1980, p.30) concluded after a lengthy discussion of the known elemental compositions of Wappenmünzen, that *'…the silver was being obtained from a number of different (at present undiscovered) sources Laurion being not yet largely exploited*'. A comparison of these then unknown lead isotope ratios with the current database indicates that at least two of the analysed Wappenmünzen (BMC3 amphora and BMC 18 gorgoneion) are consistent with the lead isotope ratios of ores from the southern Rhodope (Macedonia or Thrace), and one (BMC 1) with the samples of ores from a silver mine of Nakhlak in Iran. The remaining 3 coins have lead isotope compositions consistent with the silver mines in Spain: BMC 17 with ores from Mazzaron in eastern Spain near Murcia, the BMC 1 and BMC 9 with ores from Jaén. The largest Roman silver mines were in south-west Spain and it is known that silver was produced there also much earlier (Rothenberg and Blanco-Freijeiro, 1981, Kassianidou, 1992).

Gale (et al.,1980, p.28, table 7) published analyses of 14 Athenian 'owl' tetradrachms dated to the early years of the 5th century BC and concluded that they all are consistent with the origin from the silver mines of Lavrion (one coin listed in their table 7 as Athenian is in fact an Oresci coin with Price and Waggoner, No. 65; MPI 69). Since then, we have analysed another 8 such coins (from the Bibliothèque Nationale at Paris and from private collection of Leslie Beer) and found them all consistent with the origin from Lavrion. Two of the tetradrachms (Paris 289 and 9) are consistent with lead isotope ratios of the litharge from the 5th century BC silver extraction

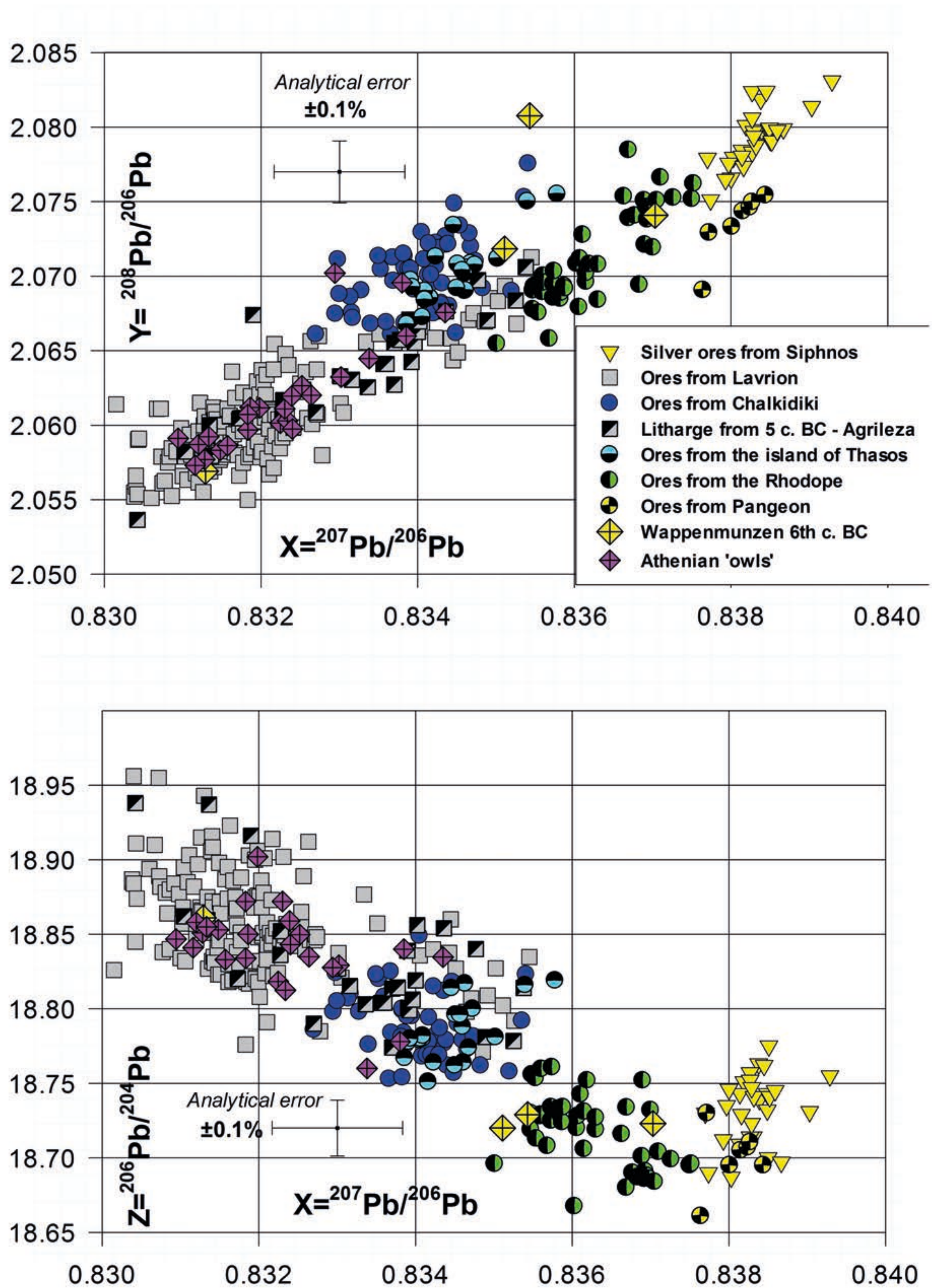

Fig. 9. Lead isotope compositions of the archaic silver coins minted by Athens, compared with the silver ores from Greece.

site at Agrileza in Lavrion (Ellis Jones, 1988). There is, however, one exception; on the Isotrace database there is a tetradrachm with a number MPI X from the Asyut hoard (before 475 BC) which seems to be consistent with the silver from Baia Mare in Romania. However, this deposit has silver only secondary to gold and it is not sure if it was exploited for silver in the 1st millennium BC, therefore this result needs to be treated with caution. Another 'outlier' listed on the database as 'Athens' is a silver ingot from the Asyut hoard (No. MPI 140c), that has lead isotope compositions which are consistent with the ores from Thasos and Chalkidiki. Therefore, it seems that indeed all 'owls' well described on the OXALID database are consistent with the origin from the silver mines in Lavrion.

Thasos

In the Archaic period the regions of Macedonia and Thrace produced a large number of silver coinage. It is said in ancient sources that the agricultural wealth of this region was supplemented by one of the most prolific silver mines in the ancient world. Only 4 Thasian coins from the Asyut hoard were analysed for their lead isotope compositions (Gale, et al., 1980), but nearly a decade later, a larger body of Thasian coins from the Ashmolean Museum in Oxford and from the Bibliothèque Nationale at Paris were analysed in the Isotrace Laboratory (Gale, et al., 1988). Altogether, there are 36 such coins listed on the OXALID database, mostly also with elemental compositions. In the publication of the results of the 31 of these coins, Gale (et al., 1988, p.218) concluded that 15 of them have lead isotope compositions consistent with their silver having come from Thasian silver ores, and three (1985, 1993 and J9) have compositions consistent with silver coming from Lavrion. When there is no doubt that the latter cannot be denied, it is difficult to find in this group of coins 15 that would be consistent with the lead/silver ores from Thasos; there are at the most 5 such coins. It is true that at present, there are still very few (22) lead isotope analyses of ores and slags from Thasos, partly because there is not much galena left for sampling after centuries of mining (mainly for zinc). Besides, isotopically there are several groups of ores in the northern Aegean that have a very similar range of lead isotope ratios. As can be seen in Fig. 10, the data for ores from Chalkidiki and Thasos are in part isotopically indistinguishable. However, on the present evidence it seems that there are many more coins consistent with the lead isotope compositions of the ores from Chalkidiki and from several deposits in the Rhodope Mountains (Kirki, Virini, Madjarovo in Bulgaria, Iasmos and Farasinon in Thrace) than from Thasos.

Further, Gale (et al., 1988, p.219) concludes that five coins are consistent with the origin from the Siphnian ores. This again cannot be confirmed, none of these coins has lead isotope ratios fully consistent with the analysed Siphnian ores.

The conclusions drawn in the paper by Gale (et al., 1988, p.221) indicate that there was a small disagreement between the numismatic and scientific evidence: *'However the study of monetary circulation, based on hoards and coins from excavations, makes it very unlikely that silver obtained from ores from Lavrion, Siphnos, Almiropotamos or the Halkidiki was used to make Thasian coins. Moreover … the coins …may well be made of silver coming …from a source located in the Thasian peraea on the mainland.'* Perhaps the famous 'prolific mines' controlled by Thasos were not located on the island itself, but on the mainland. Indeed, while it still seems that three of the coins are consistent with the origin from Lavrion, none are from Siphnos. Chalkidiki cannot be excluded, taking into account the importance of this region for silver mining (Wagner, et al., 1986). Additionally, there are four coins amongst the Thasian group that at present do not match any of the analysed silver ores. It must be said that the Rhodope Mountains and Pangeon where there are many ancient mines and slag heaps are very good candidates for the origin of silver with such lead isotope ratios and it seems that these mines and slags should be thoroughly investigated by archaeometallurgists. Finally, there are two Thasian coins that are consistent with the origin from the Apuseni Mountains in Romania and one which has lead isotope ratios of the silver mines in southern Spain.

Chios

Chios was an important ally of Athens in the Delian League and since there are no local deposits of silver on this island, its coinage provides important information about its economy in the 5th c BC. Seventeen coins from Chios, and 2 from its only colony Maronea, were analysed for their lead isotope and elemental compositions (Hardwick et al. 1998).The lead isotope ratios of some of these coins are plotted in Fig. 10. Three other coins fall outside the range of lead isotope ratios on this diagram: number 1949-4-11.809 dated to c. 510 BC, is identified in Hardwick (et al., 1998, p.380) as of uncertain origin ('*Tirebolu or mixture'*). In fact, its lead isotope ratios are 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).

With slight adjustments of the possible provenance of silver based on the TestEuclid results it seems that out of the remaining 17 coins from Chios and Maronea 10 are fully consistent with Lavrion, 2 with Chalkidiki and 3 with the lead isotope data for the ores in the south Rhodope Mountains. The division into these 3 groups is particularly well visible on the plot showing ratios $^{206}Pb/^{204}Pb$ on the lower part of Fig. 10. Additionally, two coins (as concluded before) are consistent with silver originating from the Iberian Peninsula, and in particular with the silver extraction site at Monte Romero in Huelva (Kassianidou, 1992 and OXALID).

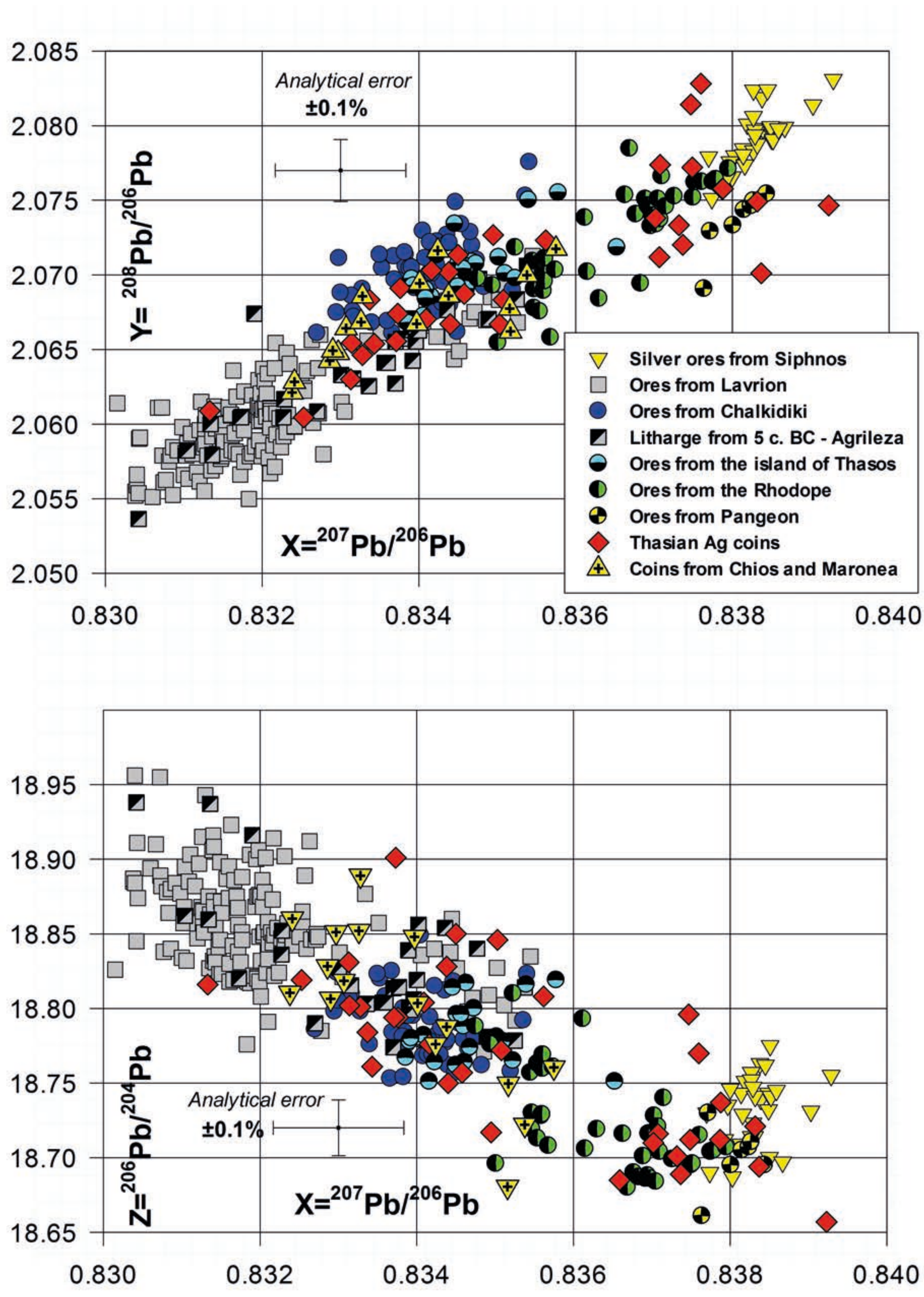

Fig. 10. Lead isotope ratios of Archaic silver coins from Thasos and Chios, compared with the silver ores from Greece.

Silver from the South Carpathians and the western Mediterranean in the 1st millennium BC Aegean

It is perhaps pertinent to briefly discuss here the possibility of silver from Transylvania being used in the first millennium BC by the Greek city states. The gold-silver deposits in modern Romania might have been exploited since the Bronze Age and there is some evidence that the silver from this region found its way into the Mycenaean shaft graves (Stos-Gale, 2014). Fig. 11 shows a comparison of the lead isotope compositions of the published ore samples from Romanian gold-silver-copper deposits with the earlier silver objects found in Greece and the archaic coins that are consistent with these lead isotope ratios. It is evident from this plot that silver from Lavrion was also exploited in the Bronze Age, but there is a considerable group of silver vessels in the Mycenaean Shaft Graves and on some other BA sites that concerning lead isotope and some archaeological evidence is consistent with the origin from the Carpathians (Stos-Gale, 2014).

The lead isotope data for the ores from Romania became available only in the recent years (Baron, 2010; Marcoux, 2002) and therefore, the possible origin of metals from the north of the Aegean was never raised in the discussions of the prehistoric sources of metal in the Aegean. However, there is no doubt that the silver deposits in the Apuseni Mountains and Rosia Montana (to a less extent) were significant, since even in the second half of the 20thcentury over 30 tons of silver a year were extracted in Romania (Dunning, et al., 1982, p.287). Out of 183 Archaic Greek silver coins analysed so far for their lead isotope compositions nine coins have lead isotope compositions consistent with the ores from Rosia Montana (4) and Baia Mare (5). They are from several different mints: 1 from Athens, 2 from Aegina, 2 from Thasos, 2 from Chios, one from Zankle on Sicily and an ingot C with turtle stamp from the Selinus hoard found on Sicily (Beer-Tobey, et al., 1998).This result suggests that a small amount of silver from Transylvania circulated in the south of Europe in the 1st millennium BC. The archaeometallurgical research in the gold-silver mines of Romania is not very advanced yet. It seems possible that the silver mining in this region started in the prehistoric times and continued before the Roman period. Therefore, mapping the chronological and archaeometallurgical exploitation of these deposits could be an interesting line of research.

Much more information is available for silver extraction from ores on the Iberian Peninsula. There are several recently published papers concerning the Bronze Age and Phoenician silver extraction in Spain (for example: Renzi, et al., 2009 and 2012; Bartelheim, et al., 2012; Montero Ruiz, et al., 2009) and the historical sources suggest that silver from Spain was used in the Aegean in the early first millennium BC (as explained, for example, in Hardwick, et al., 1998, pp.375-376), so finding some coins consistent with the lead isotope ratios which are characteristic of Spanish ores is no surprise.

More surprising is an indication that a small amount of silver might have been exploited at that time in the Massif Central in southern France, too. So far, 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 (Brevart, et al., 1982) 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 southern France in the 1st millennium BC, so the hypothesis of the origin of silver from this mines for the Archaic coins proposed here is very tentative. In his book on Roman mining in Europe (1935, pp.77-78 and pp.81-83), Davis mentions many ancient silver mines in southern Gaul, but much more information and lead isotope data is needed to confirm this hypothesis.

Conclusions

The lead isotope compositions of the analysed coins indicate that the great majority of the silver used by the Archaic Greek mints was from Lavrion, Chalkidiki and the deposits in the Rhodope Mountains, including Pangeon. However, small amounts of silver might have originated in the West Mediterranean and possibly also in the Carpathians. It might be surprising and going somewhat against the earlier evaluations of the compositions of the Greek Archaic silver coins, that silver from Siphnos and Thasos does not feature prominently in this group. First of all, it has to be said that many more analyses of the earliest coins from different mints need to be analysed to confirm this hypothesis – the majority of coins analysed so far is from one hoard found in Egypt (100 out of 183) which might not be entirely representative for the whole population of the coins minted at the end of the 6th and beginning of the 5th century BC. The other two large groups are of coins from the north Aegean islands: Chios and Thasos, so the predominance of silver from northern Greece can be related to the distance from these mines. Besides, the interpretation of lead isotope data presented here relies on very few analyses of ores from Pangeon, Thrace and Macedonia, in particular from the mine sites known from the writings of Herodotus, and other sources. Therefore, only extensive archaeometallurgical research into the silver mining in northern Greece with many more lead isotope and chemical analyses can confirm or contradict this hypothesis. Additionally, not much is known about the silver production in pre-Roman Dacia and in the northern Rhodope (Bulgaria) where there are also large amounts of lead slags and known silver mines; these regions should be investigated, too.

Fig. 12 shows a plot of all Greek Archaic silver coins of the discussed here (all data is available on the OXALID). This plot is useful as a demonstration of two points of

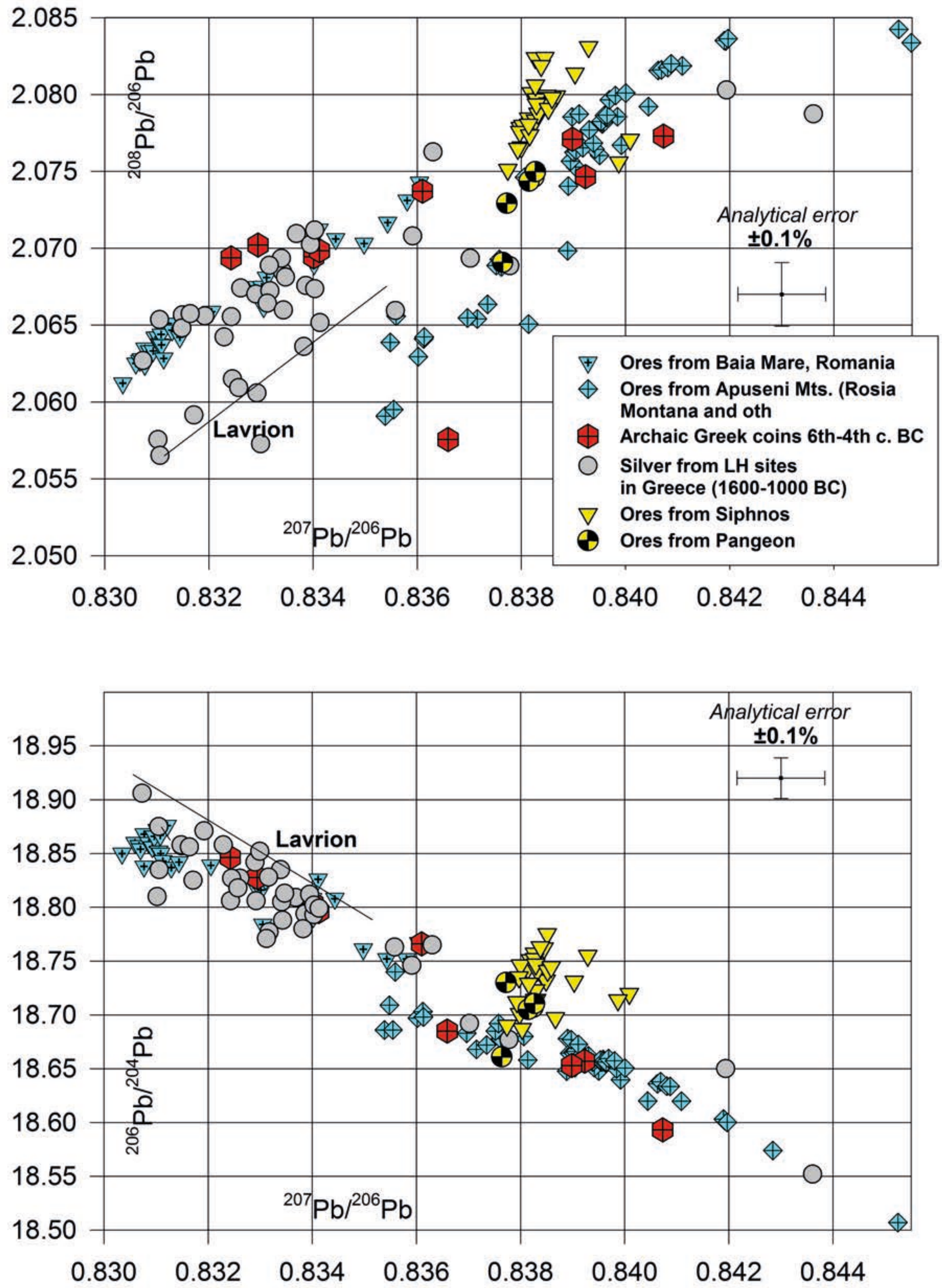

Fig. 11. Lead isotope ratios of ores from two gold-silver-copper deposits in the eastern Carpathians (Romania) and the Archaic silver Greek coins that seem consistent with the origin from these ores. In the same figure there are plotted data for the Mycenaean silver discussed previously by Stos-Gale (2014).

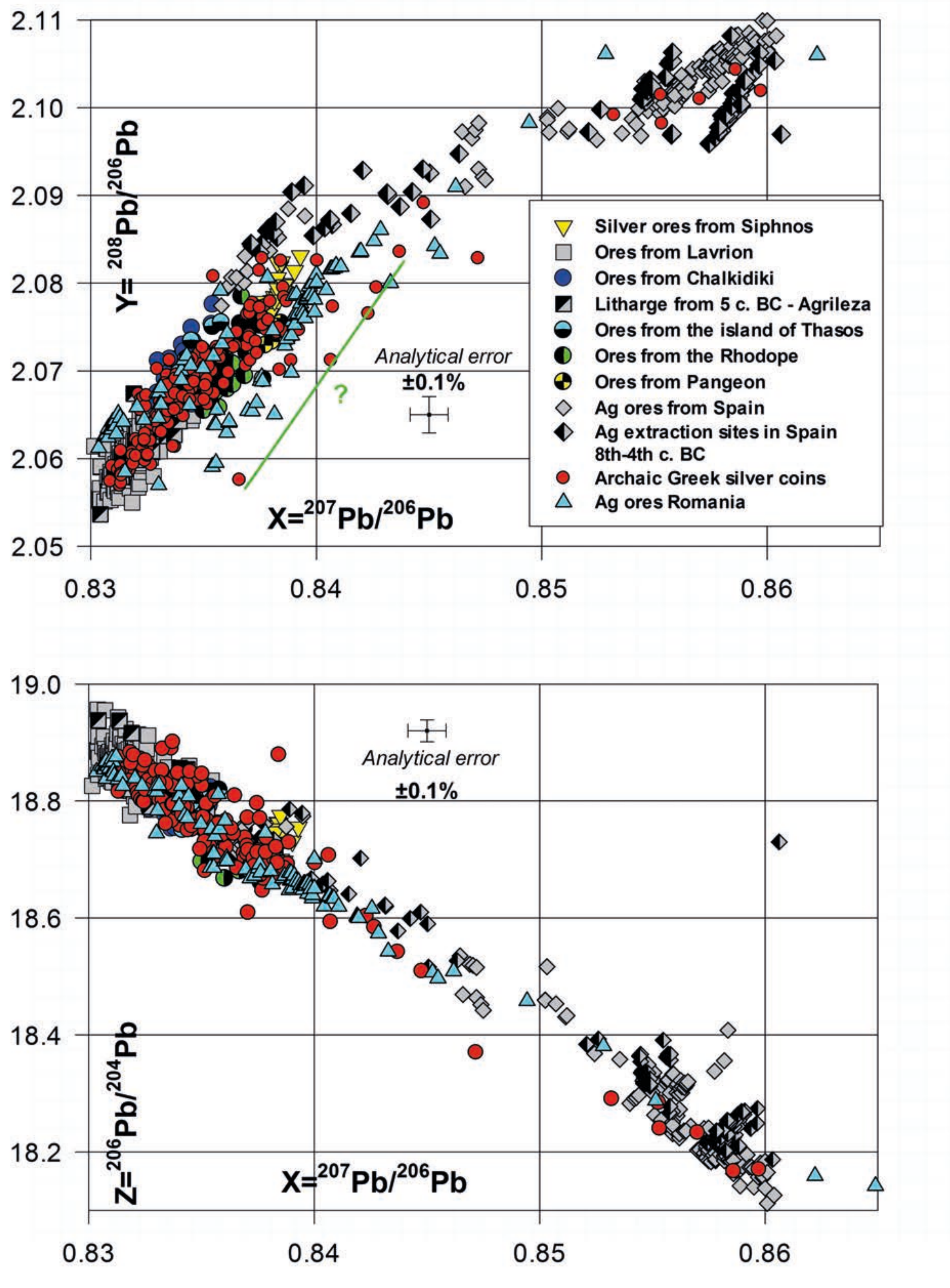

Fig. 12. Plot of all data available at present for the Greek silver coins dated to 6th-4th century BC. Of particular interest is a small group of coins: 1 from Thasos, 2 from Aegina and 2 from Athens that have lead isotope compositions which are not consistent with any of currently known silver ore deposits.

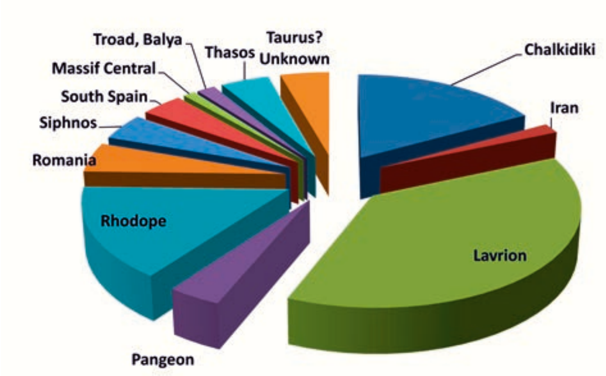

Fig. 13. Possible origins of silver used for the 6th–4th century BC Greek coins as indicated by their lead isotope compositions.

the lead isotope interpretation: firstly that there are several coins with lead isotope ratios that at present do not match any of the analysed silver ores (marked with '?' in Fig. 12), and secondly that the distribution of data points on this plot does not indicate convincingly that the Iberian silver was extensively mixed with the Aegean metal. Such mixing would result in a random scatter of data points between the two group of ores and that is not the case. It seems more likely that the amount of silver originating in the Western Mediterranean and the Aegean is assessed correctly. As a working hypothesis for further consideration by numismatists and archaeometallurgists this re-evaluation of published lead isotope data for the Archaic Greek silver coins suggest a rather complex pattern of the origin of silver used for these coins. Tab. 1 lists the mints and the number of coins analysed, as well as the suggested sources of silver based chiefly on their lead isotope compositions. Fig. 13 shows a pie chart based on this interpretation. This count shows that 38 % of silver is consistent with the origin from Lavrion, 17 % from Chalkidiki, 15 % from Rhodope. Thasos, Siphnos and Pangeon contribute 4 % each; this indicates that for these 183 coins nearly the same amount of silver originated from Lavrion as from the northern Aegean. The Western Mediterranean ores contribute 5 % (Spain and southern France), while another 4 % are from unknown source. It must be emphasized that this interpretation of the lead isotope data is only tentative and still opened to re-interpretation, mainly in conjunction with the reliable elemental data.

In the two papers quoted above (Gale, et al., 1980 and 1988) the authors are discussing in very detailed manner the elemental analyses of major and trace elements in the coins and ore samples. It is believed that, in comparison with the lead isotope data, the chemical compositions of coins might give a quite new perspective. For example, the gold and bismuth contents in the ores and silver coins are usually quite significant in disentangling or strengthening the attributions made on the basis of lead isotope compositions. Unfortunately, the number of trace elemental analyses of these coins is very small; many published analyses were made by ED XRF which gives only contents of Pb, Cu, Au and Ag in concentrations above c. 0. 1 %, and many were not analysed at all. Considering all available analytical data, at present it seems that they are not at all conclusive or even helpful. Combining lead isotope data with the elemental compositions show that even in the coins that are fully consistent with the lead isotope ratios of the mines in Lavrion, the contents of gold, lead and copper can vary considerably. Therefore, it seems that at present the elemental compositions cannot help with the interpretation and perhaps this is a topic for another paper.

Though the powerful combination of lead isotope plus trace element analyses have already made numismatic studies much more interesting and rewarding, there clearly remains a great scope for further work. This is particularly true for the earliest Greek coins. Price (1980) pointed out that, though the work reported then on Greek coins by Gale *et al.* represented a substantial advance, a more significant advance would likely be made if a really large scale analytical programme was to be mounted in this field. He drew attention to a number of questions of great concern to the numismatist which might be addressed by lead isotope analyses, apart from the central question of the travelling of silver. In the Archaic Greek field they include a knowledge of mining sources which can be gleaned from a study of the Macedonian tribal coinage and similar coinage like that of the Aegean islands and Lycia, together with an expanded sampling of ores from ancient mine workings. So for example, the Orescii were amongst a number of peoples in northern Macedonia who at the time of their coinage were almost certainly mining communities, so that the varied coinage of Macedonia offers a rich field of enquiry to discover how many, and which, sources of silver were available to the cities which struck coins. For the Persian sigloi, Price suggested that an extensive study is needed of the issues of Croesus, including the posthumous issues, in conjunction with the early sigloi. Incidentally, he also expressed a mild surprise at the identification of Siphnos as a major source of silver, in view of the scarcity of coinage attributable to that island, which now seems justified. Price urged the need for further work on the island coinage some of which, as Paros, coined silver to a much larger extent. He advocated further detailed work on the early owls and Wappenmünzen in order to help resolve still controversial issues in the Athenian coinage. It seems that 35 years later, these questions are still waiting for an answer.

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