Origin and fate of the greatest accumulation of silver in ancient history

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Received: 11 January 2022 / Accepted: 26 February 2022 / Published online: 22 March 2022
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Abstract
The capture of the Achaemenid treasuries in 331–330 BCE by Alexander the Great in Persepolis and Susa marked the demise of the 300-year-old Persian Empire and the advent of Hellenistic kingdoms. Alexander seized the equivalent of about 5000 tons of silver, which represented the accumulated tributes paid by subjugated people from the Aegean Sea to the Indus to their Achaemenid rulers. Die studies show that this gigantic amount of silver, the so-called Persian mix, had been used to produce most of the coinage of Alexander the Great himself and to an even greater extent those of the Diadochi, his successors. What remains to be understood is the origin of the silver of this immense treasure. Lead isotope abundances determined on both Persian sigloi and alexanders struck from Achaemenid silver trace the bullion source to the southern Aegean, Macedonia, and Thrace. Lead in pseudo-coinage from early Indian kingdoms is isotopically different from the rest, which attests to a limited Indian contribution to the Achaemenid treasuries. Studies of Iron Age hoards from the Levant leave open the possibility that the making of the Persian mix may have predated the Achaemenid expansion of the seventh century BCE. We speculate on the motivations of such massive hoarding by the Persian kings and on its economic implications.

Keywords Silver coins · Pb isotopes · Achaemenid treasures · Alexander the Great · Greece · Persia · India · Convex hull

Introduction
The 331 BCE defeat of the Persian Achaemenid king Darius at Gaugamela, next to modern Erbil, Iraqi Kurdistan, opened the road to Susa, Babylon, and Persepolis to Alexander the Great. The colossal amount of wealth plundered by the Macedonians, in particular from the royal treasury in Persepolis, has been described by a number of ancient writers such as Curtius, Diodorus, Plutarch, Arrian, and Justin (Callatay 1989; Holt 2016) and may have reached up to 200,000 talents of Attic standard (1 talent = 25.9 kg), which in modern units correspond to a staggering silver weight of about 5200 metric tons. This estimate is an aggregated value of gold and silver converted to Attic silver talents, for example, 2600 tons of silver and 260 tons of gold. This figure has to be seen from the mercenary perspective: a Greek hoplite received a daily stipend of about a drachm of 4.3 g. As such, 200,000 talents represent 1.2 billion daily wages, enough to pay in fresh coins for an army of 50,000 soldiers during more than 60 years.

Although heritage of silver accumulation by the Neo-Assyrian (911–605 BCE) and Neo-Babylonian (626–539 BCE) empires in what would become the Persian Empire by looting, trade, and tribute was certainly significant, the Achaemenid dynasty organized the captation of silver resources on a regional scale very efficiently. As reported by Herodotus (III.95), the yearly tribute was 14,560 talents. The looting of Persian treasuries by Macedonian armies created one of the most massive releases of precious metals, superior to any other booty known from Classical antiquity, such as the Egyptian treasury brought back to Rome by Augustus (Nicolet 1984). How such a bullion deluge affected the various economies at the time, and in particular commodity prices, has been the subject of much interest (Van der Spek and van Leeuwen 2014), but, beyond the impact on commodity prices in Babylonia for less than a generation (Jursa 2010), its effect on the Aegean market is not well documented.

What is known, however, is that, over three decades (ca. 332–301 BCE), most of the Persian treasuries were

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converted into coins. Different forms of “money” existed in Mesopotamia for millennia, and among them barley and silver were the most prominent (Powell 1996; Jursa 2010). The silver shekel, originally a measure of weight (8.3 g), had also gradually been accepted as a unit of account and been used physically for trade, although far from exclusively. Silver coinage was only briefly used in the western part of the empire for military purposes (Alram 2012; Le Rider 2001). As pointed out by van der Spek et al. (2018), the conquest by Alexander in 331 ushered in minted silver as the primary currency. The many die studies conducted on the coinages of Alexander and his successors reveal that the full production issued in gold and silver exceeded 100,000 talents (Callatay 1989; Callataÿ 1993; Holt 2016; Meadows 2014). Moreover, coin metal analyses have shown that, for both gold and silver, nearly all eastern production, as well as a substantial part of western production, notably in Macedonia, are likely to have been issued from this bullion, hereafter referred to as the “Persian mix”. Mixed bullion is consistent with both historical accounts attestinbullion, hereafter referred to as they to a Persian policy of remelting tribute and the homogeneous Au/Ag of silver Alexander issues (Olivier et al. 2017).

Despite some modern discredit cast on Herodotus’ list of tributes to Darius (Armayor 1978; Bresson 2020), this author famously testifies to the reality of the hefty tributes paid to the King of Kings (the title used by Achaemenid Persian kings) by each satrapy (III.89–97). Most revenues are expressed in silver talents but with some still paid in kind such as white horses or frankincense, while it is also made clear that India paid in gold. Whether the actual tributes were paid in silver, gold, horses, or frankincense cannot be known, but the massive minting of silver coinage by Alexander and the Diadochi demonstrates that the Achaemenid palaces must have been packed with vast amounts of bullion.

From where came the dormant silver heaps of the Persepolis and Susa vaults attested to by ancient writers (Callatay 1989; Holt 2016)? The present work investigates the issue of the origin of the Persian mix using high-precision lead isotope analysis in an attempt to understand whether silver ores other than those well-acknowledged in the Greek world were involved in the treasures amassed by the King of Kings and what were the particular motivations behind the hoarding of so much bullion.

In addition to Pb isotope measurements of silver Alexander coinage (alexanders), the present work also presents data on two other types of silver coinage that were unlikely to have been minted from the central Persian treasury. First, silver sigloi (shekel) are the only significant coinage produced by the Persian Empire in its western satrapies (Alram 1993; Tuplin 2014). They are known, together with archaic Greek coins and Indian punch-mark coinage from Gandhara, from the Kabul hoard deposited ca. 350 BCE (Schlumberger 1953), but so far have not benefited from isotopic work (e.g., Kraay and Emelius 1962). Second, although no known evidence substantiates a significant input of Indian silver to Persian treasury (Herodotus, III.98–105), the present work provides Pb isotope data on early Indian punch-mark coinage to corroborate this conjecture by objective, concrete means (Reddy 2014).

Materials and methods

The present work presents high-precision Pb isotope data on ancient silver coins produced in Persia during the Achaemenid reign and in the Hellenistic world in the immediate aftermath of Darius’ defeat. The measured Pb isotope compositions were treated using novel statistical tools in the form of calculated Pb model ages combined with convex hull theory (see below), which allow the tracking of silver provenance with greater accuracy and precision than possible when using only raw Pb isotope ratios and manually comparing artifacts with known ores on a one-to-one basis. The coin types analyzed here are (1) silver alexanders, minted both during the king’s lifetime and shortly after his death; (2) silver sigloi; and (3) shatamanas (bend silver bars and imprinted pieces) from Gandhara and Kamboja Janapadas (kingdoms), Northern India, generally dated from the sixth to the fourth centuries BCE. (4) A subset of Greek silver coins further was included for reference. The analytical techniques used for the determination of Pb isotope compositions have been described elsewhere (Milot et al. 2021) and involve anion-exchange chromatography for Pb separation and multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) for Pb isotopic analysis. Here it suffices to state that all coins of (1), (2), and (3) were drilled, whereas coins of (4) were leached (cf. Milot et al. 2021). Repeated measurements of NIST 981 throughout each analytical session consistently yielded an external reproducibility of < 100 ppm (0.01%) for 204Pb-normalized ratios and < 50 ppm (0.005%) for 207Pb/206Pb and 208Pb/206Pb. In-run errors systematically were smaller than the external reproducibility for all samples. Table S1 (Supplementary Information) compiles relevant coin information with the corresponding Pb isotope data acquired in this study.

Lead isotopes and the convex hull strategy

The prevalent method of assessing provenance of silver artifacts is by means of Pb isotopes. Contrary to the relative abundances of stable isotopes of elements such as Cu and Ag, which vary with environmental conditions, the relative abundances of Pb isotopes vary predominantly as a result of uranium and thorium radioactive decay and consequent lead radiogenic ingrowth. Isotopic variations are
controlled by the U/Pb and Th/Pb ratios of the rock from which the Pb ore was born and by the time elapsed up to that point. Time (Pb model ages), U/Pb, and Th/Pb can be calculated from measured Pb isotopic compositions and be used to deduce the tectonic context in which the ore occurred. In practice, however, archeologists and numismatists simply manually compare the measured Pb isotopic compositions of artifacts in pairs of 2-dimensional (2D) plots, such as $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{204}\text{Pb}/^{206}\text{Pb}$ vs $^{207}\text{Pb}/^{206}\text{Pb}$, with those of ores stored in a database until they find a match that is acceptable. However, it takes more than a match in one pair of diagrams to establish whether a data point falls into the 3-dimensional (3D) field of Pb isotopic ratios of a particular mining district (Fig. 1a). The Pb isotopic data must be visualized in 3-dimensional space (as dictated by the number of parent isotopes, $^{238}\text{U}$, $^{235}\text{U}$, and $^{232}\text{Th}$); although the projections of two different points may coincide on the $x$–$y$ and $x$–$z$ planes, they can be distinct on the $y$–$z$ plane. Prior attempts to address this issue (Delile et al. 2014; Westner et al. 2020) have demonstrated the multiple difficulties of assessing meaningful distances between points. Here we therefore take a different approach, that of the so-called convex hull (Fig. 1b), which was previously proposed under the name of “isotopic niche” in Ecology (Eckrich et al. 2020) before it found its way into Archeology in general (Robinson...
The Pb isotope data on the different groups of coins, e.g., *sigloi*, are enclosed in the minimal (circumscribing) 3-dimensional volume (Fig. 1c), the convex hull, which was expanded by 5% to take into account potential analytical uncertainties. The algorithm finds all the ore samples that are plotting inside the sample convex hull. The benefit of testing each potential ore against the convex hull of the sample set, and not the other way around (Longman et al. 2018), which would amount to testing each sample against geographic groups of ores with consistent Pb isotope compositions, is that the sample hull is robustly defined by high-precision data. The downside of the convex hull approach is that some ore districts are over-represented in the database with data variability at a given site being not specifically considered. It is clear that the database contains an inordinate amount of Lavrion samples, yet the hit maps are different for different samples (Gentelli et al. 2021, and this work). The effect of unequal sample representativeness for densely populated mine fields could be adjusted by normalizing the number of hits to sample density, but such a correction would make little sense for isolated ores with a very small number of samples, such as mines in Iran and North Africa. Rather, careful manual examination of local densities of individual hits will limit such potential bias as has been demonstrated by a previous application of the convex hull method to multiple Iron Age *hackisilber* hoards (Gentelli et al. 2021) which showed no false-positive identifications of bullion sources. Each Pb isotope datum extracted from a ca. 6700-entry database on galena samples encompassing Europe, North Africa, and Western Asia is then tested for inclusion in the convex hull. Data from major copper ore deposits, such as those found in Cyprus and the Iberian Pyrite Belt, are unlikely to be significant Ag sources and hence were left out from the search. Figure 2 shows the position of the ores comprising the database. An ore found to be included is considered a hit and therefore a potential Pb source, whereas ores plotting outside the hull (considered a miss) can be safely excluded as potential Pb sources. In order to minimize analytical errors and mass-dependent fractionation of Pb in ores, we opted for using $^{206}\text{Pb}$-standardized ratios, i.e., $^{204}\text{Pb}/^{206}\text{Pb}$, $^{207}\text{Pb}/^{206}\text{Pb}$, and $^{208}\text{Pb}/^{206}\text{Pb}$. The hit densities are finally contoured on a geographic map shown in Fig. 3 for Greek silver coins, *alexanders*, and *sigloi*. Figures 4 and 5 show the raw Pb isotopic compositions of the hits identified by the convex hull approach on a grid of Pb model ages and $^{238}\text{U}/^{204}\text{Pb}$ ($T_{\text{mod}}(\mu)$) values in $^{207}\text{Pb}/^{204}\text{Pb}$-$^{206}\text{Pb}/^{204}\text{Pb}$ space. A grid of Pb model ages and $^{232}\text{Th}/^{238}\text{U}$ ($T_{\text{mod}}(\kappa)$) values was not added to the $^{208}\text{Pb}/^{204}\text{Pb}$-$^{206}\text{Pb}/^{204}\text{Pb}$ plot as this would require adopting a single $\mu$ value for all samples, which would be incorrect. A single grid could instead have been drawn using the $T_{\text{mod}}(\mu*\kappa)$ doublet, but this would be much less informative.

**Results and discussion**

The coin Pb isotope data are listed in Table S1 (Supplementary Information). Figure 3 shows the distribution of Pb ores consistent with the present results on coins, i.e., falling within the convex hull of the data set, with histograms of model ages as insets.

First, cluster analysis was applied to the samples using techniques implemented by commercial (Matlab) or public domain (R) packages (Albarède et al. 2021) (Fig. 1c). Each coinage is satisfactorily accounted for by two clusters, which also stand out as separated peaks in the histograms of model ages.
Fig. 3 Maps of the Pb isotope “hits” observed for sigloi (bottom panel), alexanders (middle panel), and Greek silver coins (top panel) using the convex hull algorithm. The histograms of model ages (insets) show how well grouped the results are. The total number of hits is the number of matches between coin and ore Pb isotopic compositions. The Pb ore database consists of about 6700 European, North African, and Middle Eastern ores significantly expanded and updated from a smaller core of data on Pb ores initially compiled in the OXALID database (Stos-Gale and Gale 2009) after careful removal of artifacts, slags, and Cu ores. Isolated hits (cyan-colored symbols) may reflect minor production sites, but may also reflect analytical issues and local geological intricacies; they are not localities where substantial silver production has ever been documented and hence are considered as fortuitous. Red-shaded fields represent areas with a hit density > 10% per degree-squared normalized to the entire population of hits, which attest to the most frequent provenances. Sigloi are therefore dominated by Attic and peri-Attic silver (Sifnos, Milos), with alexanders including additional Thraco-Macedonian sources.

Fig. 4 Plot of the hits obtained for sigloi. In the 3-dimensional space of Pb isotopic ratios, two clusters are first identified by cluster analysis. One of them comprises only two points and, hence, no convex hull can be calculated. The convex hull of the second cluster shows hits largely dominated by Laurion (Lavrion) lead. Convex hulls are expanded by 5% to take analytical uncertainties into account. The samples labeled “Tunisia” may indicate that silver from the Carthage hinterland has been neglected by ancient literature (Delile et al. 2019) or that other fields, such as Chalkidiki, were poorly sampled for Pb isotopic analysis. The “other” group represents isolated Pb mines insufficiently documented by Pb isotope analysis. The model age isochrons and the growth curves for different $\mu$ values calculated with Albarède and Juteau’s (1984) parameters are shown for reference in the bottom panel.

Ages (Fig. 3, insets), though one of the clusters identified by sigloi has only two elements, which is not enough for a convex hull to be defined in the 3D space of Pb isotope
compositions. The various Greek silver coins used for reference emphasize the diversity of ore provenance but with a predominance from Lavrion. Some districts, such as northwestern Sardinia, show more hits, which are consistent with evidence of Sardinian silver sources identified in one Levant hoard of hacksilber (Eshel et al. 2019; Gentelli et al. 2021). Delile et al. (2019) suggested that Tunisian silver sources may have been overlooked by ancient literature and that they can explain the surprisingly fast revival of the Carthage economy after the crushing defeat of the Second Punic War and the ensuing war penalties. More isolated points, typically located in Gaul and Britain, cannot be formally discounted, but have not been proven so far to be significant silver producers. The Cévennes in southern France (Munteanu et al. 2016; Ploquin et al. 2010), the British Pennines (Raistrick and Jennings 1983), and Germany (Körlin 2006) also show evidence of ancient silver mining activity, but no records exist to document that any of these regions produced significant amounts of silver before Roman times. For both sigloi and alexanders, the hits are concentrated around the Aegean and include Sifnos, Lavrion, Macedonia, and Thrace (red fields in Fig. 3). For the 18 sigloi, Lavrion and Sifnos define a coherent hot spot. As expected, Macedonia is also an important bullion source for alexanders. These results highlight the major mining districts that made Athenian and Macedonian political and military successes possible.

The Pangaion area in Macedonia was already extensively mined when the Persians conquered and controlled this area for a third of a century (512–479 BCE). Their one-time presence in the west prompted large productions which would fade with the battle of Salamis and the Persian retreat after the Second Invasion of Greece. Bresson (2015; 2020) estimates the yearly production of Lavrion, Thrace, and northern Greece to 1500 talents. Callataï (2016) used die studies to raise the total amount of bullion to 10,000 talents (260 tons). How much silver extracted from other localities contributed indirectly, e.g., by trade or military movements, is not clear. A likely scenario now emerges in which Persians, who defeated the Lydians in 547 BCE and from then onwards were in contact with monetized precious metals, took full advantage of the silver extraction and minting processes once they became masters of the Pangaion area.

Following the retreat of the Persians from Europe after the Second Invasion, the Achaemenid economy returned to the normal standard of the time in Babylonia and other parts of the empire, which was to use silver for payment but largely in its unminted form (Jursa 2010).

On the Indian side, Gandhara and Kamboja shatamans (1827 hits) show an extreme scatter in Pb isotopic compositions. Model ages fall into two groups (Fig. 6). One group with future (= negative) Pb model ages, which are mostly found in volcanic rocks, is missing from the record of East Mediterranean ore deposits. The other group is characterized by positive Pb model ages (> 100 Ma) but its large number of hits is clearly due to an extreme spread of the data in Pb isotope space. From the British Isles to Spain, Greece, Turkey, and Iran, this group singles out no specific province that could attest to a potential bullion provenance. The spread of the data, and notably of the model ages, in each group suggests the existence of multiple but modest sources of Ag ores in the Middle East.

Fig. 5 Plot of the hits obtained for the analyzed alexanders. As in Fig. 4, two clusters are identified. The convex hull of the cluster with older Pb model ages represents poorly documented mines from unexpected localities in Gaul, Britain, and Asia Minor. The cluster with younger Pb model ages points to the Cyclades, Thasos, Chalkidiki, and Rhodope. As in Fig. 4, the model age isochrons and the growth curves for different μ values calculated with Albarède and Juteau’s (1984) parameters are shown for reference in the bottom panel.
The outcome of the present work is twofold: the data on Persian sigloi show the prevalence of metal components with the strong Pb isotopic signature of Laurion (Lavrion) (Fig. 4), while alexanders further reveal additional Thraco-Macedonian, Thasos, Cycladic, and other unknown sources (Fig. 5). The possibility of sources in Tunisia remains enigmatic but may also reflect some overlap with sources in Chalkidiki. The difference between sigloi and alexanders suggests that sigloi were struck from local Ionian sources. The present isotopic data complement the trace element data of Olivier et al. (2017) on alexanders. The comparison of alexander Au/Ag and Pb/Ag data with those of archaic Greek coinage (Davis et al. 2020) (Fig. 7) shows that alexanders are consistent with a mixture of gold-rich Thraco-Macedonian and gold-depleted, lead-rich Attic sources. Given that in most cases Greek silver coins retained a tight Pb isotope source signature, any mixing must have happened at a late stage. Whether mixing should be assigned to bullion melting at the time of tribute collection, as reported by Herodotus, or to reprocessing of the Persian treasury by Macedonians for minting is still open to question. There is no necessity for Greek bullion to have journeyed directly from Greece to Persia as formal tribute; intermediaries of all sorts over arbitrary time intervals could have achieved the same result. Trade, war indemnities, and deposits in temples such as Delphi or Ephesus efficiently redistributed silver all around the eastern Mediterranean. In this respect, the case of Egypt, which according to Herodotus (II.91) had to pay its tribute partly in silver (700 talents), while no silver mine is known in this area, is illuminating. Even if Egypt, a country which benefitted from strong exports based on barley and wheat, could not fully meet the Persian demand in silver, it is probable that at least part of the tribute must have been paid in metal, both minted and unminted.

Although some west–east circulation of Greek and sigloi silver coins in the Achaemenid Empire is attested to in particular by the hoards of Kabul (Schlumberger 1953), Babylon (Reade 1986), and Malayer, next to Ecbatana (Kraay and Moorey 1968), hoarding of Persian sigloi in Persepolis and other major urban centers at the heart of the empire was uncommon and an essentially “silverized” but coin-less character of the Persian economy is usually favored (Jursa 2010; Meadows 2005) with possible exceptions during the reign of Artaxerxes III (Alram 2012). Additionally, Indian bent silver bars differ markedly in Pb isotopic composition...
from the *sigloi* and the *alexanders*. Again, this is no surprise since neither literary sources nor monetary circulation attested to by deposits indicate any flow of silver from the far east to the center of the empire. As explained below, it should be noted that no records exist for Achaemenid era silver mines in either modern Iran, Afghanistan, Pakistan, Turkmenistan, or India, or, if such records did exist, they have been lost. Although silver extraction from Pb ores is mentioned for the Sassanid Period (224 AD–670 AD; Ghorbani 2013), the comparative chemistry of Parthian and Sassanid coinage is elusive about Persian sources (Sodaei et al. 2013). In modern Iran, silver is mostly mentioned in connection with gold and lead deposits (GhORBANI 2013), rarely in the form of silver ore. Porphyry copper deposits are abundant in Iran (Zürcher et al. 2019), but because molten Ag is sparingly soluble in Cu with which it forms a eutectic at 28.1 wt.% Cu (Subramanian and Perepezko 1993), the costly extraction of minor silver from copper ores simply may not have been profitable. The US Geological Survey reports on Afghanistan ore deposits but does not flag any significant silver-rich ores (Peters et al. 2011). The geologically old and otherwise basaltic India is an unlikely source of silver and lead, but the recent discovery of the major Huoshao-yun Zn-Pb deposit in the Karakorum Range (Li et al. 2019) suggests that sources of silver and lead, now exhausted and unrecorded in the extant literature, may have existed to support the manufacturing of early Indian coinage. Significant Asian sources of silver contributing to the Achaemenid treasure therefore remain highly speculative.

Most silver used to strike both the silver *alexanders* and the Persian *sigloi* presumably came from peri-Aegean metal sources. It is therefore appealing to consider that the Persian mix reflects the tribute exacted from the Greeks or, indirectly, from other satrapies which traded with the Greeks. Nevertheless, the Persian mix is occasionally found in hoards of *hacksilber* buried in the Early Iron Age (eleventh–tenth centuries BCE) in modern Israel (Eshel et al. 2019; Gentelli et al. 2021). In addition, pollution of Alpine glaciers by Pb and Sb during the Iron Age, both strong markers of silver metallurgy, is barely measurable compared to values during the Roman era (Preunkert et al. 2019), which reflects that silver mining prior to the Persian expansion of the sixth century BCE may have been insignificant. What is currently defined as the Persian mix could also be a long-lived eastern Mediterranean mix dominated by circum-Aegean sources, where most silver had already been melted again and again all the way back to the Bronze Age.

We finally briefly speculate on why Persian kings hoarded bullion to an extent never seen at any other time in antiquity. Unproductive bullion accumulation was certainly a common habit of many societies, but the massive melting and underground storage of silver described by Herodotus reached an unparalleled practice which deserves scrutiny. Beyond the Persian treasuries, it is difficult to estimate the volume of silver used for transactions within the Achaemenid Empire, but it should not be minimized and transactions could have been taking place as early as the sixth century BCE (Jursa 2011; Pirngruber 2017). As attested to by the presence of chopped Greek coins in the Babylonian Rassam hoard from the end of the fourth century BCE (Reade 1986), silver coinage clearly was not the prevalent form of currency in the central part of the empire (Afram 2012; Le Rider 2001). The silver shekel, next to barley and other in-kind commodities, nevertheless certainly was present both physically and as a unit of account (Jursa 2011; Powell 1996; van der Spek et al. 2018). The noticeable price deflation observed in Babylonia during the fifth and fourth centuries BCE was assigned to intensified captation of silver through taxes (Stolper 1985), but demography and improvement of cash-crop agriculture may also have been important alternative factors (Monerie 2013). Using concepts from modern mainstream economics, which were almost certainly not part of the Persian culture, massive hoarding resulted in a much longer bullion residence time in royal treasuries and was effective at slowing down large-scale bullion circulation. The clamping down on silver supply, in both its minted and unminted forms, combined with the massive silver tributes imposed on subjugated societies, which were otherwise allowed to keep their political system, drained regional silver resources on a massive scale into the royal treasury. If tribute was an efficient way of drawing off silver accumulated by potential adversaries such as Egypt and Ionian Greece, long-distance trade was the long arm of this scheme, certainly cheaper and less risky than launching distant military campaigns. Considering that the much-coveted Greek hoplites were usually paid in silver and gold coins, a major side effect of this policy must have been that it helped render the recruiting of large mercenary forces a royal privilege (Bresson 2020), thereby reducing the threats, both domestic and from abroad, to the throne. But eventually, the systematic storage of very large amounts of silver in the royal vaults, whether intentional or not, contributed to the collapse of the Persian Empire and ushered in its replacement by the Hellenistic kingdoms of Antigond Macedon and Ptolemaic Egypt, and by the Seleucid Empire in the East.

**Conclusions**

The Achaemenids’ ruling of old Persia achieved the largest accumulation of precious metals reported in ancient history, equivalent to about 5000 metric tons of silver. While research has shown how Alexander the Great and his successors processed these gigantic quantities by striking coins, the origins of the silver have so far remained largely unknown. Lead isotope abundances determined in
this work on both Persian and Alexander silver coinages trace the bullion sources to the southern Aegean, Macedonia, and Thrace, while lead from pseudo-coinage from early Indian kingdoms is markedly different from the rest, hence excluding India as a source. Fully understanding how and when such huge amounts of Aegean silver were extracted and eventually arrived in the Persian treasuries is emerging as a new challenge for future studies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12520-022-01537-y.

Acknowledgements Albarede F, Desaulty AM, Blichert-Toft J (2012) A geological perspective on the use of Pb isotopes in archaeometry. Archaeometry 54(5):853–867

Albarède F, Blichert-Toft J, de Callataÿ Fd, (2016) Putting Southern Aegean coinages in perspective. In: Kerstin Höghammar Symposium, vol., Uppsala

Author contribution JBT and FA designed the research and wrote the paper with input from FdC; FA selected the coins for purchase; JBT produced the Pb isotope data with assistance from technical staff; PT ensured instruments were working.

Data availability The data in Table S1 are available in the Supplementary Information.

Conflict of interest The authors declare no competing interests.

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References

Albarède F, Juteau M (1984) Unscrambling the lead model ages. Geochim Cosmochim Acta 48(1):207–212

Albarède F, Desaulty AM, Blichert-Toft J (2012) A geological perspective on the use of Pb isotopes in archaeometry. Archaeometry 54(5):853–867

Albarède F, Blichert-Toft J, de Callataÿ F, Davis G, Debernardi P, Gentelli L, Gitler H, Kemmers F, Klein S, Malod-Dognin C (2021) From commodity to money: the rise of silver coinage around the Ancient Mediterranean (sixth–first centuries BCE). Archaeometry 63(1):142–155

Alram M (1993) Dareioskos und Siglos: Ein neuer Schatzfund achaimenidischer Sigloi aus Kleinasien. Res Orientales 5:23–53

Alram M. (2012) The coinage of the Persian Empire. In: Metcalf W.E. (ed) The Oxford handbook of Greek and Roman coinage, vol. Oxford University Press, Oxford, pp 61–87

Armayor O.K. (1978) Herodotus’ catalogues of the Persian Empire in the light of the monuments and the Greek literary tradition. Transactions of the American Philological Association (1974-) 108:1–9

Blichert-Toft J, Delile H, Lee CT, Stos-Gale Z, Biliström K, Andersen T, Hamou H, Albarède F (2016) Large-scale tectonic cycles in Europe revealed by distinct Pb isotope provinces. Geochem Geophys Geosyst 17(10):3854–3864

Bresson A (2015) The making of the ancient Greek economy: institutions, markets, and growth in the city-states. Princeton University Press

Bresson A (2020) Silverization, prices, and tribute in the Achaemenid Empire. In: Tuplin CJ, Ma J (eds) Aršâma and his world the Bodleian letters in context, vol III, vol. Oxford Univ. Press, Oxford, pp 209–248

Callataÿ F.d. (1989) Les trésors achéménides et les monnayages d’Alexandre: espèces immobilisées et espèces circulantes? Revue Des Études Anciennes 91(1):259–274

Callataÿ F.d. (1993) Le monde grec hellénistique. In: Callataÿ F.d., Depeyer G., Villaronga L. (eds) L’argent monnayé d’Alexandre le Grand à Auguste Brussels, vol. Cercle d’études numismatiques, Bruxelles, pp 13–46

Callataÿ F.d. (2016) Putting Southern Aegean coinages in perspective. In: Kerstin Höghammar Symposium, vol., Uppsala

Davis G Gore DB Sheedy KA Albarède F. (2020) Separating silver sources of Archaic Athenian coinage by comprehensive compositional analyses. Journal of Archaeological Science 114:105068

Delile H, Mazzini I, Blichert-Toft J, Goiran J-P, Arnaud-Godet F, Salomon F, Albarède F (2014) Geochemical investigation of a sediment core from the Trojan basin at Portus, the harbor of ancient Rome. Quatern Sci Rev 87:34–45

Delile H, Pleuger E, Blichert-Toft J, Goiran J-P, Fagel N, Gadhoun A, Abichou A, Jerbania IB, Fentress E, Wilson AI (2019) Economic resilience of Carthage during the Punic Wars: insights from sediments of the Medjerda delta around Utica (Tunisia). Proc Natl Acad Sci 116(20):9764–9769

Eckrich CA, Albike SE, Flaherty EA, Bowyer RT, Ben-David M (2020) rKIN: Kernel-based method for estimating isotopic niche size and overlap. J Anim Ecol 89(3):757–771

Eshel T, Erel Y, Yahalom-Mack N, Tirosh O, Gilboa A (2019) Lead from pseudo-coinage in the west Mediterranean. Proc Natl Acad Sci 116(13):6007–6012

Gentelli L, Blichert-Toft J, Davis G, Gitler G, Gitler H, Albarède F (2021) Metal provenance of Late Bronze to Iron Age Hacksilver hoards in the southern Levant. Journal of Archaeological Sciences 134:105472. https://doi.org/10.1016/j.jas.2021.105472

Ghorbani M (2013) Economic geography of Iran. Springer

Hurford FL (2016) The treasures of Alexander the Great: how one man’s wealth shaped the world. Oxford University Press

Jursa M. (2010) Aspects of the economic history of Babylonia in the first millennium BC. Economic geography, economic mentalities, agriculture, the use of money and the problem of economic growth:119

Jursa M. (2011) Taxation and service obligations in Babylonia from Nebuchadnezzar to Darius and the evidence for Darius’ tax reform. In: Rollinger R., Truschnegg B., Bichler R. (eds) Taxation and service obligations in Babylonia from Nebuchadnezzar to Darius and the evidence for Darius’ tax reform, vol. Wiesbaden, Harrassowitz Verlag, pp 431–448

Körlyn G. (2006) Römischer Bergbau auf dem Lüderich bei Rösrath, Rheinisch-Bergischer Kreis. Kölnhre, Reininghaus W, Stöllner
Th (eds) Bergbau im Sauerland Westfälischer Bergbau in der Römerzeit und im frühen Mittelalter Schriften der Historischen Kommission für Westfalen 20:21–31
Kraay C.M., Emeleus V.M. (1962) The composition of Greek silver coins: analysis by neutron activation.
Kraay CM, Moorey PRS (1968) Two fifth century hoards from the Near East. Revue Numismatique 6(10):181–235
Le Rider G. (2001) La naissance de la monnaie: pratiques monétaires de l’Orient ancien. Presses Universitaires de France-PUF.
Li H, Xu X-W, Borg G, Gilg HA, Dong L-H, Fan T-B, Zhou G, Liu R-L, Hong T, Ke Q (2019) Geology and geochemistry of the giant Huoshaoqun zinc-lead deposit, Karakorum Range, northwestern Tibet. Ore Geol Rev 106:251–272
Longman J, Veres D, Ersek V, Phillips DL, Chauvel C, Tamás CG (2018) Quantitative assessment of Pb sources in isotopic mixtures using a Bayesian mixing model. Sci Rep 8(1):6154. https://doi.org/10.1038/s41598-018-24474-0
Meadows AR (2005) The administration of the Achaemenid Empire. Forgotten Empire: The world of ancient Persia:181–209
Meadows A. (2014) The spread of coins in the Hellenistic world. In: Explaining monetary and financial innovation, vol. Springer, pp 169–195
Milot J Malod-Dognin C Blichert-Toft J Télouk P Albarède F. (2021) R-Pirngruber 2017 The economy of late Achaemenid and Seleucid Babylonia Cambridge University Press
Nicolet C (1984) Pline, Paul et la théorie de la monnaie. Athenaeum
Peters SG King TV Mack TJ Chornack M.P. (2011) Money, currency and crisis: in search of trust, 2000 BC to AD 2000, vol. Routledge, London, pp 102–131
Pirngruber R (2017) The economy of late Achaemenid and Seleucid Babylonia Cambridge University Press
Raistrick A Jennings B (1983) A history of lead mining in the Pennines. George Kelsall, Littleborough
Read J (1986) A hoard of silver currency from Achaemenid Babylon. Iran 24(1):79–87
Reddy D.R. (2014) The emergence and spread of coins in Ancient India. In: Explaining monetary and financial innovation, vol. Springer, pp 53–77
Robinson JR (2021) Investigating isotopic niche space: using rKIN for stable isotope studies in archaeology. J Archaeol Method Theory. https://doi.org/10.1007/s10816-021-09541-7
Schlumberger D. (1953) L’argent grec dans l’Empire achéménide. In: Curiel R., Schlumberger D. (eds) Trésors monétaires d’Aghanistan, vol. Klinksieck, Paris, pp 199–222
Sodaei B Hajivaliei M Nadooshan FK. (2013) Possible sources for extraction of silver by comparison of Parthian and Sasanian coins in Mede satraps. Mediterranean Archaeology & Archaeometry 13(1)
Stolper M.W. (1985) Entrepreneurs and empire: the Murašû archive, the Murašû firm, and Persian rule in Babylonia. Nederlands historic-archeologisch institut, Stos-Gale ZA, Gale NH (2009) Metal provenancing using isotopes and the Oxford archaeological lead isotope database (OXALID). Archaeo Anthropol Sci 1(3):195–213
Subramanian P, Perepezko J (1993) The Ag-Cu (silver-copper) system. Journal of Phase Equilibria 14(1):62–75
Tuplin C. (2014) The changing pattern of Achaemenid Persian royal coinage. In: Explaining monetary and financial innovation, vol. Springer, pp 127–168
Van der Spek R van Leeuwen B. (2014) Quantifying the integration of the Babylonian economy in the Mediterranean world using a new corpus of price data, 400–50 BC. Long-term quantification in ancient history:79–102
van der Spek R Dercksen J Kleber K Jursa M (2018) Money, silver and trust in Mesopotamia. In: van der Spek R., van Leeuwen B. (eds) Money, currency and crisis: in search of trust, 2000 BC to AD 2000, vol. Routledge, London, pp 102–131
Westner KJ Birch T. Kemmers F Klein S. Höfer HE. Seitz H.-M. (2020) Rome’s rise to power. Geochemical analysis of silver coinage from the Western Mediterranean (4th to 2nd centuries BCE). Archaeometry 62(3):577–592 https://doi.org/10.1111/arch.12547
Züchner L, Bookstrom A.A., Hammarstrom JM, Mars JC, Ludington S, Zieniek ML., Dunlap P, Wallis J (2019) Tectono-magmatic evolution of porphyry belts in the central Tethys region of Turkey, the Caucasus, Iran, western Pakistan, and southern Afghanistan. Ore Geology Reviews 111:102849

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