

This pdf of your paper in *Economic Circularity in the Roman and Medieval Worlds* belongs to the publishers Oxbow Books and it is their copyright.

As author you are licenced to make up to 50 offprints from it, but beyond that you may not publish it on the World Wide Web until three years from publication (November, 2026), unless the site is a limited access intranet (password protected). If you have queries about this please contact the editorial department at Oxbow Books (oxbow@oxbowbooks.com).

AN OFFPRINT FROM

Economic Circularity in the Roman and Early Medieval Worlds

New Perspectives on Invisible Agents and Dynamics

*Proceedings of the conference held at the Centre for Urban Network
Evolutions/Moesgaard Museum, Aarhus (7–8 September 2022)*

Edited by

Irene Bavuso, Guido Furlan,
Emanuele E. Intagliata and Julia Steding

*Hardback edition: ISBN 978-1-78925-996-4
Digital Edition: ISBN 978-1-78925-997-1 (epub)*

 **OXBOW** | books
Oxford & Philadelphia

Chapter 6

Identifying episodes of recycling in the archaeological record

Jonathan R. Wood

Incomplete data

According to a recent meme, there are two types of people in this world: 1) Those who can extrapolate from incomplete data.

This is obviously flippant. Nonetheless, archaeology has no choice but to deal with incomplete data, and it could be argued that it became an academic discipline because of it. Archaeological science attempts to increase the amount of archaeological data. Analysing the chemical compositions of artefacts, for example, can provide information about objects that were invisible to the people who made them.

More data, however, can lead to competition between data types. For example, A. Bernard Knapp (2012, 14–25) provides an illustrative example of a copper axe/adze (KM 457) and a piece of copper ore (KM 633) found at Kissonerga-Mosphilia (Late Chalcolithic/Pre-Bronze Age 1), a site which provided crucial data for the earliest stages of indigenous metalworking and casting activities in Cyprus. Lead isotopic analyses (LIA) conducted on the ore were consistent with Cypriot sources, but the copper axe was not (Gale 1991; Fig. 6.1). The axe's LIA signature does not overlap with Cypriot ores. It falls within hand-drawn and constructed ellipses but not within the kernel density estimates (KDE) that aim to represent Cyprus' LIA ore field; in fact, it lies closer to the ores of the Troad in northwest Anatolia (Pernicka *et al.* 1984, 557–558; Wagner *et al.* 1985; Wagner *et al.* 1986; Gale 1991). Three years after the initial study, Zofia Stos-Gale and Noel Gale (1994) published a LIA data point for ore from Akoursos in the west of Cyprus (an area with known deposits of copper and malachite), just inland from Kissonerga, which plots midway between KM 457 and the Cypriot ore field. This new information was used to support that copper ores in Cyprus could have been exploited outside the Troodos belt and that the Kissonerga axe (KM 457)

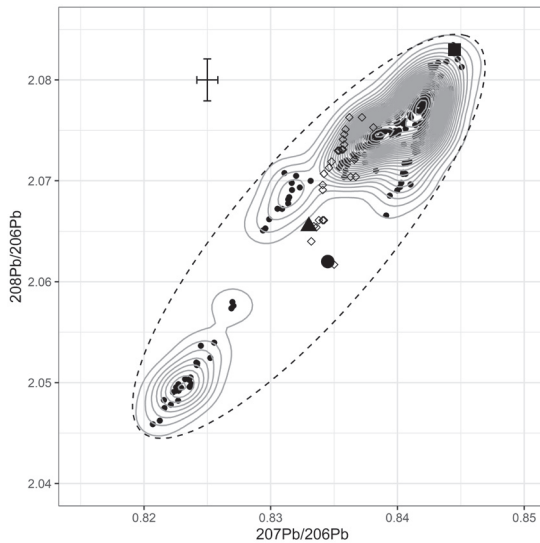


Fig. 6.1 LIA plot showing a copper axe/adze (KM 457) (large filled circle) and a piece of copper ore (KM 633) (large filled square) found at the Kissonerga-Mosphilia (Late Chalcolithic/Pre-Bronze Age 1), Cypriot ores (small filled circles) (OXALID 2022), ore from Akoursos (large filled triangle) (Stos-Gale and Gale 1994, 107) and ores from north western Anatolia (open diamonds) (Wagner et al. 1985). The contours represent the kernel density estimate for the Cypriot ores. The ellipse drawn around the Cypriot ore dataset includes all LIA ore data, but it also includes areas without ores, thereby losing its discriminatory power. Note that ^{204}Pb values were not available for the Akoursos ore, the copper axe/adze (KM 457) or the copper ore (KM 633).

was made from local ores, thereby negating the need for a foreign ore source requiring foreign contacts.

Axe/Adze KM 457, however, is considered typologically distinct within Cypriot metalwork: it has a significantly broader butt than the few known early axes from Cyprus, which suggests that it may not be Cypriot (Dikaios in Gjerstad 1972, fig. 84; Stewart in Gjerstad 1972, 249). In fact, in terms of size, it falls comfortably within the range of those found in the Aegean (Croft *et al.* 1998), thereby supporting a north Anatolian origin.

This example highlights that different types of data can be in conflict. It also shows that the same type of data, in this case LIA measurements, can be interpreted differently, particularly for provenance investigations. Furthermore, ruling one location out does not mean necessarily that the other should be ruled in, particularly when there are differences in the amounts of LIA sampling that make the number of viable alternatives difficult to determine without archaeological

evidence. Disagreements over the provenance of KM 457 have yet to be resolved.

Hierarchy among data can also manifest itself in the methods of measurement and the analytical procedures applied to interpret the data they generate. For instance, Noel Gale *et al.* (2003) dealt with discrepancies in LIA measurements of Bulgarian ores, between those measured by the Oxford group and those by another laboratory (Amov *et al.* 1979), by only including data which clustered with their own. This was classified as 'safe practice' (Gale *et al.* 2003, 155). However, neither Amov's laboratory nor the Oxford group found the extreme spread of data that was found in a third dataset by the Mainz group (Pernicka *et al.* 1993): that for Rudna Glava, attributed to a wide range in the U/Pb ratio of these ores. As the Oxford and Mainz groups took samples from different parts of the same shaft in the mine, the differences in values suggested that there were large differences in LIA measurements *within one mine*.

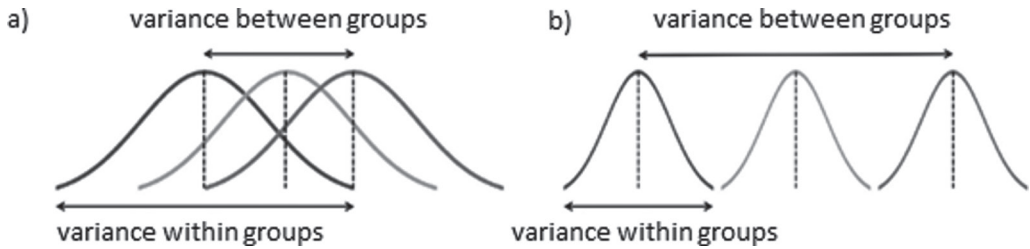


Fig. 6.2 Distributions of a continuous trait: a) the variance within groups is greater than the variance between groups; b) the variance between groups is greater than the variance within groups.

The issue here is not that different research groups using different instruments can produce conflicting results (unfortunately, this is common), but that these differences can threaten the provenance postulate (that is, variation within a source should not be greater than the variation between sources; Fig. 6.2) and, therefore, the application of LIA to trace objects to their geological sources. As there was less variation in the Oxford group's measurements than the Mainz group's, it was considered that the Oxford group's samples might have been contaminated with exogenous lead prior to arriving at the laboratory (Gale *et al.* 2003, 156).

Nonetheless, the differences in the results obtained for the Bulgarian ores highlight that placing too much emphasis on one type of data can be problematic. This is particularly evident in the research conducted on the ritual bronzes of the Chinese Shang dynasty (c. 1500–1046 BC), which identified sources in Africa as a probable region for their provenance, by matching highly radiogenic LIA signatures (Sun *et al.* 2016; Sun *et al.* 2018). This radical proposition has been strongly refuted by other researchers (Liu *et al.* 2018a; 2018b) applying archaeological and geological data (and by recognising that the distance travelled was probably prohibitive for this Bronze Age society). Furthermore, a recent multivariate approach (Wood and Liu 2022) that analysed both lead isotopes and elemental data from these ritual bronzes has shown that interpretations emerging from LIA and elemental data are in conflict: whereas lead isotope analyses can suggest various origins around and beyond China, elemental analyses suggest that the same ore deposits were exploited throughout the Chinese Bronze Age – potentially ore deposits that lie within the heartland of the Shang and Zhou dynasties. In effect, if there is systematic zoning of radiogenic and common lead within a deposit (Cannon *et al.* 1963), any change in isotopic signature could simply mark the expansion of mining in the same deposit rather than signalling changes in geographical location (Wood and Liu 2022); that is, lead isotopes can lose their discriminatory power to provenance from ore to object.

Recycling

Matching chemical signatures can be further complicated by recycling. Until recently, recycling was regarded as being not particularly significant in prehistory. For example,

the practice of burying silver objects with their owners, thereby removing silver from circulation, was believed to have sustained a demand for new silver during the Aegean Bronze Age (Gale and Stos-Gale 1981). Furthermore, isotopic matches between oxide ingots recovered around the Mediterranean and copper ore sources in Cyprus were considered sufficient to negate the possibility that similar signatures could emerge by mixing metals from different sources (Gale 2001). Recycling was also the first hypothesis to be rejected in favour of an assumed chemical compositional profile of an unprovenanced geological source to explain the presence of cobalt-copper glass in Egypt and Mycenae (Smirnou and Rehren 2013). As Mark Pollard *et al.* (2018, 38) highlight, many studies 'have either ignored completely the potential complexities arising from the mixing or recycling of metal from different sources, or have acknowledged that such practices would invalidate the simple hypothesis of provenance, but have then largely dismissed the problem.'

Recycling is difficult to identify when mixing is involved. However, examination of continuous data, such as chemical and isotopic data, can be used to identify mixed signatures associated with episodes of recycling. Nonetheless, despite being common in the archaeological literature, care must be taken with bivariate plots of elements and compounds used to identify mixing lines, as their application can lead to erroneous interpretations (Wood 2022).

To demonstrate this point, the bivariate plot shown in Figure 6.3 plots iron oxide against silica for glazes from Parthian and Sasanian glazed pottery (Wood and Hsu 2020). As these glazes are from many different archaeological sites, they are unlikely to have derived from the same melting pot. Nevertheless, a linear relationship can emerge (Fig. 6.3). Here, the three graphs plot *exactly* the same data (FeOwt% vs SiO₂wt%): the first plot closes the data to 1 (or 100%) for the following variables (SiO₂, Al₂O₃, FeO, MgO, CaO, K₂O and Na₂O); the second plot closes the data around the first four oxides (SiO₂, Al₂O₃, FeO and MgO); and the third plot closes the data around the two plotted variables (SiO₂ and FeO). The plots clearly show that closing a sub-composition does not necessarily produce similar or compatible patterns, even if some of the components are irrelevant to the variables being studied. This occurs because of a geometrical artefact of compositional data: the relationship between variables is not a real relation but one which is compelled, *i.e.* as the proportion of one component increases, the proportions of other components *must* decrease, which in the extreme case of a two-component system would always result in a correlation coefficient of -1. Although this 'spurious correlation' (Chayes 1949) may seem evident to many researchers, it is perhaps worth reiterating that it means that any regression lines drawn to represent the interaction between the two components (in this case SiO₂ and FeO) cannot be trusted, *i.e.* such an induced correlation may conceal true relationships among variables. Furthermore, the plots highlight that absolute compositional percentages are difficult to compare when different numbers of components are analysed. This issue has been approached by applying logratio analysis (Wood and Greenacre 2020).

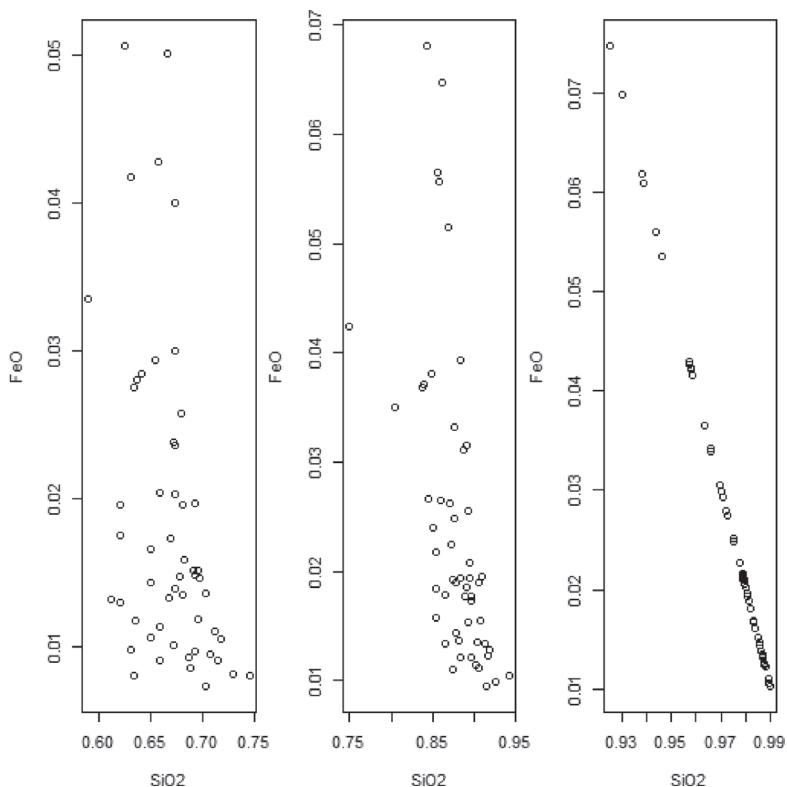


Fig. 6.3 Plots of glaze legacy data normalised to 1 (or 100%): closed around seven oxides (left), four oxides (middle) and two oxides (right). Note the change in scales and the emergence of linearity in the data as the number of elements used to close the data decreases. Refer to Wood and Hsu 2020 for details regarding the legacy data.

In addition to issues surrounding mathematical operations of closure or normalisation, linearity can emerge erroneously from plotting mathematically inconsistent combinations of compositional variables. Figure 6.4 shows data plotted by Ian Freestone (2015) for one of the few large sets of data from the Roman period that include analyses from a single archaeological assemblage of both antimony- and manganese-decolourised glasses, together with green-blue glasses (Silvestri 2008; Silvestri *et al.* 2008). This assemblage is the glass in the cargo of the *lulia Felix*, a ship that sank in the Adriatic in the 2nd or 3rd century AD.

On first inspection, the plot of $\text{MnO}/(\text{Sb}_2\text{O}_3 + \text{MnO})$ vs. Al_2O_3 produces what Freestone (2015) considered to be a mixing line between batches of low-alumina-antimony decolourised glass and high-alumina-manganese decolourised glass (Fig. 6.4). However, there is no reason for the percentages of decolourisers in glass to add up to a unique value, which makes limiting values difficult to interpret: that is, if MnO approaches zero, $\text{MnO}/(\text{Sb}_2\text{O}_3 + \text{MnO})$ approaches zero, regardless of the amount of Sb_2O_3 ; similarly,

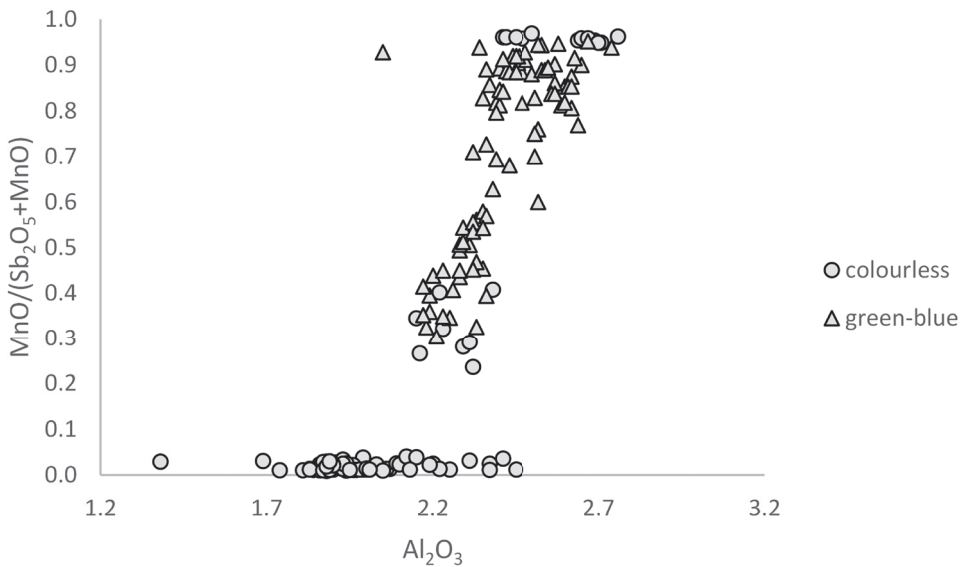


Fig. 6.4 Proportions of manganese and antimony in the glass of the Iulia Felix versus the alumina content. The data was considered to show a mixing line between the low-alumina antimony-decolorised glass and the high-alumina manganese-decolorised glass (Freestone 2015). Data from Silvestri 2008 and Silvestri et al. 2008.

when Sb_2O_3 approaches zero, $\text{MnO}/(\text{Sb}_2\text{O}_3+\text{MnO})$ will always approach 1, regardless of the amount of MnO. Furthermore, when the denominator is zero, the limiting value is undefined. In effect, although mixing may have occurred, forced linearity can affect archaeological interpretations as it could imply, perhaps incorrectly, the mixing of two components (or batches) rather than simply non-structured variation.

To address issues such as these, compositional data can be combined with lead isotope analytical data as both can reflect episodes of recycling but are *not* interdependent. For example, silver is often geologically associated with low concentrations of gold which, due to its chemical inertness, can survive silver smelting and refining operations. Moreover, silver is often geologically linked with lead, and lead is often used in silver extraction and cupellation. The isotopic signatures of the lead and the concentrations of gold associated with silver can therefore be used to provenance silver (Wood *et al.* 2019).

This method of combining compositional data and LIA data has been used to investigate silver from Iron Age hoards in the southern Levant (Fig. 6.5) by applying the following strategy (Wood *et al.* 2017; Wood *et al.* 2019): (1) LIA values are used to calculate the Pb crustal age (also known as the model age) of the ore, measured in millions of years (Ma), from which the silver (or, more correctly, the lead associated with the silver) derived; this age is then (2) plotted against the levels of gold found in

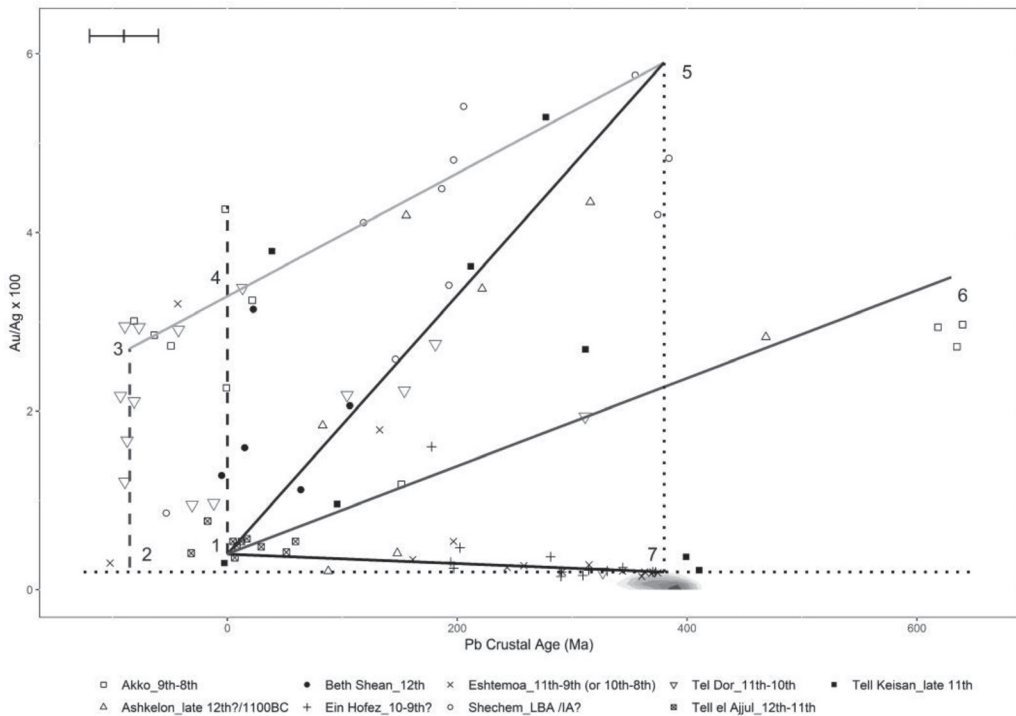


Fig. 6.5 Au/Ag $\times 100$ versus Pb crustal age (Ma) for the Late Bronze Age/Early Iron Age silver hoards of the southern Levant. The density map at around 380 Ma is derived from compositional data (measured by ED-XRF) (OXALID 2022) and lead isotope data for Bronze Age silver found in Iberia (Bartelheim et al. 2012; Murillo-Barroso 2013; Comendador Rey et al. 2014, 285–308; Murillo-Barroso et al. 2015). For further details refer to Wood et al. 2019.

silver, given that gold is a useful geological indicator for a silver source as it is likely to survive silver processing. This approach allows two types of data to be plotted together, providing two parameters which would encourage any variation due to the mixing of components to form mixing lines. In effect, since time (Pb crustal age) and concentration (Au/Ag) are linear variables, linear mixing lines should emerge when two components are mixed. In effect, if it is assumed that endmembers are non-recycled silver (which, in some cases, can be related to archaeologically attested locations that produced silver), the relatively linear lines represent mixtures of these components.

Recycling and silver isotopes

Recently, archaeological science has approached silver coinage through the lens of geological provenance (e.g., Birch et al. 2020; Albarède et al. 2021; Milot et al. 2022; Vaxevanopoulos et al. 2022). However, as with the hacksilver from the southern Levant in Figure 6.5, it needs to be recognised that *any* object which could be thrown back into a melting pot might have been recycled before it entered the archaeological

record. Furthermore, an archaeological artefact made from recyclable material, such as glass or metal, may neither be the original object nor resemble it, with the consequence that a successful ancient recycling economy can become invisible when recycling is synonymous with re-melting rather than reuse (Freestone 2015; Ponting and Levene 2015).

Silver isotopes have been proposed as possible geochemical tracers of silver for silver coinage (*e.g.*, Desaulty *et al.* 2011, Albarède *et al.* 2016; Vaxevanopoulos *et al.* 2022) in part because lead used for refining silver does not necessarily derive from the same location as the source of the silver (that is, LIA signatures are likely to reflect the source of the lead rather than the source of silver). Unfortunately, Ag isotopic variation appears to be controlled by ore genesis rather than geology (Arribas *et al.* 2020), making them of marginal interest for provenance studies (Milot *et al.* 2022). Despite this limitation, some research groups have continued to pursue silver isotopes for provenance investigations (Albarède *et al.* 2021; Eshel *et al.* 2022; Vaxevanopoulos *et al.* 2022). Galena ores from Iberia, for example, have been proposed by Jean Milot *et al.* (2022) as the source of silver for Roman *denarii* of different origins and ages of minting, based on the narrow range of $\epsilon^{109}\text{Ag}$ (that is, the deviation per 10,000 of the ^{109}Ag isotope of a given sample relative to the U.S. National Institute of Standards and Technology [NIST] 978a Ag standard), compared to the wider range of $\epsilon^{109}\text{Ag}$ in silver-bearing base metal (Pb, Zn, and Cu) ores. Concentrations of antimony, bismuth, and arsenic in the silver coins, which have been attributed to pre-existing galena acting as a trap for fluids containing these elements in argentiferous ores (Milot *et al.* 2022), have been considered to further support this provenance.

Despite the application of two types of data (isotopic and elemental), this geological mechanism perhaps becomes moot when archaeological/historical evidence and recycling is taken into consideration. First, although it is well-known that Iberia was a major source of silver for the Phoenicians, Carthaginians and Romans, silver was derived from deposits of silver-bearing jarosite ore (especially around the mining region of Riotinto in southwest Iberia) rather than solely argentiferous lead ores, such as galena (*e.g.*, Rothenberg and Blanco-Freijeiro 1981; Hunt Ortiz 2003; Anguilano *et al.* 2009; Murillo-Barroso *et al.* 2015; Wood and Montero-Ruiz 2019). Roman lead ingots stamped with the Cartagena mark (Salkield 1982, 137–147; Salkield 1987, 15), some 400 km away in southeast Iberia, recovered at Riotinto and production slag (Anguilano 2012) exhibiting a potential influence of a Cartagena LIA signature, support that lead was added to these lead-poor jarosite ores to extract silver.

Second, silver was often debased with copper to make coinage (Butcher and Ponting 2015). This debasement process could have conceivably introduced antimony and arsenic into the silver if the copper derived from fahlore (that is, a solid solution of tetrahedrite $\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$ and tennantite $\text{Cu}_{12}\text{As}_4\text{S}_{13}$; Pernicka *et al.* 2016). Moreover, concentrations of bismuth in silver coinage are perhaps better explained by recognising that the lead used in the cupellation process to refine silver can contain bismuth (L'Heritier *et al.* 2015).

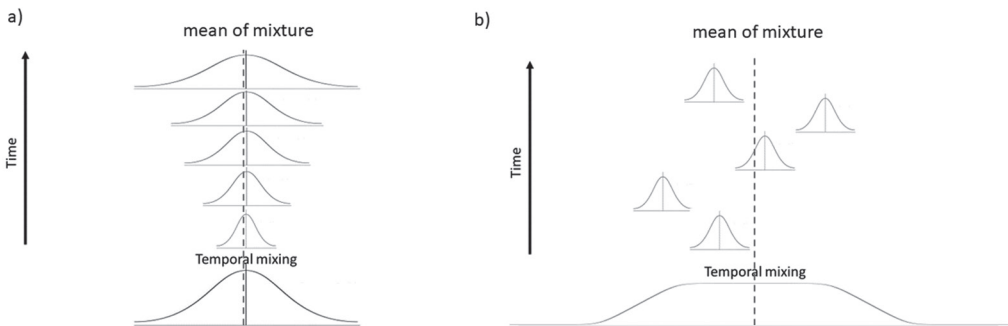


Fig. 6.6 Mixing increases variance: a) a stable mean and fluctuating variance (i.e., the mean of the mixture remains constant); b) a fluctuating mean and stable variance (i.e., the means of the individual groups converge in the mixture). (Adapted from Perreault 2019, fig. 3.12).

Third, and perhaps most significant, silver coinage was most likely recalled, reminted, and reissued (Butcher and Ponting 2015). Mixing of silver and/or silver coinage would have affected elemental and isotopic signatures. Figure 6.6 presents changes associated with mixing for any continuous variable (Perreault 2019) and highlights that the provenance postulate (Figs 6.2a and 6.2b) can be affected by mixing. Figure 6.6a shows that if silver and/or silver coins all derived from one silver source and were smelted and refined using the same raw materials over time, the mean would remain relatively constant after recycling, even if differences in processing (e.g., between batches) caused fluctuations in the variance of the distributions. In fact, a stable mean but changing variance would result in a time-averaged distribution in which the central values are overrepresented. However, if silver coins from different origins were mixed together (perhaps during reminting and/or debasement), the mean values of the coins would likely fluctuate over time and the variance in the time-average assemblage would be much larger than it ever was at any single point in time (Fig. 6.6b): that is to say, even for a constant variance, the distribution of the mixture would be wider, flatter and converging to a uniform distribution. The mean of this mixture would lie between the means of the individual batches.

Essentially, recycling can explain the narrow range of silver isotope values with respect to the standard (that is, $\epsilon^{109}\text{Ag}$) not only for Roman coins (Milot *et al.* 2022) but also for Hellenistic, medieval and modern silver coins and hacksilver (Desaulty *et al.* 2011; Desaulty and Albarede 2013; Albarède *et al.* 2016; Albarède *et al.* 2021; Milot *et al.* 2021; Eshel *et al.* 2022; Milot *et al.* 2022; Vaxevanopoulos *et al.* 2022) which all report $\epsilon^{109}\text{Ag}$ values that have narrower ranges than those reported for hypogene and supergene ores (Mathur *et al.* 2018; Arribas *et al.* 2020). This would cast doubt on the regions in Iberia identified for the provenance of the silver used for Roman coinage (Milot *et al.* 2022), or at least the procedure used to arrive at this provenance.

In summary, refining, debasement, and recycling of silver coinage would potentially negate the need for a geochemical mechanism to explain the concentrations of

antimony, arsenic and bismuth, and the narrow range in the silver isotopic signatures of coins compared to those found in argentiferous ore deposits. To some extent, the issues raised here regarding the interpretation of silver isotopes when recycling is involved are similar to those levelled against lead isotopes over 40 years ago.

Approaches to dealing with recycled objects

Recycling is now being addressed by not focusing exclusively on the provenancing of objects (Pollard *et al.* 2018) and through the development of theoretical frameworks which advocate the inclusion of the mutability of artefacts in the chaîne opératoire (Sainsbury *et al.* 2021). Nonetheless, before any discussion can be held on the motivating factors for and the implications of recycling, it is necessary to identify whether the artefacts, which provide evidence for such discussions, have been recycled or not.

There are two main ways in which archaeology can approach recycling: the first is to identify material that is out of place in an archaeological context which can be deduced to have been recycled; the second is by investigating the recycling event (such as those events suggested by the emergence of mixing lines in Figure 6.5), as episodes of recycling can result in the deliberate or accidental introduction, dilution, and loss of components compared with those in the original object. Both scenarios require that something is known about the original non-recycled material, such as its chemical composition (often referred to as an endmember when discussing recycling in terms of mixing) before it can be suggested that recycling must have occurred.

Out-of-context material

An example of an out-of-context material is that of Roman glass being recycled and reused to glaze Parthian pottery. First, the archaeological context supports that this process could have occurred: Parthian glazed pottery was recovered at the Roman military outpost of Ain Sinu in northern Mesopotamia (modern-day Iraq), which was contested territory for both the Parthian and Sasanian empires and was occupied by the Romans between AD 197 and 364 (Oates and Oates 1959). Second, some of the Parthian glazes recovered at this site exhibit not only different chemical compositional signatures to other Parthian and Sasanian glazes (Fig. 6.7a–c) but also have similar compositions to Roman glass (Table 6.1); that is, since Roman glaze production used lead-based glazes (Hatcher *et al.* 1994; Walton and Tite 2010), this would indicate that Roman natron glass was recycled to glaze Parthian pottery.

The analyses of the glaze data are presented elsewhere (Wood and Hsu 2020; Wood and Greenacre 2021). However, it is perhaps the differences between Roman glass and the glazed pottery that are most relevant to recycling. The K_2O concentration is several times higher in the 'natron' glazes than for Roman glass. This could indicate that another source of potash entered the glaze systems, other than that associated with plant ash used for Mesopotamian glazed pottery, *i.e.*, a source unrelated to the initial

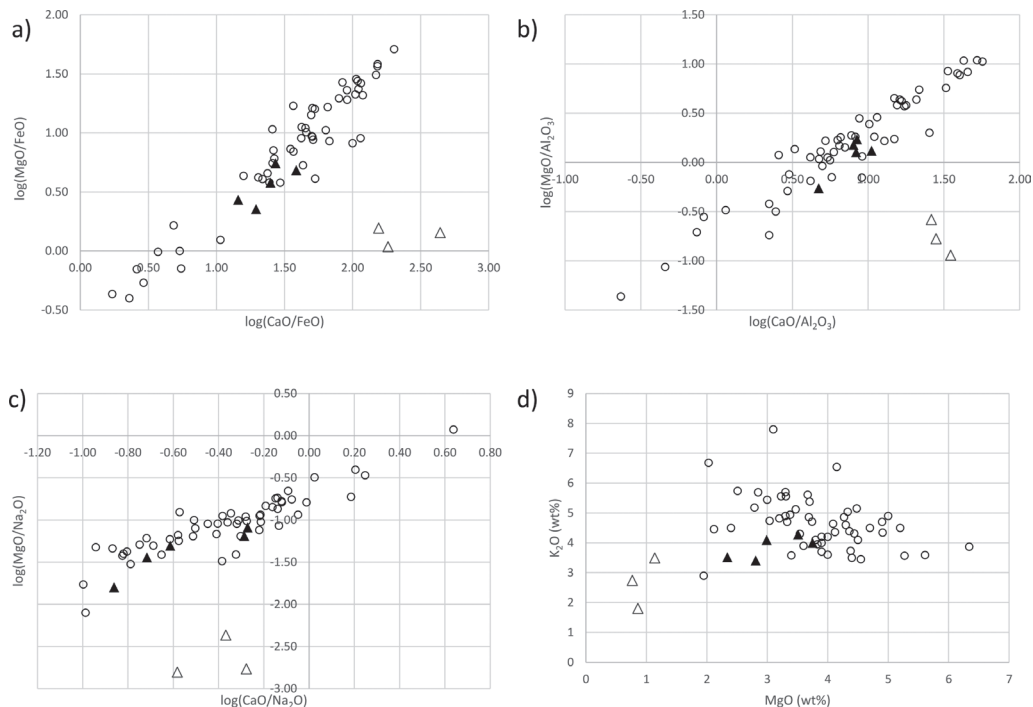


Fig. 6.7 (a-c) Logratio plots of the glaze compositions for the legacy data and the Ain Sinu glazed sherds. (d) is a bivariate plot of K_2O (potash) vs. MgO (magnesia). Open circles are from the legacy data. Triangles show the samples from Ain Sinu (Wood and Hsu 2020). Open triangles are those glazes from Ain Sinu which appear to have been fluxed using natron, i.e., Roman glass.

Table 6.1 Composition of typical Roman glass (Freestone 1991) with Sb_2O_5 values from Jackson and Paynter (2016) and the mean compositions of the three 'natron' samples which fall outside the legacy data bands and the remaining five samples from Ain Sinu (Fig. 6.7). n denotes the number of sherds. BDL denotes levels below the detection limit. Note the similarity between the Ain Sinu 'natron' glazes and the typical composition of Roman glass for these oxides, apart from K_2O .

	Na_2O	MgO	SiO_2	K_2O	CaO	Sb_2O_5
Typical Roman glass (Freestone 1991)	16	0.5	68	0.5	8	0.54
Ain Sinu 'natron' glazes (n=3)	12.88	0.92	68.10	2.68	8.56	0.41
Ain Sinu (n=5)	11.93	3.08	64.84	3.86	6.97	BDL

composition of the glaze. Sarah Paynter (2009) suggests that differences between Mesopotamian glasses and glazes could be a consequence of contamination from fuel ash or vapour, especially hard-wood fuel. Since glazes have a higher surface area-to-volume ratio compared to glass heated in a crucible, ash or vaporised potassium compounds are more likely to affect the composition of a glaze by adhering to the molten surface. This would suggest that levels of K_2O in the glazes investigated (legacy and Ain Sinu glazes) could be a consequence of potassium compounds from the plant

ash flux and the type of fuel used in Parthian and Sasanian kilns. This is supported by the invariance of K_2O with increasing concentrations of MgO on a bivariate plot for the legacy data and the majority of the Ain Sinu glazes (Fig. 6.7d). Essentially, the contamination argument outlined above could suggest that the three 'natron' samples (open triangles in Fig. 6.7) were produced in the same tradition as the other glazes, but that the starting composition of the glass was different to the other glazes from Ain Sinu and to those of the legacy data.

To some extent this scenario feeds into the theoretical approaches on mutability (Sainsbury *et al.* 2021), in that changes in function can be viewed through variation in chemical markers that occur during recycling (in this case, increases in K_2O with the change from glass to glaze) in a similar fashion to how volatile compounds such as arsenic compounds found in copper alloys (McKerrell and Tylecote 1972; Bray and Pollard 2012) and in cobalt-blue glass (Wood and Hsu 2019) can be lost on remelting. In effect, the three samples from Ain Sinu started out with lower concentrations of K_2O (because they are Roman glass, fluxed using natron) but were contaminated with K_2O because they were produced in the same tradition as the other glazes.

The presence of Roman glass reapplied as a glaze on Parthian pottery is a good example of a material which is out of context and provides convincing evidence that glass was being recycled at Ain Sinu. In fact, if Parthian potters had not used Roman glass, it would have been much more difficult to identify that recycling had occurred. As only eight samples from Ain Sinu were offered by the British Museum for testing, it could be argued that the data generated from these few samples should be used to support a larger study. However, it is perhaps here that archaeological science needs to resist attempts to create a series of compositional typologies for materials from various chronologies and regions; that is, instead of searching for artefacts that support the hypothesis that 'all swans are white' (Popper 2002, 82–83) it may be better to look for the 'black swan' and recognise that ancient recycling will disturb any attempts at neat categorisation. In effect, archaeological science might be better utilised to investigate the repercussions of exceptions. For instance, extending recycling from Roman glass to indigenous glass production could provide an additional reason to weathering of glass as to the relatively low numbers of Parthian and Sasanian glass artefacts in the archaeological record (that is, each glass vessel could have been recycled to glaze two or three pots of equivalent size). Furthermore, evidence of recycling indicates that glass and glaze were regarded as the same material in Mesopotamian production and that potters made their own frit specifically to glaze pottery, with recycling potentially reflecting interruptions in supply chains from, as yet undiscovered, glass production sites in Mesopotamia.

Recycling with mixing

Variation in compositional data of artefacts can be interrogated using histograms (*e.g.*, Pollard *et al.* 2019; Wood and Hsu 2019), with the caveat that samples must derive from many different objects. This condition may sound trivial; however, differences

in compositional signatures from, say, sherds of glass or glass beads found in the same context are unlikely to represent variation related to provenance or recycling but to represent variation in processing within a batch. Furthermore, the underlying assumptions behind distributions can affect the identification of recycling, as mixing affects distributions by increasing variance (Perreault 2019). This increase is potentially irrespective of whether mixing was a consequence of an ancient melting pot (Fig. 6.6) or whether archaeologists combine artefacts from several contexts into one mixed assemblage after excavation. If several archaeological contexts deposited at different points in time are analysed together, the variance within each chronological context will collapse into the variance that exists between chronological contexts. In fact, a similar increase in variance would happen if the same process occurred when different locations (perhaps on the same site) were combined, that is, different areas with different means and/or variance from the same chronological setting. Essentially, an archaeologist measuring and recording a continuous trait, such as the diameter, weight, or chemical composition of artefacts etc., may combine different contexts, probably inadvertently, in the analysis. The greater the between-contexts variance, the more inflated the variance would be when assemblages are mixed together (Fig. 6.6b).

A punctuated shift in the mean or a gap in the sequence of mixed contexts, however, would lead to a bimodal distribution. Figures 6.8a and 6.8b show slow change punctuated with a period of rapid change. For compositional data, this means that if it can be assumed that punctuation is not a consequence of missing data (*i.e.*, the absence of part of the sequence), a bimodal distribution for compositional data could suggest a sudden change in recipe.

The following histograms (Fig. 6.9) plot cobalt-blue glass from New Kingdom Egypt (Wood and Hsu 2019), showing a very similar pattern to those in Figure 6.8. The upper plot shows 30 compositional analyses from Abe *et al.* (2012): 26 different 18th-Dynasty objects from museum collections in Japan, provenanced to Malkata and Amarna, and four 18th-Dynasty objects recovered at the site of Dashur. The lower figure plots 20 compositional analyses from different objects from 19th-

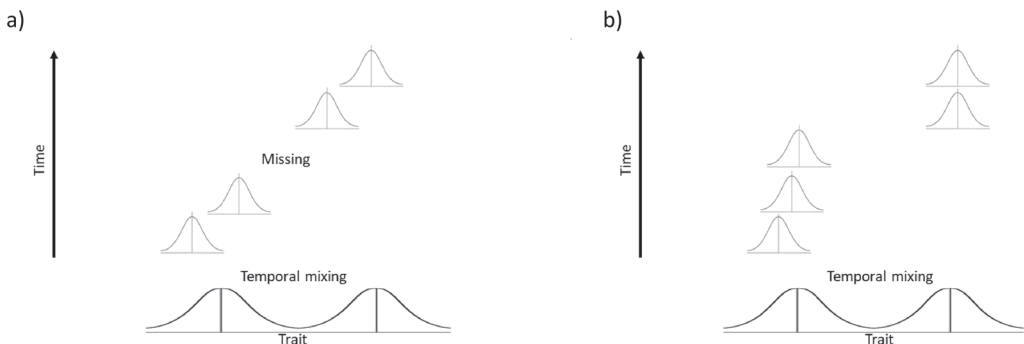


Fig. 6.8 Mixing increases variance in archaeological assemblages: a) Noncontinuous time averaging; b) Slow change with punctuated period of rapid change (adapted from Perreault 2019, fig. 3.12).

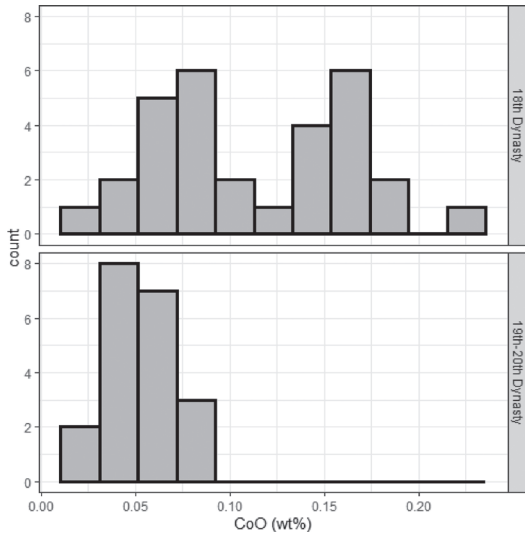


Fig. 6.9 Frequency histograms of the cobalt oxide (CoO %) in cobalt-blue glass from Egypt in the 18th and 19th–20th Dynasties. Data from Abe *et al.* (2012). The upper plot exhibits a bimodal distribution with the higher peak having about twice the concentration of CoO as the lower peak from the 18th-Dynasty objects. The 19th–20th-Dynasty cobalt glass has similar levels of CoO to the lower peak from the 18th-Dynasty cobalt glass.

(*i.e.* glass without cobalt colourant) thereby diluting the amount of cobalt in the mixture to about 0.8wt%CoO. The 19th–20th-Dynasty glass objects were potentially made from this mixture (or perhaps from a 1:1 dilution of remelted glass from both distributions found in 18th-Dynasty contexts with a base glass). This dilution is also reflected in the concentrations of other oxides associated with the colourant, such as NiO and MnO (Wood and Hsu 2019). In effect, this bimodal distribution would be consistent with a recycling process which also included dilution. Although such dilutions were probably derived empirically, it is interesting to note that the cobalt level in the glass from 19th–20th-Dynasty Dashur (average CoO = 533ppm) was around the lower limit to maintain a rich, deep blue (Henderson 2000). This fits well with the narrative that glass was not produced in significant amounts after *c.* 1250 BC (Shortland 2016, 95), with glassmakers reducing the levels of cobalt through dilution with a base glass to the point where the colour was still effective. Recycling is also supported by broad distributions of PbO and Sb₂O₃, which indicate unintentional mixing due to the failure to separate all the white opaque glass (calcium antimonate) as well as yellow glass (lead antimonate) from cobalt-blue glass during recycling (Wood 2022).

20th-Dynasty contexts at Dashur. Although differences in composition between the two periods have been attributed to the exploitation of a new cobalt source in the 19th Dynasty (Abe *et al.* 2012), it is proposed that glass recycling is perhaps a more parsimonious interpretation.

Figure 6.9 (upper) shows that the distribution of cobalt oxide concentration in the 18th-Dynasty glass appears to be bimodal, with the lower peak having about half the CoO level of the higher peak. The 19th–20th-Dynasty glass (Fig. 6.9 – lower) has a distribution which is similar to the lower peak of the 18th-Dynasty cobalt-blue glass. Assuming that the bimodality is not due to missing data (which seems a reasonable assumption for sites which have been thoroughly excavated), this could suggest that the original glass was the higher peak in the upper plot (*i.e.* the peak with a mean around 0.16wt%CoO), which was diluted in a 1:1 ratio with a base glass

Essentially, the compositional data suggests recycling and dilution (and its associated accidental introduction of contaminants) rather than a deliberate reduction in the amounts of cobalt added to new glass in this later period. It would also suggest that certain Egyptian and Mycenaean blue glasses, which have both copper and cobalt as colourants, are *not* deliberate mixtures to produce specific shades of blue or due to compositional variability in the geology of the colourant source (Smirnou and Rehren 2013) but rather the accidental mixing of different types of blue glass during recycling.

This mechanism further indicates that recycling became necessary in New Kingdom Egypt and that the change in composition of cobalt-blue glass was not because a new source of cobalt was exploited in later periods (Abe *et al.* 2012) but because cobalt sources were no longer available to provide the colour cobalt-blue. In effect, if a source was no longer available, but cobalt glass continued to be used, and a new source was not exploited, then recycling must have occurred. This would question conventional wisdom concerning the accepted sources of cobalt for the New Kingdom period, that is the Kharga and Dakhla Oases of Egypt's Western desert (*e.g.*, Kaczmarczyk 1986, 369–376; Shortland 2000; Rehren 2001), and raise the possibility that less local sources were used (*e.g.*, Lucas 1962; Dayton 1981; 1993; Stern and Schlick-Nolte 1994; Lee and Quirke 2000, 111; Wood and Hsu 2019) which would have been more susceptible to interruptions due to changes in the political landscape affecting supply chains.

Other compositional investigations such as those conducted by Varberg *et al.* (2015; 2016) demonstrate that glass of Mesopotamian origin reached Egypt. However, it is perhaps the archaeological evidence in Egypt that tips the balance regarding the provenance of the cobalt-blue colourant used for New Kingdom Egyptian glass. The Hall of the Annals at the Temple at Karnak, in Thebes, has a scene on one wall depicting Thutmose III's spoils from his successful campaigns in the Levant and Syria (Fig. 6.10), including gold, silver and glass (Sherratt and Sherratt 1991), with glass referred to as 'stones of casting' in the Amarna letters. Three baskets are dark-blue, and their contents are depicted in two forms: one basket has five round objects, the other two are baskets of irregularly shaped lumps. The round objects appear human-made and are potentially dark-blue glass ingots (Shortland 2012, 140–145). Although one of the baskets with irregularly shaped lumps could be lapis lazuli, the second is denoted differently, which suggests that it is not lapis lazuli but is also dark-blue glass.

Concluding remarks

The main point made in this article is that recycling needs to be considered before any type of archaeological data is extrapolated to make interpretations about societies, economies, and trade, even though it can make interpretations less definitive. As Perreault (2019, 2) puts it, 'archaeologists often settle on an explanation on the sole basis it can be made consistent with their data, thereby ignoring the fact that there are a number of alternative explanations that are just as consistent with the data.' It

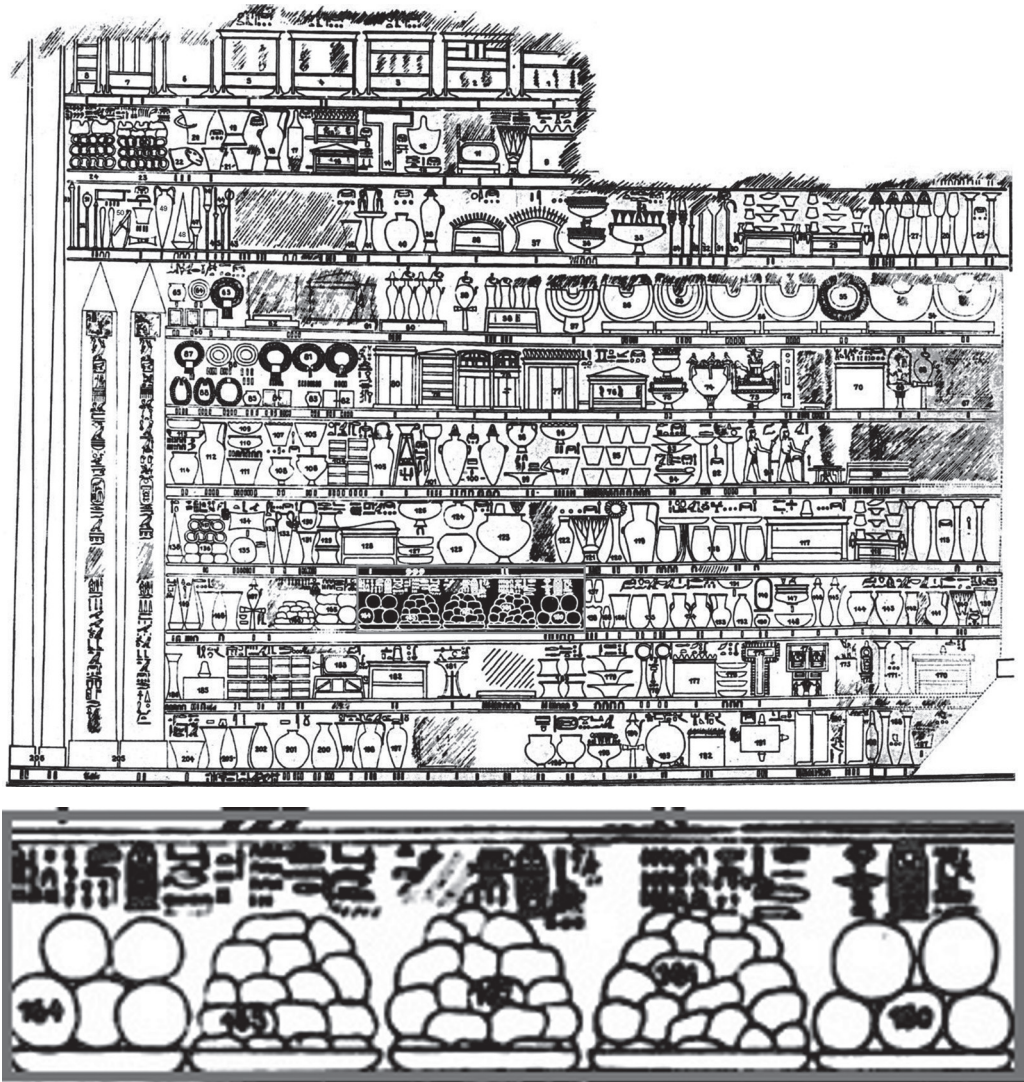


Fig. 6.10 (upper) Depiction of the Hall of the Annals scene at Karnak showing the tribute given by Thutmosis III to the temple. (lower) Close-up showing baskets of glass and precious stone. The scene reads right to left: basket 1 with the five round objects is at the far right with two baskets of irregularly shaped lumps to its left (adapted from a drawing in Wreszinski 1931). See also <https://www.flickr.com/photos/manna4u/20629027214/in/photostream>.

is clear that without considering recycling, the numbers of alternative explanations required for blurred elemental and isotopic signatures increases dramatically. However, this blurring cannot be attributed solely to variation in the signatures of geological sources; that is, although it may be possible to match the analytical signature of an artefact to a geological source (especially when the source exhibits

high variation), this does not mean necessarily that the source was exploited to make that artefact. In effect, analytical signatures of artefacts should only be attributed to specific geological sources when there is archaeological and/or historical evidence to support that these sources were exploited at the time when the objects were made. Furthermore, this article highlights that placing too much emphasis on one type of data can lead to erroneous archaeological interpretations, which may remain in the academic literature long after the limitations of the techniques and analyses that produced the data are well known. Nonetheless, although there is no one-size-fits-all approach to investigate ancient recycling, there are methods that align with the data available that may provide insight well beyond elemental composition that can delimit and inform on raw material availability and supply chains over time, the process of manufacture and how these might relate to external economic and political circumstances. It is therefore imperative that recycled material can be identified with some certainty in the archaeological record.

Acknowledgements

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 835180).

Bibliography

- Abe, Y., Harimoto, R., Kikugawa, T., Yazawa, K., Nishisaka, A., Kawai, N., Yoshimura, S. and Nakai, I. (2012) Transition in the use of cobalt-blue colorant in the New Kingdom of Egypt. *Journal of Archaeological Science* 39.6, 1793–1808.
- Albarède, F., Blichert-Toft, J., Rivoal, M. and Telouk, P. (2016) A glimpse into the Roman finances of the Second Punic War through silver isotopes. *Geochemical Perspective Letters* 2, 127–137. <https://doi.org/10.7185/geochemlet.1613>
- Albarède, F., Blichert-Toft, J., de Callataÿ, F., Davis, G., Debernardi, P., Gentili, L., Gitler, H., Kemmers, F., Klein, S., Malod-Dognin, C., Milot, J., Télouk, P., Vaxevanopoulos, M. and Westner, K. (2021) From commodity to money: the rise of silver coinage around the Ancient Mediterranean (sixth–first centuries bce). *Archaeometry* 63.1, 142–155. <https://doi.org/10.1111/arcm.12615>.
- Amov, B., Incheva-Stefanova, I.M. and Baldjieva, T. (1979) New data on the lead isotope composition of galenas from the stratabound polymetallic deposits in the western Stara Planina Mountain, Bulgaria. *Geokhimiya* 4, 535–554.
- Anguilano, L. (2012) *Roman lead and silver smelting at Rio Tinto: the case study of Corta Lago*. Unpublished thesis, University College London.
- Anguilano, L., Rehren, T., Muller, W. and Rothenberg, B. (2009) Roman jarosite exploitation at Rio Tinto (Spain). In A. Giunilia-Mair and A. Hauptmann (eds) *Archaeometry in Europe II 2007*, 21–29. Milano, Associazione Italiana di Metallurgia.
- Arribas, A., Mathur, R., Megaw, P. and Arribas, I. (2020) The isotopic composition of silver in ore minerals. *Geochemistry, Geophysics, Geosystems* 21.8, e2020GC009097. <https://doi.org/10.1029/2020GC009097>
- Bartelheim, M., Contreras Cortes, F., Moreno Onorato, A., Murillo-Barroso, M. and Pernicka, E.

- (2012) The silver production of the South Iberian El Agar culture; A first look at production and distribution. *Trabajos de Prehistoria* 69, 293–309.
- Birch, T., Westner, K.J., Kemmers, F., Klein, S., Höfer, H.E. and Seitz, H.-M. (2020) Retracing Magna Graecia's silver: coupling lead isotopes with a multi-standard trace element procedure. *Archaeometry* 62.5, 81–108.
- Butcher, K. and Ponting, M. (2015) *The Metallurgy of Roman Silver Coinage: From the Reform of Nero to the Reform of Trajan*. Cambridge, Cambridge University Press.
- Bray, P.J. and Pollard, A.M. (2012) A new interpretative approach to the chemistry of copper-alloy objects: source, recycling and technology. *Antiquity* 86, 853–867.
- Cannon, R.S.J., Pierce, A.P. and Delevaux, M.H. (1963) Lead isotope variation with growth zoning in a galena crystal. *Science* 142, 574–576.
- Chayes, F. (1949) On correlation in petrography. *The Journal of Geology* 57, 239–254.
- Comendador Rey, B., Millos, J. and Alvarez-Iglesias, P. (2014) Provenance of the prehistoric silver set of Antas de Ulla North-Western Iberia, using lead stable isotope ratios. In H. Meller, R. Risch and E. Pernicka (eds) *Metals of Power—Early Gold and Silver: 6th Archaeological Conference of Central Germany, October 17–19, 2013 in Halle (Saale)*, 285–308. Halle (Saale), Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt, Landesmuseum für Vorgeschichte.
- Croft, P., Peltenburg, E. and Tite, M. (1998) Other artefacts. In E. Peltenburg, D. Bolger and E. Baxevani (eds) *Excavations at Kissonerga-Mosphilia 1979–1992, Volume II.1A. Lemba Archaeological Project, Studies in Mediterranean Archaeology Vol: LXX:2*, 188–201. Jonsered, Paul Åströms Förlag.
- Dayton, J.E. (1981) Geological evidence for the discovery of cobalt blue glass in Mycenaean times as a by-product of silver smelting in the Schneeberg area of the Bohemian Erzgebirg. *Revue d'Archaeometrie* 1, 57–61.
- Dayton, J.E. (1993) *The Discovery of Glass: Experiments in the Smelting of Rich, Dry Silver Ores, and the Reproduction of Bronze Age-Type Cobalt Blue Glass as a Slag*. Cambridge, Harvard University Press.
- Desaulty, A.-M. and Albarede, F. (2013) Copper, lead, and silver isotopes solve a major economic conundrum of Tudor and early Stuart Europe. *Geology* 41.2, 135–138.
- Desaulty, A.-M., Telouk, P., Albalat, E. and Albarède, F. (2011) Isotopic Ag–Cu–Pb record of silver circulation through 16th–18th century Spain. *Proceedings of the National Academy of Sciences* 108.22, 9002–9007. <https://doi.org/10.1073/pnas.1018210108>
- Eshel, T., Tirosh, O., Yahalom-Mack, N., Gilboa, A. and Erel Y. (2022) Silver isotopes in silver suggest Phoenician innovation in metal production. *Applied Sciences* 12.2, 741. <https://doi.org/10.3390/app12020741>
- Freestone, I.C. (1991) Looking into glass. In S. Bowman (ed.) *Science and the Past*, 37–56. Toronto, University of Toronto Press.
- Freestone, I.C. (2015) The recycling and reuse of Roman glass: analytical approaches. *Journal of Glass Studies* 57, 29–40.
- Gale, N.H. (1991) Metals and metallurgy in the Chalcolithic period. *Bulletin of the American Schools of Oriental Research* 282/283, 37–62.
- Gale, N.H. (2001) Archaeology, science-based archaeology and the Mediterranean Bronze Age metals trade: a contribution to the debate. *European Journal of Archaeology* 4, 113–130.
- Gale, N.H. and Stos-Gale, Z.A. (1981) Lead and silver in the Ancient Aegean. *Scientific American* 244, 176–193.
- Gale, N.H., Stos-Gale, Z., Raduncheva, I., Panayotov, I., Ivanov, I., Lilov, P. and Todorove, T. (2003) Early metallurgy in Bulgaria. In P. Craddock and J. Lang (eds) *Mining and Metal Production through the Ages*, 102–168. London, British Museum Press.
- Gjerstad, E. (1972) *The Swedish Cyprus Expedition IV.1A*. Lund, Swedish Cyprus Expedition.
- Hatcher, H., Kaczmarczyk, A., Scherer, A. and Symonds, R.P. (1994) Chemical classification and provenance of some Roman glazed ceramics. *American Journal of Archaeology* 98, 431–456.
- Henderson, J. (2000) *The Science and Archaeology of Materials: An Investigation of Inorganic Materials*. London/New York, Routledge.

- Hunt Ortiz, M.A. (2003) *Prehistoric Mining and Metallurgy in South West Iberian Peninsula*. Oxford, British Archaeological Reports.
- Jackson, C.M. and Paynter, S. (2016) A great big melting pot: Exploring patterns of glass supply, consumption and recycling in Roman Coppergate, York. *Archaeometry* 58.1, 68–95.
- Kaczmarczyk, A. (1986) The source of cobalt in ancient Egyptian pigments. In J.S. Olin and M.J. Blackman (eds) *Proceedings of the 24th International Symposium on Archaeology*, 369–376. Washington D.C., Smithsonian Institution Press.
- Knapp, B.A. (2012) Metallurgical production and trade on Bronze Age Cyprus: views and variations. In V. Kassianidou and G. Pappasavvas (eds) *Eastern Mediterranean Metallurgy and Metalwork in the Second Millennium*, 14–25. Oxford, Oxbow Books.
- Lee, L. and Quirke, S. (2000) Painting materials. In P.T. Nicholson and I. Shaw (eds) *Ancient Egyptian Materials and Technology*, 108–111. Cambridge, Cambridge University Press.
- L'Heritier, M., Baron, S., Cassayre, L. and Tereygeol, F. (2015) Bismuth behaviour during ancient processes of silver-lead production. *Journal of Archaeological Science* 57, 56–68.
- Liu, S., Chen, K., Rehren, T., Mei, J., Chen, J., Liu, Y. and Killick, D. (2018a) Did China import metals from Africa in the bronze age? *Archaeometry* 60.1, 105–117.
- Liu, S., Chen, K., Rehren, T., Mei, J., Liu, Y. and Killick, D. (2018b) Lead isotope and metal source of Shang bronzes: a response to Sun et al.'s comments. *Archaeometry* 60.5, 1040–1044.
- Lucas, A. (1962) *Ancient Egyptian Materials and Industries*, 4th edition. London, Edward Arnold.
- Mathur, R., Arribas, A., Megaw, P., Wilson, M., Stroup, S., Meyer-Arrivillaga, D. and Arribas, I. (2018) Fractionation of silver isotopes in native silver explained by redox reactions. *Geochimica et Cosmochimica Acta* 224, 313–326.
- McKerrell, H. and Tylecote, R.F. (1972) Working of copper-arsenic alloys in the Early Bronze Age and the effect on the determination of provenance. *Proceedings of the Prehistoric Society* 38, 209–218.
- Milot, J., Malod-Dognin, C., Blichert-Toft, J., Télouk, P. and Albarède, F. (2021) Sampling and combined Pb and Ag isotopic analysis of ancient silver coins and ores. *Chemical Geology* 564, 120028. <https://doi.org/10.1016/j.chemgeo.2020.120028>.
- Milot, J., Blichert-Toft, J., Ayarzagüena Sanz, M., Malod-Dognin, C., Télouk, P. and Albarède, F. (2022) Silver isotope and volatile trace element systematics in galena samples from the Iberian Peninsula and the quest for silver sources of Roman coinage. *Geology* 50.4, 422–426. <https://doi.org/10.1130/G49690.1>
- Murillo-Barroso, M. (2013) *Producción y Consumo de Plata en la Península Ibérica. Un Análisis Comparativo entre la Sociedad Argárica y los Primeros Asentamientos Orientalizantes*. Unpublished thesis, Universidad de Granada.
- Murillo-Barroso, M., Montero-Ruiz, I. and Aranda Jiménez, G. (2015) An insight into the organisation of metal production in the Argaric society. *Journal of Archaeological Science: Reports* 2, 141–155.
- Oates, D. and Oates, J. (1959) Ain Sinu: A Roman frontier post in Northern Iraq. *Iraq* 21, 207–242.
- OXALID (2022) <http://oxalid.arch.ox.ac.uk/default.html>. Last accessed 12/12/2022.
- Paynter, S. (2009) Links between glazes and glass in mid-2nd millennium BC Mesopotamia and Egypt. In A.J. Shortland, I. Freestone and T. Rehren (eds) *From Mine to Microscope: Advances in the Study of Ancient Technology*, 93–108. Oxford, Oxbow Books.
- Pernicka, E., Seeliger, T.C., Wagner, G.A., Begemann, F., Schmitt-Strecker, S., Eibner, C., Öztunali, Ö. and Baranyi, I. (1984) Archäometallurgische Untersuchungen in Nordwestanatolien. *Jahrbuch des Römisch-Germanischen Zentralmuseum Mainz* 31, 533–599.
- Pernicka, E., Begemann, F., Schmitt-Strecker, S. and Wagner, G.A. (1993) Enolithic and Early Bronze Age copper artefacts from the Balkans and their relation to Serbian copper ores. *Præhistorisches Zeitschrift* 68, 1–54.
- Pernicka, E., Lutz, J. and Stöllner, T. (2016) Bronze Age copper produced at Mitterberg, Austria, and its distribution. *Archaeologia Austriaca* 100, 19–55.
- Perreault, C. (2019) *The Quality of the Archaeological Record*. Chicago, University of Chicago Press.

- Pollard, A.M., Bray, P., Cuénod, A., Hommel, P., Hsu, Y.-K., Liu, R., Perucchetti, L., Pouncett, J. and Saunders, M. (2018) *Beyond Provenance: The Interpretation of Chemical and Isotopic Data in Archaeological Bronzes*. Leuven, Leuven University Press. <https://doi.org/10.2307/j.ctv7xbs5r>
- Pollard, A. M., Liu, R., Rawson, J. and Tang, X. (2019) From alloy composition to alloying practice: Chinese bronzes. *Archaeometry* 61.1, 70– 82. <https://doi.org/10.1111/arc.12415>.
- Ponting, M. and Levene, D. (2015) Recycling economies, when efficient, are by their nature invisible: a first century Jewish recycling economy. In M. Geller (ed.) *The Archaeology and Material Culture of the Babylonian Talmud*, 39–65. Leiden, Brill. https://doi.org/10.1163/9789004304895_004
- Popper, K. (2002) *The Logic of Scientific Discovery*. 2nd edition. London, Routledge.
- Rehren, T. (2001) Aspects of the production of cobalt-blue glass in Egypt. *Archaeometry* 43.4, 13–24.
- Rothenberg, B. and Blanco-Freijeiro, A. (1981) *Studies in Ancient Mining and Metallurgy in South-West Spain: Explorations and Excavations in the Province of Huelva*. London, Institute of Archaeo-Metallurgical Studies.
- Sainsbury, V.A., Bray, P., Gosden, C. and Pollard, A.M. (2021) Mutable objects, places and chronologies. *Antiquity* 95, 215–227. <https://doi.org/10.15184/aqy.2020.240>
- Salkield, L.U. (1982) The Roman and Pre-Roman slags at Rio Tinto Spain. In T.A. Wertime and S.F. Wertime (eds) *Early Pyrotechnology: The Evolution of the First Fire-Using Industries*, 137–147. Washington D.C., Smithsonian Institution Press.
- Salkield, L.U. (1987) *A Technical History of the Rio Tinto Mines: Some Notes on Exploitation from pre-Phoenician Times to the 1950s*. London, Institute of Mining and Metallurgy.
- Sherratt, A.G. and Sherratt, S. (1991) From luxuries to commodities: the nature of the Mediterranean Bronze Age trading systems. In N.H. Gale (ed.) *Bronze Age Trade in the Mediterranean: Papers Presented at the Conference Held at Rewley House, Oxford, in December 1989*, 351–386. Jonsered, Paul Åströms Förlag.
- Shortland, A.J. (2000) *Vitreous Materials at Amarna: The Production of Glass and Faience in 18th Dynasty Egypt*. Oxford, British Archaeological Reports.
- Shortland, A. (2012) *Lapis Lazuli from the Kiln: Glass and Glassmaking in the Late Bronze Age*. Leuven, Leuven University Press.
- Shortland, A. (2016) Towards an understanding of the origin of Late Bronze Age glass. In E. Kiriati and C. Knappett (eds) *Human Mobility and Technological Transfer in the Prehistoric Mediterranean*, 94–101. Cambridge, Cambridge University Press.
- Silvestri, A. (2008) The coloured glass of *Iulia Felix*. *Journal of Archaeological Science* 35.6, 1489–1501.
- Silvestri, A., Molin, G. and Salviulo, G. (2008) The colourless glass of *Iulia Felix*. *Journal of Archaeological Science* 35.2, 331–341.
- Smirnou, M. and Rehren, T. (2013) Shades of blue – copper-cobalt coloured blue glass from New Kingdom Egypt and the Mycenaean world: a matter of production or colourant source?. *Journal of Archaeological Science* 40.12, 4731–4743.
- Stern, E.M. and Schlick-Nolte, B. (1994) *Early Glass of the Ancient World 1600BC-AD50*. Ostfildern, Verlag Gerd Hatje.
- Stos-Gale, Z. and Gale, N. (1994) Metals. In A.B. Knapp and J.F. Cherry (eds) *Provenience Studies and Bronze Age Cyprus: Production, Exchange, and Politico-Economic Change*, 92–121. Monographs in World Archaeology 21. Madison, Prehistory Press.
- Sun, W., Zhang, L., Guo J., Li, C., Jiang, Y., Zartman, R.E. and Zhang, Z. (2016) Origin of the mysterious Yin-Shang bronzes in China indicated by lead isotopes. *Nature Scientific Reports* 6.1, 23304. <https://doi.org/10.1038/srep23304>
- Sun, W., Zhang, L-P., Guo, J., Li, C-H. and Zhang, Z-F. (2018) Comment on ‘did China import metals from Africa in the bronze age? *Archaeometry* 60.5, 1036–1039.
- Varberg, J., Gratuze, B. and Kaul, F. (2015) Between Egypt, Mesopotamia and Scandinavia: Late Bronze Age glass beads found in Denmark. *Journal of Archaeological Science* 54, 168–181.

- Varberg, J., Gratuze, B., Kaul, F., Hansen, A.H., Rotea, M. and Wittenberger, M. (2016) Mesopotamian glass from Late Bronze Age Egypt, Romania, Germany and Denmark. *Journal of Archaeological Science* 74, 184–194.
- Vaxevanopoulos, M., Davis, G., Milot, J., Blichert-Toft, J., Malod-Dognin, C. and Albarède, F. (2022) Narrowing provenance for ancient Greek silver coins using Ag isotopes and Sb contents of potential ores. *Journal of Archaeological Science* 145, 105645.
- Wagner, G.A., Pernicka, E., Seeliger, T.C., Öztunali, O., Baranyi, I., Begemann, F. and Schmitt-Strecker, S. (1985) Geologische Untersuchungen zur fruhen Metallurgie in NW-Anatolien. *Bulletin of the Mineral Research and Exploration Institute of Turkey* 101/102, 45–81.
- Wagner, G.A., Pernicka, E., Seeliger, T.C., Lorenz, I.B., Begemann, F., Schmitt-Strecker, S., Eibner, C. and Öztunali, Ö. (1986) Geochemische und isotopische Charakteristika fruher Rohstoffquellen fur Kupfer, Blei, Silber und Gold in der Turkei. *Jahrbuch des Römisch-Germanischen Zentralmuseum Mainz* 33, 723–752.
- Walton, M.S. and Tite, M.S. (2010) Production technology of Roman lead-glazed pottery and its continuance into Late Antiquity. *Archaeometry* 52.5, 733–759.
- Wood, J.R. (2022) Approaches to interrogate the erased histories of recycled archaeological objects. *Archaeometry* 64.S1, 187–205. <https://doi.org/10.1111/arc.12756>
- Wood, J.R. and Greenacre, M. (2021) Making the most of expert knowledge to analyse archaeological data: a case study on Parthian and Sasanian glazed pottery. *Archaeological and Anthropological Sciences* 13, 110. <https://doi.org/10.1007/s12520-021-01341-0>
- Wood, J.R. and Hsu, Y-T. (2019) An archaeometallurgical explanation for the disappearance of Egyptian and Near Eastern cobalt blue glass at the end of the Late Bronze Age. *Internet Archaeology* 52. <https://doi.org/10.11141/ia.52.3>
- Wood, J.R. and Hsu, Y-T. (2020) Recycling Roman glass to glaze Parthian Pottery. *Iraq* 82, 259–270. <https://doi.org/10.1017/irq.2020.9>
- Wood, J.R. and Liu, Y. (2022) A multivariate approach to investigate metallurgical technology: the case of the Chinese ritual bronzes. *Journal of Archaeological Method and Theory*. <https://doi.org/10.1007/s10816-022-09572-8>
- Wood, J.R. and Montero-Ruiz, I. (2019) Semi-refined silver for the silversmiths of the Iron Age Mediterranean: A mechanism for the elusiveness of Iberian silver. *Trabajos de Prehistoria* 76, 272–285. <https://doi.org/10.3989/tp.2019.12237>
- Wood, J.R., Charlton, M.J., Murillo-Barroso, M. and Martínón-Torres, M. (2017) Iridium to provenance ancient silver. *Journal of Archaeological Science* 81, 1–12. <https://doi.org/10.1016/j.jas.2017.03.002>
- Wood, J.R., Montero-Ruiz, I. and Martínón-Torres, M. (2019) From Iberia to the Southern Levant: The movement of silver across the Mediterranean in the Early Iron Age. *Journal of World Prehistory* 32, 1–31. <https://doi.org/10.1007/s10963-018-09128-3>
- Wreszinski, W. (1931) *Das Inhaltsverzeichnis der von Thutmosis III: Erbeuteten Karnak Schätze* (The index of Thutmose III. Karnak looted treasures). Leipzig.

