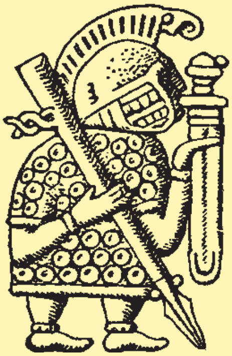

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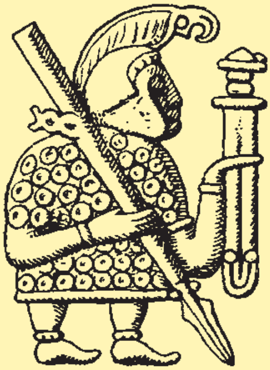

2024/2

Local supply and long-distance imports

New evidence for the origin of brass, copper and lead at Helgö

By Jane Kershaw and Stephen W. Merkel

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Long-running excavations at the 'central place' of Helgö in Lake Mälaren uncovered an unprecedented range of primary metal alloys, mainly in association with a Migration-period workshop. Since primary metals are extremely rare in Migration-period contexts, the source(s) of these metals is a central question with the potential to yield new insights into resource acquisition, international contacts and supply and exchange networks in fifth- to early sixth-century Sweden. Using a combination of lead isotope and trace element analyses, we assess the provenance of 19 artefacts of lead, copper and brass, including ingots, rods and casting waste. While the origin of the copper could not be determined with certainty, the results of the brass and lead were intriguing. Three lead melts stem from Swedish lead ore, and represent the earliest direct archaeological evidence for lead extraction in Sweden. By contrast, the brass was imported over long distances. We propose that it reached Helgö as part of a routinized trade with the Byzantine Empire, potentially the eastern Mediterranean region, with one ingot having probable origins in Asia. The results thus indicate both the local exploitation of available ores and far-reaching contacts, which may have extended as far as the Silk Road.

Keywords: Helgö, brass, lead, copper, lead isotopes, Migration Period

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The early medieval 'central place' of Helgö ('Holy Island') in Lake Mälaren, Sweden, is renowned as a settlement, cult centre and metal workshop, the latter providing unrivalled evidence for high-quality non-ferrous metal casting in the Migration Period (c. 400–550 AD) (fig. 1) (Clarke & Lamm 2017; Grandin et al. 2008). Excavations spanning 1954 to 1977 yielded a vast number of metal finds, particularly prominent among which was raw material and casting waste composed of copper-alloys: sheets, rods, ingots and sprues. Thanks to chemical analysis in the 1970s and again in 2008, it was established that metals from Building Complex 3 – a major metalcasting workshop – principally comprised primary alloys, that is, pure brass (an alloy of copper and zinc) and copper, as opposed to the mixed alloys or gunmetals more common in other parts of the site (Grandin & Hjärthner-Holdar 2008). Such primary alloys

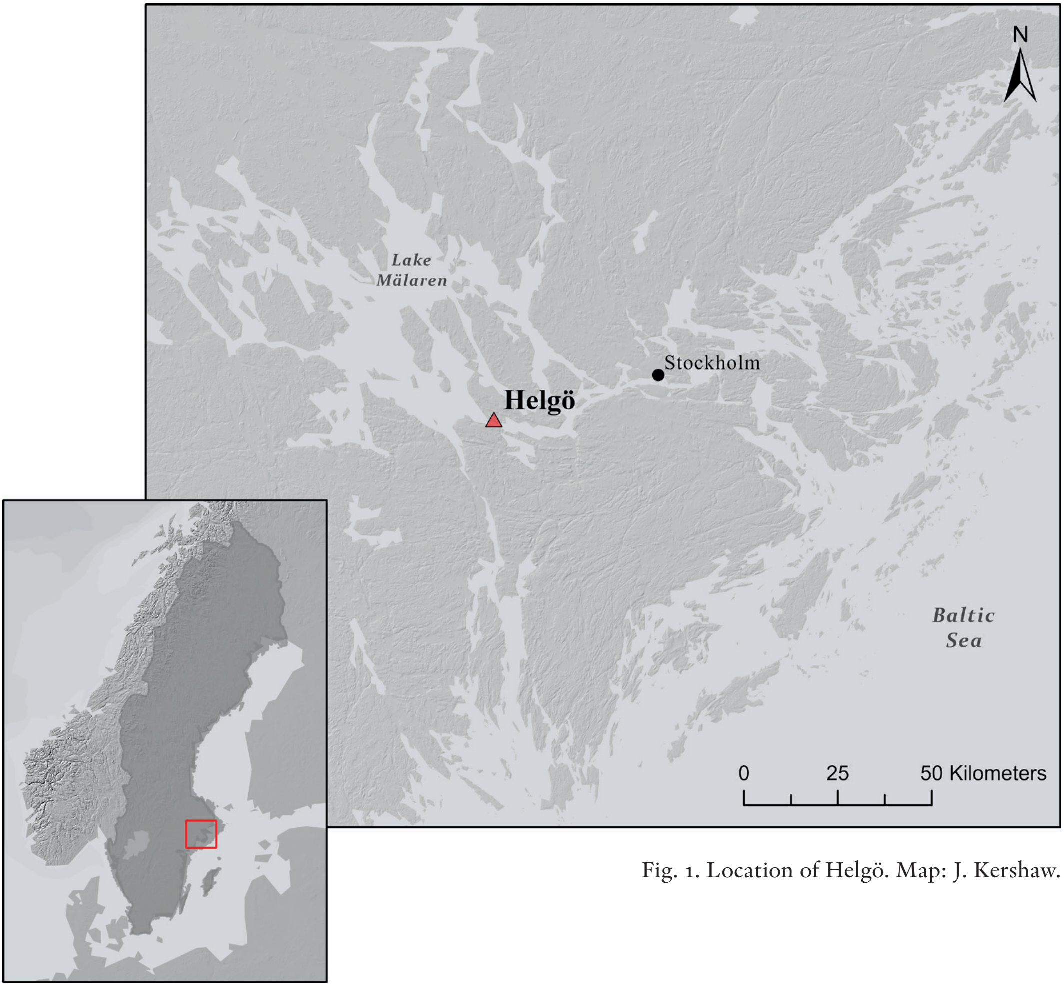

Fig. 1. Location of Helgö. Map: J. Kershaw.

are atypical of Migration-period workshops in Scandinavia (cf. Hjärthner-Holdar, Lamm & Magnus 2002) and must have been imported. From where were they sourced?

Addressing this question has the potential to cast new light on the trade contacts and supply networks provisioning Helgö. Today, the island lies in an inland lake, but in the Migration Period it was situated within a bay of the Baltic, with riverine connections to inland Sweden. As a 'hub in a maritime landscape' (Zachrisson 2020, p. 102) Helgö was thus well situated for receiving both imports from abroad and raw materials from Sweden's interior. Indeed, previous work has demonstrated that Helgö was supplied with sandstone from the local area (J. P. Lamm 2008, p. 123), soapstone hones from western Sweden and Norway (Kresten 2008), iron from the region north of Lake Mälaren (Zachrisson 2020, pp. 101–106; Hjärthner-Holdar 2014) and a large number of flints which likely came from Skåne (J. P. Lamm 2008, p. 116). Far reaching contacts are evident from the garnets and, potentially, glass beads, imported from South Asia (Sode et al. 2017; Gratuze et al. 2021). Unique exotic finds: a sixth-century brass Buddha from Kashmir, late antique bronze ladle possibly from the east Mediterranean or North Africa, and an eighth- or ninth-century Irish crozier-head, offer further, tantalising glimpses of the site's

Fig. 2. Helgö brass artefacts investigated in this study. We sampled areas within the large drill holes created in earlier analyses. Object key, see Table 1. Photo: Thomas Eriksson, National Historical Museums, Stockholm.

Fig. 3. Helgö copper artefacts investigated in this study. Object key, see Table 1. Photo: Thomas Eriksson, National Historical Museums, Stockholm.

long-distance trade contacts, even if uncertainty surrounding their precise chronology and depositional context limits understanding of how and when they reached Helgö (Clarke & Lamm 2004; Hedenstierna-Jonson 2020, p. 55).

Provenancing Helgö's primary metals, mainly in the form of ingots and rods, builds on this earlier work, but brings a new perspective, for the objects represent a deliberate effort to create raw material in a standardized, efficient and transportable form. Rather than representing special objects that may reflect unique series of events, ingots and rods point to a 'routinization' of trade which required a degree of organisation behind it (Sindbaek 2003). They thus offer a window onto regular, embedded long-distance exchange networks during the Migration Period.

To address the question of metal origins, we used lead isotope and trace element analysis to provenance 16 brass and copper objects from Helgö (figs. 2–3). In addition, we analysed three lead melts (casting waste), again with the aim of identifying source ores (fig. 4) (tab. 1). The analysed items are directly related to casting. They comprise, in addition to the melts, ingots and rods, as well as two sprues. They derive predominantly from Building Group 3, but items from Building Groups 1, 2, 4 and 5 are also represented (for an overview of the Building Groups at Helgö, see Clarke & Lamm 2017,

Sample No.	SHM Object ID/ FID	SHM Acquisition Number/ Förvärv	SHM Find no/ Fyndnummer	Photo	House Gr.	Type	Mass (g)	Alloy
1	125317	25514	2225	2g	2	Casting sprue	17,3	Brass
2	132403	27258	7172	2b	1	Bar ingot	14,1	Brass
3	139192	27950	8740	2d	5	Bar ingot frag.	11,1	Brass
5	142621	28480	9432	2e	3	Wire/rod	0,7	Brass
6	142675	28480	9831	2a	4	Bar ingot frag.	130,8	Brass
7	142693	28716	9905	2f	3	Rod	0,7	Brass
9	142825	29094	10925	2h	3	Casting sprue	14,7	Brass
12	142859	29592	11508	2c	3	Bar ingot frag.	5	Brass
4	140009	27950	8764	3a	3	Ingot	10,2	Copper
8	142817	29094	10849	3b	3	Wire/rod	2,6	Copper
10	142836	29094	11051	3c	3	Rod	8,4	Copper
11	142847	29435	11328	3d	3	Bar ingot/rod	3,9	Copper
15	142912	29870	12308	3e	3	Wire/rod	0,3	Copper
16	142914	29870	12330	3f	3	Wire/rod	0,3	Copper
13	142875	29592	11828	4a	3	Casting Waste	5,9	Lead
14	142903	29870	12271	4b	3	Casting Waste	90,3	Lead
17	142926	30595	12432	4c	3	Casting Waste	18,7	Lead

Tab. 1. Brass, copper and lead artefacts investigated in this study.

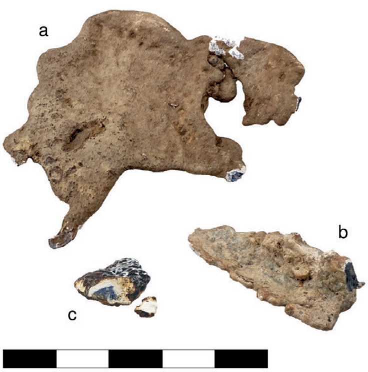

Fig. 4. Helgö lead melts investigated in this study. Object key, see Table 1. Photo: Thomas Eriksson, National Historical Museums, Stockholm.

pp. 16–26). Indeed, we show that brasses from different Building Groups have diverse origins, which may elucidate the relative chronologies of, and relationships between, the various settlement complexes. In general, however, the brasses, copper and lead cannot be grouped together, but have distinct and unrelated origins.

The results of our analyses are presented below according to each metal type following an overview of the metals' archaeological context and dating, and a brief description of methodology. Two notable and unexpected results stand out. First, the brass from Building Complexes 3, 4 and 5 likely has an eastern origin from a location within the Byzantine Empire or bordering regions, rather than a Roman/western European origin as might be assumed. Second, the lead is most likely Swedish. To our knowledge, it represents the earliest known direct archaeological evidence for lead extraction in Sweden.

Background to the metals and research questions
Lead is not common at Helgö, but is represented by several melts from Building Group 3 (BG3) in addition to one piece of sheet, and seven weights from various Building Groups (Kyhlberg 1980, pp. 292–293; K. Lamm 2008a, p. 35; 2008b, pp. 274–275). It also forms part of copper alloys at the site (Grandin & Hjärthner-Holdar 2008). In general, the Helgö lead has received little attention. However, elemental analysis in 2008 estab-

lished that three melts (the same three analysed in this study) were pure, with no other element being detected with any certainty (Grandin & Hjärthner-Holdar 2008, p. 61). Questions linger as to the function of the melts: were they related to the lead weights, or connected to the working of precious metals in the workshop, for example, for making casting models or as a crucible flux? (Grandin & Hjärthner-Holdar 2008, p. 61). The lead melts were found only in BG3: a complex with Migration-period metalcasting, but which also has evidence for Vendel-period activity focused on bead making and iron production, and later Viking-age activity related to ordinary habitation (Clarke & Lamm 2017, pp. 25–26). Given that the melts relate to metalcasting, we consider it most likely that they belong to the Migration-period workshop activity, but nonetheless remain open-minded as to their date.

The source of the lead has never been discussed and, since it survives as melts, we cannot know its original form. Occupation at Helgö falls in the period between Roman and Medieval production at major lead districts in northern Europe (McConnell et al. 2019; Tylecote 1986, pp. 61–70). Lead mines in Britain or on the Continent represent two feasible sources. They were worked in the Roman period, and also supplied Scandinavia during the Viking Age, from c. 800 AD (Kershaw & Merkel 2023). In particular, lead weights from the Viking-age proto-urban centre of Birka, Sweden, comprised lead predominantly sourced from Derbyshire, England (Stos-Gale 2004a). We sought to establish if the Helgö lead also originated from Britain, elsewhere in western Europe, or came from another source altogether.

In addition to the lead, 1.2kg of copper and copper alloys are documented from Helgö. Along with the 230kg of crucibles and abundant evidence of clay moulds for jewellery production, this attests metal casting on a significant scale (Lamm 2012, p. 146). Earlier elemental analysis of over 50 items encompassing raw material, casting waste and finished artefacts, established that Migration-period metalworking at BG3 focused almost exclusively on pure copper and high-zinc brass. By contrast, metalworking at BG2 and BG4 relied much more heavily on mixed gunmetals derived from recycling (Grandin & Hjärthner-Holdar 2008). This has led to the suggestion that the metalworkers at BG3 were the first generation of metalsmiths, with access to imported, primary alloys, whereas those at BG2 and 4 arrived later, operating at 'a time when good raw materials were no longer available' meaning they 'had to make do with scrap' (Clarke & Lamm 2017, p. 30). It is worth noting, however, that only a sub-set of the metals at BG3 have been analysed, while pure brass is found in all Building Groups (Grandin & Hjärthner-Holdar 2008, p. 45).

At Helgö, pure copper and brass occurs only as raw material, and not as finished artefacts. Nonetheless, the presence of brass sprues indicate that pure brass was cast at Helgö – indeed, the high zinc content of the brasses (over 15%) made the metal particularly suitable for casting (Grandin & Hjärthner-Holdar 2008, p. 44). The brass and copper ingots undoubtedly represent 'products brought in by the Helgö craftsmen' (Grandin & Hjärthner-Holdar 2008, p. 65) but primary brass and copper metal is rare in Migration-period contexts, and their origins are intriguing. Brass in particular is a special alloy: it is produced by cementation, reacting copper with zinc compounds, a manufacturing process that required specialist knowledge and would have been possible only in a few locations with access to zinc ore. In addition, brass loses its golden colour and other valuable properties upon recycling, limiting multiple uses. Fresh, golden-coloured high-zinc brass may have been a highly prized and exotic commodity.

In the publication of the copper and brass, it was suggested that these metals derived from recycled Roman vessels (Lamm 2012, p. 146), with the brass ultimately originating from zinc-rich deposits in Germany (Grandin & Hjärthner-Holdar 2008, p. 65). Given archaeological evidence for the presence at the site of late Roman gold solidi, as well as items such as Rhenish pottery and glass indicating connections with the Continent, this was a reasonable suggestion (Lamm 2012, pp. 144–146). However, metalcasting activities at BG3 are primarily dated to the Migration Period (400–550 AD), with a floruit in the period 480–530 suggested by the stylistic dating of large numbers of moulds (Waller 2002; Fischer & Victor 2011, p. 89; Clarke & Lamm 2017, pp. 12–13). The dating of the other Building Groups is complex, and complicated by incomplete radiocarbon dating (Kyhlberg & Strucke 1999), but the earliest phase at Helgö is dated from the late fourth century (Clarke & Lamm 2017, p. 12, Tables 2A–B). At the same time, it is well established that pure brasses, with 20–28% zinc, only occur in Roman alloys in the first century BC to early second century AD; thereafter they decrease (Pollard et al. 2015, Fig. 1, p. 706). At the periphery of the Empire, brass became extremely rare by the fourth century AD (Dungworth 1997). Centuries of recycling of Roman brass would have lowered the zinc content. Invariably, the metal would have been mixed with non-brass alloys. Yet, as noted above, many of the brass bars from Helgö are clean and probably freshly made (i.e. the direct product of cementation).

While a Roman origin therefore seems unlikely for the primary alloys, there appears to have been no fresh brass production in western Europe during the Migration Period (Pollard et al. 2015). Brass was re-introduced to northern Europe during the Viking Age, as attested by finds of brass bars and jewellery (Rehren & Martinón-Torres 2008, p. 173). Its origins at this point are unclear: earlier suggestions that the brass came from northern Europe, particularly the Rhine area, have been tempered by recent archaeometallurgical investigations pointing to more diverse origins (Sindbæk 2003, pp. 58–59; Merkel 2018; 2022). The same is true for copper ingots and bars. The large-scale, multi-period legacy dataset study of Pollard et al. (2015) shows that pure copper was as inaccessible as pure brass in northwest Europe in the late fifth/early sixth centuries.

Conversely, brass, including pure brasses with high zinc contents, was common in both the Byzantine and medieval Islamic worlds (see, for instance, Ströbele 2017; Ponting 1999; 2012; Craddock, La Niece & Hook 1998). High purity copper is found in both Byzantine and Islamic coinage and metalwork, although its appearance fluctuates over time (Korn 2003; Ponting 2012; Birch et al. 2019; Orfanou et al. 2020). At Jerash, Jordan, for instance, pure unalloyed copper is rare during the early Roman and late Islamic period, but relatively common during the early Byzantine and Umayyad periods (Orfanou et al. 2020). Could the copper and brass from Helgö have originated from an eastern (Byzantine or Islamic) source?

Method and reference data

A small-scale lead isotope study conducted in 2011 by Hjärthner-Holdar and Grandin on five copper-alloys from Helgö sought to establish the origin of the copper contained in two brasses, two bronzes and one item of pure copper (Hjärthner-Holdar & Grandin 2013; Clarke & Lamm 2017, p. 30). The hypothesis to be tested was that the copper derived from the famous copper mines of Falun, Dalarna, Sweden, which, at the time, were thought to have evidence for working in the sixth and seventh centuries. The results revealed that the copper ores were from younger bedrock than is typically found in Sweden, ruling out a local source. The authors pointed instead to potential matches in Cyprus, Bulgaria/the Balkans or, less likely, the British Isles (Hjärthner-Holdar & Grandin 2013; Clarke & Lamm 2017, p. 30).

Here, we pursue combined lead isotope and trace element analysis for all the 19 analysed artefacts as a means of establishing contender sources (for a discussion of this approach, see Kershaw & Merkel 2021). While lead isotope analysis of high-purity copper is expected to provide information about the source of the copper, the interpretation of lead isotope ratios in brass is more nuanced, since the lead analysed may relate to the zinc-based ore (calamine) or copper ore (Merkel 2018; 2021). Our interpretational approach prioritizes the comparison of regional and chronologically-distinct metal stocks over direct comparison with ore sources. We sampled two items previously analysed for lead isotopes by Grandin and Hjärthner-Holdar (Sample 11, a copper rod, and 12, a brass ingot fragment, both from BG3), and our results are within error (Hjärthner-Holdar & Grandin 2013). For each object, we took small physical samples of c. 5mg, from areas that had previously been drilled in the 1970s and 2008, in order to minimize fur-

A	Sample No.	Type	Alloy	Cu%	Zn%	Sn%	Pb%	Fe	Ni	As	Ag	Sb	Bi	Co
				EPMA	EPMA	EPMA	EPMA	EPMA	EPMA	EPMA	EPMA	EPMA	EPMA	EPMA
	13	Melt	Lead	0,29	n.d.	n.d.	98,61	n.d.	n.d.	10800	200	n.d.	n.d.	n.d.
	14	Melt	Lead	0,81	n.d.	n.d.	99,05	n.d.	n.d.	1300	n.d.	n.d.	n.d.	n.d.
	17	Melt	Lead	0,37	n.d.	0,02	99,42	n.d.	n.d.	2000	n.d.	n.d.	n.d.	n.d.

B	Sample No.	Type	Alloy	Cu %	Zn %	Sn %	Pb %	Fe %	Ni %	As %	Ag %	Sb %	Bi %	Co
				pXRF	pXRF	pXRF	pXRF	pXRF	pXRF	pXRF	pXRF	pXRF	pXRF	pXRF
	13	Melt	Lead	<0.33	<0.28	<0.14	97,36	n.d	<0.40	<0.68	<0.28	<0.16	<0.58	n.d.
	14	Melt	Lead	<0.34	<0.19	<0.31	97,57	n.d	<0.76	<0.81	<0.49	<0.33	<0.67	n.d.
	17	Melt	Lead	<0.42	<0.16	<0.26	97,64	n.d	<1.13	<1.05	<0.47	<0.42	<0.80	n.d.
	17r	Melt	Lead	<0.45	<0.29	<0.34	97	n.d	<0.74	<1.21	<0.66	<0.34	<1.14	n.d.

Tab. 2. Elemental results for the lead melts A) measured by microprobe analysis after Grandin & Hjärthner-Holdar (2008, 51-2) and B) measured by pXRF for the current study.

ther impact on the objects, as well as to ensure that the core metal was sampled. A full description of the methodology, instrumentation and standards is given in the Appendix.

Results

Lead

Portable X-ray florescence (pXRF) analysis of the lead melts showed that all the melts are pure lead with no other element being detected with any certainty, as the electron probe microanalysis (EPMA) results of Grandin and Hjärthner-Holdar likewise show (tab. 2). The purity and homogeneity of the lead suggest a lack of mixing, recycling or alloying. The lead (Pb) isotope ratios of the three archaeological samples from Helgö are also uniform and exhibit strongly radiogenic isotopic values, with high $^{207}Pb/^{206}Pb$ ratios (tab. 3). This is completely different from the lead isotope ratios of Viking-age lead weights from Birka (Stos-Gale 2004a) and suggests that the Helgö weights belong to an earlier context, most likely the Migration-period workshop. The results point to an extremely old crustal source for the lead ore, which drastically constrain the possible geologic sources.

Brass and Copper

Previous indications that the analysed brasses from Helgö had relatively high zinc contents (Grandin & Hjärthner-Holdar 2008, Table 2) were confirmed by our analyses. The eight brasses contain ca. 13–28 wt. % zinc (tab. 4). One D-sectioned bar ingot fragment has 28% zinc, which is amongst the highest for brasses in the 1st Millennium AD (Craddock & Eckstein 2003, p. 224; Werner & Willet 1975, p. 142). These high zinc levels suggest that the brass was produced by cementation (the calamine process). An alternative method of production, of reacting sublimated zinc oxide with molten copper, was popular in the Islamic world, but resulted in lower zinc contents (Craddock, La Niece & Hook 1998; Craddock & Eckstein 2003, pp. 223–226).

Since zinc contents of brasses decrease upon every remelting, the high levels of zinc in the Helgö brasses, coupled with the typically low levels of tin observed, are indications that most of the brasses were not subjected to repeated recycling. The brass ingot with the highest zinc can only be a product of primary production and was never remelted/recycled. Similarly, the copper cast ingot and hammered bars and wires are all very pure. All elements other than copper are in the minor-to-trace elemental range (<1%) (tab. 4).

Comparison of the minor and trace elements between the unalloyed copper and brasses reveals that there are important source-related differences in the uses of base copper. The brasses have considerably higher arsenic contents. Using the alloy classification of Bray et al. (2015), most brasses (seven of eight) are arsenic rich, forming various constellations of As-Sb-As-

Sample No.	Type	Material	^{206}Pb/^{204}Pb	Uncert.	^{207}Pb/^{204}Pb	Uncert.	^{208}Pb/^{204}Pb
1	Casting sprue	Brass	18,253	0,00	15,596	0,002	38,168
2	Bar ingot	Brass	18,124	0,002	15,646	0,002	38,193
3	Bar ingot frag.	Brass	18,788	0,002	15,700	0,002	38,946
5	Wire/rod	Brass	18,844	0,002	15,691	0,002	38,958
6	Bar ingot frag.	Brass	18,629	0,002	15,653	0,002	38,748
7	Rod	Brass	18,842	0,002	15,693	0,002	38,987
9	Casting sprue	Brass	18,589	0,002	15,659	0,002	38,713
12	Bar ingot frag.	Brass	18,759	0,002	15,684	0,002	38,862
4	Ingot	Copper	18,524	0,002	15,668	0,002	38,64
8	Wire/rod	Copper	18,515	0,002	15,667	0,002	38,629
10	Rod	Copper	18,463	0,002	15,664	0,002	38,589
11	Bar ingot/rod	Copper	18,551	0,002	15,674	0,002	38,711
15	Wire/rod	Copper	18,706	0,002	15,696	0,002	38,925
16	Wire/rod	Copper	18,551	0,002	15,673	0,002	38,713
13	Melt	Lead	23,995	0,007	16,374	0,007	46,613
14	Melt	Lead	23,87	0,007	16,357	0,007	46,235
17	Melt	Lead	23,969	0,007	16,369	0,007	46,618

Tab. 3. Lead isotope results for all the analysed objects.

Sample No.	Type	Alloy	Cu%	Zn%	Sn%	Pb%	Fe	Ni	As	Ag	Sb	Bi	Co
			pXRF	pXRF	ICP	ICP	ICP	ICP	ICP	ICP	ICP	ICP	ICP
1	Casting sprue	Brass	75,51	22	n.d.	0,12	2398	145	8833	1345	679	n.d.	n.d.
2	Bar ingot	Brass	78,29	15,45	0,01	4,3	1069	105	2110	816	716	123	n.d.
3	Bar ingot frag.	Brass	66,25	28,11	0,29	2,85	694	1083	3013	354	350	3	38
5	Wire/rod	Brass	78,08	19,1	0,003	0,16	337	603	1687	521	184	76	90
6	Bar ingot frag.	Brass	70,99	22,44	0,05	4,08	1234	485	7266	536	2033	1044	n.d.
7	Rod	Brass	75,4	21,63	0,01	0,97	2890	734	794	288	134	60	251
9	Casting sprue	Brass	80,15	13,41	1,02	3,17	5045	742	5146	1748	2218	567	88
12	Bar ingot frag.	Brass	78,05	19,33	0,1	0,16	3353	937	5040	1216	732	172	118
4	Ingot	Copper	97,81	0,18	0,1	0,23	3371	635	674	1257	477	25	n.d.
8	Wire/rod	Copper	97,15	0,06	0,01	0,59	184	382	678	2838	514	81	n.d.
10	Rod	Copper	97,3	0,06	0,83	0,55	1737	186	229	945	620	n.d.	n.d.
11	Bar ingot/rod	Copper	95,99	0,07	0,07	0,09	358	281	11	942	354	4	n.d.
15	Wire/rod	Copper	97,51	0,09	0,01	0,07	287	140	58	2386	202	n.d.	n.d.
16	Wire/rod	Copper	97,2	0,08	0,18	0,47	440	266	109	1612	459	29	n.d.

Tab. 4. Elemental results for the brass and copper artefacts.

Bi-Ni-bearing alloys. By contrast, none of the copper objects are arsenic rich. They are instead characterised as silver-bearing (four of six) or are classified as having none of the above elements in concentrations above 0.1 wt. % (two of six). Using the ratios of the elements arsenic, antimony and silver, the brasses can be seen as distinct from the copper objects (fig. 5). Since smelting and refining processes do not affect silver concentrations in copper and only slightly impact arsenic and antimony (Pernicka 2014), it is clear that the copper used for the brasses and for the unalloyed copper objects come from different ore sources.

Uncert.	$^{207}Pb/^{206}Pb$	Uncert.	$^{208}Pb/^{206}Pb$	Uncert.	T(Ma)	µ	κ
0,007	0,85442	0,00004	2,09096	0,0002	309	9,629	3,868
0,007	0,86327	0,00004	2,10727	0,0002	497	9,865	3,987
0,007	0,83566	0,00004	2,07291	0,0002	111	9,922	3,959
0,007	0,83269	0,00004	2,06739	0,0002	52	9,876	3,926
0,007	0,84027	0,00004	2,07999	0,0002	137	9,771	3,945
0,007	0,83288	0,00004	2,06913	0,0002	57	9,885	3,942
0,007	0,84235	0,00004	2,08254	0,0002	179	9,803	3,955
0,007	0,83607	0,00004	2,07163	0,0002	101	9,866	3,93
0,007	0,84582	0,00004	2,08596	0,0002	244	9,852	3,964
0,007	0,84617	0,00005	2,08634	0,0002	249	9,85	3,963
0,007	0,84841	0,00004	2,09002	0,0002	281	9,85	3,976
0,007	0,8449	0,00004	2,08672	0,0002	236	9,87	3,985
0,007	0,83909	0,00004	2,08085	0,0002	164	9,923	4,000
0,007	0,84487	0,00004	2,08681	0,0002	234	9,866	3,985
0,026	0,68240	0,00010	1,9426	0,0006	-2210	11,890	4,220
0,026	0,68530	0,00010	1,9369	0,0006	-2160	11,840	4,170
0,026	0,68290	0,00010	1,9449	0,0006	-2204	11,880	4,230

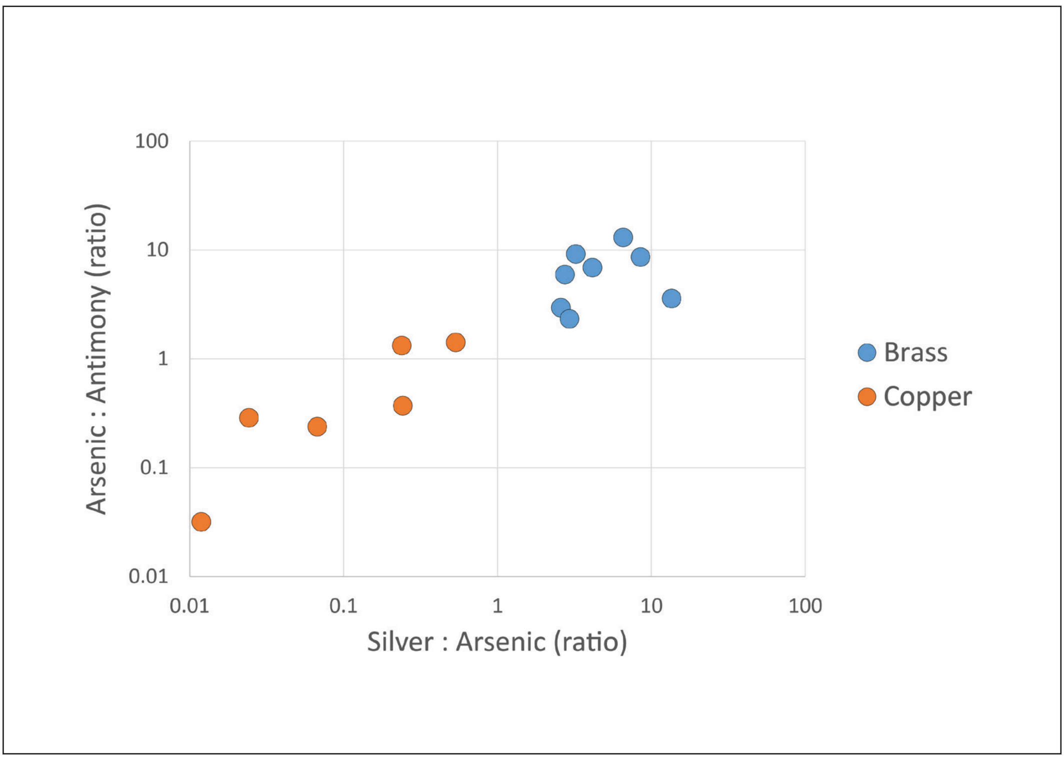

Fig. 5. Contrasting ratios of copper source-related elements (arsenic, antimony and silver) between the Helgö brass and copper objects. The sources of copper for brass and unalloyed copper are different.

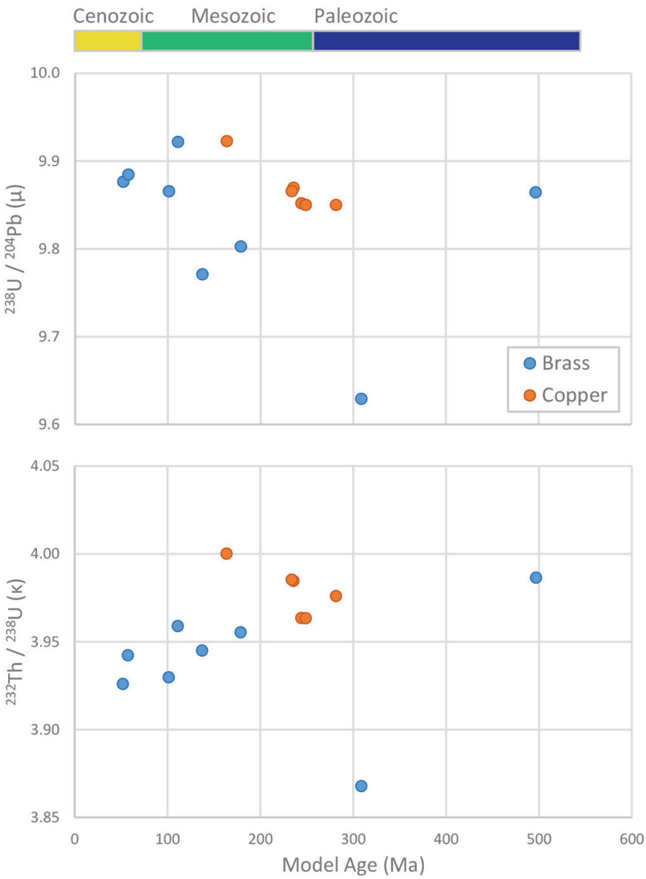

Fig. 6. Lead isotope characteristics of the Helgö brass and copper objects shown as model ages, μ and κ.

Lead isotope ratios can be used to further probe the origins of the brass and copper. They show that the brasses derive from a geologically younger ore source than the copper. The lead isotope ratios of six brasses form a cluster, with geological model ages between 52–179 Ma (million years ago) and two outliers (for a background to the geochemistry of lead isotopes, see Albarède et al. 2012) (tab. 3) (fig. 6). The lead in all but one of the brasses point to a dominant upper crustal ore source. The two outliers contain lead that is geochemically older than the others. One of these (Sample 1, model age 309 Ma) contains lead that likely formed during the Variscan Orogeny but with unusually low μ and κ values, pointing to a lead source with a higher mantle contribution (see Zartman & Doe 1981). The second (Sample 2, model age 497 Ma) contains lead that originated from geologically old crust. Turning to the six copper items, five form a cluster, with model ages between 234–281 Ma. One is a geochemically younger outlier (Sample 15, model age 164 Ma). All point to a dominantly upper crustal source.

Interpretation of results – provenance of the metals

To determine candidate ore sources, we compared our data to a wide range of published reference data covering Scandinavia, Europe, North Africa, the Mediterranean, the Near East and Asia. A full list of reference data is provided in the Appendix.

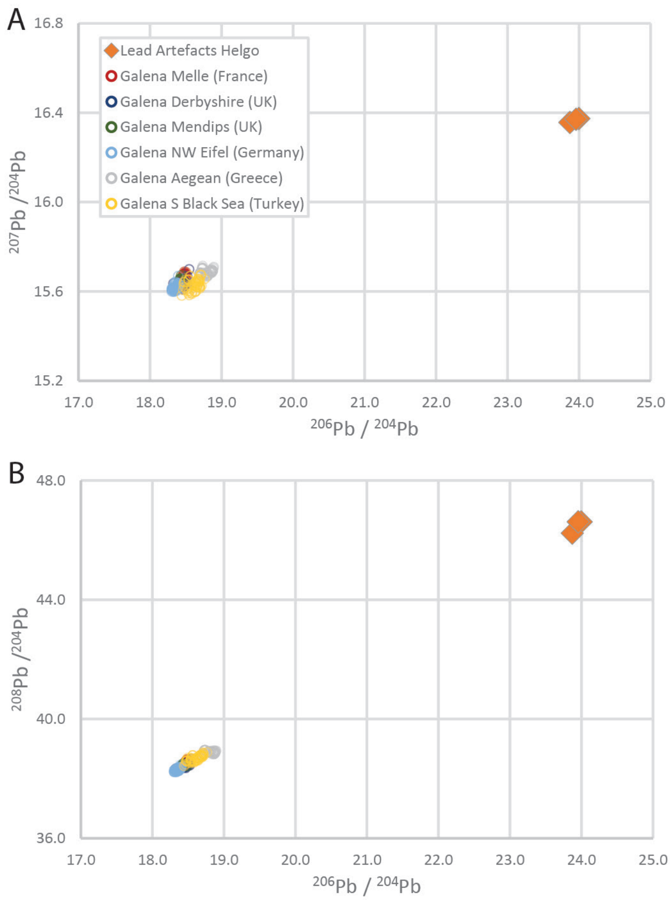

Fig. 7. Lead isotope results of the Helgö lead compared with lead ore from France (Melle, Téreygeol et al. 2005), Britain (Derbyshire and Mendip, Rohl 1996), the northwest Eifel (Bode 2008; Schneider 1994) the Mediterranean (Greece: Pangeon, Laurion, Siphnos, Chalkadiki, Vaxevanopoulos et al. 2022) and the Black Sea coast (Sayre et al. 2001).

Lead

The high $^{207}Pb/^{206}Pb$ ratios of the Helgö lead melts point to an extremely old crustal source. They are entirely inconsistent with all known analyses of Roman and Medieval lead objects from mainland Europe (Durali-Müller 2005; Merkel 2016a; Pedersen et al. 2016; Stos-Gale 2004a), the British Isles (Hanel et al. 2013; Ponting 2018; Kershaw & Merkel 2023), the Mediterranean Basin (Bode et al. 2021; Stos-Gale 2004b) and the Middle East (Van Ham-Meert et al. 2019). As compared to lead-bearing ore deposits assumed to be associated with Late Antique and Early Medieval European metal production, the lead isotope ratios of the Helgö lead are distinctively different (fig. 7).

Such ancient crust is found in geographically distant sources, including India (Radhakrishna & Naqvi 1986) and southern China (Hsu & Sabatini 2019). However, it is also characteristic of the Fennoscandian Shield (Baltic Shield), covering Fennoscandia and north-west Russia (Romer & Wright 1993; Blichert-Toft et al. 2016). Lead ore deposits in the Fennoscandian Shield have been geochemically studied (Romer & Wright 1993; Blichert-Toft et al. 2016). Those from Norway are not a good match for the Helgö lead, while those from Finland have mainly lower isotope $^{207}Pb/^{206}Pb$ ratios, although there are a few Finnish specimens that are similar to the Helgö lead (fig. 8).

By contrast, Swedish lead ore sources are a good match for the Helgö melts, and should be

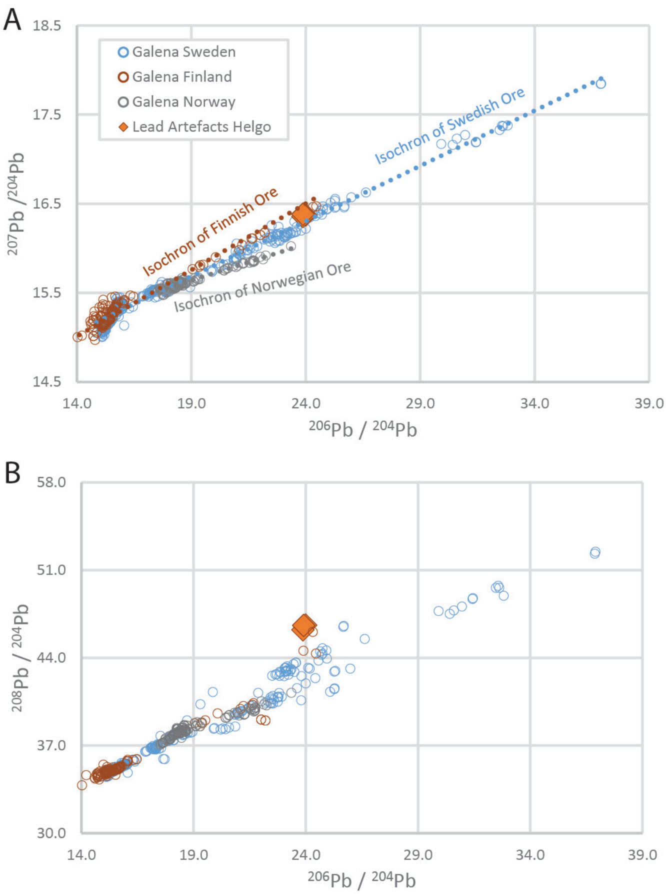

Fig. 8. Lead isotope results of the Helgö lead compared with analyses of Scandinavian galena (after Blichert-Toft et al. 2016).

considered the most likely source for the lead. Strongly radiogenic Pb ratios, as carried by the Helgö lead melts, are particularly prevalent in Phanerozoic ore deposits, which formed about 400 Ma from lead that likely derived from 1.8–2.0 Ma old Precambrian basement rock (Billström et al. 1997; Johansson & Rickard 1984). Taken together, the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ ratios for Swedish radiogenic ore reveal a pronounced linear trend (Billström et al. 1997; 2012; Johansson & Rickard 1984), with the Helgö lead artefacts positioned along it (i.e. isochron) (fig. 9a). These deposits occur in different areas of Sweden, but some famous Swedish ore deposits can immediately be ruled out as contender sources owing to their comparatively lower isotope ratios. This is the case for the zinc (Zn)-lead (Pb)-silver (Ag)-copper (Cu)-gold (Au) ore body at Garpenberg and the mainly copper ore (which nonetheless also contained lead) at Falun, both part of the extensive Bergslagen mining area in central Sweden (fig. 9a).

It is possible to further discriminate between Swedish and Finnish sources via variation in thorium concentrations of the crust: this generates diversity in the $^{208}Pb/^{204}Pb$ ratios, enabling us to identify localities with higher lead isotope ratios more similar to the Helgö lead (fig. 9b). None of the available data points to an exact match for the Helgö lead. Nonetheless, the Pb isotope characteristics of the Helgö lead artefacts are most like ore deposits of Caledonian age (Johansson & Rickard 1984). Some of the closest isotopic parallels are found in northern

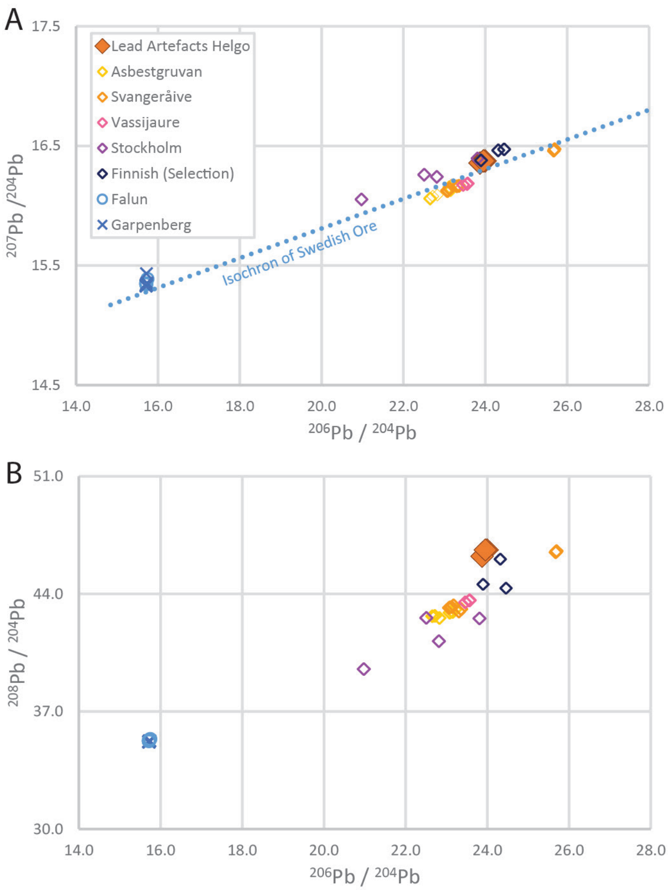

Fig. 9. Lead isotope results of the Helgö lead compared with select Swedish and Finnish lead ore (after Blichert-Toft et al. 2016).

Finland, for example the Kittilä and Lehtoselkä region, even though Finnish ore deposits are, on the whole, not a good match for the Helgö lead (Billström et al. 1997; Mänttäri 1995). In Sweden, Caledonian ore deposits are found predominantly in remote parts of north-west Sweden, along the Norwegian border, and include, for instance, the calcite-galena-flourite veins at Svangeråive and Asbestgruvan, and the quartz-galena veins of Vassijaure, all of which plot extremely closely to the Helgö lead (fig. 9a) (Johansson & Rickard 1984; Romer &Wright 1993). In south-east Sweden, galena in calcite veins from the Revsund granites have similar ^{206}Pb/^{204}Pb ratios to the Helgö lead, but lower ^{208}Pb/^{204}Pb ratios (Alm & Sundblad 2002, p. 14).

Significantly, comparable ores also occur in the Gulf of Bothnia and Baltic Sea regions (Romer & Wright 1993, Table 3). Within this area, calcite-galena veins in the township of Stockholm have the most analogous lead isotope ratios to the north-west Swedish Caledonian deposits and Helgö lead melts (Romer & Wright 1993, p. 2564). At least 18 veins were known in the Stockholm area in the 1970s (Åhman 1974). Importantly, these were outcrops, visible at the surface, and may thus have been easily identifiable in the Migration Period. On the basis of the lead isotopes, the Stockholm veins, south-east Swedish and north-west Swedish veins are all contender sources, and it must be remembered that none of the current data provides an exact match for the Helgö lead. Yet given the

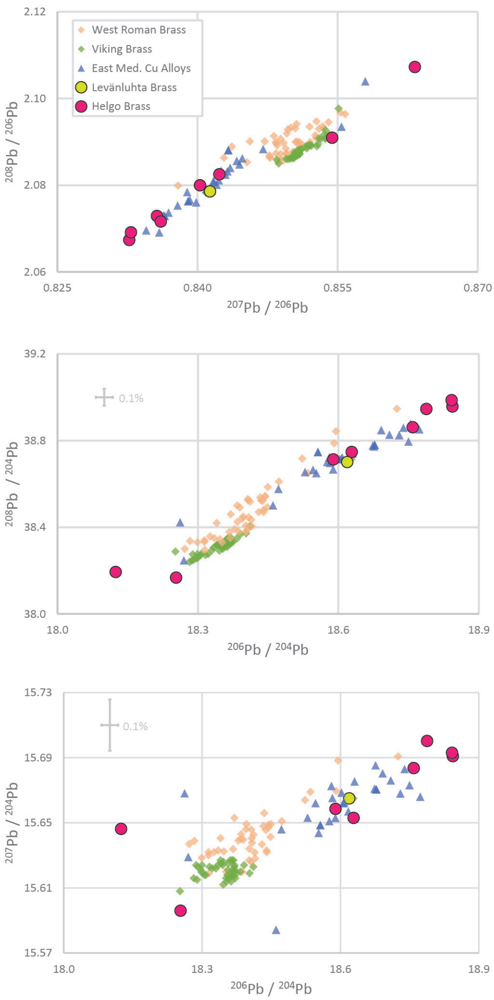

Fig. 10. Helgö brasses and Migration-period brass from Levänluhta (Finland) compared to Roman brasses from western Europe, Viking-age brasses from Scandinavia and East Roman/Byzantine brasses and other copper alloys. References, see Appendix.

geographical proximity of viable sources in the Stockholm area, we conjecture that these lead outcrops are the most likely source for the Helgö metalworkers.

Brass and Copper

The Helgö brasses indicate access to fresh brass unrelated to the metal available earlier. Isotopically, the core group of six objects, from BG 3, 4 and 5 (excluding, momentarily, the two outliers) are inconsistent with published data on western Roman brasses, which mainly relates to brass artefacts from western or central Europe linked to zinc ore from the Massif Central (Hanel & Bode 2016; Bursak et al. 2022; Merkel 2021a), northern Italy (Merkel 2021b) and the Eifel region of Germany (Merkel 2021a; 2021b) (fig. 10).

Viking-age brasses from Scandinavia have variable lead isotope ratios, the majority of which are consistent with the Rhenish Massif (Merkel 2016b; 2022) and others of which relate to ore in southern Europe (Merkel 2018). The core group of six Helgö brasses are incompatible with those linked to the Rhenish Massif and thus are not connected to production in Westphalia and near the German/Belgian border. They most likely pre-date Viking-age production.

Instead, close matches are provided by stocks of brasses and other copper-based alloys of late antique date from the Byzantine Empire, particularly the eastern Mediterranean (fig. 10). While brass use declines significantly in western Europe in late antiquity, it continued to be produced and was widely used in the Byzantine-controlled eastern Mediterranean (Craddock et al. 1998; Ponting 2012; Orfanou et al. 2020). The Helgö brasses are isotopically consistent with late antique copper artefacts and coinage from Jerash, Jordan, as well as with copper coinage from Constantinople and Alexandria (Brill & Shields 1972; Birch et al. 2019; Orfanou et al. 2020) (fig. 10). A number of high-zinc brasses ranging from 11–28% zinc from sixth-century contexts from the early Byzantine Cardo and Nea church (Israel) have thousands of ppm arsenic, like the Helgö brasses (Ponting 2012). This pattern signals access to freshly produced brass, no doubt supplied by the networks of the Byzantine Empire. Within the region, prominent sources of zinc ore lie in Anatolia. Indeed, the Helgö brasses are consistent with ore deposits along the southeast European and Anatolian segments of the Tethyan Eurasian Metallogenic Belt (TEMB), that is, modern-day Turkey and the Balkans, south and east of the Black Sea (Sarye et al. 2001; Blichert-Toft et al. 2016).

Two of the Helgö brasses are outliers and not compatible with the bulk of Byzantine copper alloys (fig. 10). One (Sample 1, casting sprue) is on the periphery of Viking-age brass from the Rhenish Massif, but is also near an outlying east Mediterranean copper alloy, so the results are inconclusive. The second outlier is a complete brass ingot (Sample 2), which is isotopically inconsistent with Roman, Byzantine and Viking (Rhenish Massif) brasses. It is more similar to fifth- and sixth-century brasses and bronzes found in the Himalayas (compare with Massa et al. 2019) and is identical to a diffusion-gilded fifth- or sixth-century silver funerary mask from Samdzong, Tibet, with cultural ties to Central Asia and the Silk Road (Massa et al. 2019, pp. 76–77). This alloy we interpret as being Asian, without further specification due to the poor state of research.

The outlier Samples 1 and 2 derive from BG2 (Terrace I) and BG1 respectively, while the other six brasses derive from BG3, 4 and 5. BG2 Terrace I has evidence for building structures and has both a phase dated to the Migration/ Vendel-period transition (c. 550 AD), and a significant later Viking-age phase, characterised by finds of dirhams, imported Continental pottery and a Thor's hammer pendant (Clarke & Lamm 2017, p. 21). Although the nature of the Viking-age occupation is unclear, it is possible that the brass ingot (Sample 1) is Viking-age in date. BG1 belongs to the same complex as BG4 (a workshop) and appears to have been a farmstead, which nevertheless had evidence for metalworking in its early phase (c. 500 to the early seventh century) (Clarke & Lamm 2017, p. 22). If the ingot belongs to this period, rather than a later phase when BG1 was a 'substantial farmstead', it provides evidence for the varied sources of brasses, and diverse trade contacts, at Helgö in the Migration Period.

How exactly the brass ingots reached the Swedish Baltic is an open question: we have identified parallels with metal stocks circulating within the Byzantine-controlled eastern Mediterranean, but pinpointing a more precise origin within this extensive region is challenging. It is interesting to note the presence of a high-zinc brass arm-ring from Levänluhta, Finland, which is elementally and isotopically comparable to the brass at Helgö (Holmqvist et al. 2019, Sample F) (fig. 10). It may have a similar source, which could indicate an eastern trade network to Helgö. In addition, brass and copper ingots of very similar form and elemental composition to those from Helgö, but without lead isotope data, have been recorded in the Volga/Kama region of Russia (Vyazov et al. 2019; Zhomartova et al. 2022). These bar ingots date from AD c. 450 to 700 (Vyazov pers. comm. June 2019). The zinc content of the brass ingots is in the range of 11–32%, similar to that of the Helgö brasses (Zhormatova et al. 2022). The ingots are concentrated at the confluence of the Volga/ Kama rivers and are not present before the start of the Migration Period. Their distribution suggests that they entered the region from the southern waterways, making both sources in the Black Sea region and/or the Islamic world and routes along the Silk Road possible.

The source of the copper is less clear (fig. 11). The lead isotope ratios of the copper are inconsistent with a local ore source within Scandinavia, and we thus agree with the conclusion of Grandin and Hjärthner-Holdar that they do not stem from mining at Falun, Sweden (Clarke & Lamm 2017, p. 30). Indeed, although the mines in Falun were once thought to have been worked in the sixth and seventh centuries, this early date has been overturned by more recent studies (Bindler & Rydberg 2016). The copper objects are not similar to the brasses. Nor are they comparable to Viking-age copper from Hedeby (fig. 11) (Merkel 2022). There are no direct parallels with western Roman (as opposed to Byzantine) copper, for instance, with Roman copper ingots from southern Spain (compare Klein et al. 2007). Isotopically, the cluster is similar to copper linked to the Cévennes region (Massif Central) in southern France (compare Rico et al. 2005). However, this copper is much richer in antimony and nickel than the Helgö copper and is thus not compatible elementally. Indeed, geologically, the Cévennes region is not thought to have been a major source of this metal (Klein et al. 2007, pp. 216–217).

The cluster of five items share some isotopic similarities with western Roman bronze (both leaded and unleaded) (fig. 11). However, these lead isotope ratios are not exclusive to Roman

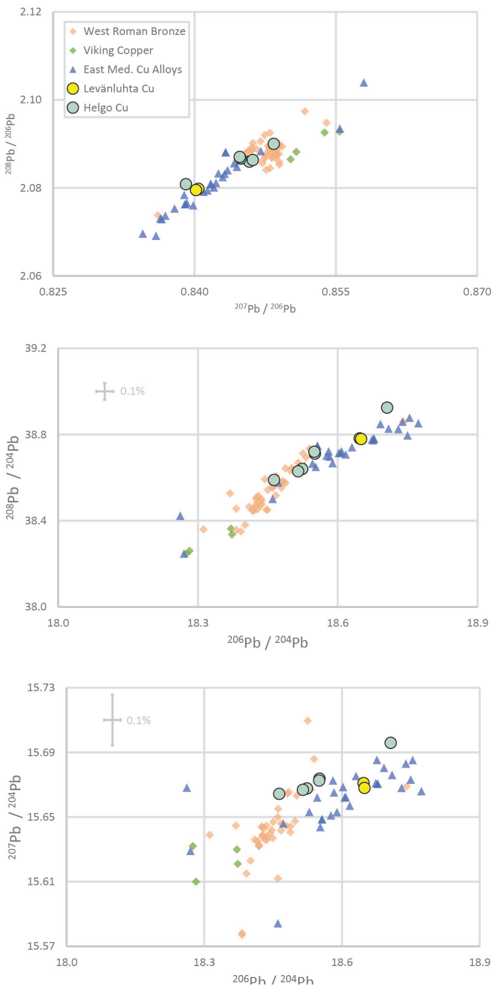

Fig. 11. Helgö copper and Migration-period copper from Levänluhta (Finland) compared to lead isotope data on Roman bronze from western Europe, Viking-age copper and East Roman/Byzantine copper alloys. References, see Appendix.

Europe, and similar lead isotope characteristics can be found in copper ore deposits in the Black Sea Region, particularly in the Pontic Mountain region of northern Anatolia (compare Sayre et al. 2001). The copper outlier (Sample 15) is consistent with ore from the Central Rhodope in Bulgaria (compare OXALID Bulgaria). Two copper arm rings from Levänluhta, Finland, dating to the period 550–800 AD, also have lead isotope ratios consistent with Rhodope copper deposits in Bulgaria (fig. 11) (Holmqvist et al. 2019, Samples B and C) and it may be that primary copper reached Helgö via an eastern trade route, in much the same way as the brasses. The source of copper for the Helgö objects nevertheless remains uncertain. In-depth studies of eastern and western copper in Late Antiquity and the Migration Period are lacking, and further analyses would be needed to characterize regional metal stocks.

Discussion

Turning first to the lead, it is clear that lead sources in Sweden are the most likely origin of the Helgö melts, although specific deposits in northern Finland are also contenders. Since lead is not common at Helgö, the scale of this exploitation may have been modest. Nonetheless, the result is highly unexpected, as the extraction of metals in Sweden is normally thought to have been a later development. The earliest mining of metal ore in Sweden (as distinct from the domestic production of secondary sources, such as bog iron) is conventionally dated from the late thirteenth century, when historical records first indicate the mining of iron and copper in central Sweden (Bindler et al. 2017). However, recent efforts to identify early metallurgy through lake sediment and peat analysis tell a different story, revealing much earlier mining of non-ferrous metals at the Garpenberg ore field within Bergslagen. Here, indirect evidence for copper mining was detected from the pre-Roman Iron Age. Mining continued in the fifth century before it expanded rapidly in the thirteenth century (Bindler et al. 2017).

The lead isotopes of the Helgö melts rule out Garpenberg as a source of lead (which could be found along with the copper), but the evidence signals the potential for early lead extraction in Sweden more broadly. Thus far, no other indications of lead mining have been positively identified: earlier assertions that copper/lead mining took place at Falun in the fifth to eighth centuries (Lundkvist 1963; Eriksson & Qvarfort 1996) have been undermined by new geochemical analyses (Bindler & Rydberg 2016). The evidence of the Helgö melts provides a new perspective from archaeological lead. It raises the possibility that lead veins in remote regions of north-west Sweden or northern Finland, or, more likely, local outcrops in the Stockholm region, were exploited in the Migration Period.

By contrast, the source of the bulk of the analysed brass ingots lies in a different direction, southeast towards the Byzantine Empire, whereas an additional ingot may have originated in regions further east: the other possibilities of them being recycled western Roman brass or them being made in the Rhine region are invalidated by this study. There is a scattering of other evidence for Byzantine or Byzantine-related objects within Migration-period Sweden more generally and at Helgö in particular: a single amethyst bead from BG2, a late antique (probably eastern Mediterranean) bronze ladle and associated silver bowl, also from BG2, as well as an 'overlay' glass sherd from the Black Sea region, with a probable Greek inscription (Ljungkvist 2008, p. 33; 2010, p. 430). While the bronze ladle and silver bowl are, at present, unparalleled (Ljungkvist 2010, p. 430), the amethyst bead and glass vessel sherd may have been part of a wider export of such goods to the Baltic (Ljungkvist 2008, Fig. 1).

Indeed, it is well established that certain types of glass vessels originating in the Black Sea region or south-east Europe – in areas within or bordering the Byzantine empire – were deposited in elite graves and at 'central place' sites in Scandinavia between the third and fifth centuries (Lund Hansen 2011; Ljungkvist 2008). They are best interpreted as the result of sustained, long-distance trade between Scandinavia and south-east Europe that began in the late Roman period (Lund Hansen 2011). The core group of brass bars may represent another, relatively late, strand to this trade, signalling the import over vast distances of standardized, yet exotic, raw material, in what must have been regular, embedded exchanges with the Byzantine Empire or neighbouring regions.

There are, of course, also hints that Helgö's extensive communication networks stretched further eastwards. The brass Buddha was produced in Kashmir, while garnets and, potentially, red/orange glass beads from the site originate in India or Sri Lanka (Gratuze et al. 2021; Sode et al. 2017). However, the garnets belong to the Vendel period (the seventh and eighth centuries) (Clarke & Lamm 2017, p. 40) and the date of arrival of the Buddha remains uncertain; although produced in the sixth century, it may have been centuries old when it reached Helgö (Hedenstierna-Jonson 2020, p. 58). Brass ingot Sample 2 is unfortunately not dated with certainty, but we assume a Migration-period date on the basis that it was during this period that BG1 was used as a workshop. If this is correct, and the metal does indeed have Asian origins, it provides an especially early indication of Sweden's Eurasian exchange network, a precursor to the 'Northern Arc' of the Viking Age (see, in this context, Arrhenius 2015, p. 148).

Conclusions

Combined lead isotope and trace element analysis of brass, copper and lead from Helgö provides new perspectives on local resource acquisition and long-distance supply networks in Migration-period Sweden, revealing an astonishing breadth of resources available to metalsmiths at Helgö. The results from the three lead melts provides the earliest direct archaeological evidence for the exploitation of lead in Sweden, most likely in the Stockholm area. As such, they contribute to the increasing evidence for the mining of metal ore in Sweden in the early medieval period, in addition to demonstrating the ability of people at Helgö to exploit their local landscape. By contrast, the brasses and copper are not local to Sweden. The unalloyed copper may ultimately stem from Bulgaria, but a lack of comparable reference data means that it sources are unclear. We have nonetheless demonstrated that the origin of the unalloyed copper objects is not the same as the brass, which points to different pathways of resource acquisition. We propose that the bulk of the brass ingots reached Helgö from the eastern Mediterranean. Given their standardized form, they likely reached Sweden via routinized exchange networks with the Byzantine Empire, adding to the small, yet growing, corpus of archaeological evidence for Byzantine objects in Migration-period Sweden. One brass ingot may have come from Asia. This is just a single item, but it represents an important first step for evaluating the hypothesis that Helgö served as the western terminus of an eastern trade in raw materials along the Silk Road.

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Appendix: Methods and Materials

Lead

For the three lead melts, small physical samples were taken by drill with a 1mm drill bit.

The lead samples were screened by portable X-ray fluorescence (pXRF) (Niton™ XL3t XRF Analyzer). Lead was the only element that could be detected. The alloys are clearly of high purity and unalloyed, confirming the earlier EPMA results of Grandin & Hjärthner-Holdar (Table 2, main text). Next, ca. 1mg pieces of metallic lead were dissolved in dilute nitric acid and diluted to a concentration of 25ppb. The solutions were analysed using a Thermo Scientific Neptune multicollector-ICPMS using standard sample bracketing to correct for instrumental mass fractionation. The lead isotope data are normalised to the values of Thirlwall (2002). The whole method blank was measured to be 24 pg, which is negligible. The lead isotope results are presented in Table 3 in the main text. The measurement uncertainty reported is the propagated error combining the variation of multiple measurements of the in-house standard (2SD) with the variation of the individual sample measurements (2SE).

Copper and Brass

For the copper and brass objects, we collected 5mg of fresh metal from areas previously sampled in the 1970s and in 2008. The samples were analysed by portable X-ray fluorescence and quantified using the fundamental parameters algorithms in combination with a calibration using reference materials (see Heginbotham et al. 2010) (Appendix Table 1). Drilled shavings of standards were analysed by the same method (Appendix Table 2).

Table 1. Portable X-ray fluorescence analysis of drilled reference materials compared to given values. (n.g. = not given).

		Cu	Zn	Sn	Pb	Fe	Co	Ni	As	Ag	Sb	Bi
Standard Brass BCS344	Measured	68.5	30.6	<0.01	0.03	0.01	<0.01	<0.01	0.01	<0.01	0.02	<0.01
Standard Red Brass NIST111	Measured	86.4	12.7	0.01	0.05	0.01	<0.01	0.02	0.02	<0.01	<0.01	<0.01
Standard Leaded Gunmetal BCS 183/4	Measured	82.4	3.4	7.28	4.73	0.05	<0.01	1.26	0.12	0.05	0.27	0.01
31X 7835.8 (Drillings)	Measured	69.6	24.6	0.41	3.64	0.31	0.28	0.15	0.17	0.30	0.14	0.13
Standard Brass BCS344	**Given**	**69.0**	**31.0**	**n.g.**	**n.g.**	**n.g.**	**n.g.**	**n.g.**	**n.g.**	**n.g.**	**n.g.**	**n.g.**
Standard Red Brass NIST111	**Given**	**87.1**	**12.8**	**0.02**	**0.013**	**0.01**	**n.g.**	**0.022**	**n.g.**	**n.g.**	**n.g.**	**n.g.**
Standard Leaded Gunmetal BCS 183/4	**Given**	**84.8**	**3.5**	**7.27**	**3.15**	**0.06**	**n.g.**	**1.30**	**0.13**	**n.g.**	**0.23**	**0.01**
31X 7835.8	**Given**	**69.1**	**24.8**	**0.52**	**3.00**	**0.10**	**0.30**	**0.05**	**0.15**	**0.45**	**0.10**	**0.10**

Table 2. New pXRF analyses of drilled shavings. Results in weight %.

VU	No.	Alloy	Cu	Zn	Sn	Pb	Fe	Co	Ni	As	Ag	Sb	Bi	Total
f737	1	Brass	75.51	22.00	<0.01	0.20	0.32	<0.01	0.03	0.97	0.12	0.09	<0.01	99.24
f738	2	Brass	78.29	15.45	0.12	5.61	0.25	<0.01	0.06	0.12	0.11	0.14	<0.01	100.15
f739	3	Brass	66.25	28.11	0.29	3.81	0.41	0.017	0.14	0.24	0.11	0.18	0.02	99.58
f741	5	Brass	78.08	19.10	0.22	0.20	0.38	0.012	0.11	0.13	0.16	0.41	0.03	98.83
f742	6	Brass	70.99	22.44	0.08	5.20	0.34	<0.01	0.04	0.68	0.07	0.17	0.15	100.16
f743	7	Brass	75.40	21.63	0.12	0.84	0.56	0.026	0.10	0.10	0.15	0.18	0.02	99.13
f745	9	Brass	80.15	13.41	0.67	4.03	0.53	0.015	0.09	0.56	0.16	0.18	0.08	99.88
f748	12	Brass	78.05	19.33	0.11	0.26	0.44	0.019	0.10	0.46	0.17	0.08	0.04	99.06
f740	4	Copper	97.81	0.18	0.08	0.36	0.38	<0.01	0.08	0.06	0.14	0.05	0.01	99.15
f744	8	Copper	97.15	0.06	0.26	0.75	0.26	<0.01	0.11	0.10	0.25	0.14	0.02	99.10
f746	10	Copper	97.30	0.06	0.73	0.65	0.20	0.012	0.06	0.07	0.11	0.07	<0.01	99.26
f747	11	Copper	95.99	0.07	0.53	0.26	0.33	<0.01	0.28	0.08	0.46	0.46	0.03	98.49
f749	15	Copper	97.51	0.09	0.18	0.10	0.31	<0.01	0.05	0.01	0.48	0.12	0.01	98.86
f750	16	Copper	97.20	0.08	0.49	0.38	0.15	<0.01	0.07	0.05	0.32	0.30	0.02	99.06

For high resolution minor and trace element analysis and measurement of lead isotope ratios, the samples were then digested in 1mL of dilute nitric acid. For elemental analyses, an aliquot was taken for ICP-MS (Thermo Scientific X-Series II). The elements measured were ^{118}Sn, ^{208}Pb, ^{56}Fe, ^{60}Ni, ^{75}As, ^{107}Ag, ^{121}Sb, ^{209}Bi, ^{55}Mn, ^{59}Co and ^{114}Cd. A six-point calibration was prepared using elemental standard solutions to match the matrix and the expected range of the elements. Manganese was below detection in all samples, and there was an isobaric interference of tin with cadmium, so cadmium is excluded. Brass standard 31X 7835.8 was analysed for reference (Appendix Table 3). The combined main, minor and trace element data are presented in Table 4, main text.

Table 3. Triplicate ICPMS analyses of Standard 31X 7835.8 (CHARM) compared to reference values.

	Sn%	**Pb%**	**Fe**	**Ni**	**As**	**Ag**	**Sb**	**Bi**	**Mn**	**Co**	**Cd**	**Total**
Given	0.52	3.15	1000	1580	1430	4630	1150	1120	930	3130	870	100
C(95%)	*0.01*	*0.03*	*30*	*50*	*40*	*60*	*20*	*50*	*30*	*30*	*30*	-
Measured	0.47	3.02	1158	1478	1276	4086	988	1126	940	3265	924	97.2
2SD	*0.02*	*0.32*	*586*	*543*	*2*	*156*	*45*	*122*	*38*	*137*	*25*	*5.4*

For lead isotope analyses, an aliquot containing 500µg of lead was placed in a Savillex beaker, reacted with 6M HCl and dried down. The samples were re-dissolved in 0.3 mL 0.7 M HBr. The solution was then processed by ion-exchange chromatography using AG®1-X8 anion exchange resin (analytical grade, 200–400 mesh, chloride form). Sample repetitions were spread across multiple batches of column separation. The concentration of the Pb fraction was determined by ICPMS. Once Pb concentrations were known, 2 mL 1% HNO_3 solutions were made containing 100 ng of Pb (50 ppb). The solutions were analysed using a Thermo Scientific Neptune MC-ICPMS using standard sample bracketing (SSB) to correct for instrumental mass fractionation. An in-house secondary standard was measured repeatedly throughout the run to assess the accuracy and variability. The whole method blank was measured to be 55 pg, which is negligible. The lead isotope ratios of the samples were normalised using the NIST981 values of Thirlwall (2002). The lead isotope results are presented in Table 3, main text. The measurement uncertainty reported is the propagated error combining the variation of multiple measurements of the in-house standard (2SD) with the variation of the individual sample measurements (2SE).

Data Quality

The artefacts investigated in this study were previously analysed for elemental data by XRF and atomic absorption spectroscopy (AAS) in the 1970s, and by wavelength dispersive (WDS) electron microprobe analyses (EPMA) in 2008 (all the previous elemental results are presented in Grandin & Hjärthner-Holdar 2008).

For the brasses, the correlation (r^2) of the elements of Zn and Cu from the older analyses with the new pXRF are 0.88–0.90. The new results, from the present study, indicate that Find Number 10925, a casting sprue, contains significantly more lead and much less tin than earlier reported (Table 4, main text). The pXRF over estimates lead concentrations when present above 1%, which may be a systematic error as a consequence of analysing drill shavings rather than solid metal. It is also poorer at measuring elements in the minor-to-trace element range (<1%). Therefore, the discussion of the elemental data is based on the compositions provided in Table 4, main text, which combines pXRF (copper and zinc) with the ICPMS data (all other elements).

The analyses of the lead isotope ratios were carried out in two sessions. For the brass and copper analyses, all lead isotope ratio measurements of the in-house secondary standard were accurate, and their variability during the session was smaller than the laboratory's long-term variability of the instrument, which is 0.003 for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ and 0.007 for $^{208}Pb/^{204}Pb$. Therefore, it can be expected that the measurements of the samples are accurate within this range. Greater variation was witnessed in the session in which the lead objects were measured. During this session the in-house secondary standard had larger variation than the long-term variability of the instrument, and as a consequence, the precision of the measurements is lower. This is reflected in the higher uncertainties of the lead objects in Table 3 in the main text.

Comparanda

We compared the analytical results against the following published datasets:

Brass and Copper

Brass and other copper alloys from the eastern Mediterranean/ Byzantine Empire

- 9 analyses, copper and leaded copper coins from Imperial Roman eastern mints (Brill & Shields 1972)
- 10 analyses, copper and leaded copper coins from late Roman / Byzantine Jerash, Jordan (Birch et al. 2019)
- 7 analyses, brasses and bronzes from late Roman, Byzantine and Umayyad Jerash, Jordan (Orfanou et al. 2020)

Copper Alloys from Asia

- 6 analyses of copper alloys from Tibet (AD 450–650) (Massa et al. 2019)

Western Roman Brass

- 16 analyses, brass artefacts and coins, Imperial Roman, Germany (Merkel 2021a)
- 7 analyses, brass ingots, 3rd century AD, Corisca (Hanel & Bode 2016)
- 3 analyses, brasses, Imperial Roman, Rhineland, Germany (Reichmann et al. 2018)
- 12 analyses, brasses, Imperial Roman, Rhineland, Germany (Durali-Müller 2005)
- 8 analyses, brasses, eye brooches and knob-end bracelets, Imperial Roman, Estonia (Roxburgh 2023)

Western Roman Bronze

- 16 analyses, bronzes, Imperial Roman, Northern Germany (Merkel 2021a)

- 4 analyses, bronzes, Imperial Roman, Rhineland, Germany (Reichmann et al. 2018)
- 20 analyses, bronze coins, Imperial Roman western mints (Brill & Shields 1972)
- 5 analyses, bronzes, Imperial Roman, Rhineland, Germany (Durali-Müller 2005)

Western Roman Copper
- 106 analyses of copper ingots, Early Imperial Roman, western Mediterranean (Jézégou et al. 2011; Klein et al. 2007; Rico et al. 2005)
- 149 analyses of copper coins, Early Imperial Roman (Klein et al. 2004; Klein et al. 2012)
- 4 analyses of copper artefacts, Imperial Roman, Rhineland, Germany (Durali-Müller 2005)

Viking-Age Brass
- 44 analyses, brass / leaded brass ingots and artefacts, Viking period, Hedeby, Northern Germany (Merkel 2022)

Viking-Age Copper
- 4 analyses, copper artefacts, Viking period, Hedeby, Northern Germany (Merkel 2022)

Lead: Metal Artefacts
Roman Lead
- 154 analyses of lead from the Rhine region (Durali-Müller 2005)
- 28 analyses of lead ingots (Hanel et al. 2013; Bode et al. 2021)
- 23 analyses of Iron Age and Roman lead from England (Ponting 2018)

Sasanian Lead
- 34 Sasanian lead alloy coins (Van Ham-Meert et al. 2019)

Viking-Age Lead
- 18 lead objects from Hedeby, Germany, 9^{th}–11^{th} century AD (Merkel 2016a)
- 37 analyses of lead from Gokstad Norway, 9^{th} century AD (Pedersen et al. 2016)
- 25 analyses from Birka, Sweden, 9^{th} –10^{th} century AD (Stos-Gale 2004a)
- 26 analyses from York (Kershaw & Merkel 2023)

Byzantine Lead (11^{th} century AD)
- 71 analyses of lead and lead glaze from the Serçe Limani shipwreck off the coast of Turkey, 11^{th} century AD (Stos-Gale 2004b)

Lead: Galena Ore Analyses
Northwest Continental Europe
- 12 analyses from Melle, Aquitaine (Téreygeol et al. 2005)
- 55 analyses from the northwest Eifel (Bode 2008; Schneider 1994)

British Isles
- 23 analyses from Derbyshire and 15 analyses from Mendip Hills (Rohl 1996)

Greece
- 55 analyses of ore from Laurion, Pangaeon, Siphnos and Chalkadiki (Vaxevanopoulos et al. 2022)

Turkey
- 58 analyses of lead and polymetallic ore from south Black Sea coast region (Sayre et al. 2001)

Scandinavia
- 139 analyses from Finland, 109 from Norway and 518 from Sweden (Blichert-Toft et al. 2016 and references therein)

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