

ORIGINAL ARTICLE

Silver recycling in the Viking Age: Theoretical and analytical approaches

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Abstract

The recycling (remelting) of precious metals is commonly seen as a major impediment in provenancing studies. Yet in cases where known silver sources are both limited and geochemically well-characterized, there are opportunities to evaluate silver flows at different temporal and geographical scales. Here, we provide a theoretical and analytical framework for assessing the impact of precious metal recycling in a historical context in which silver remelting was the norm: Viking Age Scandinavia (c.800–1050 CE). Harnessing new, large-scale, Pb isotope and trace element datasets, we demonstrate the potential for revealing the contribution of Western European and Islamic silver sources to discrete archaeological assemblages and defined coin and artefact groups. We then use chemical markers of change in imported silver to assess the longevity of circulating silver stocks. Rather than acting as a barrier to understanding, recycling provides a lens through which to evaluate long-distance trade networks, the movement of silver and the frequency of recycling events.

KEYWORDS

cupellation, Pb isotopes, recycling, silver, trace elements, Viking Age

INTRODUCTION

Silver was crucial to the Scandinavian world of the Viking Age, enabling people without access to traditional forms of capital, such as land or cattle, to acquire and pass on wealth. Alongside its scarcity and durability relative to other commodities, its value lay in its mutability, or ability

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to change form and substance (Sainsbury et al., 2021). Silver could be assembled in different forms from diverse sources, split into precise amounts, cast into objects for storage, ornament or currency, cut up when required, and remelted and recast for an entirely different purpose. The reworking, melting, casting, modification, recirculation and reliquidation of silver was thus embedded in the Scandinavian silver economy, enabling it to flow between different circulatory spheres.

The fact of frequent recycling impacts on our understanding of the scale of silver import and the lifespan of silver stocks (Kershaw et al., 2021), and raises hitherto unanswered questions about the social values attached to casting and object transformation. It also prompts concerns about the usefulness of analytical approaches in attempting to identify original silver source(s). Recycling, often taken as being synonymous with mixing, is generally seen as a major impediment for archaeometallurgists seeking to track the source of metals because it can introduce an extra level of uncertainty and ambiguity on top of an already challenging task (Pernicka, 2014, 256–259; Killick et al., 2020, 89–90). For this reason, the study of recycling and recycled metal tends to be discouraged (Craddock, 1985, 59) or avoided altogether; the use of ‘recycling’ and ‘mixing’ become catch-alls to explain everything that does not fit into a clean source-based model.

This highlights the theoretical difficulties recycling poses to traditional metal provenance studies, but also points to potential theoretical inadequacies of the traditional paradigm, which recent work is now striving to address from other angles (e.g., Bray, 2020; Ponting & Levene, 2015; Sainsbury et al., 2021). As Bray (2020, 246) notes, it is important to ‘unpack the recycling box’ to deconstruct and critically examine the assumptions associated with recycling. Here, we harness archaeological and geochemical data for Viking Age silver to provide a new theoretical framework for silver recycling in the period c.800–1100 CE, focusing on the implications of recycling for analytical and provenance studies. Rather than emphasizing the difficulties recycling poses, we give examples where recycling has the potential to elucidate long-distance trade networks and silver supplies.

DEFINING AND IDENTIFYING RECYCLING

For Viking Age silver, an important point of departure is that silver was not mined in Scandinavia during this period, and thus *all* silver had to be imported and recycled in some way. The period c.800–1100 was characterized by economic bouyism across the Baltic and North seas. It witnessed a growth in long-distance trade networks, market centres and the use of silver currency, developments underpinned, in part, by a boom in extractive metal industries both in Europe and the Islamic Caliphate. Thanks to the survival of imported coin in Viking Age silver hoards, it is clear that most silver imported into Scandinavia took the form of coinage: Islamic and Western European coinages in the ninth and early 10th centuries, and German and Anglo-Saxon coinages from the late 10th to 11th centuries (Jonsson, 1990; Noonan, 1994), although intact and fragmentary imported silver objects, including jewellery, are a secondary presence in Viking Age contexts (Baastrup, 2013). To judge from the widespread presence of ingots and ingot moulds, and certain styles of silver ring, there is widespread agreement that this coined silver was melted down within Scandinavian contexts and cast into Scandinavian-style objects. Thus, unlike other early medieval examples of recycling, in which recycling is assessed (appropriately) as a response to shortfall or crisis, as a means of extending the lifespan of an object or perpetuating its commodity value amid a decline in the fresh supply of raw materials (e.g., Fleming, 2012; Swift, 2012), recycling in the Viking Age was widespread and took place against a backdrop of economic buoyancy.

In his recent discussion of Cu alloy recycling, Peter Bray identified multiple different ‘pathways by which a new object can be formed from an old one, even if the alteration is slight or

even just contextual' (Bray, 2020, 247, fig. 7.3). Embracing a wide definition of recycling to include 'any object that has been modified from its "original" or "prime" shape, composition, ownership or chronological context' (Sainsbury et al., 2021, 217) and taking inspiration from Bray's schema, we suggest the following four categories of silver recycling in the Viking Age:

- *Reclamation*: At its most straightforward, silver could be reused without modification in a different temporal and cultural context, an example of 'reclamation' to use Bray's terminology. Here, the transformation is conceptual rather than physical, its identification in the archaeological record requiring knowledge of what constitutes an old or foreign element in 'a new social world' (Bray, 2020, fig. 7.3). Coins imported from the Carolingian Empire or Islamic Caliphate and preserved as complete coins in Viking Age hoards in Scandinavia provide an example (e.g., Garipzanov, 2009). They have been removed from their intended monetary sphere and reconceptualized as a store of bullion rather than official coinage in a different temporal, cultural and economic context. Although repurposed, they remain physically and geochemically unchanged.
- *Refashioning*: Silver could also be reused with modification to its form: Remodelled or reworked without remelting to modify its properties or to transform it from one artefact class to another. The only requirement for this process is that the metal to be reformed is equal in size to or larger than the desired product, is in a compatible form, and that the alloy is correct, possessing the necessary qualities such as malleability, ductility, softness/hardness and fineness. Such processes are encapsulated in the hammering of cast bar ingots into arm-rings: a prerequisite stage of manufacture for all such products (Sheehan, 2009, 68–9); the piercing of coins for use as necklace ornaments (Audy, 2018); and the rolling of dirhams (Islamic silver coins) into beads (Kilger, 2008, 317). By definition, such modifications must be visually recognizable; indeed, in many instances, such as the production of arm-rings from ingots, the original form of the silver becomes obsolete, obscuring the process of object transformation. Refashioned objects might undergo changes to their appearance, function and alloy properties (e.g., hammering will harden the alloy), but their chemical composition does not change.
- *Remelting*. Silver could be melted down, either on its own or with other silver, with the intent of being transformed into one or more new artefacts. Remelting is used when the raw materials are smaller than required, or otherwise in incompatible shapes/forms, or the composition needs to be adjusted by alloying. Remelting silver is relatively straightforward, requiring only crucibles, moulds, a heat source, tools and a smith knowledgeable of the task. However, evidence for it is often intangible. The melting and remelting of silver serves to keep metal in circulation, with scrap silver or unsuccessfully cast items returned to the melting pot, rather than deposited in such a way that it becomes part of the physical record. Scanning electron microscopy (SEM) analysis of 60 melting crucibles recovered from the Viking Age settlement of Kaupang, Norway, revealed that silver was the most frequently melted metal, despite the fact that it was rarely discernible as melting drops and was rare among scrap metal from the settlement area (Pedersen, 2016, 125, 191–192). This indicates the very careful handling of precious metal, which is likely to lead to its under-representation in archaeological contexts such as casting workshops.

Nevertheless, finds of crucibles and moulds at Viking Age emporia such as Hedeby, Schleswig-Holstein (part of Viking Age Denmark) (Drescher, 1983; Merkel, 2016, 209–221; Resi, 1979, 61–64) and Kaupang, Norway (Pedersen, 2016), attest vibrant silver casting industries producing objects such as ingots, rods and rings. The discovery at Kaupang of a remarkable, partially melted crucible charge provides a rare glimpse of an interrupted remelting process (Blackburn, 2008, 32–33; Pedersen, 2016, 167). The fused melt weighed nearly 30 g, well within the estimated capacity of Viking Age crucibles (about 70–100 g). It contained two items of deliberately cut or hack-silver, along with fragments of 12 coins, two of which were identified

as Islamic Abbasid dirhams dating to the second half of the eighth to early ninth centuries. Five other samples, taken from different areas of the melt and analysed with SEM using energy-dispersive X-ray spectrometry (EDX), indicate silver compositions very similar to the dirhams, highlighting dirhams as the major silver source (Pedersen, 2016, 167). This mix of hack-silver – itself a product of remelting and recasting – and coin is likely to have been typical of the items brought together as raw material for silver working and demonstrates the fluidity of the movement of silver between the monetary and metalworking spheres. It has profound implications for the geochemistry of Viking Age silver.

- *Refining.* In addition to being remelted, silver could be refined or cupelled: heated together with lead, in order to sequester the precious metal from impurities. Cupellation was required in the initial production of silver to extract silver from the (typically argentiferous lead) ore, but was also deployed secondarily to remove impurities and raise the silver standard. Such practices may be undertaken to achieve a certain silver standard, for instance, in the minting of coinage, or for some forms of metalworking. Viking Age silversmiths exercised considerable control over silver alloys, selecting those that would best exploit their material properties. Analyses have shown that silver jewellery executed in filigree and granulation has consistently higher silver contents than less or non-ornamental items such as plain rod rings or ingots, which implies (but need not necessitate) the use of cupellation to reduce impurities (Hårdh, 1976, 115; Eniosova & Mitoyan, 2011, 583). Not only does the higher fineness of silver impart a higher melting temperature, and thus a wider thermal tolerance during soldering, it also decreases the hardness of the metal, making it more ductile and malleable for the creation of intricate patterns (Mecking, 2010, 53–54; Merkel, 2016, tab. 2.1).

Significantly, while secondary cupellation could be a one-off event, it could also be ongoing, occurring multiple times during the alloy's lifetime. Depending on the Pb content of the ore, lead may or may not have been added to the silver during primary cupellation, but secondary cupellation required the addition of exogenous lead. Since the added lead outweighs the Pb content of the silver, it will dominate the Pb isotope ratios. Lead originating from a source distinct from that of the silver will, then, impart on the silver a Pb isotope ratio independent of the silver source. In this way, refining has the potential to be a major barrier to provenancing studies.

ANALYTICAL APPROACHES TO SILVER RECYCLING: REMELTING

In the above scheme, only the remelting and refining of silver has the potential to impact its alloy and geochemistry. The Pb isotopes and combination of trace elements found in silver objects cast out of recycled and/or refined silver will differ from those of 'first generation' silver products using only silver from a single ore source (for parallels in Cu alloy recycling, see Ponting & Levene, 2015; Pollard et al., 2015; Bray et al., 2015). The remelting of silver without refining, and the remelting of silver with refining each brings its own analytical constraints, and opportunities.

The first is the straightforward remelting of silver, from a single or multiple sources, as exemplified by the Kaupang crucible melt described above. Since coin was likely the dominant form in which silver was imported into Scandinavia, it follows that the casting of, for instance, a 50 g ingot or ring would have required the melting down of numerous coins (each 2–3 g) or other small pieces of silver, potentially of diverse origin. This process homogenizes the silver both elementally and isotopically, creating an average composition reflecting the proportions of its components.

While in provenance studies situations producing 'mixtures' are normally highly undesirable, the real value of this kind of information becomes apparent as the number of knowns

increases. In the case of Viking Age silver, extant coins and artefacts preserved in silver hoards indicate that the total number of major silver sources is limited to just two broadly defined groups: silver coin and plate originating in Western Europe, notably Britain and the Carolingian Empire, in the ninth century; and dirhams originating in the Islamic Caliphate. While these sources are internally varied, they can be distinguished from each other both elementally and isotopically. For instance, the Au content of Abbasid dirhams is, on average 0.2 wt%, whereas ninth-century Anglo-Saxon and Carolingian coins commonly have Au contents three to four times this level (Kershaw & Merkel, 2019; Sarah, 2010). Thus, mixtures of these two sources can provide information about their relative abundance in any analysed artefact (Merkel, 2019; Sarah, 2008, 2019). Admittedly, this cannot be done in all periods and for all assemblages, but when a framework of knowns can be constructed, information about mixing can lead to a greater understanding of the circulation and movement of metal particularly in the areas between sources.

We recently used laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-(MC)-ICP-MS) to obtain Pb isotope and trace element measurements for nine items of hack-silver from an early Viking Age silver and bead hoard from Kettilstorp, Västergötland, in south-west mainland Sweden (t.p.q. 850–1) (Hårdh, 2008, 117) (Fig. 1). In addition to the hack-silver, the hoard contained eight Umayyad and 22 Abbasid dirhams (particularly from Wasit, Madinat al-Salam (Baghdad) and Samarkand mints, although mints could not be attributed to 12 dirhams) alongside eight Carolingian coins. Most of the latter were minted in Melle, Aquitaine, France: both a major lead-silver mine and mint in the Carolingian Empire (Mäkeler & Berghaus, 2009). The combination of Western European and Arabic coinage raises questions about the origin of the hack-silver in the hoard. Was it cast from Carolingian or Arabic silver, neither or both?

Both Pb isotope ratios and elemental concentrations of the nine hacksilver artefacts were measured at the Vegacenter, Swedish Museum of Natural History, Stockholm. The data were captured by minimally destructive laser-ablation, and the methods are fully described by Kershaw et al. (2021). Briefly summarized, *in-situ* Pb isotope analysis was carried out using a Nu II multi-collector inductively coupled plasma mass spectrometry (ICP-MS) connected to a nanosecond 193 nm laser. Glass standard NIST-612 and a series of matrix-matched silver reference materials were analysed regularly. MBH-133X-AGA3 (AGA-3) was the primary standard used to bracket the samples for linear drift correction using solution values measured at the Earth Sciences Department at the University of Oxford. The artefacts were ablated in three separate locations, and the standard deviations (2σ) of the artefacts are commonly under 0.3% for all of the Pb isotope ratios. Elemental concentrations were measured by laser coupled to a SC-HR (single collector-high-resolution)-ICP-MS. Reference material MBH-133X-AGA-3 was



FIGURE 1 Hoard from Kettilstorp, Västergötland, Sweden. Photo: Swedish Historical Museum [Color figure can be viewed at wileyonlinelibrary.com]

the primary standard used for sample bracketing and quantification. Each object was measured on three 85 μm spots for 50 s. The relative standard deviations of Cu, Au and Pb are on average around $\pm 20\%$ (SD) but Zn and Sn values are significantly more heterogeneous, and due to a Pb tailing effect, it not possible to quantify Bi. For the Pb isotope and elemental results, see Tables 1 and 2.

We compared the analytical results from the Kettilstorp items against a series of data on contemporary Carolingian and Islamic silver. To assess the contribution of Carolingian silver, we compared our analytical results with published Pb isotope data for the Melle mine, as well as published trace element and Pb isotope data for Carolingian coinage from the Melle mint (Gratuze et al., 2018; Sarah, 2008; Téreygeol et al., 2005). Assessing the contribution of Umayyad and Abbasid dirhams was more complicated, owing to the wide geographical span of mints represented in the hoard and to the fact that 12 of the dirhams possessed no mint information. Our own Pb isotope and trace element dataset of over 140 precisely dated Islamic Umayyad and Abbasid dirhams from mints stretching from North Africa to Central Asia indicates stark regional differences in elemental concentrations as well as Pb isotope ratios (Merkel et al. in prep.). Rather than trying to compare the Kettilstorp hack-silver with individual dirhams, we therefore sought to compare it with a homogenized dirham stock representative of the dirhams reaching Scandinavia in the ninth century. We modelled the average Pb isotope composition of several ninth-century dirham hoards from the Swedish Baltic island of Gotland to generate estimates of the isotopic and elemental composition of dirham silver (mainly Abbasid) present in these hoards (Kershaw et al., 2021). The results provide a proxy dataset for a homogenized Islamic silver stock in ninth-century Sweden, providing further comparanda for the Kettilstorp data.

The Kettilstorp items vary both isotopically and elementally, particularly between large, cast items and smaller jewellery fragments (Tables 1 and 2). Elementally, the analysed objects are made of sterling or higher quality silver, with between about 3–5 wt% Cu. Most objects have notable traces of Zn and Sn, contaminants from minor amounts of Cu alloys (i.e. brass, bronze, gunmetal) intentionally or unintentionally added to the silver. Such impurities are atypical for Islamic silver but are more common in Western European silver, but such contaminants/alloying components could have entered the alloy independently of the silver stock. The Au contents of most objects fall between about 0.25 and 0.5 wt%, which could reflect Islamic dirhams or mixtures with or without the contribution of Carolingian/Western European silver. Average Umayyad silver contains about 0.7 wt% Au, which lowers to an average of about 0.2–0.3% in the Abbasid period (Merkel et al., in prep), while early ninth-century Anglo-Saxon (794–840) and Carolingian coinage during the reigns of Louis the Pious and Pepin II of Aquitaine (813–852) both have an average of 0.23 Au/100 Ag (Metcalfe & Northover, 1989; Sarah, 2008). The Au contents of two objects in the Kettilstorp hoard fall outside of this range, the silver band (No. 4) with low Au (0.14 wt%) and the bar-like ingot (No. 1) with high Au (1.14 wt%), possibly mixed with gilded silver.

We plotted the Pb isotopes of the four large cast items against modelled average isotope compositions of ninth-century Gotlandic dirham hoards and reference data from Melle. All these objects plot within or fall between these two source groups (Fig. 2). One object (No. 4, a silver band) is clearly dominated by dirham-like ratios; together with its low Au content, this points to an exclusive or near-exclusive source based on dirhams. The other three objects border on dirham hoard averages, but may be influenced by a slight contribution of Western European silver. In sum, the large, cast items produced from multiple coins appear to carry homogenized lead isotope (LI) values.

In contrast, the five smaller objects are much more diverse. One is consistent with Melle reference data in all LI ratios (No. 8, a conical bead). Another is more similar to homogenized dirham hoard ratios (No. 9, a round bead). The three remaining items (Nos 5–7) are distinct from both reference datasets, but are consistent with individual dirhams minted in Jibal

TABLE 1 Pb isotope ratios of Viking period objects discussed in the text

	<i>Size</i>	<i>Object</i>	<i>206/204</i>	<i>2 SD</i>	<i>207/204</i>	<i>2 SD</i>	<i>208/204</i>	<i>2 SD</i>	<i>207/206</i>	<i>2 SD</i>	<i>208/206</i>	<i>2 SD</i>	<i>208/207</i>	<i>2 SD</i>
1	Kettilstorp	Massive Bar	18.516	0.017	15.650	0.016	38.58	0.07	0.8452	0.0006	2.084	0.002	2.465	0.001
2	Kettilstorp	Massive Duesm. ring	18.525	0.022	15.662	0.026	38.67	0.11	0.8455	0.0008	2.087	0.004	2.469	0.002
3	Kettilstorp	Massive Ring 4915:2	18.511	0.013	15.655	0.012	38.63	0.07	0.8457	0.0005	2.087	0.002	2.468	0.001
4	Kettilstorp	Massive Band	18.606	0.023	15.673	0.028	38.82	0.12	0.8424	0.0008	2.086	0.004	2.477	0.002
5	Kettilstorp	Small Flat sheet	18.317	0.026	15.641	0.026	38.55	0.08	0.8539	0.0007	2.105	0.003	2.465	0.001
6	Kettilstorp	Small Ring	18.416	0.011	15.643	0.010	38.57	0.06	0.8494	0.0004	2.094	0.002	2.465	0.001
7	Kettilstorp	Small Rolled sheet	18.428	0.014	15.646	0.013	38.57	0.07	0.8490	0.0005	2.093	0.002	2.465	0.001
8	Kettilstorp	Small Bead conical	18.483	0.019	15.647	0.024	38.55	0.11	0.8466	0.0007	2.086	0.003	2.464	0.002
9	Kettilstorp	Small Bead round	18.537	0.020	15.667	0.025	38.66	0.11	0.8452	0.0007	2.086	0.004	2.469	0.002
10	Alvara Öland	Massive Perm'/Glazov ring	18.575	0.024	15.656	0.029	38.71	0.12	0.8428	0.0008	2.084	0.004	2.4725	0.007
11	Hedeby	Massive Perm ring terminal	18.574	0.008	15.660	0.008	38.68	0.02	0.8431	0.0001	2.0823	0.0002	2.4698	0.0005

Note: The artefacts from Kettilstorp and Alvara, Öland, were analysed by nsLA-MC-ICP-MS (for methods, see Kershaw et al., 2021). One previously published analysis of a perm'/Glazov ring terminal from Hedeby is provided for comparison (Merkel, 2016)

TABLE 2 Elemental concentrations of Viking period objects discussed in the text

	Size	Object	Cu (%)	2 SD	Au (%)	2 SD	Pb (%)	2 SD	Zn (ppm)	2 SD	Sr (ppm)	2 SD	Bi (ppm)
1	Kettilstorp	Massive	Bar	3.96	0.73	1.14	0.06	0.48	0.12	1336	2767	1704	< 130
2	Kettilstorp	Massive	Duesm. ring	4.99	0.10	0.24	0.02	0.67	0.04	80	2163	139	< 970
3	Kettilstorp	Massive	Ring 4915:2	4.75	0.09	0.53	0.02	0.92	0.06	246	1067	40	< 470
4	Kettilstorp	Massive	Band	3.17	0.26	0.14	0.01	0.98	0.23	155	367	116	< 990
5	Kettilstorp	Small	Flat sheet	3.74	0.48	0.53	0.10	0.81	0.14	1397	730	111	> 500
6	Kettilstorp	Small	Ring	5.19	0.06	0.23	0.01	1.09	0.04	10 480	540	52	< 660
7	Kettilstorp	Small	Rolled sheet	3.10	0.23	0.25	0.03	0.89	0.07	60	20	23	< 870
8	Kettilstorp	Small	Bead conical	4.46	0.23	0.50	0.08	0.96	0.05	1153	813	243	> 560
9	Kettilstorp	Small	Bead round	4.17	0.47	0.35	0.16	0.95	0.22	4453	1087	260	< 530
10	Alvara, Öland	Massive	Perm'/Glazov ring	4.64	0.73	0.98	0.13	0.64	0.19	427	592	209	< 290
11	Hedeby	Massive	Perm ring terminal	6.5	0.7	0.36	0.04	0.84	0.08	2910	1310	130	780

Note: The artefacts from Kettilstorp and Alvara, Öland, were analysed by LA-ICP-MS (for methods, see Kershaw et al., 2021). One previously published analysis of a perm'/Glazov ring terminal from Hedeby is provided for comparison (Merkel, 2016).

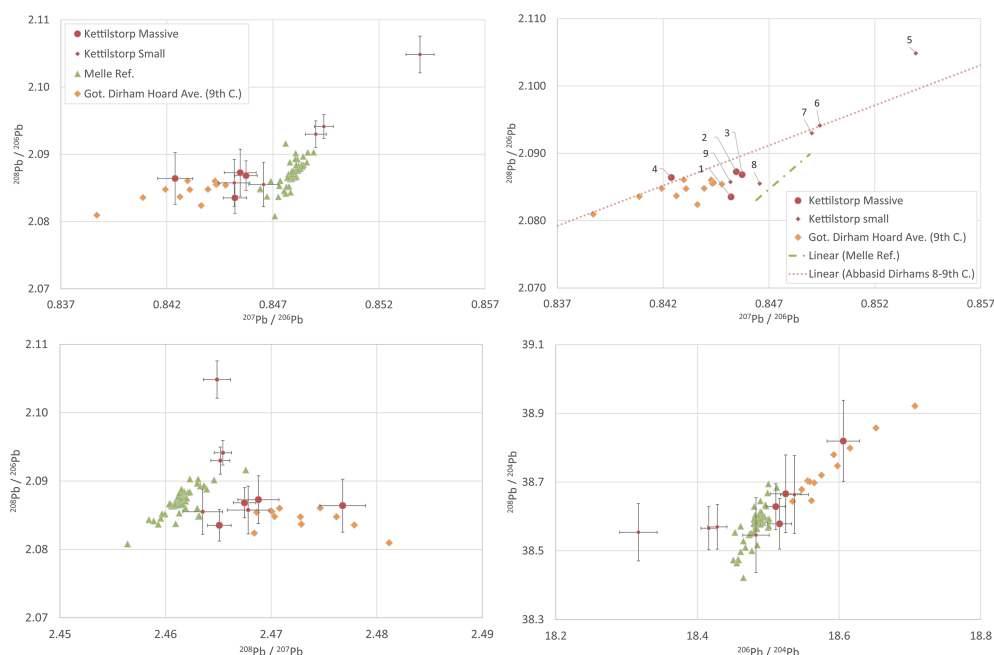


FIGURE 2 Pb isotope diagrams comparing the Kettilstorp hoard items with reference data for Melle, France, and homogenized dirhams in ninth-century Gotland hoards (references in the text) [Color figure can be viewed at wileyonlinelibrary.com]

(al-Muhammadiyya, Iran) and Khorasan (a historical region of north-east Iran, Uzbekistan, Tajikistan and Afghanistan) in the ninth century (Merkel et al., in prep). These items are so small that they could have been made from a single coin, and thus their LI values fall at diverse points within the field of recorded values.

Analysis of the Kettilstorp silver demonstrates how geochemistry can be used to evaluate the relative abundance of two well-characterized sources of silver within a discrete assemblage by providing evidence for mixed compositions. But what about instances of ‘like with like’ mixing (Duckworth, 2020, 304, 345)? This question is especially pertinent to more easterly areas of Scandinavia, where, to judge from extant hoards, Islamic dirhams constituted the predominant silver source, with less evidence for the presence of Western European coinage. In the case of homogenized Eastern silver, a large dataset that takes into account temporal and geographical trends in dirham production, and corresponding shifts in dirham compositions, might elucidate patterns of dirham recycling over time.

Past studies have used trace element analysis to investigate the connection between Islamic dirhams and ninth- and tenth-century Scandinavian and Slavonic jewellery. Using atomic absorption spectroscopy, Arrhenius et al. (1972–73) determined that silver bars contained in a silver hoard from Hesselby, Gotland, Sweden, were not cast purely from Abbasid dirhams. The bars had higher contents of Cu, Zn and Pb than was typical for these coins, suggesting either a different raw material source or the addition of other silver to a mainly Abbasid silver stock. More recently, Eniosova and Mitoyan (2011) used portable XRF (pXRF) to compare the composition of Samanid dirhams, minted in the first half of the 10th century, to silver jewellery in 10th-century hoards from Gnezdovo, Russia. They concluded that the high Bi content detected in the silver jewellery originated from high-Bi Samanid dirhams (Eniosova & Mitoyan, 2011, 583). However, the jewellery items had consistently lower Cu, Pb and Bi contents relative to the dirhams, suggesting either that dirham silver was cupelled prior to manufacturing into jewellery, or that the silver was of mixed source.

Analysing trace elements in combination with Pb isotopes adds a further dimension to analytical studies. One of the earliest silver ring types that circulated in Viking Age Scandinavia was the so-called Perm' or Glazov ring. Perm'/Glazov-type rings are large, weight-adjusted striated rings often made in units of 200, 300 and 400 g, which originated in the Volga–Kama–Vyatka regions in Russia (Fig. 3) (Hårdh, 2016). Their main period of manufacture is dated from *c.*800 and is connected to the fur trade (Hårdh, 2016, 32). However, while an Eastern source for their silver seems likely, the exact origin(s) remains uncertain. One hypothesis is that the rings were made from recycled North African dirhams, which are common inclusions in Russian hoards from the first decades of the ninth century (Kilger, 2008, 214; Noonan, 1980, 421, 423). Another is that Oriental vessels imported into Russia from Central Asian served as raw material, alongside Islamic dirhams (Hårdh, 2016, 35–37). Due to their large size, Perm'/Glazov arm-rings are likely to have been cast from multiple individual components; in the case of coins, an arm-ring weighing 400 g would have utilized over 130 dirhams, each weighing close to 3 g. Thus, we would expect that their composition reflects a high level of homogenization.

We analysed two Perm'/Glazov rings/ring fragments, the first by solution MC-ICP-MS and the second by LA-MC-ICP-MS (Table 1). The first piece, from a ring terminal, was recovered at Hedeby (Schleswig-Holstein, Germany), while the second is a nearly complete ring from the Alvara Hoard, Öland (Merkel, 2016, cat. no. 176; Kershaw et al., 2021). Isotopically, the two rings are extremely similar. They do not match available isotopic data on eighth-century North African dirhams, nor do they correlate with this dataset elementally. North African dirhams are characterized by very low Au contents (< 0.01 wt%) (Merkel et al., 2020a), whereas the Perm'/Glazov rings from Alvara and Hedeby contain 0.98 and 0.35 wt% Au, respectively (Table 2).

Instead, the Pb isotope compositions are nearly identical to the average Pb isotope composition of 28 analysed late seventh- to eighth-century Umayyad dirhams (Fig. 4) (Merkel et al., 2020b). This dirham dataset mainly comprises dirhams from the mint of Wasit, the most productive Umayyad mint, but the dataset spans the Umayyad Caliphate, and is expected to be broadly representative of Umayyad dirham silver as a whole. There are significant shifts in the Pb isotope ratios of dirhams beginning around the last quarter of the eighth century, and thus the Pb isotope ratios of the arm-rings signal the use of silver predating this shift. The Au levels observed in the analysed artefacts also fit with this interpretation. While Umayyad dirhams with 1 wt% Au were fairly common, particularly at the mints in Damascus, the Caucasus (Arminiya) and in Khorasan (Gordus, 1972; Merkel et al., 2020b), from *c.*720 the Au content



FIGURE 3 Permian ring from the Alvara hoard, Öland, Sweden. Photo: Swedish Historical Museum) [Color figure can be viewed at wileyonlinelibrary.com]

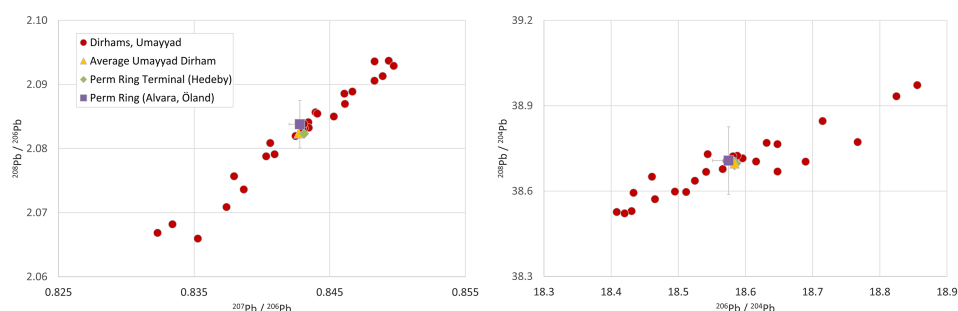


FIGURE 4 Pb isotope diagrams comparing Umayyad dirhams (Merkel et al., 2020b) with two perm'/Glazov rings. The analytical error (2 SD) for individual analyses is smaller than the symbol unless otherwise shown. The isotopic similarity of the perm'/Glazov rings with the average ratios of Umayyad dirhams means that ring could have been made from a mixture of dirhams [Color figure can be viewed at wileyonlinelibrary.com]

of dirhams declined, and high Au dirhams are scarce after *c.*750 (Gondonneau & Guerra, 2002, 582–583). The high Au content of the Alvara Perm'/Glazov ring thus points to an early silver source, dating to before the mid-eighth century, most likely recycled Umayyad dirham silver arriving in Perm before this date.

ANALYTICAL APPROACHES TO SILVER RECYCLING: REMELTING WITH REFINING

Refining or cupellation has a profound impact on metal alloys, decreasing or removing many trace elements and imparting Pb isotope values which may not relate to the original source of silver. If multiple cupelled silver items are melted down together, their Pb isotope values will reflect a mixture of the various sources of lead used to refine them. For this reason, refining is commonly regarded as a major impediment to provenancing studies (Artoli et al., 2020, 66). This is particularly the case in studies of silver coinage, since the need for high Ag purity levels in combination with the need to regularly remind the existing coin stock created many opportunities for silver recycling and refining (e.g., Birch et al., 2020; Guénette-Beck et al., 2009).

How extensive was silver refining in Viking Age Scandinavia? Certainly, Ag purity was of paramount importance in the Scandinavian bullion economy, as indicated by the frequent 'nick' and 'peck' marks made to silver to interrogate its metal purity and identify plated forgeries. The control of Ag alloys for the production of fine silver jewellery necessitated silver refining, even from 'pure' to 'hyper-pure' levels. Such refining is likely to have been particularly necessary during temporary periods of debasement in the source coinage, such as that which occurred in the mid-ninth century in coinage from Anglo-Saxon England and the Carolingian Continent (Metcalf & Northover, 1985; Sarah, 2008) or towards the end of the stream of dirham import into Scandinavia in the 950s and 960s, when the Ag content of dirhams dropped to the region of 70–80% (Ilisch et al., 2003; Jankowiak, 2020).

However, the need for refining was mitigated by several factors. First, notwithstanding periods of temporary debasement, the source coinages imported to Scandinavia during the Viking Age were characterized by high Ag purity. In particular, Islamic dirhams typically constituted over 95% silver, with very low levels of trace elements (Ilisch et al., 2003). The decline in their Ag content towards the mid-10th century resulted almost immediately in their increased hoarding within Scandinavia and their ultimate rejection by the local population in favour of new, higher quality silver coins from Germany (Jankowiak, 2020).

Second, the very fact that Scandinavians developed methods for assessing the quality of silver ('nicking'/'pecking') suggests that they were aware of the possibility of debased silver, which in turn implies that silver was not routinely cupelled. Indeed, later legal and literary texts suggest an acute awareness of silver fineness and strict social codes governing the distribution of debased metal (Kilger, 2011, 271–273). Archaeological evidence for cupellation processes, such as litharge and cupellation hearths, is extremely scarce at Viking Age settlements, with the few documented examples dated to the 11th century (Söderberg, 2011; Söderberg & Gustafsson, 2006). At Fröjel on Gotland, for instance, silver cupellation took place in connection with the casting of Gotlandic silver arm-rings and penannular brooches, the former of which were punched with uniform symbols on their sides and likely circulated as both a form of jewellery and a means of exchange before the introduction of a local coinage in the 12th century (Gustafsson, 2013, 108).

Finally, evidence for large-scale silver cupellation is slim. Authors have noted the presence of 'cupellation crucibles' or heating trays at sites such as Kaupang (Pedersen, 2016, 129–135) and Hedeby (Drescher, 1983). These ceramics are small (30–90 mm diameter), open-faced crucibles with a vitreous inner surface, often Pb-rich, and always have traces of Ag and/or Au. This method of recycling used only tiny amounts of metal, probably less than 20 g, the alloys being cleaned by the creation of a Pb silicate slag and oxidizing melting atmosphere. The process likely represents small-scale refining for the production of jewellery (Pedersen, 2016, 130, 133; Merkel, 2016, 209–220; for a discussion of the potential use of these cups in Ag assaying, or analytical cupellation, see Söderberg, 2011, 14). Indeed, these sites have not yielded evidence of litharge cakes or larger cupellation crucibles (diameter of 10 mm and over), such as has been found, for instance, in late Anglo-Saxon York and Winchester, or at Fröjel (Bayley, 1991, 120–121).

In any geochemical analysis of Viking Age silver, it is nevertheless important to assess if silver could have been cupelled. One method is through an analysis of trace elements. Experiments have shown that many elements (for instance, Sn, Zn) are reduced to very minimal levels through cupellation. However, Au, Pt and Bi survive cupellation intact (in the case of Bi, until the very end of the process). Factors such as the scale and duration of the cupellation process may effect elemental behaviour; nevertheless, these elements ought to be present in concentrations reflecting those in their original ore source (Flament et al., 2017, 278–279; L'Héritier et al., 2015; McKerrell & Stevenson, 1972; Pernicka & Bachmann, 1983). The purity and trace element characteristics of Ag thus allows freshly refined Ag to be distinguished from Ag that has contamination indicative of alloying and mixing, while the levels of source-indicator elements are useful for discriminating between potential sources.

A complementary approach is to combine elemental analysis with an isotopic analysis of Pb. It is generally believed that, because of its density and low economic value, lead used in cupellation processes did not travel as far as silver. Thus, lead used in Viking Age Scandinavia probably originated in Europe. Indeed, analyses of 79 archaeological lead items retrieved from Viking Age contexts within Scandinavia shows that all but one originated from Central or Western Europe; the single exception is a lead weight from Birka, Sweden, that could have been made of lead from South-east Europe (Merkel, 2016, 223–230; Pedersen et al., 2016; Stos-Gale, 2004). Archaeological lead found in Northern Europe has little to no isotopic similarity to dirhams that travelled from the Islamic Caliphate. Therefore, where isotope data point to an Islamic source, we can rule out the possibility that silver was refined locally using a European lead source.

Since coinage is often deemed one of the more problematic categories of silver to provenance due to the potential for frequent recycling/refining, it is instructive to compare archaeological lead from Viking Age settlements to one of the earliest coinages produced in Scandinavia: that produced at Hedeby c.900–20, known as the 'Combination Group' 7 or KG 7 series (Malmer, 2007). Archaeological lead from Hedeby is well-characterized isotopically

(Merkel, 2016). In addition, lead-rich slag from small-scale refining dishes have been analysed and closely resemble the Pb isotope ratios of the lead available at Hedeby and in Scandinavia more generally. One of the current writers (SM) has previously reported that Pb isotope analyses of ten coins from the KG 7 series indicate no overlap between the Hedeby silver coinage and Northern European lead, meaning that the coinage could not have been refined with local lead (Fig. 5) (Merkel, 2016, 96–100; 2019). All the KG 7 coins have impurities in levels indicative of minor contamination from Cu alloys, the same as seen in the Gotland/Öland material, and thus the compositions do not indicate recent refining.

Comparing the data against new comparanda comprising over 140 Umayyad and Abbasid-era dirhams, as well as data from Viking Age silver hoards, now enables us to probe the results further (Fig. 5). Isotopically and in their Au and Bi contents, most of the 10 KG 7 coins are consistent with cast silver artefacts from mid-to-late ninth-century hoards from Gotland, which themselves likely reflect a homogenized stock of dirhams reaching the Baltic in the early/mid-ninth century (Kershaw et al., 2021). However, one KG 7 coin is more similar to reference data for Melle, France. This coin unfortunately lacks elemental data and thus it is unclear whether the Pb isotope results relate to Pb used in cupellation to ‘clean’ the Ag, or to Pb naturally contained within the Ag, reflecting its ore source (Merkel, 2016, cat. no. 117). Either Melle silver was available for casting at Hedeby, or Melle lead was available for cupellation, or both.

While contrasting Pb isotope ratios of available lead with cast silver objects/coins silver is a means of by-passing the problem of refining, there are situations where this cannot be applied due to similarities in the Pb isotope ratios between the available lead and the silver. More experimental work on the cupellation process is required to provide a firmer foundation for its identification based on the elemental analyses of archaeological silver. The early ground-breaking

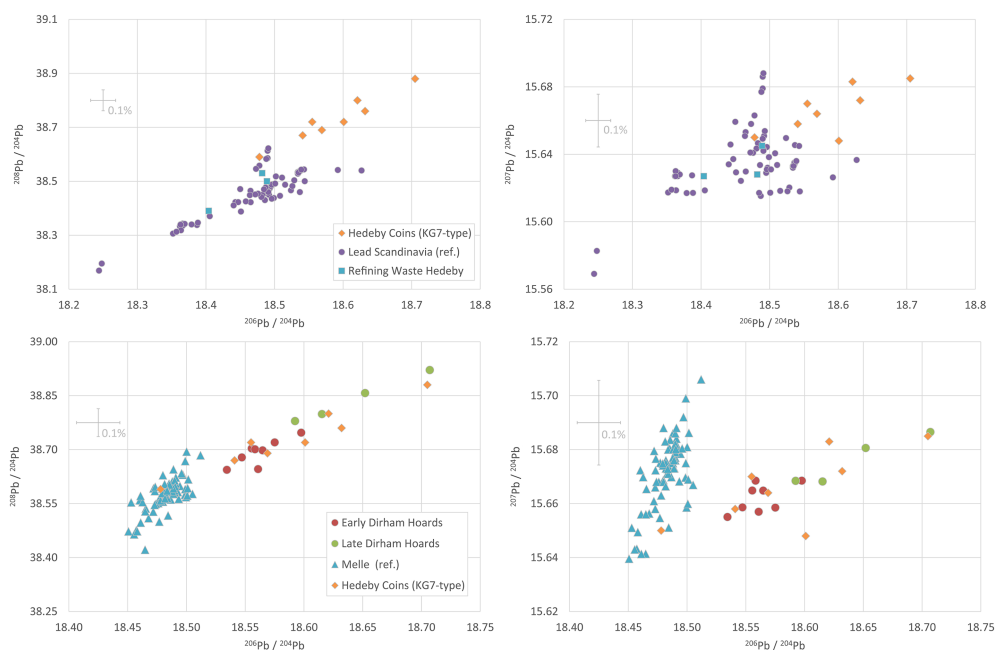


FIGURE 5 Pb isotope diagram comparing the Hedeby KG 7 coinage with archaeological lead from Viking Age Scandinavian contexts (Scandinavian Pb) and lead-based refining waste from Hedeby (upper two diagrams), and Melle lead/slag/silver and homogenized Umayyad/Abbasid dirhams from Gotland hoards (references in the text) (lower two diagrams). The Hedeby coinage is isotopically distinct from the available lead, indicating that the silver could not have been refined in Northern Europe [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

experimental studies on cupellation are now decades old (McKerrell & Stevenson, 1972; Pernicka & Bachmann, 1983) and can be updated with greater detail and state-of-the-art instrumentation. The extremely informative study of the behaviour of Bi during cupellation by L'Héritier et al. (2015) was carried out under laboratory settings, making a one-to-one comparison with archaeological specimens difficult, but it provides a cornerstone for future studies. If it is possible to model the behaviour of elements such as Cu, Zn and Sn during the cupellation process in an archaeologically representative experimental set-up, relationships and limits could be delineated that would provide a basis to distinguish methods of recycling.

RECYCLING AND TEMPORALITY

Within archaeometric studies of recycling, there is a necessary focus on the analysis of archaeologically recovered material that has been either lost or deliberately deposited. Thus, geochemical data pertaining to a single ingot provide a snapshot of silver sources and use at the time the ingot was cast. It does not, however, tell us about the longer life-history of the silver with which the ingot was cast and, consequently, questions concerning the longevity and geography of circulating silver stocks remain. How can we approach the question of changing silver sources to demonstrate the movement of silver in the Viking Age?

One analytical approach is to identify chemical markers of change in imported silver, and to compare those markers against large-scale analyses of well-dated artefact groups (Sainsbury et al., 2021, 217). In Viking Age Scandinavia, a pronounced change in the origin of imported silver dirhams occurred *c.*890 when, following a period of decreased output, there was a switch in dirham supply from Abbasid issues minted predominantly in Iraq and Iran to Samanid dirhams minted in Central Asia. To judge from the dirham composition of Scandinavian hoards deposited in the first few decades of the 10th century, new Samanid dirhams quickly came to replace the former Abbasid stock, which constituted just 10% of dirhams by *c.*930 (Blackburn, 2008, 40–41, tab. 3.7). Substantial numbers of Samanid dirhams continue to arrive in Scandinavia until their debasement from the 930s, which led, ultimately, to their abandonment *c.*950 (Jankowiak, 2020). Fortunately, Samanid dirhams are well-characterized isotopically and elementally and, owing to their distinct ore sources, they are geochemically unrelated to earlier Abbasid dirhams (Merkel, 2016, 100, figs 7.10–7.11). By comparing Abbasid/Samanid silver compositions with those of cast silver artefacts dated to the 10th century, it ought to be possible to see how long it took for the wave of Samanid imports to influence the pool of silver available for casting.

This process is, of course, not straightforward. Some artefact forms, such as ingots, were ubiquitous and are therefore not subject to type-chronologies enabling close dating. Nevertheless, coin series and certain ring forms are possible to date more precisely, and their analysis points to the continued use of 'older' dirham stocks into the 10th century. One example already discussed is the KG 7 coin series, minted at Hedeby in the first two decades of the 10th century. Despite the fact that it was minted at a time when the existing dirham stock was being rapidly replaced by new Samanid dirhams, KG 7 coins bear no resemblance to Samanid silver (Merkel, 2016, 99). Instead, they are made of silver also found in mid/late ninth-century Gotland hoards, that is, a mainly Abbasid or Umayyad/Abbasid silver stock. Importantly, since Abbasid coins were increasingly rare in Scandinavian hoards deposited in the early decades of the 10th century, it is most likely that the dirhams had been transformed into other cast artefacts prior to their use for the KG 7 series. In sum, Abbasid dirham silver likely circulated in various forms for a few decades prior to be melted and formed into the Hedeby coinage.

Notably, later coins minted at Hedeby, dating to the period *c.*950–980 (KG groups 8–11) have an altogether different and varied geochemical profile, including, for instance, average higher Bi levels. This may reflect a substantial contribution of high-Bi Samanid silver, alongside

newly produced European sources of silver, for instance from the Harz mountains (Merkel, 2016, 105). Samanid dirhams arrived in Scandinavia from c.900–950, but those used in the later KG coins did not require refining and probably predate the onset of substantially debased issues from the 940s (Ilisch et al., 2003). Thus, it would appear that both the earlier and later coins minted at Hedeby utilized a dirham stock that was several decades old.

CONCLUSIONS

While early medieval recycling is often interpreted as a response to crisis, silver recycling in the Viking Age requires a different paradigm. Silver recycling via remelting was frequent and widespread, being required to convert substantial inflows of imported metal (mainly coins) into forms more appropriate for use within the Scandinavian economy. From an analytical perspective, such intensity of remelting can be regarded as problematic, particularly where the aim is to link finished items with singular and specific ore sources. However, for Viking Age Scandinavia, the limited sources of silver available, coupled with the lack of evidence for systematic cupellation, present exciting opportunities to elucidate flows of precious metal.

We aimed to demonstrate that, with large-scale analyses and comprehensive reference datasets of ores, silver and lead, it is possible to distinguish between Eastern (Islamic) and Western (European) sources of silver even within discrete assemblages or defined artefact groups. To date, our results point to the predominant use of Eastern over Western sources of silver, although the bulk of our analysis has been carried out in Sweden, and it remains to be seen whether or not this also holds true for silver from Southern Scandinavia and Western settlement areas such as Britain. The identification of dateable changes in the composition of silver entering Scandinavian enables insights into the longevity of circulating silver stocks, with results suggesting that silver circulated in recycled, cast forms for several decades before it was replaced by more recently arrived metal. These insights show how the amassing of large-scale, high-resolution data allow long-standing questions to be investigated in a new light, questions where recycling helps us to understand large-scale socio-cultural and economic phenomena.

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PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/arc.12709>.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are either provided within the paper or are available in forthcoming papers or papers that have been submitted. They are also available on request from the corresponding author. Some of the data referred to is the result of a recently-initiated ERC Project (Silver and the Origins of the Viking Age - PI Kershaw) and will be made available in a repository by the completion of the project at the latest.

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