The scale of dirham imports to the Baltic in the ninth century

New evidence from archaeometric analyses of early Viking-Age silver

By Jane Kershaw, Stephen W. Merkel, Jani Oravisjärvi, Ellen Kooijman and Melanie Kielman-Schmitt

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We present a high precision, minimally-destructive geochemical (lead isotope and trace element) analysis of nine cast silver items from early Viking-Age hoards from the Baltic. Comparing the data to a large reference dataset comprising Islamic dirhams and ninth-century Western European silver, we find that the artefacts were cast chiefly from recycled Islamic silver. Isotopic modelling reveals, further, that the Islamic silver derives from a stock that entered the central Baltic in the first half of the ninth century. This period has traditionally been characterised as one of low-level dirham import, before the escalation of the dirham trade from c. AD 860/70. Our results suggest instead that dirhams entered the central Baltic in significant numbers before c. 850, but were routinely melted down for casting into artefacts. This has two important implications. First, it suggests that the early ninth-century Baltic economy was more closely coupled to Eurasian trade networks than current appreciated. Second, it calls into question the reliance on extant dirhams as a guide to Scandinavia's engagement in long-distance trade routes.

Keywords: Viking-Age, dirhams, silver, Gotland, lead isotopes

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Introduction

The scale of Scandinavian involvement in eastern trade routes during the ninth century is a long-standing question in the field of Viking studies, with implications for the roots of the silver economy and the causes of the Viking expansions (Bolin 1953, p. 29; Callmer 2000; 2017; Sindbæk 2017). The very existence of far-reaching trade networks in the ninth century is not in doubt, with both archaeological and textual sources providing evidence for long-established routes stretching across the Baltic and Gulf of Finland and into northern Russia, along the Don and Oka rivers (Androshchuk 2013; Callmer 2017; Hedenstierna-Jonson 2020). What is questionable is the intensity in use of those routes before the Eastern trade reached its height in the tenth century (e.g. Ambrosiani 2005; Rispling 2007, p. 108). Among the various strands of physical evidence used to examine the phenomenon, extant Islamic silver dirhams have assumed a central importance (Noonan 1994; Jankowiak 2020). Dirhams are recorded in large numbers and, as precisely-dated artefacts from often well-characterised archaeological contexts, appear to offer a solid basis for examining the ebb and flow of traffic along historic eastern trade and communication networks (Kovalev & Kaelin 2007, p. 561).

However, we suggest that surviving dirhams may not be the most reliable proxy for Scandinavia's depth of connection with the east in the early Viking Age (the ninth century). Here, we report on the results of recent lead isotope and trace element analyses of cast artefacts, namely ingots and rings, from three ninth- or very early tenth-century hoards from the Swedish Baltic islands of Gotland and Öland. Comparing the data against an extensive geochemical dataset for Islamic dirhams, we find that the raw material used to cast the artefacts most likely comprises a dirham stock imported before the middle of the ninth century. We argue that the inflow of Islamic silver to the north was far more significant in the early ninth century than the extant dirham record suggests.

Background

During the Viking Age, Scandinavia received enormous quantities of Islamic coins, dirhams, acquired by Rūs traders in exchange for furs, slaves and other commodities along long-distance riverine trading routes stretching across the eastern and southern Baltic coasts and inland waterways leading ultimately towards the Caspian and Black Seas. While dirham silver could have also been obtained through means other than trade, for instance, from loot and treasure taking (Adamczyk 2020), the scale of dirham import to Scandinavia remains an important indicator of the region's engagement with eastern trading routes. At present, records of surviving dirhams from hoards, graves and settlements suggest that dirhams arrived in the central Baltic area from around AD 800, and particularly from c. 825, initiating a moderate import of coins that travelled from the Caliphate via Russia and the southern Baltic (Noonan 1994; Kovalev & Kaelin 2007, p. 569; Kilger 2007, pp. 213–214, 220–221, 243 fig. 7.23; Callmer 2015, pp. 13–16; Jankowiak 2020). Two decades of 'low-key stability' followed in the 840s and 50s (Jankowiak 2020). From c. 860, the flow of dirhams increased significantly, marking a quantitative jump in the availability of Islamic (primarily Abbasid) silver in Scandinavia. But it was not until the onset of Samanid minting in Central Asia from c. 892 that the flow of dirhams turned into a flood, which lasted until the 950s (Jankowiak 2020). This broad pattern supports a picture of relatively slow and modest beginnings in dirham trade, which accelerated from c. 860 and operated on a truly substantial scale only from c. 900.

Yet while this picture is supported by extant numismatic evidence, it sits uneasily with artefact data from ninth-century silver hoards, particularly from the Swedish Baltic islands. Here, the earliest Viking-Age hoards are characterised by very small parcels of dirhams alongside large numbers of heavy ingots and rings. Typical inclusions are weight-adjusted ingots and various forms of arm-ring, along with spiral-striated rings of Permian type (so-called because they are thought to originate in the district of Perm in Russia), often cast to multiples of c. 25g or

Fig. 1. Early Viking-Age silver hoard from Hässelby, Dalhem, Gotland, deposited after 796/7. The artefacts in the hoard outnumber the coins (not depicted) by a ratio of 72 to 1. Photo: Christer Åhlin, National Historical Museums, Sweden.

50g (Hårdh 2007, pp. 106–107, 109, table 5.6; 2016). The hoard from Hässelby, Dalhem, Gotland, serves as an example (SHM 8212; CNS 1.3.3) (fig. 1). It has a terminus post quem (tpq) of 796/7 and was probably buried before c. 825. The hoard contains 3 Abbasid dirhams, weighing 5.4g, alongside an array of complete and fragmentary rings and ingots, collectively weighing over 363g. The artefacts thus outweigh the dirhams by a factor of 72 to 1.

If the dirham flow was indeed modest during the early ninth century, where did the silver used to make such large objects come from? Was there, in fact, a more substantial flow of dirhams to early Viking-Age Scandinavia than indicated by surviving coins, one in which dirhams were not preserved in their original form but routinely melted down and cast into artefacts? Or was there a contribution from other sources of silver, for instance, deriving from Viking raids in Western Europe? Resolving this uncertainty is important, since evidence for an early, substantial import of dirhams to the Baltic would indicate that inhabitants of that area were more strongly coupled to Eurasian trade in the early ninth century than currently appreciated. Until now, however, the limited application of archaeometric provenancing methods to Viking-Age metals, coupled with a lack of integration of numismatic and artefact research, has hampered progress in addressing such issues.

An archaeometric perspective on dirham inflow

The key means of addressing the relationship between dirhams/other coins and the cast artefacts is through archaeometry (Merkel 2019; Sarah 2019). Below, we present the combined lead isotope and trace element analysis of nine ninth- or very early tenth-century ingots and rings from the islands of Gotland and Öland. We compare the results against new geochemical information we recently obtained from a large-scale analysis of precisely-dated Umayyad and Abbasid dirhams produced c. 700–950 CE at over 30 mints across the Caliphate, as well as with ninth-century Carolingian and Anglo-Saxon coin. This extensive coin data shows regional and chronological patterns in lead isotope ratios as well as trace elements – patterns that enable us to characterise the ninth-century cast artefacts and suggest their likely silver sources.

This regionally and temporally resolved coin data offers robust comparanda for the analytical results obtained as part of this study. However, we go further in using the reference data to produce theoretical lead isotope, gold and bismuth values for a series of temporally-spaced dirham hoards from the Swedish Baltic islands. Combining information on each hoard's dirham composition with our reference geochemical data enables us to model isotopically and chemically the changing dirham stock over the course of the ninth century (Appendix and fig. 7). This, in turn, allows us to compare the theoretical results against our analytical data, revealing specific chronological and regional connections between the source coinages and the cast silver artefacts. We detail the method and results of the archaeometric analysis below, following an introduction to the analysed material, and a review of theoretical considerations in silver provenancing.

The material

In total, 9 items were submitted for trace element and lead isotope analysis. The items, all rings or ingots, stem from three different hoards from the Swedish Baltic islands of Gotland and

Analysed item	**SHM number**	**Hoard**
1. Ingot, complete	SHM 11930:59	Asarve, Hemse, Gotland, tpq 878?
2. Ingot, complete	SHM 11930:59	Asarve, Hemse, Gotland, tpq 878?
3. Ingot, complete	SHM 11930:59	Asarve, Hemse, Gotland, tpq 878?
4. Lozenge-sectioned rod arm-ring	SHM 902	Hummelbos, Burs, Gotland, tpq 842
5. Lozenge-sectioned rod arm-ring	SHM 902	Hummelbos, Burs, Gotland, tpq 842
6. Ingot, fragment	SHM 902	Hummelbos, Burs, Gotland, tpq 842
7. Spiral striated ring (Permian)	SHM 15890:25	Alvara, Böda, Öland
8. Rod arm-ring, overlapping ends	SHM 15890:1	Alvara, Böda, Öland
9. Small ring, attached to no. 8	SHW 15890:1	Alvara, Böda, Öland

Table 1. The analysed material.

Öland (table 1). The hoards date on typological and/ or numismatic grounds to the ninth century or early tenth century and contain weight-adjusted artefacts characteristic of the earliest Viking-Age hoards: all analysed items are likely to have been manufactured in the Baltic region, with the exception of a spiral striated Permian ring (Alvara hoard, Böda, Öland, SHM 15890:25), likely produced in Russia (Hårdh 2007, 109; 2016; Callmer 2015) (fig. 2). In addition to Permian rings, the items include plain, lozenge-sectioned rod penannular rings, a type first recognised by Ralph Wiechmann (1996, 45, Karte 53), and weight-adjusted D-shaped ingots, cast to multiples of a c. 50g base unit (Hårdh 2007, pp. 106–107, table 5.6). While rings and ingots are occasionally found in fragmentary form, they are more often complete. Within the Scandinavian silver economy, they thus functioned primarily as a form of 'money in large units' (Hårdh 2016, p. 37).

The two hoards from Gotland both contain Islamic dirhams. The vast Asarve, Hemse, hoard contains two Abbasid dirhams, identified by Gert Rispling: one was minted in al'Abbasiyya, North Africa, between 777/8–787/8 and the second is identified as a possible product of Andaraba, northern Afghanistan, minted in 878. While the latter provides a formal tpq for the deposition of the hoard, the wide difference in date between the two dirhams means that this date is not secure. Nevertheless, the artefacts contained in the Asarve hoard are early Viking-Age types, and the assemblage was likely deposited in the late ninth or very early tenth century (Hårdh 2016, pp. 19, 62). The dirham composition of the Burs, Hummelbos, hoard is notable for containing a mix of ten Umayyad and seventy-seven Abbasid issues (latest minted in 842), along with ten, later Samanid issues minted from c. 900 to 954/61, together with a large number of unidentified fragments (CNS 1.2.30; Stenberger 1947, Nr. 67, Abb. 31). It is possible that the hoard was a savings cache, added to sporadically over a long time period

Fig. 2. Permian ring from the Alvara hoard. Photo: Ola Myrin, National Historical Museums, Sweden.

(Lowick 1975, p. 121, footnote 19). However, the three rings from the hoard all date to the early Viking period. It is more likely that the Samanid coins originate from a separate deposit, as originally suggested by Sture Bolin (Stenberger 1947, p. 33). For the Burs hoard (minus the Samanid dirhams), a date of deposition c. 850 thus seems likely, although the many unidentified coin fragments from the hoard again raise uncertainty around the specific tpq. The hoard from Alvara, Öland, is coinless and thus lacks a tpq. Marit Gaimster (née Thurborg) dated the hoard to the tenth century on account of its ring types (1988, pp. 313, 317). However, its combination of rings, including Permian and lozenge-sectioned rod rings, finds particularly close parallels in the Asarve hoard (Stenberger 1958, p. 121), suggesting a comparable, late ninth or early tenth century date of deposition.

Theoretical considerations in provenancing silver and lead isotope modelling

Before detailing the methods, it is important to comment briefly on the theory underlying silver provenancing and detail our reference comparanda. Combined lead isotope and trace element analysis is a powerful and established tool for silver provenancing, which nonetheless requires nuanced interpretation (Killick et al. 2020). A full discussion of the meaning of lead isotope and trace element characterisations, particularly gold and bismuth contents, is provided elsewhere (see Merkel 2016; 2019). For the material under analysis here, an important point of departure is that all the analysed artefacts are made from recycled metal – most likely, coinage. Rather than being connected with primary metal production, they reflect a mix of one or more silver sources, melted down and cast into a different form.

This has important implications for the interpretation of the analytical results. It means that the artefacts' geochemical signature (lead isotope ratios and trace element contents) will reflect a homogenisation of contributing components, rather than a single ore source. This is especially pertinent for larger objects, such as ingots and rings, since they require tens of individual components (i.e. coins) for casting. In addition, it increases the likelihood that the silver entering the objects has, at some stage, been cupelled: melted together with exogenous lead, and heated to a high temperature so that the lead oxidises and draws out the impurities, leaving behind fine silver. When this happens, the lead used in cupellation may introduce a foreign contamination, leading to isotope values that are unrelated to the original silver source.

These challenges require a robust and careful selection of appropriate reference data. Below, we outline our proxy reference datasets used to represent recycled Islamic and Western European coinage, followed by our method for evaluating cupellation.

1) *Proxy reference data*. Since the analysed artefacts were made of many individual components that were melted down and recast, it is important that our reference comparanda consist not of individual silver artefacts/ coins, but of homogenised silver stock. We thus compared the analytical results with two sets of proxy data, representing a Western European source and an eastern, Islamic source respectively.

For Western European silver, the available data on ninth-century Carolingian silver indicates that lead isotope ratios from Melle, Aquitaine, France (a major Carolingian mint and mine) dominate the coinage produced in much of the western Carolingian territory (Sarah 2008; Sarah et al. in prep.). Our data on ninth-century Anglo-Saxon coinage also indicates a partial overlap with Melle, suggesting the recycling of Carolingian coinage to produce Anglo-Saxon issues (Kershaw & Merkel 2019). Anglo-Saxon coinage that does not plot with Melle requires further investigation, but does not overlap isotopically or chemically with Islamic coinage. Overall, a homogenised silver stock made from Western European silver is likely to have lead isotope ratios consistent with, or heavily influenced by, Melle (compare Téreygeol et al. 2005; Sarah 2008; Sarah et al. in prep.). Fortunately, the Melle ore lead isotope signature is well characterized, and is a tight cluster that rests on lead isotope data deriving from ore, slag and glass (37 analyses after Gratuze et al. 2018).

Arriving at a proxy dataset for homogenised Islamic silver is more complex. Results from our recent lead isotope and trace element analysis of over 140 dirhams minted between c. 700 and 950 at major and minor mints spread across the Caliphate reveals broad regional trends and dynamic changes in the sources and distribution of silver in the Islamic world (Merkel et al. in prep.). Critically, our work demonstrates strong differences in silver sources between mints in the regions of North Africa, Iraq, Iran and Central Asia, as well as chronological shifts in those sources, in c. 750, 773–4, 870 and c. 892.

To evaluate the geochemical signature of dirhams circulating in the Swedish Baltic in the ninth century, we therefore modelled theoretical dirham isotope and chemical signatures on the basis of dirham compositions in a series of well-recorded Gotlandic hoards (see Appendix). We took as our input values data from our dirham analyses (Merkel et al. in prep.). The modelled hoards have tpqs ranging from the early to late ninth century and were chosen because they have more than 5 dirhams, their dirham composition is well-recorded and they contain a majority number of identified specimens.

Establishing an accurate date of deposition of these hoards is critical for our chronological framework. We accept that there will, inevitably, be a time lag between the tpq and the hoards' actual date of deposition. However, dirhams travelled at fast pace from the Caliphate to the Baltic and, given that there is little evidence for their circulation as currency in ninth-century Gotland outside of emporia, they are likely to have been deposited soon after they reached the island (Jankowiak 2020). In his recent analysis of ninth-century dirham hoards from Gotland,

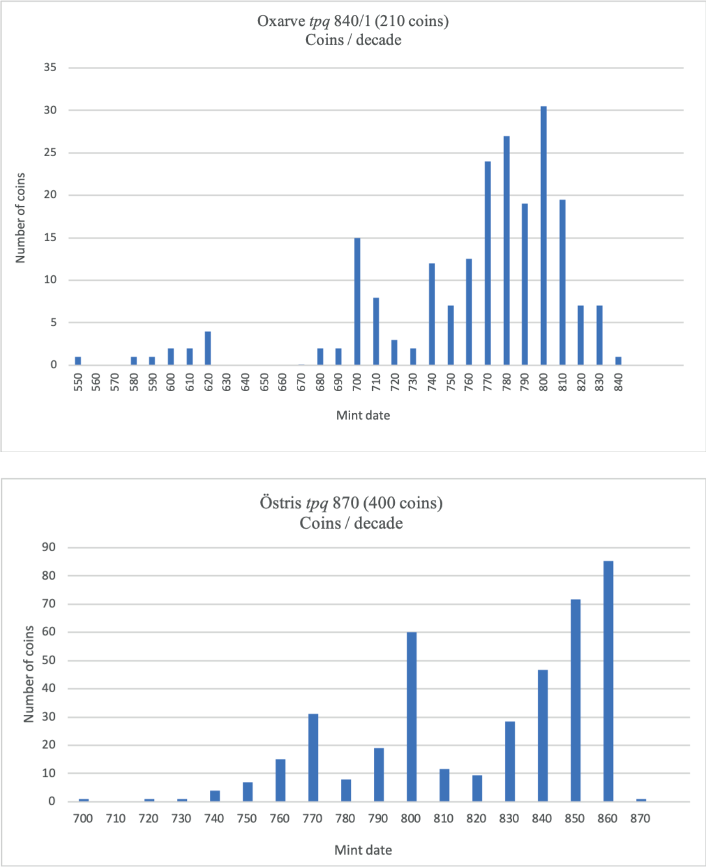

Fig. 3. Age modelling of dirhams in the Oxarve and Östris hoards. Ninth-century hoards from Gotland contain a large proportion of recently-minted dirhams, suggesting their tpq is a reliable guide to their actual date of deposition.

Marek Jankowiak concluded that ninth-century dirham hoards (unlike tenth-century hoards) contain a large proportion of recently-minted dirhams (Jankowiak 2020, fig. 6.2). Age modelling of two hoards included in this study, from Oxarve (tpq 840/1) and Östris (tpq 870), broadly support this observation: both hoards contain a large number of dirhams, with a pronounced component minted shortly before their tpq (fig. 3). We therefore judge that the tpqs will be a broadly reliable guide to the actual date of deposition.

The dirham compositions of the hoards, broken down by region and time period, are shown in fig. 4. This breakdown reveals clear changes in dirham composition over the course of the ninth century. The proportion of Sasanian/Arab Sasanian, Umayyad and North African dirhams declines over time, particularly after the middle of the ninth century. In contrast, the proportion of dirhams minted in Iraq after 773/4 increases, a trend almost certainly related to the establishment of a mint in Baghdad around a decade earlier. A similar increase is observed in coins minted after this date in Central Asia; this region includes mints such Balkh, Bukhara, Harat, Marw, Samarqand, al-Shash and Zaranj. The only dirham component to remain consistent is that from Iran. Here, the relatively stable mint output at al-Muhammadiya, coupled with later minting at Nishabur and Isbahan, meant that the proportions of Iranian dirhams reaching the Baltic remained steady over time. Fig. 4 also reveals that the number of dirhams contained within each hoard rises, on average, over the course of the ninth century, with just 22 dirhams included in the Visby hoard (tpq 817/8) and over 400 in the hoard from Östris (tpq 870). In particular, the years around c. 840 are marked by increasing numbers of hoarded dirhams. This confirms the picture of small dirham parcels in earlier hoards commented upon above, and mirrors patterns observed in the wider extant dirham corpus beyond Gotland (Jankowiak 2020).

This changing dirham composition has important implications for understanding how the isotope values of homogenised dirham stocks change over time. Our dirham analyses have shown that dirhams minted in Baghdad and other Iraqi mints after 773/4 utilise a new source

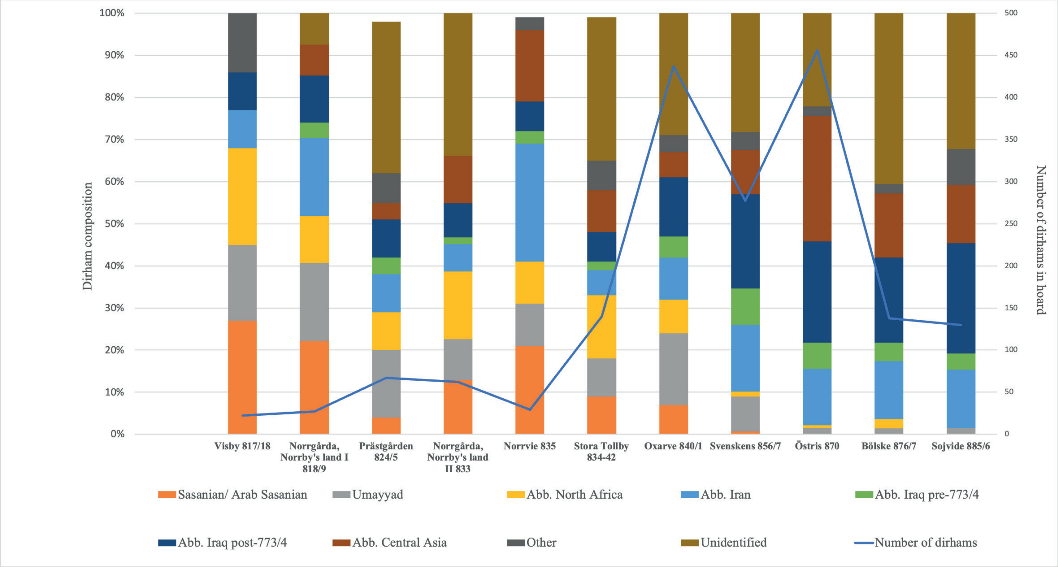

Fig. 4. Dirham compositions of eleven Gotland hoards, with tpqs ranging from the early to late ninth century.

of silver, and have geologically young lead isotope ratios which differ markedly from the ratios that characterise Sasanian/ Umayyad/ and pre-773/4 Iraqi Abbasid dirhams. Dirhams minted in Central Asia around the turn of the ninth century have lead isotope ratios which differ yet again: they are characterised by geologically old lead isotope ratios and generally have lower gold and higher bismuth contents than are found in dirhams produced in other parts of the Caliphate. These observed changes in the geochemical signature of the coins reflect marked and, in some instances, rather abrupt shifts in the location of exploited silver ores, reflecting the intensive but relatively short-lived mining of different silver-rich ores within and at the borders of the Caliphate (Merkel et al. in prep.). They allow us to trace the shifting isotope values of circulating dirham stock over time. When compared against the analytical results obtained from the three hoards under study here, they reveal intriguing and novel insights into the likely origin and date of the source silver.

2) *Cupellation*. Cupellation was used to separate impurities from silver (Merkel 2016, pp. 24–25). In Scandinavia, it may have been employed to ensure the quality of silver cast from multiple raw materials, particularly if Western European silver was a significant source of silver, since ninth-century coins from Anglo-Saxon England and the western Carolingian realm underwent periods of severe debasement (Metcalf & Northover 1985). In contrast, the high silver content of early Islamic dirhams means that batches of silver composed only of dirhams are unlikely to have been subject to this labour-intensive and time-consuming technique (Merkel 2016, pp. 31–32).

Evidence for cupellation can be found in part through trace element data, since freshly cupelled silver will contain little or none of the elements that oxidise easily during refining, such as zinc or tin. In addition, the lead isotope ratios of cupelled silver objects may also reveal signatures for locally-available lead: the lead available for use in cupellation. Items that were cupelled prior to casting ought thus to be low in impurities and have lead isotope values that reflect locally-available lead. Fortunately, archaeological lead from Viking-Age Scandinavian settlements, including Hedeby (Schleswig-Holstein), Birka (Sweden), Kaupang (Norway), is well-characterised isotopically, providing a robust reference dataset that appears to match with lead deposits in Central and Western Europe (Merkel 2016; Pedersen et al. 2016; Stos-Gale 2004).

Analytical Methods

Both lead isotope ratios and elemental concentrations were measured at the Vegacenter, Swedish Museum of Natural History, Stockholm. The data was captured by minimally-destructive laser-ablation, a fast-growing application in archaeology (Dussubieux et al. 2016). This method penetrates the surface layers to reach the bulk alloy without the need for the removal of a sample of material. While laser-ablation typically has lower precision than solution-based analysis requiring destructive sampling, it returns reproducible results with a precision sufficient for distinguishing between different candidate silver sources (Standish et al. 2021). Furthermore, it has the added benefit of not leaving any visible traces on the artefacts, and is thus suitable for the analysis of museum pieces.

The artefacts were mounted on museum-quality packing and placed in a sealed He-flushed sample holder. Lead isotope analysis was carried out using a Nu II multi-collector ICP-MS connected to a nanosecond 193nm laser. The artefacts were ablated in three separate locations, for 30 seconds, with a laser beam of 40μm (or 0.04mm) (μm = micrometre). For each artefact, the ablation spot targeted an area of flat, smooth metal. Targeted spots were pre-ablated with 3 shots using a 50μm laser beam followed by 25 second washout time to remove potential surface contamination. If the analysed ratios were still heterogeneous at the start of a measurement, this part of the data was discarded to ensure that the bulk of the sample was analysed.

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. Mercury interference was corrected and an internal thallium standard was used for fractionation correction. The analyses of reference materials can be found in table 2 and that of the artefacts in table 3. The standard deviations (2σ) of the artefacts are commonly under 0.3% for all of the Pb isotope ratios.

The artefacts were then measured for their elemental concentrations, following a similar procedure to the lead isotope analysis, but in this case the laser was coupled to a SC-HR (single collector-high-resolution)-ICP-MS. Reference material AGA-3 was the primary standard used for sample bracketing and quantification. Each object was measured on three 85µm spots for 50 s. The measured elemental concentrations of reference materials and artefacts are in table 4 and table 5. The relative standard deviations of Cu, Au, Pb and Bi are on average around ±20% (SD) but Zn and Sn values are significantly more heterogeneous.

It was discovered after the analyses that the strong correlation of bismuth and lead likely reflects a 208Pb tailing interference influencing the 209Bi signal. This could have been caused by an error in the mass calibration file or the mass resolution setting. Unfortunately, this error prevents accurate quantification of bismuth, since the bismuth contents of the primary and secondary standards fall within this overlap. While interpretation of the artefacts is still possible on the basis of the lead isotope and gold contents, and on the remaining trace elements, this does prevent a comparison of bismuth contents, which might add further clarity to the source origin of the Swedish Baltic material.

Results

The lead isotope ratios of the Gotland and Öland finds were plotted against Melle (proxy for Western European silver stock), average dirham compositions from 8 different ninth-century Gotlandic dirham hoard assemblages (proxy for Islamic silver stocks) and lead artefacts found in Scandinavia (proxy for available lead/cupellation) (fig. 5). None of the isotope values overlap with Melle, indicating that Western European silver did not make a significant contribution to the artefacts. In addition, the trendline for the Gotland/Öland data is offset from, and indeed mostly part runs parallel to, the archaeological lead from Viking-Age sites in Scandinavia. This is significant because it suggests that, with one possible exception (a small ring from the Alvara hoard, discussed further below), none of the items was freshly cupelled, a finding also supported by the presence in the analysed silver of minor elements that would be eradicated by cupellation. We note that there is an isotopic overlap between archaeological lead from Scandinavia and Melle isotope values, which points to the export of Melle lead to Scandinavia in the Viking Age (Pedersen et al. 2016).

Instead, the vast majority of the analysed artefacts (all but one) are consistent with average dirham hoard compositions with tpqs in the first half of the ninth century. None match the theoretical lead isotope values associated with dirham hoards deposited after the mid-ninth century, which, owing to their greater proportion of post 773–774 Iraqi dirhams (mainly from the Baghdad mint), have geologically younger lead isotope ratios (fig. 5). See too Appendix and fig. 7. The absence of this young isotope signature in the Gotland/Öland artefacts means that they were most likely cast from silver that predates the major inflow to the Baltic of Baghdad dirhams from c. 850. It suggests instead that they were cast from Sasanian drachms and/or Islamic dirhams likely to have been minted in the early-to-mid eighth century (Umayyad/early Abbasid periods).

The interpretation that the majority of artefacts are geochemically similar to dirham silver stocks with tpqs in the first half of the ninth century is also consistent with gold contents found in the artefacts (2000–4600 ppm, average 3300 ppm) (Appendix). The averages of the dirhams from these hoards is typically around 2800–4000 ppm (average 3400 ppm). By comparison with Carolingian silver, combining deniers from Charlemagne and Charles the Bald gives an average 4600 ppm per 100 wt. % silver (Sarah 2010), but since debased coinage is very common in the first half of the ninth century, it is likely that this silver would have required refining and thus would not have isotope ratios consistent with dirham silver. If only silver

Reference Material	Method	206/204	*2SD*	207/204	*2SD*	208/204	*2SD*	207/206	*2SD*	208/206	*2SD*	Lab.
AGA-3	Sol. MC-ICP-MS	17.411	*0.002*	15.549	*0.002*	37.288	*0.006*	0.8931	*0.00004*	2.1416	*0.0001*	1
(Uncorrected Ave.)	ns-LA-MC-ICP-MS	17.411	*0.010*	15.540	*0.011*	37.246	*0.040*	0.8926	*0.0004*	2.1393	*0.0019*	2
RMAg981-3	ns-LA-MC-ICP-MS	16.939	*0.008*	15.491	*0.014*	36.712	*0.067*	0.9145	*0.0011*	2.1674	*0.0044*	2
	Sol. MC-ICP-MS	16.940	*0.001*	15.491	*0.001*	36.704	*0.005*	0.9145	*0.00002*	2.1667	*0.0001*	1
AgDu	ns-LA-MC-ICP-MS	18.702	*0.020*	15.668	*0.031*	38.832	*0.107*	0.8378	*0.0010*	2.0764	*0.0039*	2
	Sol. MC-ICP-MS	18.688	*0.002*	15.652	*0.001*	38.777	*0.005*	0.8376	*0.0001*	2.0749	*0.0002*	1
AgNa-2	ns-LA-MC-ICP-MS	18.507	*0.007*	15.632	*0.011*	38.648	*0.070*	0.8446	*0.0008*	2.0883	*0.0042*	2
	Sol. MC-ICP-MS	18.508	*0.002*	15.638	*0.001*	38.642	*0.004*	0.8449	*0.00003*	2.0878	*0.0001*	1
RM3834	ns-LA-MC-ICP-MS	18.460	*0.024*	15.653	*0.039*	38.523	*0.127*	0.8479	*0.0014*	2.0868	*0.0047*	2
	Sol. / fs-LA	18.452	*0.008*	15.639	*0.007*	38.480	*0.019*	0.8475	*0.0002*	2.0854	*0.0005*	1, 3, 4
RM12467	ns-LA-MC-ICP-MS	18.546	*0.028*	15.678	*0.053*	38.719	*0.186*	0.8454	*0.0017*	2.0877	*0.0071*	2
	Sol. / fs-LA	18.533	*0.004*	15.660	*0.003*	38.651	*0.009*	0.8449	*0.0001*	2.0854	*0.0002*	1, 3, 4

Table 2. Lead isotope analyses of silver reference materials. 1. Oxford Earth Sciences, 2. Vegacentre, 3. Frankfurt am Main Geosciences, 4. Hanover Geosciences.

Table 3. Lead isotope ratios of Viking-period artefacts from the Swedish Baltic.

	Object	206/204	*2SD*	207/204	*2SD*	208/204	*2SD*	207/206	*2SD*	208/206	*2SD*
Burs, Hummelbos	Ingot	18.546	*0.024*	15.671	*0.023*	38.691	*0.085*	0.8450	*0.0003*	2.0862	*0.0013*
Burs, Hummelbos	Arm-ring, large	18.552	*0.010*	15.664	*0.009*	38.665	*0.061*	0.8443	*0.0005*	2.0841	*0.0020*
Burs, Hummelbos	Arm-ring, small	18.605	*0.015*	15.671	*0.014*	38.713	*0.066*	0.8423	*0.0005*	2.0808	*0.0020*
Asarve, Hemse	Ingot second shortest	18.534	*0.024*	15.679	*0.023*	38.700	*0.086*	0.8460	*0.0004*	2.0881	*0.0014*
Asarve, Hemse	Ingot shortest	18.553	*0.026*	15.678	*0.024*	38.717	*0.087*	0.8450	*0.0004*	2.0869	*0.0016*
Asarve, Hemse	Ingot longest	18.579	*0.025*	15.680	*0.024*	38.742	*0.087*	0.8440	*0.0004*	2.0853	*0.0014*
Alvara, Böda	Arm-ring	18.581	*0.023*	15.676	*0.028*	38.727	*0.116*	0.8437	*0.0007*	2.0842	*0.0034*
Alvara, Böda	Small attached ring	18.491	*0.023*	15.648	*0.029*	38.536	*0.118*	0.8463	*0.0008*	2.0841	*0.0035*
Alvara, Böda	Permian ring	18.575	*0.024*	15.656	*0.029*	38.707	*0.119*	0.8428	*0.0008*	2.0838	*0.0037*

Table 3. Lead isotope ratios of Viking-period artefacts from the Swedish Baltic.

RM3834	Cu %	SD	Au %	SD	Pb %	SD	Zn ppm	SD	Sn ppm	SD	Bi* ppm	SD
Vegacentre (n=8)	4.3	*0.3*	0.351	*0.036*	0.64	*0.12*	506	*171*	140	*37*	182	*35*
Other labs	3.4	*0.6*	0.387	*0.029*	0.49	*0.03*	367	*95*	133	*47*	143	*13*
RM12467												
Vegacentre (n=8)	5.1	*0.3*	0.166	*0.026*	1.10	*0.12*	4500	*654*	215	*39*	327	*38*
Other labs	5.5	*1.5*	0.193	*0.017*	1.07	*0.10*	4400	*750*	237	*5*	650	*14*
RMAgDu												
Vegacentre (n=6)	0.32	*0.01*	0.0014	*0.0004*	0.58	*0.04*	nd	-	nd	-	157	*8*
Oxford, Sol. ICP-QMS	0.13	-	0.00004	-	0.45	-	2	-	6	-	28	-

Table 4. LA-ICP-MS results of reference materials analysed at the Vegacentre compared to those of other laboratories. Average RM3834 and RM12467 from Merkel 2019.

	Object	Cu %	SD	Au %	SD	Pb %	SD	Zn ppm	SD	Sn ppm	SD
Burs, Hummelbos	Ingot	5.35	*0.02*	0.36	*0.02*	1.37	*0.07*	2795	*290*	2000	*195*
Burs, Hummelbos	Arm-ring, large	4.29	*0.38*	0.45	*0.10*	1.63	*0.03*	125	*20*	290	*120*
Burs, Hummelbos	Arm-ring, small	4.51	*0.15*	0.46	*0.04*	0.60	*0.25*	2485	*880*	590	*135*
Asarve, Hemse	Ingot second shortest	4.46	*0.28*	0.20	*0.01*	1.21	*0.11*	425	*125*	1150	*230*
Asarve, Hemse	Ingot shortest	4.48	*0.36*	0.29	*0.06*	0.61	*0.14*	500	*130*	400	*455*
Asarve, Hemse	Ingot longest	4.73	*0.11*	0.38	*0.05*	0.54	*0.06*	205	*125*	410	*105*
Alvara, Böda	Arm-ring	3.69	*0.66*	0.27	*0.03*	0.63	*0.10*	370	*70*	640	*130*
Alvara, Böda	Small attached ring	4.10	*0.45*	0.24	*0.02*	0.41	*0.11*	95	*45*	35	*120*
Alvara, Böda	Permian ring	4.64	*0.73*	0.98	*0.13*	0.64	*0.19*	425	*140*	590	*210*

Table 5. Elemental concentrations of the analysed artefacts.

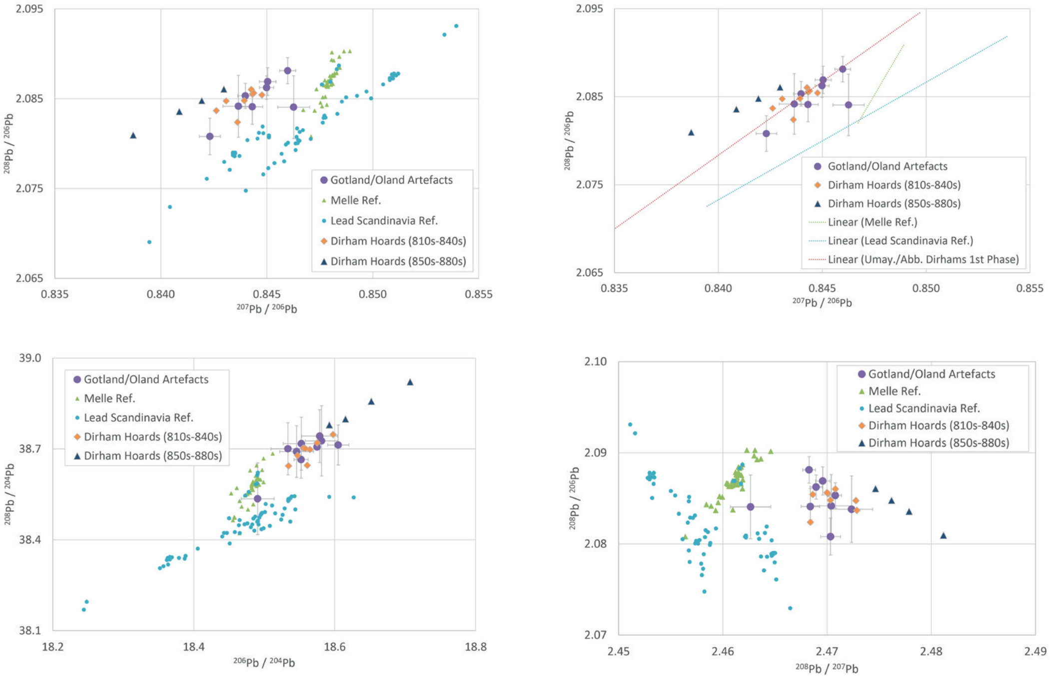

Fig. 5. Lead isotope ratios of Swedish Baltic silver compared against the reference material.

Charles the Bald deniers made from high quality silver (>90 wt. %) are used, the average gold content is 5900 ppm per 100 wt. % silver. The Carolingian gold values are thus, on average, higher than the average we see in the Swedish Baltic artefacts.

We thus propose that dirhams comparable to those deposited in early ninth-century Gotlandic hoards (i.e. a stock including significant numbers of Sasanian/Umayyad/early Abbasid coins) form the major source of silver for the analysed objects. However, it is clear that the cast silver artefacts cannot be made solely of melted-down dirham silver because the copper, zinc and tin are too high. Abbasid dirhams typically contain 1–2% copper which occurs naturally in the silver after production. They are almost never alloyed with copper, and, in the rare instances in which they are, they contain fairly pure copper, not bronze, brass or gunmetal (Merkel et al. in prep.). Early Umayyad dirhams are alloyed with up to ca. 8% copper, but the copper is pure, without tin or zinc (Merkel et al. in prep.). Therefore, if these artefacts are made of a recycled dirham stock, small amounts of mixed copper-based alloys were added to the silver (intentionally or unintentionally) after the dirhams arrived in Scandinavia. One likely interpretation is that the dirham silver was accidentally contaminated by minor amounts of copper-based alloys during recycling. The frequency of this in the analysed material shows that silver casting was regularly carried out next to the working of copper alloys, and suggests that the same crucibles were used to melt both silver and copper-alloys.

One artefact from the analyses has a different geochemical profile: a small ring, attached to a larger ring, from the Alvara, Öland, hoard. It has isotope ratios more similar to Melle, although they do not overlap, meaning that it cannot have been made from a purely Melle silver source. Its gold content (0.24%) is similar to many other Swedish Baltic artefacts, but this alone is not distinctive enough to rule out a Western source for this single small item. The ring is unusual in its low tin and zinc contents (<100 ppm). Its copper content is 4.1 wt. %: this is neither low enough to conclusively indicate cupellation, nor high enough to prove that it was not cupelled or fluxed with lead (Merkel 2016, pp. 209–220). The analytical results are thus ambiguous. It may have been refined with the addition of Melle lead – whether in Scandinavia or elsewhere, or it may have been made in part from Carolingian/western European silver.

Provenance of the Perm'/Glazov ring

Unlike all other artefacts analysed, the Permian ring (Alvara hoard, SHM 15890:25) is believed to have been made in the districts of Perm and Vijatka in Russia (Hårdh 2007, pp. 106–107, 109; Callmer 2015) (fig. 2). It has been suggested that Permian rings could have been made of North African dirhams (Kilger 2007, p. 214). This is a logical hypothesis: the main introduction of the ring type is dated from c. 800, with some evidence for earlier production (Hårdh 2016, p. 32), and early ninth-century hoards from Russia contain a significant, albeit variable, percentage (20–60%) of North African dirhams (Jankowiak 2020; Noonan 1980, pp. 421, 423). However, the analytical data from this study indicate that the Permian ring from Alvara differs from all of the other analysed artefacts from Gotland and Öland because of its very high gold content (0.98 wt. %). This immediately rules out North African dirhams as a significant source for the analysed items, because they are characterised by extremely low gold contents (Merkel et al. in prep.).

Instead, the ring was most likely cast from older (Umayyad and/or Sasanian) coin or plate. Under the Umayyads, dirhams with 1 wt. % gold were fairly common, particularly at the mints in Damascus, the Caucasus (Arminiya) and in Khorasan, such as Merv and Nishabur (Gordus 1972; Merkel et al. in prep.). However, beginning around the year 720, the frequency of dirhams with high gold contents declines, and they become scarce after 750 (Gordus 1972; Gondonneau & Guerra 2002, pp. 582–583; Meyers 2003). The high gold content of the Permian ring thus points to an early silver source, before the middle of the eighth century.

The lead isotope ratios of the Alvara ring point to an Umayyad and/or Sasanian silver stock (Umayyad and Sasanian silver is geochemically identical) (fig. 6). The ratios are within error of the average of Umayyad and Sasanian silver, and thus show no influence of characteristically Abbasid silver types. The isotope ratios of the Alvara Permian ring are the same as the only other Permian type ring subject to lead isotope analysis, one found at Hedeby (Merkel 2016), suggesting a similar date and origin of production. We thus suggest that the two Permian rings we have analysed were made of recycled Umayyad or Sasanian silver.

It is well-known that the Upper Kama region hosts a concentration of Sasanian and Byzantine silver vessels and coins (Noonan 1982). Birgitta Hårdh has noted that Oriental silver vessels 'of Sasanian, Post-Sasanian, Central Asian or Early

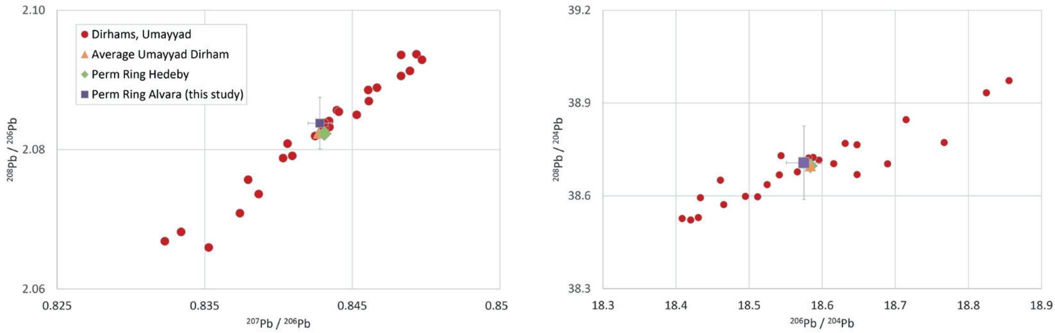

Fig. 6. Lead isotope ratios of the Permian rings from Alvara and Hedeby compared to Umayyad dirhams.

Byzantine origin' appear in significant numbers in the Upper Kama region of Russia during the ninth century, and may have been a source – alongside dirhams – for the Permian rings (2016, pp. 35–37). Notably, Sasanian/Arab Sasanian and Umayyad coins do not form a significant proportion of dirhams in recorded hoards from Russia. However, they do appear, along with Central Asian imitations of Sasanian coins and Umayyad dirhams, in eighth- and ninth-century graves from the region of Perm' (Goldina & Nikitin 1997; Callmer 2015, p. 17; Goldina & Goldina 2018). Within the graves, Sasanian coins of Chosrow II dominate, especially in the first half of the eighth century. By contrast, Abbasid dirhams are rare from these contexts. It may be that Sasanian and Umayyad coins, along with their imitations (likely struck from recycled Sasanian drachms), provided a major source of raw material for Permian rings.

We suggest that Sasanian/Sasanian imitation and Umayyad coins that reached the area of Perm were cast into weight-adjusted rings, facilitating the trade in furs. This points to the presence of an early (eighth-century) flow of oriental coins northwards, one that preceded the inflow of North African dirhams, but which left only a modest archaeological trace due to the systematic melting-down of coins. A more extensive analytical programme is needed to corroborate these preliminary results. Fortunately, such a project is currently being undertaken by Mahir Hrnjic at Aarhus University, and the results of his investigations into the topic are eagerly anticipated.

Discussion: the Baltic economy in the early Viking Age

Through minimally-invasive methods of analysis, we are able to show that the analysed silver predominantly represents a homogenisation of Sasanian and/or early Islamic silver comparable to the dirham stock found in Swedish Baltic hoards with tpqs in the first half of the ninth century, and not later. While this might be expected for the Burs, Hummelbos, hoard, with a tpq of 842, it was not anticipated for the artefacts from the enormous Asarve, hoard (tpq 878), nor from the Alvara hoard, likely deposited in the late ninth or early tenth century. That the analysed artefacts from these hoards instead utilised an older stock of dirham silver suggests that they were several decades old when assembled and deposited alongside more recently-arrived dirhams. The consistency of the results across all three hoards is significant when considering the very large volume of cast silver artefacts in early hoards from the Swedish Baltic islands. It points to a substantial inflow to the central Baltic of dirham silver during the first half of the ninth century, an inflow which is not preserved in the extant coin record.

At present, the 860s and 870s are taken to mark a profound escalation of the dirham trade, reflecting an increase in the activity of the Rūs and their penetration of the region around the Caspian and Black Sea. The 860s is traditionally associated with the rise of the semi-legendary figure Riurik, and his followers, who are said to have established themselves in Novgorod at this time, taking control of the River Volkhov-Lake Ladoga-River Neva route (Noonan 1994, p. 226). This is, of course, extensively debated (Bolin 1953, p. 29), but the 860s–70s are marked by both textual indications of increased raiding in this area around this time and by archaeological evidence for a contemporaneous expansion of Rūs mercantile activity along the Upper Volga, and seem likely to reflect a consolidation of Rūs networks. Notably, the 860s also saw the destruction of the settlement of Staraya Ladoga on the western bank of the river Volkhov, a likely indication of a 'heightening of expectations and recourse to violence, among the Scandinavians in the east' (Franklin & Shepard 1996, pp. 56, 59). From a numismatic perspective, the 860s and 870s are characterised by the expanding geographical extent of hoarding and the increase in the number of dirhams contained within hoards (Kilger 2007, fig. 7.17). This is seen most spectacularly in the hoards from Spillings, Gotland (tpq 870/1), which contain no fewer than 14,300 coins, mostly dirhams (Jankowiak 2020).

We do not dispute a quickening in the tempo of economic activity around c. 860/870. However, the data presented here suggests that this apparent sea change in activity may in fact be better characterised as a strengthening of already deep-rooted trade connections. Our data suggest that the central Baltic economy was embedded in an Eastern trade network as early as the first half of the ninth century, a finding which implies that silver-generating activity, most prominently slave- and fur-trading, but also trading in commodities such as wax, honey, walrus tusks, and sword blades, operated on a larger scale during this period than commonly assumed. This may, in turn, have implications for understanding of the scale and complexity of Rūs operations in European Russia at this time. The recent discovery of two ship burials from Salme, Estonia, dated c. 750 and containing the remains of people of likely east Scandinavian origin, appears to offer evidence for violent expeditions across the Baltic as early as the eighth century (Hedenstierna-Jonson 2020, pp. 12–13). While the exact context of the Salme burials is debated (Mägi 2021), it is possible that they signal a new phase of activity in the Baltic which prefigured more sustained contacts with the East in the early ninth century.

The data also suggests that caution is required in the way that the extant dirham record is harnessed as a proxy for Scandinavia's relationship with the east. While it will always be the case that surviving dirhams represent just a fraction of the original number reaching Scandinavia, the ratio of recycled-to-preserved dirhams is likely to have been particularly skewed in favour of the former during the earliest phases of dirham import, before coins were widely used as a means of payment in everyday transactions, and before a 'coin mentality' had developed (at least beyond the coin-using centres of Ribe and Hedeby). Within the early ninth-century central Baltic's prevailing 'status' economy, marked by the display of silver in the forms of wearable wealth, coins were more likely to be melted down as a source of raw material for casting into status objects than preserved intact as a medium for exchange, although some coins were also selected for display, for instance, by stringing on necklaces. Only from the 860s and 870s, when the number of dirhams contained in hoards increases substantially, do we appear to witness a change in attitude towards dirhams, and their increasing preservation. This change coincides with the spread of a bullion economy, with finds of hack-silver, regulated weights and fragmented dirhams all signalling the increasing use of silver as a means of payment (Williams 2011, p. 349). These source-critical issues ought to be considered when evaluating evidence for the dirham trade and the dynamics of the early Viking-Age economy.

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Abbreviations

tpq	terminus post quem (the date after which the hoard was deposited, determined by the latest coin inclusion)
SHM	Statens Historiska Museum (The Swedish History Museum), Stockholm.
CNS	Corpus Nummorum Saeculorum IX–XI qui in Suecia Reperti Sunt (Catalogue of Coins from 9th–11th Centuries found in Sweden).

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Appendix: Dirham Hoard Modelling

Here we describe our approach to theoretically modelling the lead isotope and trace element results of cast silver artefacts from eight Gotlandic hoards, with tpqs from the early to late ninth century. The method was designed to answer the question: if the dirhams within each hoard were melted down and cast into rings or ingots, how much gold and bismuth would the artefacts contain, and what would their lead isotope ratios be? Within each hoard, we attach isotope values to each discernible dirham element, then calculate the relative proportions of those values on the basis of dirham composition.

To generate lead isotope values for distinct dirham components, we matched identifiable dirhams with individual dirhams from our existing the analytical dataset (Merkel et al. in prep.). We matched the dirhams in one of five ways (listed in hierarchical order):

1. Matched by mint and year (±5 years)
2. Matched by mint and dynasty (taking into account major compositional shifts)
3. Matched by region/proximity and year (±5 years)
4. Matched by region/proximity and dynasty
5. An average composition of specific region and/or chronological segment (often for Sasanian drachms)

	Visby	Norrgårda I	Prästgården	Norrgårda II	Stora Tollby	Norrkvie I	Oxarve	Burs, Hum.	Svenskens	Östris	Bölske	Sojvide
	816/7	818/9	824/5	833	834-842	837/8	840/1	ca. 842	856/7	869/70	876/7	885/6
1. Mint/Year +/-5	9	13	21	26	50	15	124	13	120	206	49	50
2. Mint/Dynasty	5	2	9	4	14	2	15	9	20	128	12	12
3. Region/Year +/-5	0	0	1	2	2	3	13	1	5	16	9	7
4. Region/Dynasty	2	0	1	1	3	3	13	3	37	11	4	4
5. Average of Dyn. or Year Range	6	9	14	9	23	6	144	0	7	0	11	3
Total (Model)	22	24	46	42	92	29	309	26	189	361	85	76
Insufficient Ref. Data (not included)	*0*	*0*	*0*	*0*	*2*	*0*	*2*	*0*	*0*	*3*	*2*	*0*
Unspecified (not included)	*0*	*0*	*21*	*19*	46	*0*	*126*	*152*	*87*	*92*	*51*	*54*
Total	22	*24*	*67*	*61*	140	29	437	*178*	*276*	*456*	*138*	*130*

	Visby	Norrgårda I	Prästgården	Norrgårda II	Stora Tollby	Norrkvie I	Oxarve	Burs, Hum.	Svenskens	Östris	Bölske	Sojvide
	816/7	818/9	824/5	833	834-842	837/8	840/1	ca. 842	856/7	869/70	876/7	885/6
1. Mint/Year +/-5	41%	54%	46%	62%	54%	52%	40%	50%	63%	57%	58%	66%
2. Mint/Dynasty	23%	8%	20%	10%	15%	7%	5%	35%	11%	35%	14%	16%
3. Region/Year +/-5	-	-	2%	5%	2%	10%	4%	4%	3%	4%	11%	9%
4. Region/Dynasty	9%	-	2%	2%	3%	10%	4%	12%	20%	3%	5%	5%
5. Average of Dyn. or Year Range	27%	38%	30%	21%	25%	21%	47%	-	4%	-	13%	4%

Table 6. The number of dirhams matched via each method (nos. 1–5).

The methods used to calculate averages are found in table 6. In most cases, 50% of the dirhams that could be modelled could be matched by dirhams by mint and year (±5 years). Since the method is based on matching individual coins, it has the potential to produce variable results, particularly when dirham numbers are small. For this reason, the modelled hoards all have in excess of 22 dirhams, while the matching process was sensitive to regional boundaries, group homogeneity and chronological changes of silver compositions implied by the dataset as whole (Merkel et al. in prep.). We therefore obtained realistic estimations of average compositions, mimicking the dirham assemblages of the selected hoards. We highlight the fact that the Burs, Hummelbos, hoard contains a large number of fragmented dirhams that could not be identified (152 of 178) and, thus, its results may not be accurate; we included it in order to compare the theoretical results against the actual analytical results we obtained in this study. Despite the large quantity of unknown dirhams, the obtained results fit well with our theoretical projections (fig. 5).

Results and discussion

The calculated lead isotope averages are provided in table 7 and the modelled data is plotted in fig. 7. The modelled hoards are divided into chronologically early (c. 810s–40s) and late (850s–880s) groups on the basis of their hoard tpqs. The most significant factors effecting the average compositions are the number of Abbasid dirhams from Iraq (e.g. mints in Baghdad, Basra, and Samarra) minted after 773/4 CE (157AH), as these tend to contain geologically young lead. They are counterbalanced by contemporary dirhams from Central Asia and Khorasan, which tend to have the geologically oldest lead. Sasanian, Umayyad, Iranian and the earliest Abbasid Iraqi phase (pre-773/4 CE) dirhams tend to be isotopically 'neutral', plotting in the middle of the geologically old and young groups. The growth in the proportion of post-773/4 dirhams from Iraq beyond ca. 10–14% of the modelled assemblage pulls the isotope ratios toward geologically younger model ages. This occurs in Gotland hoards in the middle of the ninth century and stays consistent in the second half of the century (fig. 4).

Of all coins, Umayyad dirhams and Sasanian drachms have the highest amounts of gold (Merkel et al. in prep.). There may be a relationship between high gold contents (ie. levels between 3300 and 5000 parts per million, or ppm) estimated for the hoards and the proportion of Umayyad/Sasanian silver the hoards contain. When Umayyad coins are strongly represented and overshadow the low-gold dirham types, chiefly North African dirhams from the

	Hoard	TPQ	206/204	207/204	208/204	208/206	207/206	Au	Bi
Early Type	Visby	816/7	18.561	15.657	38.646	2.0824	0.8436	3102	423
	Norrgårda, Norrby's land I	818/9	18.556	15.665	38.703	2.0860	0.8443	3635	352
	Prästgården	824/5	18.575	15.659	38.720	2.0847	0.8431	3585	337
	Norrgårda, Norrby's land II	833	18.565	15.665	38.698	2.0848	0.8439	2449	451
	Norrkvie I	837/8	18.547	15.659	38.678	2.0855	0.8443	3239	508
	Stora Tollby	834-842	18.534	15.655	38.644	2.0854	0.8448	2784	654
	Burs, Hummelbos	ca. 842	18.558	15.668	38.701	2.0856	0.8444	4121	743
	Oxarve I	840/1	18.598	15.668	38.747	2.0837	0.8426	3389	507
Later Type	Svenskens	856/7	18.652	15.681	38.857	2.0836	0.8409	2739	512
	Östris	869/70	18.592	15.668	38.779	2.0861	0.8430	2574	905
	Bölske	876/7	18.615	15.668	38.799	2.0848	0.8419	2777	783
	Sojvide	885/6	18.707	15.687	38.921	2.0809	0.8387	2744	615

Table 7. Calculated average compositions of ninth-century dirham hoards from Gotland.

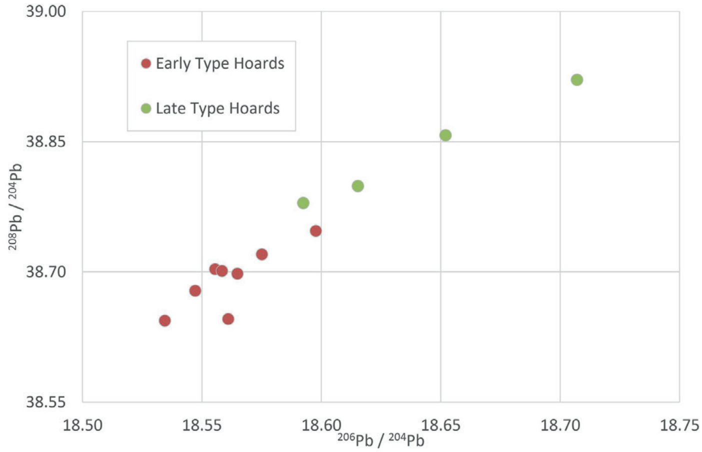

Fig. 7. Modelled dirham hoard averages divided by phases: the early phase hoards with tpqs in the 810s–early 840s and the later phase hoards with tpqs in the 850s–880s. The primary reason for the shift in isotope ratios is the growth in the proportion of Iraqi dirhams minted after 773/4 in the later-phase hoards.

last third of the eighth century, gold contents increase to above 3000 ppm. The absence of Umayyad/Sasanian silver in the stock lowers the overall gold content closer to the average of Abbasid dirhams, to around 0.22–0.25 wt. %. This trend towards lower gold contents (2100–2800 ppm) is visible in the dirham hoards belonging to the chronologically later phase.

The modelled hoard compositions appear to be an excellent proxy for ninth-century silver produced from dirham stocks, and fall in line with previous analyses of Viking period silver expected to have been made from homogenised ninth-century dirham stocks. The entire range of isotopic and gold contents seen in the dirham hoard model is observed in the low-bismuth silver found in 'Combination Group 7' or KG 7 coins minted at Hedeby in the first two decades of the tenth century, likely comprised of recycled Abbasid silver (Merkel 2019). However, while the elemental and isotopic range of KG 7 type silver corresponds to both early and late Gotland hoard groups, the cast silver artefacts analysed in the present study correspond only with hoards with tpqs in the first half of the ninth century. Gold contents in the Gotland and Öland artefacts also match the range modelled in early phase hoards: between 2000 and 4600 ppm (modelled hoard range: 2100 to 4100 ppm), and not the lower gold contents (2600–2800 ppm) observed in later-phase hoards. Lower gold contents and geologically younger isotope ratios are helpful criteria for distinguishing later ninth-century stocks from those dating to before c. 850. They enable new observations concerning the changes to elemental and isotopic compositions of silver stocks occurring over the century.