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The Provenance of Silver in the Viking-Age Hoard From Bedale, North Yorkshire

Jane Kershaw[1] | Stephen Merkel[2] | Andrew Woods[3] | Jane Evans[4] | Vanessa Pashley[4] | Simon Chenery[4]

[1]University of Oxford, Oxford, UK | [2]Vrije Universiteit Amsterdam, Amsterdam, the Netherlands | [3]York Museums Trust, York, UK | [4]British Geological Survey, Keyworth, Nottinghamshire, UK

Correspondence: Jane Kershaw (jane.kershaw@arch.ox.ac.uk)

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ABSTRACT

The acquisition of silver was a key motive propelling the Viking expansion out of Scandinavia; identifying the sources of Viking silver during the early part of the Viking Age can provide critical insights into the relative significance of western European and eastern, Islamic wealth in the Viking expansion. Here, we present new lead isotope and trace element analyses of silver ingots and rings contained in the late ninth- /early tenth-century hoard from Bedale, North Yorkshire. Comparing the results of the cast silver artefacts against an extensive reference dataset comprising ninth-century Anglo-Saxon, Carolingian and Islamic silver sources, in addition to candidate lead sources, we identify several metallurgical groups with distinct silver origins.

Silver subject to cupellation (refining) during recent recycling/casting processes can be distinguished from non-refined silver, from both western European and eastern Islamic and indeed mixed, sources. The results indicate a dominant contribution of western European silver, pointing to the fate of loot seized by the Vikings during their raids on the Continent in the ninth century. Nonetheless, Islamic silver is also present in several large ingots: silver from the east—the product of long-distance trade networks connecting Scandinavia with the Islamic Caliphate—permeated Viking wealth sources even in the western part of the Viking overseas settlement and should be seen as a significant driver of the Viking phenomenon.

1 | Introduction

In 2012, while searching in Bedale (Figure 1), North Yorkshire, metal-detectorists Stuart Campbell and Steve Caswell discovered a remarkable assemblage of 37 silver and gold objects of Viking-Age date (Figure 2). The Bedale hoard, as it is now known, represents a snapshot of the substantial wealth resources in Scandinavian hands in northern England during the late ninth or early tenth century. Alongside a gold Anglo-Saxon sword pommel—presumably acquired in England by Viking army groups—the hoard contained a spectrum of cast silver artefacts that span the Scandinavian world of the Viking Age: Hiberno-Scandinavian artefacts from Dublin, neck-rings from southern and/or western Scandinavia—including an enormous and hitherto unparalleled neck collar (on the left in Figure 2)—and many cigar-shaped ingots, which could have been cast in the Scandinavian homelands or any of the Scandinavian overseas territories.

The combination of Anglo-Saxon, Scandinavian and Hiberno-Scandinavian objects strongly suggests that the hoard was assembled in Yorkshire and is, in part, the product of the 'Hiberno-Norse axis' running between Viking-Age York and Dublin (Townend 2014, 117). But where did the silver used to cast these items originate? In broad terms, the Vikings had access to two main sources of silver, neither of which was indigenous to Scandinavia: a western European source, in the form of silver coins and plate acquired by the Scandinavians, primarily during their raids in England and on the Continent during the ninth century, and an eastern, Islamic source comprising dirhams (coins), which travelled from the Islamic lands to Scandinavia on the back

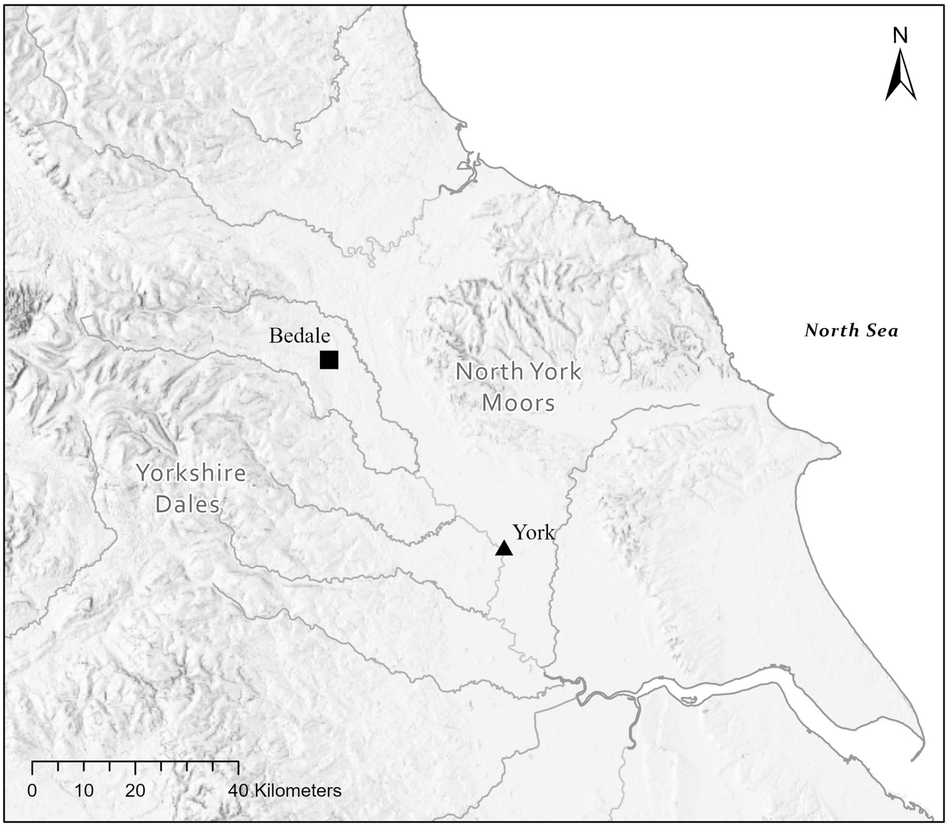

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FIGURE 1 | Location of Bedale, North Yorkshire. Map by Jane Kershaw.

of an extensive Eurasian trade in slaves and furs.[1] Islamic dirhams first arrived in Scandinavia c. 800 (Kilger 2007), but the c. 350,000–400,000 surviving examples from northern and eastern Europe (including Russia) date predominantly to the tenth, rather than ninth, century (Jankowiak 2020). By contrast, extant western European coins are scarce in Scandinavia, totalling only c. 330 specimens, while objects of silver plate number just a handful, despite the massive volumes of silver said by ninth-century chroniclers to have been extracted by Viking raiders (J. C. Moesgaard, pers. comm. 2023; Baastrup 2014; Nelson 1997, 37). This disconnect between the archaeological and documentary sources is striking and has encouraged the view that western European coins were favoured as bullion for casting into Scandinavian-style objects (Coupland 2007, 2011).

The Bedale hoard does not preserve any candidate source silver, i.e., Islamic, Anglo-Saxon or Carolingian coinage or silver artefacts: All the items have been cast from silver that has been melted down, meaning the original form of the source silver is obscure. Thus, the only way of establishing the origins of the silver in the artefacts is through geochemistry. Funded initially by a NEIF grant and then as part of the 5-year ERC funded project, *Silver and the Origins of the Viking Age*, we conducted trace element and lead isotope analyses of all but one of the silver items in the hoard and contextualised the results within a large reference dataset of candidate silver and lead sources (the latter of which is necessary to evaluate evidence of silver cupellation or refining) (Text S1).

The analysis of a hoard from North Yorkshire, where we might expect western European sources of silver to dominate, presents an opportunity to test the hypothesis that European coins served as the raw material for silver casting. The results are discussed below. Beyond yielding new information about silver sources, establishing the metallurgical profile of each silver artefact also generated unexpected insights into other salient research questions, including metallurgic links between particular artefact types and the probable date of deposition of the hoard.

2 | The Bedale Hoard

The silver and gold hoard from Bedale, North Yorkshire, was discovered by metal-detectorists in May 2012 and excavated in situ under controlled conditions by Adam Parker and Rebecca Griffiths of York Museums Trust (Griffiths and Parker 2018). The hoard appears to have been buried in open ground, rather than within a settlement, and was positioned under a flat stone and thick sheet of iron. It contains 36 items in silver, in addition to a gold-inlaid sword pommel with Anglo-Saxon decoration in the Trewhiddle style (Figure 2) (Treasure Case 2012 T373; PAS 'Find-ID' YORYM-CEE620 and Yorkshire Museum Accession Number YORYM 2014.149). According to the finders, the sword pommel lay uppermost in the hoard, with the silver jewellery items positioned below it, and the silver ingots forming the lowermost layer (Griffiths and Parker 2018).

FIGURE 2 | The Bedale hoard. Photo copyright York Museums Trust.

The silver items within the hoard encapsulate forms commonly encountered in Viking-Age hoards of Scandinavian character. These include 29 cigar-shaped ingots, three of which carry incised crosses at one end. Diagnostic Scandinavian forms of jewellery are represented by three rod neck-rings and an elaborate neck 'collar' of southern or western Scandinavian origin. A piece of striated-rod ring has a similar, southern Scandinavian background. Two further items, a broadband arm-ring and fragmentary penannular arm-ring, are Hiberno-Scandinavian products linked to Dublin. The combination of Scandinavian-type silver items with Anglo-Saxon gold is rare in Viking-Age hoards from England but finds parallel with the recently discovered hoard from Galloway, southern Scotland (Goldberg and Davis 2021).

Most of the Bedale hoard silver items are whole, but the deliberately chopped ends of five ingots, together with the fragmentary state of the penannular brooch and striated-rod ring, suggest that the hoard as a whole was treated primarily as bullion, to be weighed and used within a Scandinavian-type metal-weight economy (Kershaw 2017). This is supported by the fact that test marks or 'nicks', designed to check for plated forgeries, appear on many of the artefacts, in quite high numbers: they indicate that the silver saw active circulation in Scandinavian hands prior to its deposition. No coins are contained within the hoard, but the object typologies point to a date of deposition in the late ninth or early tenth century. The lack of coinage may suggest that the hoard was deposited prior to the re-establishment of a mint in nearby York in c. 895–900. That said, the artefacts are substantial in size, and it may be that the owner(s) of the hoard deliberately selected heavier items for deposition, ignoring circulating coinage. Whatever the case, the hoard belongs to a period following the Scandinavian capture of the Anglo-Saxon kingdom of Northumbria in 866, but prior to the takeover of York by the Anglo-Saxon king Æthelstan in 927, a period during which York was, for the most part, ruled by Scandinavian kings.

3 | Theoretical Approach

We employ a theoretical framework that combines the metallurgical and geochemical information obtained from major/minor/trace element analysis and Pb isotope ratios (Merkel 2019; Sarah 2019). The combination of elemental and Pb isotope data allows for a nuanced interpretation that considers source-related factors and recycling and refining practices (Kershaw and Merkel 2022). The source-related elements, gold and bismuth, are key to the interpretation of silver provenance: Gold is unaffected by refining processes, and bismuth is difficult to remove without causing loss of silver (L'Héritier et al. 2015). Moreover, there are strong regional and chronological variations in gold and bismuth content in comparative analyses of eastern and western silver. As we are dealing with recycled silver, that is, silver that originally took a different form, whether coin or plate, we base our interpretations on the comparison of elemental and Pb isotope data of earlier and contemporary silver coinages in Western Europe and the average silver compositions of Baltic dirham hoards (Kershaw et al. 2021). In principle, gold could have entered the silver end products through the recycling of gilded silver or gold objects, which are occasionally found within Viking-Age silver hoards. In practice, however, we rarely encounter in cast Viking-Age silver gold contents above 1%–1.2%, which is the upper limit of gold in contender source coinages, suggesting that there is not a major contribution from gilded silver. Since the silver may have been refined using locally available lead in England, on the Continent or in Scandinavia, Pb isotope ratios of lead artefacts and ore were also compared. A complete list of comparanda can be found in the Text S1.

4 | Analytical Methods

4.1 | Pb isotope Analysis

The Bedale silver objects were sampled either by shallow drilling with a 1-mm drill or by scalpel to obtain approximately 1 mg of metal; 35 of 36 silver objects were sampled (ingot no. 11 was unavailable on the day of sampling). Separation of Pb from samples was undertaken using standard AG-1 X8 ion exchange techniques. Pb isotope analysis was conducted at the Geosciences and Tracers Facility at the British Geological Survey, using a Nu Instruments Nu Plasma MC-ICP-MS (Multi Collector-Inductively Coupled Plasma Mass Spectrometer). Prior to analysis, each sample was spiked with a thallium (Tl) solution, which is added to allow for the correction of instrument induced mass bias. The sample was introduced into the instrument via an ESI 50-µL/min PFA microconcentric nebuliser attached to a desolvating unit (Nu Instruments DSN 100). Faraday collectors were configured to allow for the simultaneous detection of the following ion beams: ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb. Additionally, ^{203}Tl and ^{205}Tl were used for mass bias correction, and ^{202}Hg was used to allow correction of ^{204}Hg interference on ^{204}Pb. Each individual acquisition consisted of 75 ratios, collected at 5-s integrations, following a 60-s defocused baseline.

The precision and accuracy of the method were assessed through repeat analysis of an NBS 981 Pb reference solution (also spiked with Tl). The average values obtained for each of the mass bias corrected NBS 981 ratios were compared to the known values for this reference (Pb-double spike data taken from Todt et al. (1996): ^{206}Pb/^{204}Pb = 16.9356, ^{207}Pb/^{204}Pb = 15.4891, ^{208}Pb/^{204}Pb = 36.7006, ^{207}Pb/^{206}Pb = 0.91459 and ^{208}Pb/^{206}Pb = 2.16701) to produce nomalisation factors for each measured ratio, which were then applied to each of the unknown samples. Internal uncertainties (the reproducibility of the measured ratio) are propagated relative to the external uncertainty (i.e., the excess variance associated with the reproducibility of the NBS 981 reference material analysed during the session). The Pb isotope ratios of the samples are presented in Table 1, and measurements of MBH 133X-AGA3 are shown in Table 2.

4.2 | Elemental Analysis

The elemental compositions of all Bedale silver artefacts were analysed initially by portable X-ray fluorescence (pXRF) to obtain semiquantitative data. A Thermo Scientific Niton XL3T Analyzer was used, and all objects were analysed in three or four areas using the Precious Metals mode for 30 s. For quality control, both 133XAGA1 and 133XAGA3 were analysed three times. The data are presented in Text S2.

The elemental compositions of 18 Bedale silver objects were obtained through laser ablation–inductively coupled plasma mass spectrometry (LA-ICP-MS). This subsample represents all those items that could be placed within the laser ablation chamber (measuring 10 cm by 10 cm by 2 cm). The laser ablation unit was a NewWave (Electro Scientific Industries Inc) UP193 nm excimer system. The sample was placed in a 2-volume ablation cell with a 0.8-L·min^{-1} He flow. In addition to the samples, the silver standard MBH 133X AGA-3 was placed in the chamber for calibration purposes. The laser was fired at 4 Hz for 75 s using a beam diameter of 75 µm. Fluence and irradiance, as measured by the internal monitor, were typically 3.75 J/cm2 and 0.75 GW/cm2, respectively. The sample was transported to the ICP-MS using a helium (He) carrier gas, which is mixed, via a Y-junction, with 0.85 L·min^{-1} Ar and 0.04 L min^{-1} N2 supplied by a CETAC Aridus desolvating nebuliser. The Aridus allowed the introduction of ICP-MS tuning solutions and optimisation of the Aridus sweep gas (4 L·min-1Ar). During solids analysis by the laser, the Aridus only aspirated air. The ICP-MS used in this study was an Agilent 7500cs series instrument.

Data were collected in a continuous time resolved analysis (TRA) fashion. The dwell time for each of the 22 elements (isotopes) of interest [^{52}Cr; ^{55}Mn; ^{56}Fe; ^{59}Co; ^{60}Ni; ^{63}Cu; ^{66}Zn; ^{75}As; ^{82}Se; ^{95}Mo; ^{103}Rh; ^{105}Pd; ^{107}Ag; ^{111}Cd; ^{115}In; ^{120}Sn; ^{121}Sb; ^{125}Te; ^{195}Pt; ^{197}Au; ^{208}Pb; ^{209}Bi] was 10 ms, giving an integration time of approximately 0.25 s. Prior to laser firing, a period of at least 120 s of 'gas blank' were collected. These gas blanks were used to measure the background signals and to calculate the detection limits for each element of each sample. The reference materials and objects were ablated for 145 s, and the segment between 5 and 75 s was found to best reflect the given composition of MBH 133X AGA3 archaeological silver standard. MBH 133X AGA-3 and RMAgD-1 standards were analysed at the beginning and end of the analytical session: AGA-3 was used to calibrate the system, while the RMAgD-1 was used as a quality control (QC) material. All calculations and data reduction were performed using Iolite 2.5 laser ablation software and in Excel spreadsheets. The nature of laser ablation means there is some variability in ablation volume and transport efficiency with different materials (matrix effects). Therefore, accepted practice is to normalise results to an internal standard element. In the current study, Ag was chosen for this purpose, as its concentration is known in the standards. The compositions are presented in Table 3 and measurements of the reference material RMAgD-1 in Table 4.

5 | Results

5.1 | Pb Isotope Ratios

The ^{206}Pb/^{204}Pb ratios of the Bedale artefacts range from 18.379 to 18.678. Solely based on the Pb isotope characteristics, the Bedale objects divide into two groups, falling into lower and higher arrays in ^{206}Pb/^{204}Pb vs. ^{208}Pb/^{204}Pb space (Figure 3). This points to fundamental differences in geological origin between the two groups.

TABLE 1 | Lead isotope analysis of the Bedale objects by solution MC-ICP-MS.

Object	York. Mus. ref	Object type	Weight (g)	206Pb/204Pb	*2SE* %	207Pb/204Pb	*2SE* %	208Pb/204Pb	*2SE* %	207Pb/206Pb	*2SE* %	208Pb/206Pb	*2SE* %	Proposed Pb source
3	2014.149.8	Oblong ingot	60	18.4839	*0.010*	15.6254	*0.009*	38.4768	*0.011*	0.84535	*0.004*	2.08165	*0.005*	Yorkshire
4	2014.149.9	Oblong ingot	100	18.5415	*0.010*	15.6487	*0.009*	38.5897	*0.011*	0.84397	*0.004*	2.08122	*0.005*	Lead-Is mix
5	2014.149.10	Oblong ingot	58	18.6155	*0.009*	15.6692	*0.008*	38.7110	*0.010*	0.84172	*0.004*	2.07947	*0.005*	Islamic
6	2014.149.11	Oblong ingot cross	80	18.5487	*0.010*	15.6603	*0.009*	38.6539	*0.011*	0.84427	*0.004*	2.08393	*0.005*	Islamic/mix
7	2014.149.12	Oblong ingot cross	48	18.6431	*0.009*	15.6757	*0.008*	38.7948	*0.011*	0.84081	*0.004*	2.08091	*0.005*	Islamic
8	2014.149.13	Oblong ingot	144	18.4824	*0.010*	15.6689	*0.011*	38.5731	*0.016*	0.84780	*0.004*	2.08707	*0.008*	Melle
9	2014.149.14	Oblong ingot terminal	70	18.5110	*0.010*	15.6291	*0.011*	38.5240	*0.016*	0.84434	*0.003*	2.08116	*0.008*	Yorkshire
10	2014.149.15	Oblong ingot cross	104	18.5325	*0.009*	15.6543	*0.008*	38.6180	*0.010*	0.84468	*0.004*	2.08377	*0.005*	Mix of east and west
12	2014.149.17	Oblong ingot	86	18.5637	*0.010*	15.6676	*0.011*	38.6723	*0.016*	0.84399	*0.004*	2.08322	*0.008*	Islamic/mix
13	2014.149.18	Oblong ingot	61	18.5137	*0.010*	15.6573	*0.012*	38.5987	*0.017*	0.84572	*0.004*	2.08489	*0.008*	Mix of east and west
14	2014.149.19	Oblong ingot	97	18.6777	*0.004*	15.6801	*0.005*	38.8423	*0.006*	0.83950	*0.003*	2.07960	*0.004*	Islamic
15	2014.149.20	Oblong ingot	77	18.5273	*0.009*	15.6616	*0.010*	38.6277	*0.016*	0.84532	*0.003*	2.08491	*0.008*	Mix of east and west
16	2014.149.21	Oblong ingot	75	18.5580	*0.009*	15.6621	*0.010*	38.6611	*0.015*	0.84396	*0.003*	2.08322	*0.008*	Islamic/mix
17	2014.149.22	Oblong ingot	104	18.3794	*0.010*	15.6257	*0.009*	38.3580	*0.011*	0.85015	*0.004*	2.08696	*0.005*	Alston, Cumbria
18	2014.149.23	Oblong ingot	78	18.6602	*0.009*	15.6793	*0.011*	38.8639	*0.015*	0.84025	*0.004*	2.08270	*0.008*	Islamic
19	2014.149.24	Oblong ingot	67	18.5829	*0.009*	15.6673	*0.011*	38.7193	*0.016*	0.84310	*0.004*	2.08361	*0.008*	Islamic
20	2014.149.25	Oblong ingot terminal	113	18.5171	*0.011*	15.6561	*0.012*	38.5826	*0.017*	0.84550	*0.004*	2.08361	*0.009*	Mix of east and west
21	2014.149.26	Oblong ingot terminal	95	18.4941	*0.010*	15.6233	*0.011*	38.4745	*0.016*	0.84480	*0.003*	2.08042	*0.008*	Yorkshire
22	2014.149.27	Oblong ingot terminal	51	18.5467	*0.010*	15.6608	*0.009*	38.6447	*0.011*	0.84440	*0.004*	2.08362	*0.005*	Mix of east and west
23	2014.149.28	Oblong ingot	72	18.5086	*0.011*	15.6503	*0.012*	38.5779	*0.016*	0.84552	*0.004*	2.08427	*0.008*	Mix of east and west
24	2014.149.29	Oblong ingot	57	18.4974	*0.009*	15.6509	*0.008*	38.5856	*0.010*	0.84610	*0.004*	2.08601	*0.005*	Western

(Continues)

TABLE 1 | (Continued)

Object	York. Mus. ref	Object type	Weight (g)	206Pb/204Pb	*2SE* %	207Pb/204Pb	*2SE* %	208Pb/204Pb	*2SE* %	207Pb/206Pb	*2SE* %	208Pb/206Pb	*2SE* %	Proposed Pb source
25	2014.149.30	Oblong ingot	51	18.5216	*0.010*	15.6228	*0.011*	38.5083	*0.016*	0.84349	*0.003*	2.07914	*0.008*	Yorkshire
26	2014.149.31	Oblong ingot	71	18.5021	*0.005*	15.6186	*0.006*	38.4920	*0.007*	0.84415	*0.003*	2.08043	*0.004*	Yorkshire
27	2014.149.32	Oblong ingot	128	18.5455	*0.005*	15.6616	*0.005*	38.6386	*0.007*	0.84450	*0.003*	2.08347	*0.004*	Mix of east and west
28	2014.149.33	Oblong ingot, bent over	116	18.5669	*0.009*	15.6462	*0.011*	38.5861	*0.016*	0.84269	*0.003*	2.07824	*0.008*	Lead-Is mix
29	2014.149.34	Oblong ingot, bent over	73	18.5258	*0.010*	15.6215	*0.011*	38.4969	*0.016*	0.84322	*0.003*	2.07804	*0.008*	Yorkshire
30	2014.149.35	Oblong ingot	126	18.5913	*0.011*	15.6660	*0.009*	38.6952	*0.011*	0.84263	*0.004*	2.08130	*0.005*	Islamic
31	2014.149.36	Oblong ingot, clipped end	69	18.5213	*0.009*	15.6224	*0.011*	38.4964	*0.016*	0.84349	*0.004*	2.07847	*0.008*	Yorkshire
33	2014.149.37	Collar (wire sample)	546.4*	18.5136	*0.010*	15.6543	*0.009*	38.5875	*0.011*	0.84553	*0.004*	2.08427	*0.005*	Mix of east and west
34	2014.149.38	Neck-ring	119	18.4824	*0.009*	15.6668	*0.008*	38.5695	*0.010*	0.84765	*0.004*	2.08682	*0.005*	Melle
35	2014.149.39	Neck-ring	122	18.4896	*0.010*	15.6702	*0.009*	38.6039	*0.011*	0.84750	*0.004*	2.08784	*0.005*	Melle
36a	2014.149.40a	Neck-ring	103	18.5346	*0.009*	15.6583	*0.010*	38.6257	*0.016*	0.84481	*0.003*	2.08399	*0.008*	Mix of east and west
36b	2014.149.40b	Neck-ring	138	18.5221	*0.009*	15.6521	*0.008*	38.6025	*0.010*	0.84505	*0.004*	2.08414	*0.005*	Mix of east and west
37	2014.149.41	Striated-rod fragment	53.3	18.3898	*0.009*	15.6280	*0.008*	38.3818	*0.010*	0.84977	*0.004*	2.08710	*0.005*	Alston, Cumbria
38	2014.149.42	Band arm-ring	131.4	18.4813	*0.004*	15.6440	*0.005*	38.5089	*0.006*	0.84648	*0.003*	2.08366	*0.004*	Western
39	2014.149.43	Bossed penannular	—	18.4897	*0.01*	15.6516	*0.011*	38.5592	*0.016*	0.84648	*0.003*	2.08543	*0.008*	Western

TABLE 2 | Lead isotope analyses of MBH 133X AGA3 measured at the BGS (this study) compared to analyses of the same standard. Errors from this study are given as 2SE (absolute) while the errors of other studies are given as 2SD (absolute).

Analysis	Laboratory	206Pb/204Pb	2SE (abs.)	207Pb/204Pb	2SE (abs.)	208Pb/204Pb	2SE (abs.)	207Pb/206Pb	2SE (abs.)	208Pb/206Pb	2SE (abs.)
This study	BGS, solution	17.4090	0.0016	15.5470	0.0012	37.285	0.004	0.89302	0.000003	2.14160	0.00001
Analysis	**Laboratory**	**206Pb/204Pb**	**2SD (abs.)**	**207Pb/204Pb**	**2SD (abs.)**	**208Pb/204Pb**	**2SD (abs.)**	**207Pb/206Pb**	**2SD (abs.)**	**208Pb/206Pb**	**2SD (abs.)**
Previous	DBM, sol. Ave. 2021	17.4094	0.0003	15.5461	0.0004	37.282	0.001	0.89297	0.00001	2.14151	0.00001
Previous	Oxford, sol. 2019	17.4090	0.0010	15.5450	0.0010	37.280	0.005	0.89304	0.00005	2.14130	0.00010
Previous	Southam. ns-LA 2019	17.4110	0.0160	15.5490	0.0140	37.292	0.026	0.89300	0.00010	2.14180	0.00020
Previous	UoE, ns-LA, 2019	17.4120	0.0230	15.5450	0.0200	37.256	0.048	0.89290	0.00010	2.14010	0.00110
Previous	VU, sol. Ave. 2024	17.4107	0.0040	15.5472	0.0032	37.287	0.009	0.89297	0.00002	2.14157	0.00004
Previous	VU, pLA Ave. 2019	17.4090	0.0058	15.5475	0.0087	37.279	0.026	0.89307	0.00021	2.14134	0.00080

TABLE 3 | Elemental analysis of the Bedale objects by LA-ICP-MS. All values are given as ppm (mg/kg) unless otherwise stated. 'n.d.' means not detected.

Object	Ag (%)	Cu (%)	Au (%)	Pb (%)	Sn	Zn	As	Sb	Bi	Te	Pt	Pd	Rh	In	Ni
5	95.44	3.30	0.366	0.584	1429	1033	37	15	394	n.d.	0.72	0.90	0.65	4.27	11.8
St. dev.	*0.28*	*0.12*	*0.007*	*0.084*	*282*	*260*	*10*	*2*	*71*	—	*0.04*	*0.05*	*0.08*	*0.86*	*1.7*
7	95.38	2.84	0.321	0.872	2426	2394	450	47	463	1.73	0.63	0.82	0.77	7.71	92.8
St. dev.	*0.25*	*0.07*	*0.003*	*0.067*	*340*	*389*	*58*	*3*	*47*	*0.17*	*0.01*	*0.03*	*0.05*	*1.07*	*11.3*
14	96.31	2.62	0.222	0.627	435	756	72	10	862	1.13	0.46	0.87	0.55	1.37	13.0
St. dev.	*0.57*	*0.34*	*0.008*	*0.065*	*68*	*142*	*8*	*1*	*119*	—	*0.06*	*0.04*	*0.01*	*0.14*	*0.9*
15	94.56	3.23	1.059	0.547	2220	2160	51	19	794	n.d.	1.91	1.47	0.60	6.75	26.6
St. dev.	*0.38*	*0.27*	*0.095*	*0.061*	*581*	*191*	*15*	*5*	*327*	—	*0.47*	*0.30*	*0.08*	*0.73*	*3.9*
16	95.56	3.27	0.467	0.529	821	408	35	12	396	2.71	0.68	1.03	0.60	2.57	5.9
St. dev.	*0.23*	*0.15*	*0.024*	*0.028*	*36*	*8*	*2*	*0*	*18*	*0.38*	*0.02*	*0.08*	*0.03*	*0.22*	*0.3*
17	97.13	1.74	0.866	0.257	3.4	1.7	n.d.	0.2	19.7	0.82	1.72	1.06	0.35	n.d.	n.d.
St. dev.	*0.12*	*0.07*	*0.007*	*0.037*	*1.5*	*1.0*	—	*0.0*	*3.0*	*0.03*	*0.07*	*0.03*	*0.03*	—	—
18	93.73	4.37	0.384	0.630	1178	4509	122	63	2925	2.98	0.41	0.89	0.66	3.67	18.6
St. dev.	*0.33*	*0.20*	*0.013*	*0.026*	*23*	*382*	*11*	*4*	*156*	*0.04*	*0.01*	*0.02*	*0.03*	*0.13*	*1.0*
19	95.55	3.00	0.462	0.352	4690	691	107	32	815	0.35	0.80	0.97	0.51	14.08	14.9
St. dev.	*0.31*	*0.08*	*0.056*	*0.061*	*547*	*81*	*17*	*3*	*159*	—	*0.03*	*0.06*	*0.03*	*1.92*	*2.4*
21	97.84	1.55	0.558	0.048	0.5	2.8	n.d.	0.1	26.8	0.47	0.99	0.81	0.20	n.d.	n.d.
St. dev.	*0.20*	*0.14*	*0.015*	*0.006*	—	*0.7*	—	*0.0*	*4.4*	*0.06*	*0.09*	*0.04*	*0.02*	—	—
22	94.80	3.54	0.895	0.482	1863	497	47	12	392	n.d.	0.98	1.07	0.53	5.50	10.7
St. dev.	*0.16*	*0.10*	*0.148*	*0.032*	*105*	*19*	*2*	*0*	*35*	—	*0.11*	*0.02*	*0.03*	*0.40*	*1.0*
24	97.09	1.95	0.543	0.288	814	130	23	26	205	1.38	0.83	0.94	0.37	2.39	3.5
St. dev.	*0.25*	*0.17*	*0.053*	*0.034*	*46.6*	*4.7*	*4.0*	*0.8*	*23.7*	*0.23*	*0.03*	*0.01*	*0.03*	*0.15*	*0.2*
25	97.67	0.97	1.262	0.097	3.2	5.0	n.d.	n.d.	17.1	n.d.	1.33	0.78	0.16	n.d.	n.d.
St. dev.	*0.37*	*0.11*	*0.429*	*0.024*	*0.9*	*3.1*	—	—	*4.3*	—	*0.13*	*0.05*	*0.01*	—	—
29	96.99	1.97	0.905	0.130	1.5	4.2	0.5	0.1	4.6	0.55	1.95	1.09	0.31	n.d.	n.d.
St. dev.	*0.24*	*0.16*	*0.036*	*0.011*	*0.4*	*1.5*	*0.2*	*0.1*	*0.7*	*0.11*	*0.07*	*0.04*	*0.01*	—	—
30	95.46	3.25	0.562	0.512	1194	286	41	11	557	1.65	1.02	0.96	0.56	3.67	9.1
St. dev.	*0.02*	*0.06*	*0.026*	*0.035*	*55*	*3*	*1.2*	*0.8*	*52*	*0.05*	*0.04*	*0.07*	*0.02*	*0.08*	*0.8*
33	95.48	1.69	0.664	0.264	1226	546	17	11	280	1.25	1.20	0.84	0.31	3.57	14.3
St. dev.	*0.33*	*0.35*	*0.044*	*0.048*	*165*	*47*	*11*	*2*	*32*	*0.00*	*0.15*	*0.03*	*0.04*	*0.41*	*1.7*
34	97.44	1.87	0.431	0.121	1000	122	5	4	132	1.05	0.96	0.97	0.36	2.90	8.1
St. dev.	*0.29*	*0.25*	*0.041*	*0.031*	*490*	*50*	*1*	*1*	*23*	*0.17*	*0.04*	*0.04*	*0.05*	*1.23*	*2.8*
35	98.00	1.55	0.394	0.033	134	17	1.0	0.7	44	2.03	0.91	0.99	0.28	0.39	3.1
St. dev.	*0.12*	*0.09*	*0.003*	*0.003*	*55*	*1*	*0.2*	*0.2*	*4*	*0.37*	*0.04*	*0.04*	*0.01*	*0.13*	*0.6*
37	96.46	2.70	0.756	0.070	4.5	2.2	0.7	0.0	66.0	n.d.	1.19	1.05	0.33	n.d.	n.d.
St. dev.	*0.10*	*0.09*	*0.029*	*0.005*	*0.4*	*0.4*	*0.2*	*0.0*	*8.4*	—	*0.05*	*0.02*	*0.03*	—	—

TABLE 4 | Elemental LA-ICP-MS analyses of standard RMAgD-1 measured at the BGS (this study) compared to solution ICP-MS measured at the University of Oxford. All values are displayed in ppm (mg/kg). 'n.d.' means not detected and 'n.m.' means not measured.

	Ag (%)	Cu (%)	Au (%)	Pb (%)	Sn	Zn	As	Sb	Bi	Te	Pt	Pd	Rh	In	Ni
Oxford, sol. 2019	99.5	0.118	0.00033	0.393	0.6	1.7	n.d.	1.98	24.7	0.33	16.17	0.59	n.m.	n.d.	0.6
	Ag (%)	**Cu (%)**	**Au (%)**	**Pb (%)**	**Sn**	**Zn**	**As**	**Sb**	**Bi**	**Te**	**Pt**	**Pd**	**Rh**	**In**	**Ni**
This study	99.51	0.128	0.00036	0.358	n.d.	n.d.	n.d.	1.04	18.8	n.d.	17.82	0.46	0.16	n.d.	0.4
St. dev.	*0.01*	*0.007*	*0.00002*	*0.001*	—	—	—	*0.05*	*0.1*	—	*0.11*	*0.05*	*0.01*	—	—
This study	99.66	0.087	0.00030	0.283	0.7	n.d.	0.4	0.80	15.0	n.d.	18.59	0.35	0.16	n.d.	0.2
St. dev.	*0.04*	*0.003*	*0.00002*	*0.027*	*0.1*	—	*0.1*	*0.03*	*1.2*	—	*0.11*	*0.01*	*0.01*	—	—

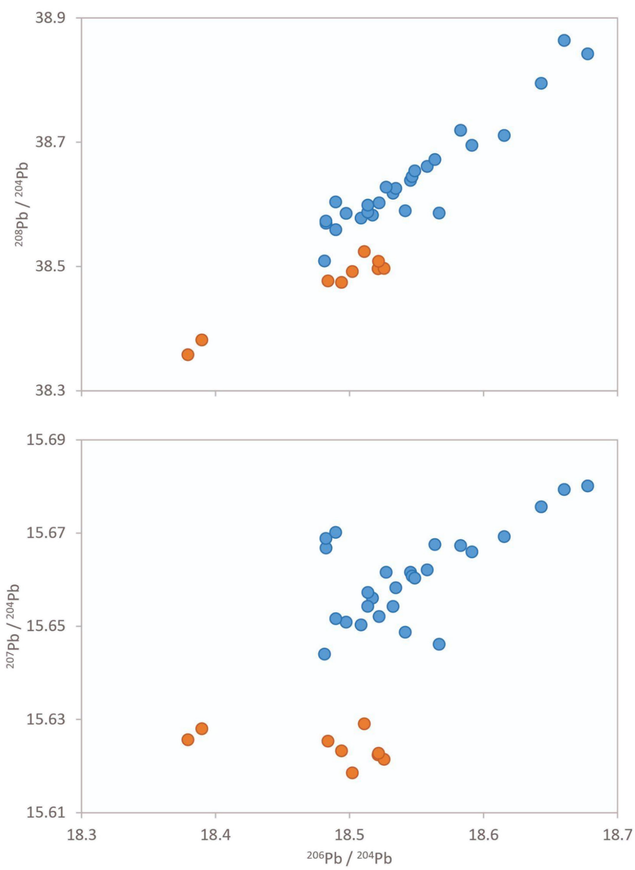

FIGURE 3 | The Pb isotope characteristics of the analysed Bedale hoard artefacts (errors smaller than the symbols). The diagrams indicate the presence of multiple clusters of two or more objects. The artefacts with low 207Pb/204Pb ratios, referred to in the text, are highlighted (orange).

5.2 | Elemental Results: LA-ICP-MS

The primary standard, MBH-133-AGA3 archaeological silver, is the most similar commercially available standard to the Bedale artefacts and was used in calibration and quantification. In all cases, the Bedale artefacts were determined to be of high fineness (93.9 to 98.1 wt.% Ag). The copper concentrations of the samples range from 0.9 to 4.2 wt.% and the lead from 327 to 8500 ppm. The gold concentrations are between 2100 ppm and 1.23 wt.%; the calibrating standard matched the lower range of gold concentrations in the Bedale samples, so higher gold levels may be associated with larger error. The detection limits for trace elements were estimated to be around 1 ppm for many transition and semimetals (Zn, Sn, Ni, As, Sb, Te, Bi Co, Mn and Cr) and 0.1 ppm for Cd and In. Tin and zinc concentrations range between single-digit ppm and 4000–5000 ppm. The bismuth concentration of AGA3 is within the middle range of the Bedale samples, and only one artefact had significantly higher bismuth (#8, 2800 ppm). Iron was difficult to quantify due to high levels of background noise and isobaric interferences. It was detected in concentrations typically less than 100 ppm; only in object (#33) was the iron around 1%–2%: this is likely related to burial conditions and severe corrosion. Chromium, manganese, cobalt and cadmium were present in amounts typically less than the detection limit or otherwise highly variable in the low ppm range; these elements, along with iron, are not shown in Table 3. We found differences in trace element patterns consistent with the two groups identified on the basis of lead isotope ratios.

5.3 | Elemental Results: pXRF

Comparison of the LA-ICP-MS data and the pXRF results shows that the data are positively correlated for most elements but are of highly variable quality and degree of agreement. Gold, for example, is unpredictably overestimated by the pXRF anywhere between 0% and 125% relative to the LA-ICP-MS value. The pXRF values for tin and iron are determined to be entirely unreliable. The two elements that are most consistent between the two analytical methods are bismuth and zinc. For further discussion of the comparison of the two methods, see Text S2. Because of the unpredictability of the pXRF data and its poor comparability to reference datasets, the pXRF data are only used in a semiquantitative and/or qualitative way to add additional information in the absence of more reliable data. Thus, the interpretation that follows is based primarily on the LA-ICP-MS results.

6 | Interpretation

The geochemical results of the Bedale hoard analysis relate to two distinct phenomena. The first is a group of objects whose silver has been subject to secondary cupellation during recycling and casting processes (rather than during the initial extraction of silver from ore) (Figure 3, orange group). Cupellation is a refining process in which lead is added to precious metals and heated above 900°C so that the nonnoble metals (e.g., most of the copper, zinc and tin) oxidise and are removed in the form of litharge (lead oxide plus other oxidised metals). Since the volume of lead added to silver in cupellation is far greater than that contained within the silver artefacts, the Pb isotope values relate predominantly to the lead employed in that process. Cupellation can be deduced for a subset of Bedale silver objects both because of their high silver purity and because they are isotopically consistent with lead found in Viking-Age archaeological contexts, rather than with silver coinage/artefacts (this is developed further below). A larger, second group of analysed artefacts possesses isotope ratios that relate to contender silver sources, rather than lead, and appear not to have been subject to the same cupellation process during casting (Figure 3, blue group).

Despite the cupelling of silver, we are able to point to candidate sources of silver for the analysed artefacts on the basis of observed trace element patterns. Overall, we identify three sources of silver in the Bedale hoard: a western European group, which may be identified with Carolingian and/or Anglo-Saxon silver; a smaller but still significant Islamic group, consistent with dirhams reaching Scandinavia in the ninth century; and a group that sits on a continuum between eastern and western silver, reflecting a mixture of both sources. Overall, the lack of very high gold contents (over 2 wt.%) suggests that gilded silver and/or silver with gold inlays was not a significant contributor to the sampled artefacts, with the gold contents instead being paralleled in contender source coinages.

6.1 | Silver Items Refined With Lead ($N = 14$)

6.1.1 | British Lead

The first group comprises nine items (nos. 3, 9, 17, 21, 25, 26, 29, 31 and 37, Tables 1 and 5). All are ingots, apart from one item, a spiral-striated-rod fragment from a so-called 'Duesminde-type' ring of presumed southern Scandinavian origin (no. 37) (for Duesminde-type rings, see Munksgaard 1963, 1965). These objects possess lead isotope ratios that do not align with candidate silver sources, but with locally available lead from Britain, i.e., lead sources likely to have been used in refining as part of the casting process (Figure 4). In addition, all analysed objects are 97% silver or over, with only traces of easily oxidised base elements (e.g., tin, zinc and lead) that do not survive the cupellation process (McKerrell and Stevenson 1972; Pernicka and Bachmann 1983) (Table 3). We acknowledge that very fine silver need not have been subject to cupellation processes (Merkel 2021). However, all analysed objects in this group have tin and zinc contents below 10 ppm (Figure 5), which is exceptionally low compared to the normal background present in Viking-Age recycled silver melted in crucibles without refining (cf. with hacksilver from Hedeby: Merkel 2016, Appendix B Table 4). The objects within this group analysed only by pXRF also confirm the high fineness, relatively low copper contents and zinc impurities below detection (<ca. 300 ppm). We thus judge that the silver has been refined during recent casting events.

The items in this group consist of a core group of seven objects and two isotopic outliers, one of which is the Duesminde-type ring fragment (Tables 1 and 5; Figure 6). In instances of silver cupellation, the lead isotope values will reflect that of lead added to silver as part of this process, meaning that the original source of silver is obscured. However, it is highly unlikely that the silver supply for these items consisted wholly or mainly of Islamic silver, as ninth-century and earlier Islamic silver dirhams are naturally very fine and thus do not require refining to raise the silver content. The high gold levels observed within this group, running from 0.54 to 1.23 wt.%, likewise rule out an exclusively Islamic origin, as ninth-century Islamic silver is low in gold (average gold content of dirhams contained in ninth-century hoards from Gotland: 0.29 wt.% SD +/−0.04) (Kershaw et al. 2021, 193; Merkel et al. 2023). Furthermore, all the items analysed by LA-ICP-MS in this group have bismuth levels below 100 ppm, which is much lower than ninth-century dirham silver (Table 3; compare Kershaw et al. 2021, Table 7). Nonetheless, Islamic silver could have been part of an old, mixed silver stock that required refining prior to casting.

Instead, the gold contents of this group are akin to mid-to-late ninth-century silver from western Europe: Anglo-Saxon and/or Carolingian coinage. Thanks to extensive elemental analysis of ninth-century Carolingian and Anglo-Saxon coinage (Geneviève and Sarah 2012; Kershaw et al. 2022b; Metcalf and Northover 1985, 1988, 1989; Sarah 2008, 2010; Sarah et al. 2016), it is possible to track an increase in the gold content of Carolingian and Anglo-Saxon coins over the course of the ninth century. While low gold levels (c. 0.2% SD+/−0.1) characterise early ninth-century coinage, moderate gold contents, of c. 0.6% SD+/−0.5, are more common around the middle of the ninth century, when both Carolingian and Anglo-Saxon currencies were strongly alloyed/debased. Even higher gold contents (0.9% SD+/−0.1) characterise Anglo-Saxon and Carolingian coinage in the later ninth century, with the highest gold-to-silver ratios (around 1.0%–1.2%) found in Anglo-Saxon coinage minted after Alfred's coin reform in 875. The reasons for the increase in gold concentrations over time are not yet clear, but the spread of gold values within this Bedale group aligns with those seen in mid-to-late ninth-century coinage.

It is notable that the mid-ninth century—a period of heightened Viking raiding in western Europe—was also marked by profound debasement in silver coins minted in England and the Carolingian Empire (Metcalf and Northover 1985; for evidence of a temporary fall in weight standard and a decline in literacy, see Moesgaard and Dhènin 2014). Coins captured by Viking raiders at Dorestad (Netherlands) in the 840 s or on the Loire (France) in the early 860 s, for instance, would

TABLE 5 | Nicks recorded on Bedale silver items, by isotope group.

Object	York. Mus. ref.	Object Type	Nicks	Isotope group
17	2014.149.22	Oblong ingot	3	Refined with British lead—Alston
37	2014.149.41	Striated-rod fragment	1	Refined with British lead—Alston
21	2014.149.26	Oblong ingot terminal	0	Refined with British lead—Yorkshire
3	2014.149.8	Oblong ingot	1	Refined with British lead—Yorkshire
26	2014.149.31	Oblong ingot	7	Refined with British lead—Yorkshire
31	2014.149.36	Oblong ingot, clipped end	2	Refined with British lead—Yorkshire
29	2014.149.34	Oblong ingot, bent over	7	Refined with British lead—Yorkshire
25	2014.149.30	Oblong ingot	12	Refined with British lead—Yorkshire
9	2014.149.14	Oblong ingot terminal	15	Refined with British lead—Yorkshire
34	2014.149.38	Neck-ring	0	Refined with Melle lead
8	2014.149.13	Oblong ingot	16	Refined with Melle lead
35	2014.149.39	Neck-ring	0	Refined with Melle lead
28	2014.149.33	Oblong ingot, bent over	15	Lead-Is mix
4	2014.149.9	Oblong ingot	10 or 11	Lead-Is mix
38	2014.149.42	HSBB arm-ring	5	Western silver
24	2014.149.29	Oblong ingot	6	Western silver
39	2014.149.43	Bossed penannular	Unknown	Western silver
23	2014.149.28	Oblong ingot	5	Mix of Western and Eastern silver
20	2014.149.25	Oblong ingot terminal	4	Mix of Western and Eastern silver
33	2014.149.37	Collar (wire sample)	0	Mix of Western and Eastern silver
13	2014.149.18	Oblong ingot	1	Mix of Western and Eastern silver
36b	2014.149.40b	Neck-ring	3	Mix of Western and Eastern silver
10	2014.149.15	Oblong ingot	4	Mix of Western and Eastern silver
36a	2014.149.40a	Neck-ring	5	Mix of Western and Eastern silver
15	2014.149.20	Oblong ingot	2	Mix of Western and Eastern silver
27	2014.149.32	Oblong ingot	9 or 10	Mix of Western and Eastern silver
22	2014.149.27	Oblong ingot terminal	4	Mix of Western and Eastern silver
6	2014.149.11	Oblong ingot	7	Islamic or Islamic mixed with western
16	2014.149.21	Oblong ingot	4	Islamic or Islamic mixed with western
12	2014.149.17	Oblong ingot	3	Islamic or Islamic mixed with western
19	2014.149.24	Oblong ingot	3	Islamic
30	2014.149.35	Oblong ingot	8	Islamic
5	2014.149.10	Oblong ingot	9	Islamic
7	2014.149.12	Oblong ingot	3	Islamic
18	2014.149.23	Oblong ingot	3	Islamic
14	2014.149.19	Oblong ingot	7	Islamic

have required refining in order to raise the fineness to levels normally achieved within the Scandinavian bullion economy (Screen 2019, 6, Figure 3). High silver contents were restored in coin reforms in the Carolingian Empire in 864 and in England in c. 875: the mid-ninth century, debased coinage is, then, a good candidate source for the silver behind the manufacture

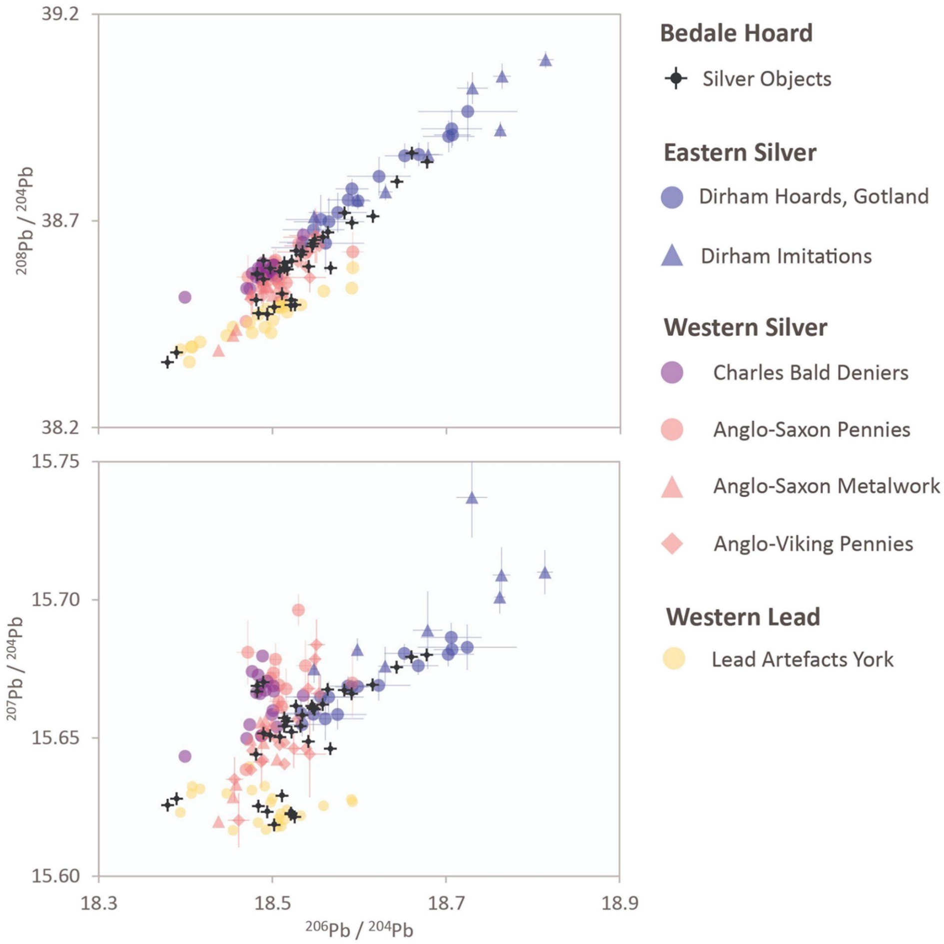

FIGURE 4 | Comparison of all analysed Bedale hoard artefacts with the Pb isotope reference data for eastern and western coinages, and lead artefacts from York. References, see Supporting Information.

of this group of items, with the higher gold levels perhaps indicating the inclusion of fine, higher gold post-reform coins. The objects could have been cast at different times and/or they could have made use of a varied silver stock encompassing both debased and fine coins minted from the mid through to the later ninth century. However, the consistency of the lead isotope values suggests that, within each group, the objects were refined, and probably cast, at the same time, suggesting the latter scenario is more likely.

Separately, the lead isotope ratios (LI) can be used to investigate the source of the lead used to refine the silver. We compared the LI ratios for this group of objects against a wide corpus of British, Irish and Continental ore sources (see Text S1). Despite the fact that this group of items divides into core and outlying isotope groups, lead from the North Pennines ore field, which includes the Askrigg and Alston blocks in modern-day Yorkshire, Cumbria and County Durham (Ixer and Vaughan 1993, 356–63), could account for all items: lead from the Yorkshire Dales (Askrigg block) plots with the main group of nine items, and lead from Alston, Cumbria, with the two outliers (Figures 4 and 6). Recent work has shown that North Pennines lead was extracted within a buoyant lead mining industry from at least c. 800 AD and was in circulation in ninth-to-eleventh-century York (Kershaw and Merkel 2023), making it probable North Pennines lead was used in refining.

However, other English sources of lead cannot be ruled out. Lead ore from Avon/Bristol overlaps in part with the core group of items, but not the two outliers, while lead ore from Mendip overlaps with the two outliers, though not the core group (Figure 6). It is possible that the core and outlier groups have different casting histories and utilised distinct stocks of lead.

The discovery that English lead was used to refine this group of items would thus seem to offer evidence that a ring type normally attributed to southern Scandinavia—the Duesminde ring—was in fact cast in England. However, lead from the North Pennines, as well as south-west England, was exported to southern Scandinavia during the ninth and tenth centuries, where it was used in casting processes. North Pennines lead was used to make weights and gaming pieces at ninth- and tenth-century rural sites in Denmark, while analysed lead artefacts from Kaupang in southern Norway can chiefly be attributed to the same source (Kershaw and Merkel 2023). It is thus entirely possible that the Duesminde ring, and indeed, some or all of the ingots were cast in Scandinavia using English lead to refine the silver.

We note that one ingot from this group (no. 21) has no nicks, while others have as many as 15 (Table 5). Did these items attract a high number of test marks because they were produced

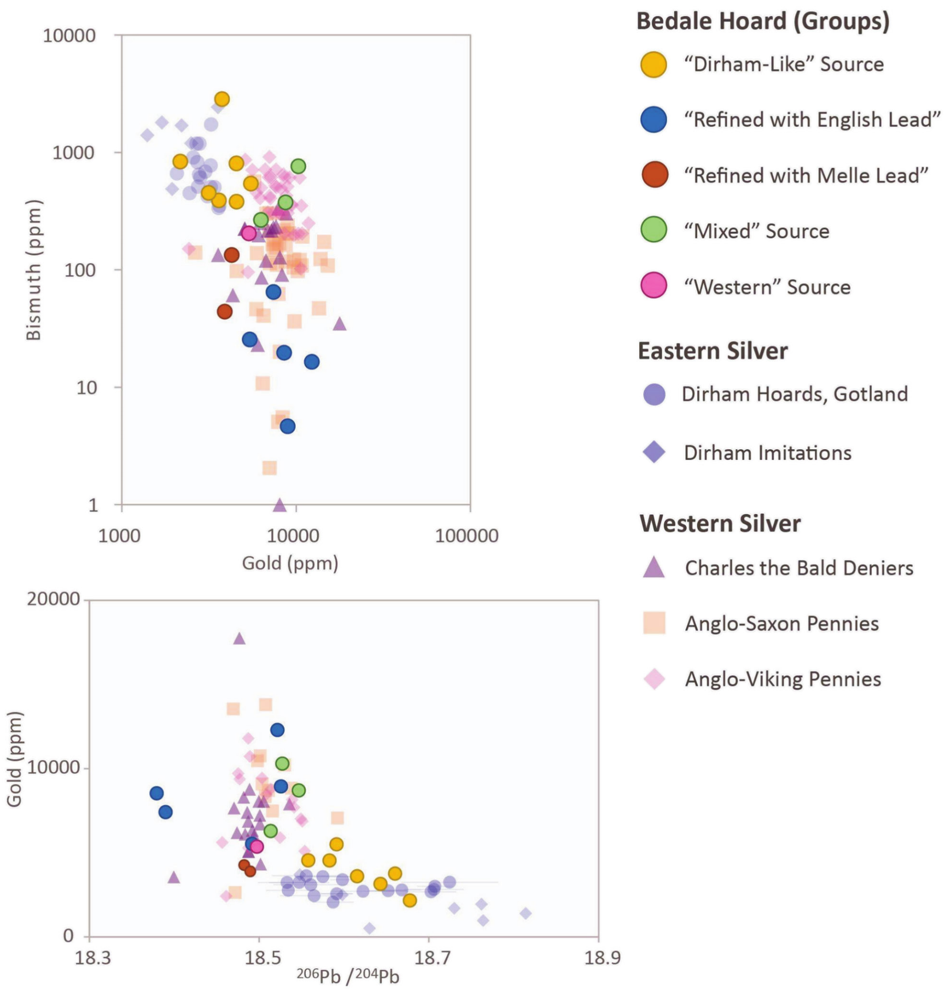

FIGURE 5 | Biplots showing elemental concentrations of the Bedale hoard artefacts divided into their isotopic groups. (A) All of the analysed artefacts were determined to be of high silver content, though there is a slight trend towards higher silver levels in the 'refined' objects. (B) The group interpreted to have been 'refined with English lead' have extremely low levels of tin and zinc, an indication that they were indeed refined immediately before casting.

at a time of debased silver currency, or because they had been in circulation for longer than other items in the hoard?

6.1.2 | Melle Lead

Three items from the Bedale hoard (nos. 8, 34 and 35) are isotopically consistent with the reference data for Melle, Aquitaine, France: they plot in the centre of the Melle field in every isotope ratio (Tables 1 and 5, compare with Téreygeol et al. 2005) (Figure 7). Two (nos. 34 and 35) are neck-rings of Hårdh's (1996, 45) Type 6, with narrow end plates, made of twisted and plaited rods, respectively, both of which have been coiled into an oval loop. The third is an oblong ingot (no. 8). The neck-rings possess similar isotope ratios and low-to-moderate gold levels (0.38% and 0.42%). They have typological analogies with material from Viking-Age Denmark (modern-day Denmark, southeast Sweden and southern Norway) and are probably a pair (Hårdh 1996, 45, Figure 4, 50–51). Owing to its large size, the ingot was not one of the objects selected for LA-ICP-MS, and it therefore lacks precise elemental data. However, it was analysed by pXRF. The pXRF data indicates a very high purity with copper less than 1%, lead below 0.4%, low zinc (0.01%) and tin below detection. It is so similar isotopically to one of the neck-rings (no. 34) that both could have been cast from the same silver stock. We thus suggest that these three items be seen as a group, with shared origins.

On the basis of only the lead isotope data, it would be difficult to know if the Melle signature reflects Melle lead used in cupellation or a Melle silver source. Melle was both a major argentiferous galena mine and mint and has been identified as a significant supplier of silver for western Carolingian coinage during the eighth and ninth centuries (Sarah 2008, this volume; Kershaw et al. 2024). However, it is clear that both neck-rings are made of very high purity silver (>97%), with extremely low lead, features that point to the thorough refining of silver. One neck-ring has very low traces of zinc and tin (20 and 130 ppm, respectively) consistent with newly refined silver (Figure 5). The other has higher tin (1000 ppm), but, given that the silver is fine and copper low, this level points to unintentional mixing (i.e., during casting) rather than deliberate alloying. It can therefore be argued that the silver of both neck-rings was refined with lead from Melle. The ingot lacks elemental data but is grouped with the neck-rings on the basis of the isotopic evidence.

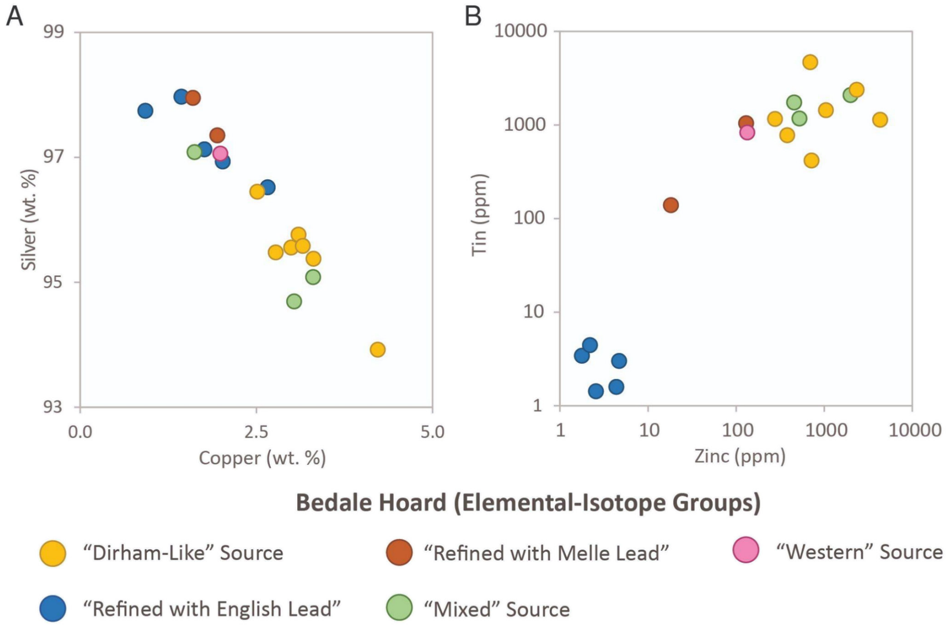

FIGURE 6 | Comparison of the Bedale hoard artefacts interpreted to have been refined with English lead with galena ore analyses from the North Pennines (A) and south-west England (B). Error bars for the ore data are 0.1%. References, see Supporting Information.

As noted above, the act of refining obscures the original lead isotope signature of the silver, but the gold and bismuth contents of the neck-rings can help to narrow down candidate sources. The bismuth contents of the two items analysed by LC-ICP-MS (132 and 44 ppm) are well below the c. 500–700 ppm observed in dirham silver of the ninth century, making a western European source probable (cf. Kershaw et al. 2021, tab. 7). The moderate (ca. 0.4%) gold levels of the two neck-rings rule out an exclusively late ninth-century western coinage source, as, at this date, gold levels in western European coinage are typically around 0.8%–1%. The gold values could reflect a mix of early and late ninth-century coins. Alternatively, they could reflect the use of mid-ninth-century coinage: The average gold-to-silver ratios seen in the *Christiana Religio* coinage of Louis the Pious, minted 822–40, are 0.45% SD+/−0.1 (average of 21 coins) and those from Anglo-Saxon England minted in the 840 s 0.35% SD+/−0.06 (average of 9 coins). As described above, starting with these coinages, both Carolingian and Anglo-Saxon coins went through a period of severe debasement in the middle decades of the ninth century before the re-establishment of fine silver coinage in 864 on the Continent and c. 875 in England. The copper contents of the coin groups mentioned above range from 5% to 23% and 6% to 43%, respectively, meaning that, unlike post-reform coins from the later decades of the ninth century, they would have required refining to raise the silver content to levels acceptable to the Vikings.

Where, then, were these neck-rings manufactured? A southern Scandinavian origin for the neck-rings is suggested on typological grounds. Extant western European coins are rare in Scandinavia, but their low number may be explained by their recycling into artefacts (Coupland 2011, 124). Melle lead was also available in the north. Melle lead-glass 'smoothers', used like irons to remove creases from linens, were exported to southern Scandinavia, and Melle lead metal is present in small quantities at Kaupang, Norway; it is also alloyed with tin in pewter objects from Gokstad, Norway (Gratuze et al. 2018; Pedersen 2010; Pedersen et al. 2016). It is thus possible that Melle lead was used in refining processes within Scandinavia.

However, current data suggest that English lead was the dominant lead source in southern Scandinavia during the Viking Age (Kershaw and Merkel 2023). It is perhaps more probable that silver refining and casting took place within the Carolingian Empire itself, or in other western areas of Scandinavian raiding and settlement in the ninth century. Silver refined and cast into ingot or rod form on the Continent could have been fashioned into neck-rings locally. Neither of the neck-rings is nicked, but the ingot has 16 nicks (Table 5), suggesting considerable circulation prior to deposition.

6.1.3 | Unknown/Mixed Lead Source

Two ingots (nos. 4 and 28) have Pb isotope ratios that do not match directly with the comparanda reference datasets; they may be best interpreted as mixtures of silver refined using lead from the North Pennines and silver of an eastern source (see Section 6.2.2). Both ingots are heavily nicked (Table 5). Only pXRF data are available for these two ingots. The gold and bismuth contents are moderate relative to the dataset as a whole, suggesting recycled mixed silver.

6.2 | Nonrefined Silver Items ($N=21$)

The remaining items in the Bedale hoard possess lead isotope ratios that are consistent with silver reference groups, rather than lead artefacts (e.g., from York), indicating that the isotope ratios relate to circulating silver and not lead. The results point to two principal silver sources: one western European and one Islamic, with the majority of items falling on a continuum (a mixing line) between the two sources.

6.2.1 | Western European Silver ($N = 3$)

Three items (nos. 24, 38, and 39) are dominated by a western European silver source. One is an ingot (no. 24), which could have been cast anywhere in the Scandinavian world of the Viking Age. The other two objects are both items produced in Viking-Age Ireland. Notably, they are the only two items in the hoard with this cultural attribution. One is a complete Hiberno-Scandinavian (i.e., produced in Ireland under Scandinavian influence) broadband arm-ring (no. 38) and the other a hitherto unknown variant of an Irish bossed penannular brooch (no. 39) (James Graham-Campbell pers. comm.). Hiberno-Scandinavian broadband arm-rings are thought to have been produced predominantly in or near Dublin, with a main period of production from c. 850–950 AD (Sheehan 1998, 177–183). The bossed penannular brooch was produced around the same time, and it is thus not surprising that the two arm-rings from Ireland belong to the same metallurgical group.

Within western European silver, the distinction between late ninth-century Anglo-Saxon/Anglo-Viking and Carolingian silver is not always clear-cut, making it difficult to narrow down origins. The fact that Anglo-Saxon coinage mirrors changes in Carolingian coinage in terms of debasement and increasing gold contents over the ninth century suggests that Carolingian coinage was a major source of silver bullion for the production of Anglo-Saxon coinage (Metcalf and Northover 1985; Sarah 2008). Nonetheless, the isotope ratios of the coinages are not identical, suggesting that any incoming Continental silver to England was recycled and/or added to an existing silver stock prior to minting. Anglo-Viking coinage, produced in East Anglia between 885 and 895, and in York in the early tenth century, is isotopically very similar to late ninth-century Anglo-Saxon coinage, on which it was modelled, and which seems to have been its chief source of bullion (Kershaw et al. 2022a, 306). However, Anglo-Viking coins tend to have slightly lower gold and higher bismuth contents compared to their contemporary Anglo-Saxon counterparts (Figure 9). We have suggested elsewhere that this reflects a modest contribution of Islamic silver to the bullion pool of Anglo-Viking rulers (Kershaw et al. 2022a, 306–308).

Isotopically, the items in this group are offset in 206Pb/204Pb 207Pb/204Pb space from the major Carolingian mint and mine of Melle, Aquitaine (Figure 7). There are closer parallels to Anglo-Saxon Trewhiddle-style silver as well as Anglo-Viking and Charles the Bald coinage, dated, as a group, to the later ninth to early tenth century (Figure 7). Unfortunately, only one item in this group, the ingot, possesses LA-ICP-MS elemental data. It has a gold content of 0.5% and a bismuth content of 205 ppm, which is in keeping with mid-to-late ninth-century western silver (Figure 9).

The isotope ratios of these three items fit neatly within the range of a larger group of 42 analysed Hiberno-Scandinavian broadband arm-rings and 28 associated ingots from the Galloway hoard, with a suggested date of deposition in the early tenth century (Kershaw and Merkel Forthcoming; Graham-Campbell 2020). In addition to Pb isotope ratios, the Galloway hoard items also possess elemental data. They have slightly elevated bismuth relative to Anglo-Saxon coinage, suggesting a better fit with Anglo-Viking, rather than Anglo-Saxon or Carolingian silver. Whether or not the Hiberno-Scandinavian objects from Bedale fit the same pattern could be confirmed by future elemental analysis. Both the gold (0.5%) and bismuth (200 ppm) contents of the ingot is encountered among the arm-rings in the Galloway hoard.

On the basis of the isotope results, the three Bedale hoard items from this group appear to have been produced from the same stock of silver as Anglo-Saxon/Anglo-Viking coinage, supporting the more extensive results from the Galloway hoard analysis. This does not necessarily mean that Anglo-Saxon and Anglo-Viking coins served as a direct source of silver, although this could have been the case. Rather, it points to a shared metal stock. Anglo-Saxon/Anglo-Viking coins could have reached Ireland (especially Dublin) directly in Viking hands, they or could have been processed into ingots (for instance) in England/the Danelaw and further worked in Dublin. Alternatively, Anglo-Saxon coins may have been recycled with small numbers of dirhams in Dublin. We note, however, that coins, whatever their origin, are rare in Dublin before the tenth century.

6.2.2 | Islamic Silver ($N = 9$)

A group of nine ingots (nos. 6, 16, 12, 19, 30, 5, 7, 18 and14) plot isotopically and elementally with models of recycled batches of Islamic coins reaching the Baltic island of Gotland (Sweden) during the ninth century (Kershaw et al. 2021; Merkel et al. 2023; see too Birch et al., In Preparation) (Figures 4 and 8). The ingots plot fairly evenly across the modelled date range for the ninth century, meaning they reflect the average isotope signatures of dirhams deposited in Gotland hoards of this date: primarily Abbasid issues from locations including Iraq and Iran, but also older Umayyad issues, alongside decreasing quantities of pre-Islamic, Sasanian coin (Kershaw et al. 2021, Figure 4). They also share the low gold and moderate bismuth profiles of these ninth-century dirhams (average gold content of seven ingots with elemental data: 0.39% SD+/−0.10) (Table 3, Figure 8). Three ingots (nos. 6, 12 and 16) plot in an isotopic space that borders western European silver sources and may well include some western silver: This may be the case with ingot no. 16, with a higher gold content (0.47%) and slightly lower bismuth content (396 ppm) than would be expected for pure dirham silver (Table 3). Other ingots in this group correlate with dirham parcels deposited in the very late ninth century (nos. 5, 7, 14 and 18), making a casting date around this time possible (Figures 4 and 8). Indeed, the bismuth content of ingot no. 18 (2925 ppm) is above that seen in Abbasid dirhams and may reflect a contribution of silver from early Samanid issues produced in Central Asia, which began to arrive in Scandinavia in the last decade of the ninth century (cf. Merkel 2016, Appendix C, Table 1 nos. 13–49).

In addition to the modelled ninth-century dirham data from Gotland, this group of ingots also plots with so-called 'imitation' dirhams minted in Khazaria, north of the Caspian Sea and Volga Bulgaria, at the confluence of the Volga and Kama rivers (Figure 4). These 'imitation' dirhams are very common in hoards from Scandinavia and the Baltic. They were minted outside of the official Islamic mints yet copy the weight, fineness and other salient features of regular (i.e., official) dirhams. A case has recently been made that imitations were produced to maintain liquidity in a marketplace at times when regular (official) dirhams were in short supply and relied for their bullion on older stocks of dirhams that had travelled up from the Caliphate and been stored in reserves—a hypothesis confirmed by recent lead isotope analysis of a small corpus of coins (Jankowiak 2021, 73–74; Merkel 2016, 99–100). Khazaria produced imitation dirhams from the 830 s, and especially the 860 s, while Volga Bulgar imitations are thought to have been produced from the early tenth century, with a peak of production in the 930 and 940 s (Jankowiak 2021). The latter are thus too late to constitute a viable silver source for the Bedale objects in themselves, but we suggest that the ninth-century Islamic dirham silver that the imitations capture is also present in the Bedale ingots. Thus, we propose that these nine ingots were cast from a majority or exclusively Islamic coin stock. This is typical of silver ingots and rings cast in the Baltic region (Kershaw et al. 2021), making a place of production within Scandinavia probable.

Notably, the Bedale hoard objects are distinct isotopically and elementally from one particular group of dirhams: high-bismuth Samanid dirhams, produced in Central Asia from the late ninth century (Figure 8). The appearance of Samanid dirhams in Scandinavia marks a major eastwards shift in the origin of dirhams travelling north: they entered Scandinavia from c. 890–900 and quickly came to dominate coin stocks (Blackburn 2007, 39–41; Williams 2011, 66). Their absence as a sole raw material for the Bedale hoard objects is thus a good indication that the hoard items were cast prior to this date.

All the ingots in this group are nicked, with between three and nine nicks each: an indication that the ingots circulated prior to deposition (Table 5). In addition, two of the ingots (nos. 6 and 7) carry a Latin cross, in each case incised at one end along the centre of the upper surface, in the same manner as one other ingot from the 'mixed' group (no. 10). As John Sheehan has remarked, these crosses are consistent in their placement, proportions and execution and should be seen as a discrete group (Sheehan 2019, 117). Cross-incised ingots seem to have an Irish Sea association: two of the oblong ingots in the Silverdale, Lancashire, hoard (deposited 900–910) also carry crosses, while equal-armed crosses, or Xs, also appear among the ingots from the Galloway hoard, buried c. 900 (Goldberg and Davis 2021, 29). What the crosses signify is unclear. Ingots with raised, integrally cast crosses are known from the Cuerdale hoard, as well as sites in Ireland, including from ecclesiastical estates, leading John Sheehan to suggest they were 'produced for use in Irish ecclesiastical circles' (Sheehan 2019, 118). Whether the incised crosses can be considered as part of this group remains to be seen, but a period of circulation in northern or north-west England for the Bedale ingots seems probable.

6.2.3 | Mixed Silver ($N = 9$)

The remaining group of nine objects in the Bedale hoard forms a 'mixing line' between western European and Islamic silver sources: they represent a continuum of western and eastern silverwork. The western source is difficult to pinpoint, but the group is offset from Melle ore, so Melle silver is not the exclusive

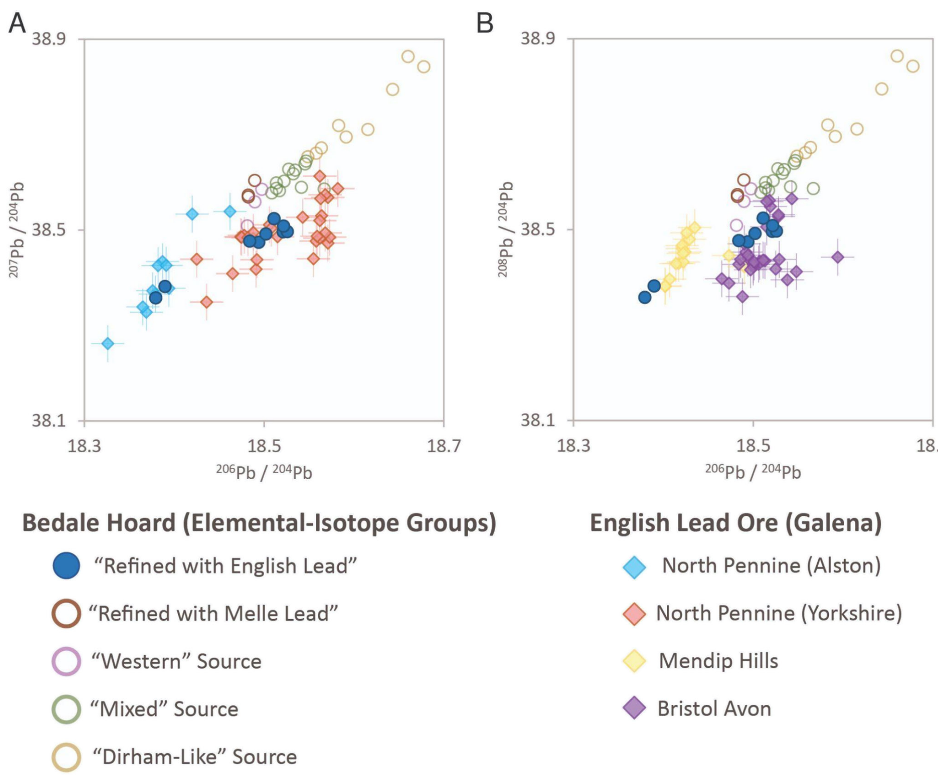

FIGURE 7 | (A) Comparison of the Bedale hoard artefacts with ore/slag/glass analyses from Melle (Aquitaine). The group of three Bedale objects consistent with Melle are highlighted. (B) Comparison of Bedale hoard artefacts with Western European coin analyses. The symbols represent the average of extant data and the size of the symbol reflects the standard error. A group of three Bedale objects are highlighted. References, see Supporting Information.

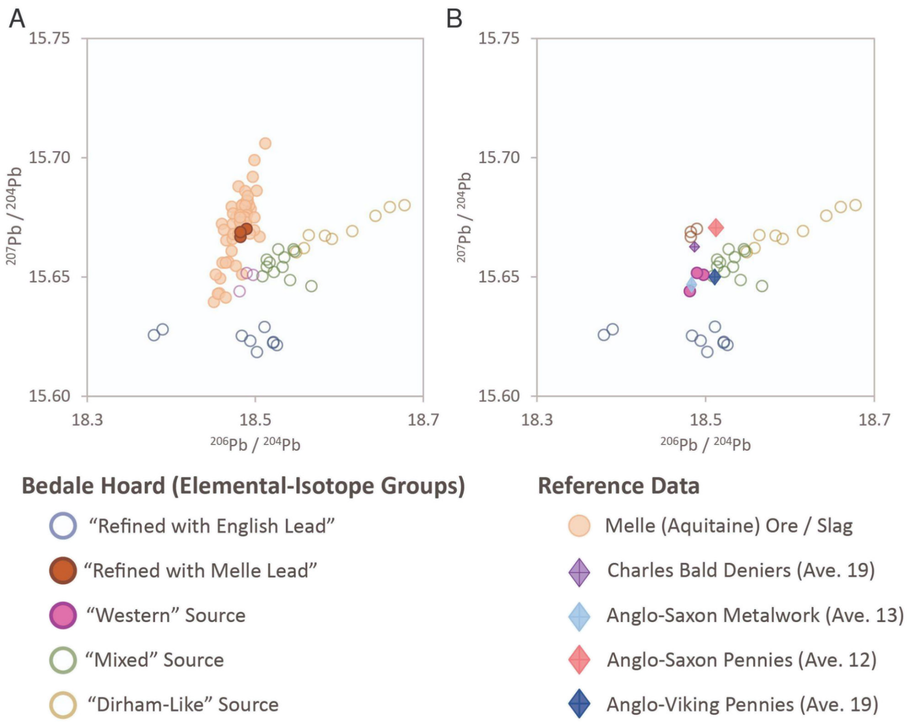

FIGURE 8 | Comparison of the Bedale hoard artefacts and the modelled average dirham compositions of 30 Baltic dirham hoards (Kershaw et al. 2021; Merkel and Kershaw this issue). The dirham hoard averages are divided into chronological groups based on the last coin in the hoard (terminus post quem). The error bars of the hoard averages represent the standard error.

source (Figure 7). Instead, the mixing line plots between Anglo-Saxon Trewhiddle-style metalwork and coinage and/or post-reform (864) deniers of Charles the Bald, and Islamic silver (Figures 4 and 8).

The items in this group include seven ingots/ingot fragments (nos. 10, 13, 15, 20, 22, 23 and 27), one neck-ring (two rods sampled: no. 36 'a' and 'b') and a wire from an enormous neck 'collar' (nos. 32 and 33). The three objects with elemental data, namely, the wire from the collar and two ingots, show medium-to-high gold contents (0.6%–1.0%), consistent with later ninth-century Western European coinages. In addition, the two ingots have elevated bismuth (376–763 ppm) (Table 3). This points to an admixture from dirham silver and is similar to levels seen in Anglo-Viking coinage (Figure 9). Given that the silver in this group was not refined prior to casting, it is reasonable to suggest that the western silver postdates the re-establishment of fine silver coinage in the later ninth century. Overall, the ratio of contributing western and eastern sources of silver will have been different for each item: Most of the items plot closer, isotopically, to western European sources, while three ingots, including one with an incised cross, have higher LI ratios, pointing to a predominantly Islamic source.

The places of manufacture for these items are difficult to pin down. They may have been cast in areas of western Scandinavian activity, or within Scandinavia itself. It is significant that both the neck-ring and 'collar' belong to the same metallurgical group, since the neck-ring appears to copy the design of the 'collar', or vice versa. Both are unusual 'West Viking' variants, meaning that they have analogies with material from Norway, western/southern Sweden and Denmark, although no exact parallels, a fact which may indicate manufacture in northern England. We analysed two rods from the neck-ring (36a and 36b), and the silver is not isotopically identical (Table 3); thus, the rods were not cast from the same batch of silver.

7 | Discussion

What does the geochemical analysis of the Bedale hoard artefacts reveal about the acquisition of wealth by Scandinavians in northern England in the late ninth/early tenth century? There are several notable findings. First, the lion's share of the silver in the hoard derives from western European sources: coinage minted on the Carolingian Continent and/or in Anglo-Saxon England, during the mid-to-late ninth century. While a full or partial trade source cannot be ruled out, this wealth probably represents the fate of 'loot' acquired by Viking groups during their persistent ninth-century raids in western Europe, in particular the Carolingian Continent and England, from the 840s onwards. This analysis thus offers support to the notion that such silver—a large part of which would have been debased—was regularly transformed into cast ingots and rings, in keeping with a Scandinavian bullion economy.

There are grounds for thinking that the silver that was melted down originally took the form of coinage, rather than plate. First, we do not see the high gold levels that the systematic re-cycling of gilded plate would produce. In addition, we do not see

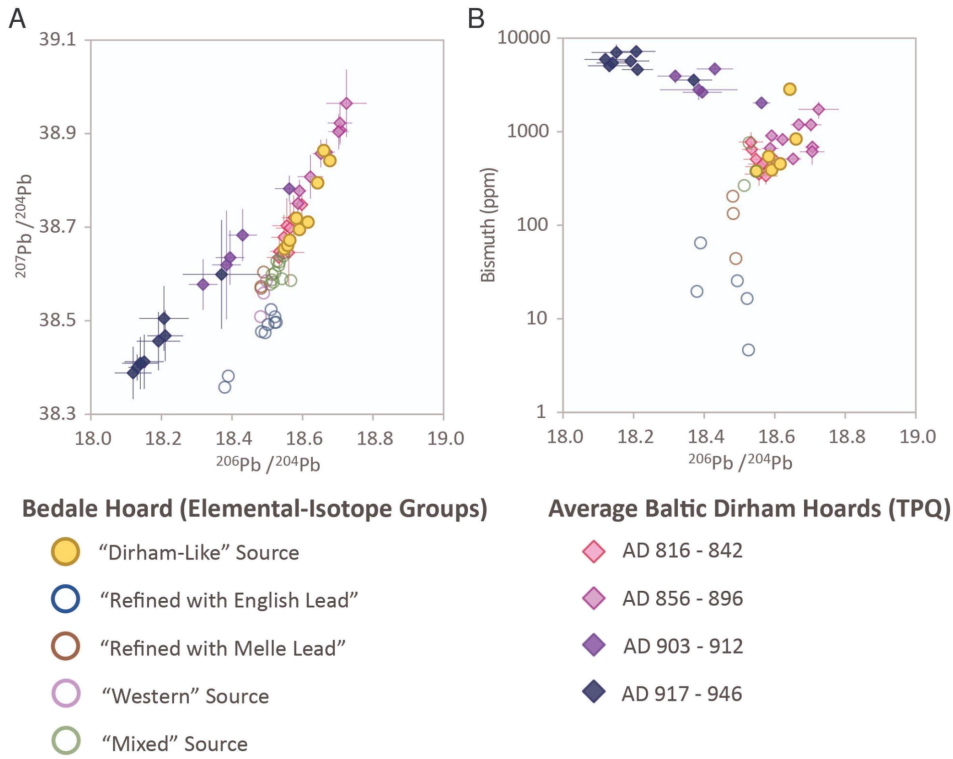

FIGURE 9 | Comparison of the Bedale hoard artefacts with eastern and western coinage reference data. The Bedale hoard artefacts are divided into groups based on their elemental and isotopic characteristics. The errors on the Gotland dirham hoard averages represent one standard error. References, see Supporting Information.

heterogenous lead isotope ratios that we might expect if old and diverse stocks of silver, stored as plate, were liquidated for payments to the Vikings. This is surprising: the Frankish annals report that church treasuries were sometimes mobilised in order to pay huge ransoms to Viking raiders. In 858, for instance, the *Annals of St Bertin* record that church treasuries in Charles the Bald's territories were 'drained dry, at the king's command' (ed. Nelson 1991, 86). Potentially looted silver artefacts also appear in Viking-Age silver hoards, most notably a gilded silver Frankish baldric mount from the Hjälarp hoard from Skåne, southern Sweden (Hårdh 1976, Taf. 48:I(4)) and a small group of Frankish silver liturgical vessels, including examples from Fejø and Ribe in Denmark, and Halton Moor and the Vale of York, England (Ager 2020).

Such examples are rare, however, and monasteries also made payments 'in cash' (ed. Nelson 1991, 85). In 866, a tax, to be paid in denarii, was 'imposed throughout the realm', including on merchants and priests. A similar tax had been levied 6 years previously; on both occasions, the accumulated silver had been weighed out by the 'Northmen … according to their scales' (ed. Nelson 1991, 131, 92; Coupland 2007). Such coin is easily accounted for within the analytical data presented here. The results, then, suggest that ornate/gilded items may have been valued for display, and thus preserved in their original form, over and above their bullion content.

Thus, western coinage appears to have made a significant contribution to the Bedale hoard silver. Perhaps the debased nature of much of ninth-century coinage made it unattractive as a store of wealth, necessitating its refining and conversion into artefacts. However, given the location of Bedale, just 35 miles north-west of York, and its suggested date of deposition, at the end of the ninth or beginning of the tenth century, we might expect that *all* of the silver in the hoard be derived from western European sources (Coupland 2007). This is clearly not the case—nine ingots were cast, we suggest, using majority dirham silver, presumably within Scandinavia, while dirham silver in varying quantities also formed part of the bullion pool for a further group of artefacts from a 'mixed', i.e., eastern/western silver source. Islamic silver may have also been present, in small quantities, in silver stocks that were subsequently refined.

The contribution to the hoard of Islamic silver is thus significant. The nine ingots together weigh 715 g, equivalent to some c. 240 dirhams, roughly the total number of dirhams recorded in hoards and as single finds in England to date (Naismith 2005; Kershaw 2017). The Vikings were not only extracting wealth locally; they were also bringing it into England via long-distance trade networks.

It is not just the quantity of Islamic silver that is relevant, but its early, ninth-century date: The Bedale hoard artefacts align with isotope models for dirham hoards deposited from the 840 s to the 890 s. The traditional view, based on the extant corpus of dirhams in the Baltic and Scandinavia, is that the volume of dirhams reaching Scandinavia was modest in the early ninth century, increased from c. 860, but reached substantial levels only from c. 900, with the import of Samanid dirhams

(Jankowiak 2020). The significant quantity of ninth-century dirham silver, preserved in cast form in the Bedale hoard, implies that this picture is inaccurate—far greater quantities of Islamic silver reached Scandinavia and travelled westwards than the relatively small number of dirhams preserved in ninth-century hoards and settlement contexts implies. We contend that, at the beginning of the import of eastern silver, dirhams were more likely to be treated as bullion for metalworking, rather than kept in coin form (Kershaw et al. 2021).

Due to the movement of silver and the buoyant North Sea trade in English lead, it is difficult to pin down a place of manufacture for the artefacts on the basis of metallurgical data. The items subject to cupellation could have been cast in Scandinavia or England/the Continent, for instance; the same is true for the artefacts made of mixed Islamic and western silver sources. The exception is the group of ingots made from Islamic silver: The fact that they are large, heavy objects, made predominantly or exclusively from dirham silver, makes it probable they were cast in a location where this silver was the only/majority available form—eastern Scandinavia or the Baltic region is their expected origin. Notably, none of the items need have been made in England; and while the Hiberno-Scandinavian group of objects can be linked to Dublin, all the remaining items could have been produced in Scandinavia.

The metallurgical groups visible in the Bedale assemblage nevertheless help to trace relationships between the items. The neck-ring (no. 36) and collar (nos. 32 and 33) are related typologically and by their metal profiles and probably travelled together from southern/western Scandinavia. The same is true of the two other neck-rings (nos. 34 and 35) and the associated ingot: their Melle isotope profiles suggest that they were cast on the Continent or in Scandinavia, using Melle lead in refining. Whether the group of (mainly ingot) silver cupelled with English lead has a singular source is difficult to say, given the widespread availability of such lead. The two distinct lead sources visible in the data may indicate separate groups that were only united in the deposition of the hoard, but the Duesminde ring and ingot no. 17, both refined with Alston lead, are probably connected.

Finally, the geochemical data, particularly the evidence for gold levels coupled with evidence for silver refining, help to reveal the chronologies of the different object groups, as well as the date of deposition of the hoard itself. The group of items refined with lead probably derives from debased coin captured during the mid-to-late ninth century and may well be among the oldest items within the hoard. This fits with the known chronology of the Duesminde-type ring (Hårdh 2007, 111), as well as with twisted and plaited neck-rings of Hårdh's Type 6 (Kershaw 2022, 129), all of which belong to this group. By contrast, the Hiberno-Scandinavian items, together with the linked neck-ring and collar, are made of post-reform silver characteristic from 864 (on the Continent) and 875 (in England) and appear to have been younger when deposited. The group of ingots made with Islamic silver could span the mid-to-late ninth century, but notably includes types with geochemical analogies to very late ninth-century dirham hoards. A clear end date for casting the Bedale hoard items around c. 900 is nonetheless suggested by the absence of Samanid-type lead isotope ratios. The geochemical groups thus appear to possess distinct chronologies, but it is likely the assemblage was deposited prior to the first decade of the tenth century.

8 | Conclusions

Overall, the geochemical analysis reveals the diversity of backgrounds from which the silver items originated: The Bedale hoard encapsulates multiple parcels of silver objects, with distinct life histories, which circulated in England and came together in North Yorkshire. In building an extensive reference dataset of regional metal stocks and candidate source ores for both lead and silver, we have been able to identify instances of refining as well as the mixing of silver sources: a prerequisite when dealing with Viking-Age silver. The results demonstrate the efficacy of combining lead isotope and trace element data for silver provenancing, generating insights into silver sources simply not possible through any other means.

Acknowledgements

Thank you to Dr. Guillaume Sarah (CNRS, Orleans) for sharing his unpublished data on Carolingian coinage.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

Endnotes

[1] It is possible that dirhams from Spain were seized during Viking raids on the Iberian Peninsula: Vikings raided Seville in 844, for instance. However, Spanish dirhams are very rare in Scandinavia, totalling around c. 50 specimens dated to the ninth/tenth century (Jani Oravisjärvi, pers. comm.). Moreover, the fact that they are also found in Russia suggests that they formed part of the general circulation of dirhams that travelled northwards through Russia to enter Scandinavia via the Baltic (Noonan 1984, Table 1).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** pXRF analyses of quality control standards. The results were normalised to 100 wt.% and are presented in wt.%. **Figure S1:** pXRF analyses vs. LA-ICP-MS measurements of Bedale hoard artefacts by element. **Figure S2:** Relationship between (A) pXRF gold values and lead isotope ratios compared to (B) LA-ICP-MS gold values and lead isotope ratios. Both show the same general trend (polynomial average). **Figure S3:** Relationship between (A) pXRF bismuth values and lead isotope ratios compared to (B) LA-ICP-MS bismuth values and lead isotope ratios. Both show the same general trend (polynomial average). **Table S2:** Semiquantitative composition averages of Bedale artefacts based on surface pXRF measurements. Based on comparison with the LA-ICP-MS results, the pXRF gold contents are overestimated up to a factor of 2. Tin had a high detection limit (ca. 1%) and could only be reliably detected in areas with tin-bearing solder. Iron, reflecting minor surface contamination, was detected in small amounts ($<1\%$) and is not presented. The results were normalised to 100 wt.% and are presented in wt.%.