Silver and the Silver Economy at Hedeby

Stephen William Merkel

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RITaK 2

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Cover image
Reconstruction of a dock into the Hedeby harbor. The wooden platforms were not only used to dock boats, but probably the area functioned as the market place. (Photo S. Merkel).

Frontispiece
This is a photo of the Steinfeld hoard consisting of coins probably minted at Hedeby (10th century AD). Image courtesy of Archäologisches Landesmuseum in der Stiftung Schleswig-Holsteinische Landesmuseen Schloss Gottorf.

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Preface

In 2011 the Senate of the Leibniz Association granted funding for a three and a half year Graduate School with the title “Raw Materials, Innovation and Technology of Ancient Cultures” (RITaK). The RITaK School was and is organized in collaboration between the Deutsches Bergbau-Museum Bochum (DBM) and the Ruhr-University Bochum (RUB). It provided a number of doctorate students an ideal research environment but also stimulated and strengthened the institutional collaboration between the DBM and RUB.

Through this initiative, it became possible to explore archaeological questions within a broader multidisciplinary approach: Eleven doctorate candidates worked side by side with their supervisors and other associated researchers to study the access to, use and significance of raw materials for early societies in all their complexity. Empirical research and theory were used to search for the role of technical knowledge and the meaning of innovation in early societies. Going beyond the economic worth of things, material and objects became transmitters of ideas as they became “charged” with cultural meaning and importance. The social side of material culture helped raw materials and technologies to be accepted and incorporated into the social practices of communities, thus stimulating the transformation of culture and the economy.

The Graduate School lasted officially until the end of 2014 with the conclusion of nearly all of the PhD research projects that started at the beginning. It is a fantastic achievement for the doctoral students who pursued their goals with passion and energy. The success of the Graduate School was also a result of the friendly and supportive atmosphere that the DBM and RUB research teams could provide for “our” PhD students. I gratefully acknowledge our Advisory Board, particularly Professor Dr Barbara Ottaway (Exeter) and Dr Beatrice Cauuet (Toulouse), who always encouraged our students to persevere in following their pathways. As coordinator, Dr Petra Eisenach was vital to the School and helped us to avoid the many pitfalls and to overcome all sorts of difficulties. She also undertook the layout of this second volume of the RITaK publication series.

One of the first to conclude his studies was Stephen William Merkel. Stephen attended the program from the beginning. He arrived a few weeks late and was really exhausted by traveling from the USA, but he managed to be the first to lay his excellent thesis on our table. Stephen worked constantly and with passion on the silver from Hedeby, always supported by our DBM laboratory team, but also by the Hedeby research team in Schleswig where he profited much from close collaboration with Dr Volker Hilberg. His interests quickly expanded far beyond Central and North Europe to the Islamic East in Central Asia and the Middle East. The fruits of his work are now in front of our eyes. I am sure that the study will become a seminal work for understanding Viking silver and the far-reaching exchange networks that were connected with it.

Thomas Stöllner

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There are many individuals to thank who contributed to the development of this thesis. Firstly, I would like to thank Andreas Hauptmann. As my primary supervisor, he provided me with ample opportunities to learn and always encouraged me to broaden my perspective in the fields of archaeometallurgy and archaeometry. I am greatly in his debt for the countless lessons that have helped me to grow as a researcher. Secondly, I would like to recognize the diligent support of Volker Hilberg. As an advisor he has provided me with much insight into the workings of the early medieval world and has helped to guide me through a number of mazes: medieval numismatics, the research history of Hedeby, the magazines of Schloss Gottorf, just to name a few. Thirdly, I would like to thank Christoph Bartels. Through our numerous conversations he has challenged me to think outside the box and has increased my understanding of medieval mining and metal production exponentially.

The analytical data produced in this study could not have been obtained without the help of several individuals. I would like to acknowledge the work of Robert Lehmann and Daniel Fellenger from the Leibniz Universität Hannover. The expertise of Robert in the use of laser ablation was invaluable and the data produced forms the foundation of the present thesis. From the Goethe-Universität Frankfurt-am-Main, Sabine Klein has also made a valuable contribution by performing lead isotope analysis and her effort is recognized. The staff at the material science laboratory of the Deutsches Bergbau-Museum must also be recognized for their work. Michael Bode has helped greatly in many ways, and I would like to thank him for his hard work. I would also like to thank Andreas Ludwig, Sandra Morszeck, Regina Samme, Dirk Kirchner, Marion Jung, and Michael Prange for help and advice.

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Last, and most of all, I would like to thank my wife, Ellen. My wife and my new family in Germany have been exceptional and have provided me with constant support.

Abstract

In the 10th century there is an archaeologically detectable transition in the origins of silver in the Baltic region from an eastward focus on Russia and Central Asia to a westward focus on Anglo-Saxon England and the Ottonian Empire. Since Hedeby was an important gateway of the eastern trade and the western European trade at this time, it is an ideal place to study this transition. The aim of this project is to study silver, primarily in the form of coins from Central Asia and western/Central Europe to compare them to the locally minted coins from Hedeby to learn more about the potential sources of silver and to better understand the movement of silver in the 10th-11th centuries. Lead isotope data and elemental compositions will be used to look closely at the transfer of metals during this time period. In addition, evidence for the processing and purification of silver uncovered at Hedeby will be investigated to possibly gain information on the value of silver and the importance of silver purity in the early medieval economy. The use of multi-collector laser ablation inductively coupled plasma mass spectrometry (MC-LA-ICP-MS) has not previously be utilized to characterize lead isotope signatures of Viking-age silver objects from northern Europe and Central Asia. It is a promising technology that allows for the microscopic sampling of objects to obtain the isotope information needed to reliably source silver and lead. This study will explore the application of this technique in the analysis of silver objects of the Viking Age, and its usefulness in the study of the medieval trade of silver will be critically evaluated.

1. Chapter
Introduction to Silver and the Silver Economy of Hedeby

Silver and the Vikings

The silver hoards of the Viking Age attest to the importance of silver in the society of early medieval Scandinavia. The theme of silver in the Viking Age is the focus of numerous scholarly books and articles, and yet it has never lost an air of mystery nor the ability to captivate. This is because the silver of the Vikings provides a seemingly boundless source of information about the economic and cultural development of Viking Scandinavia, which was inseparably connected to the developments of a large expanse of the world (see Graham-Campbell/Williams 2007; Graham-Campbell et al. 2011; Skre 2008). Silver acquired a special significance in Scandinavia over the course of the Viking Age not only as a material of prestige but as a medium of exchange. It is relatively scarce in the 9th century in Scandinavia, but evidence for its use grows exponentially in the 10th century (Sawyer 1990, 285-286). It is commonly accepted that the majority of this silver was brought to Scandinavia by long-distance trade (Lieber 1981); why so much silver ended up in Scandinavia and where it came from are not new questions, but are still current topics actively discussed in academic circles.

The exchange network that connected Scandinavia to lands both near and far was complex and dynamic. The finding of Islamic silver dirhams in Scandinavia clearly demonstrates this point. From these dirhams scholars of Viking history have known for over 150 years that during the Viking Age trade routes crossed the Caucasus and the steppes of Central Asia linking Russia and the Baltic to the Islamic world (Lowick 1976, 24). The transportation of silver over such expanses in the Viking Age seems to be counterintuitive; epitomized by Spufford (1988, 68), where he states, “... the dirhams survive as a witness to this strange long-distance trade.” For those familiar with the historical accounts of Viking raids on western Europe it seems more sensible to assume that the silver used and hoarded by the Vikings was stolen, extorted, or plundered from the Christian West.

Ideas of the role of the Vikings in the growth of maritime commerce are in continual movement and are constantly being reinterpreted as new evidence comes to light. Gradually our understanding of the Viking period from the written sources is becoming merged with the archaeological record, a merger that is not without contention and discrepancy. Following Lieber (1981, 12), the looting and pillaging of monasteries and towns is well-known through the annals of history and the sagas, and to this day the Viking Age is cognitively associated with violence, brutality, and tumult; the economic matters of the time such as peaceful trade, acquisition of resources, and production are rarely mentioned in the texts of the period. The role of commerce and production in the Viking Age is an area where the archaeological record provides the greatest evidence (see Sawyer 1990). The methods of archaeology form a basis for the exploration of such mundane ‘everyday’ matters through the physical remains of material culture left behind. Just as archaeology offers alternative frames of reference from the historical and literary sources in understanding the past, the field of archaeometry, which is the interdisciplinary study of archaeological remains with methods borrowed from chemistry, material science, and geology, provides further perspectives and can be used to discover aspects of the past that cannot be found in any other way.

Archaeological Questions and Approach

A number of silver objects have been discovered at Hedeby, a trading center of extraordinary importance for the Danes and the Viking world at large. Remains of the recycling of precious metals have been found in addition to numerous silver coins and fragments. There is an academic consensus that a mint was located at Hedeby and that it operated intermittently from the 9th to the 11th century (Malmer 2002; Wiechmann 2007). As there are no silver mines in the area of Hedeby, the coins produced at Hedeby must have been made of recycled silver imported via the long-distance trade routes, trade routes that stretched from Samarqand in the east to the North Atlantic in the west. The relative chronology of the Hedeby/Danish coinage of the 9th to 11th centuries has been established, and this chronology spans a period where the archaeological and numismatic evidence indicate several shifts in the trade routes of silver. Several tantalizing questions can be asked: is it possible to determine where the silver used to make these Danish coins came from? What can be learned about the origin and use of silver from the archaeometry of silver artifacts, crucibles, and production debris? What can elemental compositions and lead isotope ratios reveal about the state of silver mining, commerce, and technological development in the early medieval period? This thesis is an attempt to apply modern analytical techniques to explore these basic questions.

The use of archaeometry to better understand the trade and production of silver in the early medieval period greatly expanded in the 1960s and the present study is a continuation upon this tradition; however, the current study departs from this tradition by the state-of-the-art methods of analysis. Through a combination of techniques, and chiefly through laser ablation mass spectrometry, new information is made available that has never before been obtained from Viking silver. Recent developments in laser ablation techniques and mass spectrometry allowing for the precise and accurate determination of elemental and lead isotope compositions show great promise for the study of archaeological silver and have the potential to answer questions concerning the provenance and technological aspects of metal production and use.

In spite of these ground-breaking improvements, the interpretation of elemental and lead isotope compositions of the silver of this period is no simple task. There are precedents for the methods and interpretation of the archaeometric analysis of silver; however, the present study requires an approach specifically adapted to the material and cultural context. Any interpretation must be grounded in a fundamental knowledge of metallurgical and geochemical processes and must take into consideration the body of archaeological, historical, and numismatic research about trade and metal production in the early medieval period. Only within this context can the archaeometric analysis of Viking silver be applied with any hope of success in providing information about the past.

The coin finds and silver objects from Hedeby form the core material for this study, and the primary research goals are to characterize and interpret the changes to the silver stock in southern Scandinavia during the 10th and 11th centuries. Coins are arguably the most informative inorganic object type found in the Viking period. Their inscriptions and stylistic details make it possible to determine their origin to an extraordinary degree and to date their production in some cases to the year. For these reasons coins form a central focus. Although the primary goal of this study is to understand the composition of the silver stock used for the Hedeby / Danish coins, this cannot be understood without understanding the metallurgical processes used during the early medieval period nor the potential origins of the silver. Therefore, several themes must be explored simultaneously to build an interpretational framework for the understanding of silver compositions. The research questions have been divided into five themes, each exploring diverse but interrelated aspects of the study of silver during the Viking Age. In order to investigate these themes, interdisciplinary methods are needed that integrate the fields of archaeology, history, numismatics, and the natural sciences through archaeometry. The five themes are as follows:

1. Silver Recycling in the Viking Age

The Vikings obtained foreign silver to be recycled and refashioned into new objects such as the Hedeby coins, ingots, and jewelry. Silver was certainly recycled at Hedeby and elsewhere in the Viking world, but the question is how this was carried out. Was it refined and cleansed of its impurities? This theme is meant to explore the recycling, refining, and testing / assaying technologies used by the Vikings to develop an understanding of metallurgical knowledge and the economic role and consciousness of silver purity.

2. Silver of the Islamic World

The Vikings had access to the silver of the Islamic world; however, there is little clarity concerning the state of mining in the Islamic world during the Viking Age. The goal of this theme is to explore the historical, archaeological, and archaeometric evidence and chronological development of silver mining in regions under control of the Islamic dynasties and to characterize the composition of silver used with the analysis of dirhams and production debris from production sites in the Arabian Peninsula and Central Asia.

3. Early Medieval Silver Mining and Silver Coin Composition

The aim of this theme is to contrast evidence for mining obtained through historical and archaeological records with the evidence obtained by elemental and lead isotope analysis of silver coins. This comparison can help to support arguments for or against mining in various regions in the early medieval world. The elemental and lead isotope analysis of silver can provide indirect evidence for the existence of mines that are presently unknown. Due to compositional dissimilarities, silver can be divided into types that, in all probability, do not stem from the same origin, and vice versa. The archaeology and historical accounts of mining regions from the early medieval period can not be deemed as sufficient in representing the actual state of mining during this period because neither record is complete. Although all traces of mining may now be destroyed, arguments of early medieval silver production can be built using a combination of factors such as silver composition, existence of suitable ore deposits, evidence for earlier or later mining, prolific minting near a deposit, etc. Though firm evidence is rare in such cases, the evidence should be considered because it may be the only still existent. Long standing issues like the beginning of large-scale silver mining in the Harz Mountains and the possible production of silver in Anglo-Saxon England will be explored.

4. Composition of Hedeby / Danish Coins and Its Implications

The minting episodes at Hedeby in the 10th and 11th centuries form a foundation of this study, and the aim of this theme is to characterize the changes to the silver stock used in southern Scandinavia over time. The chronological framework provided by the Hedeby / Danish coins is an excellent backdrop to study the movement of silver during the period of focus. The composition of the coins can be compared to known coin compositions and to imported coins analyzed in this study for comparison. Changes to the silver stock can be documented and interpreted.

5. Relationship of Non-Minted Silver and Minting at Hedeby

Much has been said about coins thus far, but coin finds are not the only forms of silver found at Hedeby. Non-minted silver objects such as bar ingots, wires, jewelry fragments, and production waste found at the settlement have been analyzed alongside the coin finds to elucidate any relationships among the elemental and lead isotope compositions and the object forms and the coin types.

Structure of the Thesis

These themes are explored in the following seven chapters and four supplementary archaeometallurgical studies, three of which are presented as **Appendices G-I**. Directly following this chapter, **Chapter 2**, titled the Archaeometallurgy of Silver, provides information about the ore types, processes of extraction, and secondary alloying. It explores the technological aspects of silver metallurgy with a particular focus on the early medieval period. **Chapter 3** introduces the settlement of Hedeby, its meaning in the Viking period, and how silver fits into the economic development of Hedeby and the broader Viking world.

Chapter 4 is an overview of the evidence of mining in various regions of the medieval world based on the archaeological and historical evidence. This overview of mining in the early medieval period is then combined with the archaeological and numismatic evidence of silver export. **Chapter 5**, on the archaeometry of Viking-age silver, introduces the theory of the analysis of archaeological silver and places the present study in the context of earlier studies of early medieval silver. The analytical methods and sampling strategy are developed. Detailed descriptions of the analytical procedure and each of the instruments used in this study are given in **Chapter 6**. The data processing, correction, and data quality are discussed. The analytical results are presented and discussed in **Chapter 7**, which is divided into chronological segments mirroring the Hedeby / Danish coin groups analyzed. Finally, the conclusions of the thesis are presented in **Chapter 8**, along with recommendations for future studies.

In addition to the catalogue of finds and tables of analytical data, the results of three case studies dealing with, or otherwise related to, the metallurgy of silver in the early medieval period are provided. These case studies are written as independent articles, and although tangential to the primary research focus, which is the silver from Hedeby, each of these case studies touch upon one or more of the research questions stated above. Technical ceramics from Hedeby were sampled and analyzed to evaluate the recycling practices of gold and silver, and the results are presented in **Appendix G**. Due to the important relationship of lead metallurgy to silver, a selection of lead and lead-tin alloy objects and lead-rich refining debris from Hedeby were analyzed; the results of this study are found in **Appendix H**. Two case studies of silver production in the Islamic world were undertaken to widen our understanding of early medieval extractive metallurgy and to characterize the potential ore exploited. First the results of a study of Samanid silver production in Central Asia are presented in **Appendix I**. This case study focuses on the relationship of the exploitation of polymetallic silver ore in the Ilak region of Uzbekistan and the prolific production of dirhams at the major Samanid Central Asian mints, dirhams that were found at Hedeby. A forth case study concerning silver production in early medieval Yemen was carried out, but the results are published separately (MERKEL et al. 2016). This study centers on al-Radrād, a mine historically known through the 10th century account of al-Hamdānī (TOLL 1968), which has been investigated jointly by the German and French archaeological teams. Production remains and ore collected during these surveys have been analyzed to reveal information about the type of ore used and the smelting technology, and to characterize the ore and slag for use in future provenance studies.

2. Chapter

Archaeometallurgy of Silver. An Overview of the Early Medieval Period

2.1 Introduction

The interpretation of the composition of Viking-age silver begins with a firm understanding of the production history or the *chaîne opératiore*, but it does not end there. Ottaway (2001, 88) emphasizes that the metallurgical process is a cycle that begins with mining and ends with the corrosion of the metal. Not only are the production processes important, but what happened to the material over the course of its life-span, both past and present, alters and affects the material in significant ways. The factors resulting from natural and anthropogenic process that influence the composition of silver will be explored to produce a foundation for the interpretation of alloy compositions determined through the material science analysis of silver. In the framework of this thesis, a survey of the types of ore, smelting technologies, refining, alloying, and recycling practices with particular reference to the early medieval period will be outlined using historical, archaeological and archaeometallurgical evidence.

2.2 Silver Ore

The silver of the early medieval age was mined, smelted, and refined in various parts of the world. All silver began as ore, which was sought and processed. The use of the word 'ore' is at times not always clear: the word itself requires definition (Shackleton 1986, 2). In the English language, ore has a specific meaning and its definition depends on the cost of extraction - i.e. the economic feasibility of metallurgical extraction.[1] By this definition metalliferous minerals can be called ore only when the price of the metallurgical products[2] outweighs the price of extraction. The economic profitability of metal extraction before documents were kept is an unclear subject with many unknown factors. Only through the archaeological, mineralogical, and geological investigation of ancient mining areas and archaeometallurgy can an attempt be made at understanding what was considered 'ore' in the past.

The term 'ore' is thus inextricably connected to factors outside the quality of minerals themselves. Technological capabilities in mining and metallurgy have substantial implications to which minerals were sought and are directly tied to profitability of extraction. The organization of mining, access to labor and resources, political stability, and protection are all factors that are linked to the success or failure of medieval silver mining operations.

Types of silver ore and ore quality mined in the past are difficult issues for several reasons. The richest silver mineralizations are usually near the surface of the deposit and are the most easily accessible ore for mining. Silver-rich deposits may have been completely exhausted in antiquity, perhaps with very little trace of what might have been originally there. Additionally, the ore found in archaeological contexts may not reflect what was being sought because it is impossible to know if the ore was lost or thrown away. The type / quality of ore used in prehistoric metal production can be evaluated with varying success through a combination of methods such as studying the traces of early mining, geological surveys in archaeological mining areas, and the archaeometric analysis of production debris and metallic objects.

Bachmann (1993) identified three major categories of ore used in silver production since the Bronze Age: lead-based ore, fahlore, and jarosite ore. With lead ore, Bachmann refers to galena and cerussite as the most common types of ores used to produce silver. Fahlore, which are copper, antimony, arsenic, and sulfur containing minerals, like tetrahedrite, tennantite, and freibergite can contain substantial amounts of silver and have been important silver ores in the past. Jarosites are complex hydroxy-sulfates of iron and are typically found in the gossan of an ore deposit (Bachmann 1993, 487-8).

Meyers (2003) builds a slightly different classification system based on the elemental traces of ore type found in archaeological silver objects. He classifies the objects and ore types using a system that is both technologically and geologically informed and argues that chronologic trends can be distinguished that relate to changes in production technology and the ore types extracted. After Meyers, the classification follows from

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[1] http://www.oxforddictionaries.com/definition/english/ore (accessed 30.10.2013).

[2] Silver was produced in association with lead but also occasionally copper. The relationship could be complex with silver as the main economic product, but silver could be a by-product of the extraction of base metals.

richest to poorest, and easiest to smelt to the most technically challenging and labor intensive.

Lead-Free Silver Ore => Cerussite (Oxidized Ore) => Galena (Sulfidic Ore)

Before the third millennium BC, it is thought that silver ore such as native silver, cerargyrite, and acanthite may have played a major role in silver production (Meyers 2003). Some of these ores could have been so rich that they could have been smelted without cupellation (Craddock 1995, 212). A change occurred in the eastern Mediterranean / western Asia at some point between the third and second millennia to using lead-based silver metallurgy (Meyers 2003).

2.2.1 Silver and Lead-Based Ore: Cerussite and Galena

The lead-based ores can be split into two main groups: cerussite and galena or better still lead-based ore from supergene and hypogene deposits. Cerussite and Anglesite are the carbonate and sulfate forms of lead and occur in the oxidation zone, or the supergene zone, of base-metal ore deposits. They are both white to clear crystalline material that form from the chemical weathering of galena and other primary lead minerals. Due to chemical weathering processes, gold and silver can become enriched in supergene deposits (Craddock 1995, 213). The supergene cerussite would likely have been extracted earliest because of the higher silver contents and the ease of mining and smelting. One of the richest silver-bearing minerals found archaeologically on the British Isles is a cerussite from a Roman context with a silver content of 0.52 percent, but galena from the nearest lead ore deposit had much less silver (Tylecote 1986, 54).

At al-Radrād (al-Jabali) in Yemen silver-rich oxidize ore (al-Ganad 1994, 44; Mondillo et al. 2011) was exploited from the pre-Islamic period until the 9th century AD (Robin 1987).[3] Zinc-lead-silver ore was extracted, which probably contained silver sulfide, native silver and silver-bearing zinc minerals. Although there is discussion of a transition in the Islamic world in the 8th and 9th centuries AD from the use of cerussite to galena for silver production (Meyers 2003, 277), this is clearly an oversimplification of the reality. It would perhaps be more productive to describe it as a transition from the mining of supergene deposits enriched in silver-bearing minerals to the use of hypogene silver-bearing ore. The work of Gordus (1972) is cited as an example marking this transition period. The elemental composition of Umayyad dirhams from Wasit (Iraq) changed around the year 720 AD from a stable gold content of close to one percent to a heterogeneous mixture of high and low gold contents, as low as 0.02 percent (Gordus 1972; Meyers 2003). The ore from the oxidation zone of an ore deposit can often be enriched in gold in relation to silver (Gale/Stos-Gale 1981; Pernicka 1981, 399), and the higher gold content in the silver coins may be characteristic of supergene ore while low gold concentrations in the later coins may indicate the use of hypogene sulfides.

In western Asia, the transition from supergene to hypogene lead-silver ore seems to have occurred in the early Islamic period (see Gondonneau/Guerra 2002, 582-3; Meyers 2003, 277). This transition not only represents cost-intensive technological changes allowing for deeper mining (i.e. requiring extraction systems for groundwater in mines and ventilation) as well as better controlled smelting processes, but it also denotes a change to the extraction of ore with possibly lower silver contents. The relatively late transition to hypogene ore in the medieval period in western Asia is due to the extensive supergene deposits found in this region (Meyers 2003, 277). In other parts of the world, such as at the silver mining region of Laurion, in Greece, the transition to hypogene ore may have been much earlier, as the supergene lead-silver deposits were possibly exhausted (Meyers 2003, 278-80).

Galena, or lead sulfide, is often associated with other base metal sulfides like sphalerite, pyrite, and chalcopyrite. Galena can contain varying quantities of silver. When present, the concentration of silver in galena is typically under 0.1 percent when no other silver-bearing minerals are present (Ramdohr 1980, 646). The early medieval mine of Melle operated in the 7th to 10th centuries and primary sulfides, namely argentiferous galena, were extracted for their silver content. The content of silver associated with the galena of Melle according to modern and archaeological samples is around 0.15 percent (Téreygeol 2002). The medieval mining of galena is not always associated with silver production because in many deposits the silver content was too low to have been economically extracted. Galena was extensively mined and smelted in Roman Britain, but it is thought that any associated silver production played little to no role (Craddock 1995, 214).

2.2.2 Fahlore as Silver Ore

Fahlore occurs in hypogene deposits with polymetallic sulfides like chalcopyrite, bornite, pyrite, galena, and sphalerite. Due to the importance of lead in silver production, the use of fahlore in medieval silver production is often associated with the mining and smelting of galena. Fahlore minerals are frequently found as microscopic / macroscopic inclusions in galena, which can be responsible for higher silver contents (see Gasparrini/Lowell 1985; Stedingk 2012, 13). Fahlore minerals are copper-antimony-arsenic-sulfides such as freibergite, tetrahedrite, and tennantite and can incorporate between 12 and 36 percent silver into their crystal structure (Dimitrova et al. 2007, 41; Riley 1974, 118). Fahlore

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[3] There is some indication that mining (or re-use of the mines) may have continued in the 11th-14th centuries due to radiocarbon dating (Peli/Téreygeol 2007, 196).

minerals have been important for medieval silver production (Bachmann 1993, 487) and are particularly known from Central Europe (Bartels 2008, 31; Rehren et al. 1999, 82; Schneider 1998).

The Upper Harz ore district contains numerous veins of silver-bearing minerals and argentiferous tetrahedrite, and some ore shoots contain a mixture of galena and argentiferous tetrahedrite (Stedingk 2012). Bartels maintains that the art of mining in the early medieval Harz demonstrates that miners were looking for ‘bonanzas’ or high-grade silver ore that could have a silver content in the range of 10 percent: only in the 17th century, did silver production based on galena become economically viable in the Harz mountains (Bartels 1992, 25-9, 125-6, 138). These veins of silver-rich fahlore were sought in the medieval period and the silver-poor galena played little economic role. Also in Siegerland the medieval silver production centered on the ore deposits where silver-rich fahlore minerals occurred. The post-Variscan galena deposits were mined, but the isotope ratios of medieval silver coins seem to indicate the use of ore from the geologically older fahlore mineralizations (Rehren et al. 1999; Schneider 1998).

2.2.3 Jarosite as Silver Ore

Jarosite is a type of supergene ore that forms in enrichment zone under the gossan of some ore deposits. Jarosite generally fits the formula $XFe_3(SO_4)_2(OH)_6$, where X could be K, Na, Ag, Pb, or NH_4. A famous example of jarosite ore exploitation is in southern Spain at Rio Tinto (Anguilano 2012; Craddock 1995, 216-21). The enrichment zone at Rio Tinto can have up to five times the concentration of gold as the hypogene ore (Garcia Palomero 1990, 26), so like cerussite-based ores, relatively high gold contents can be associated with the silver produced. Jarosite deposits are often associated with bismuth, antimony, lead, barium, tin and arsenic but are generally low in zinc and copper (Anguilano 2012, 29-30). Although jarosite is most well-known from Iron Age and Roman silver extraction in southern Spain, deposits containing jarosite are common elsewhere in western Europe and beyond.[4]

2.2.4 Sphalerite as Silver Ore

There are two examples of medieval mining where zinc minerals may have been a source of silver. The mines of ar-Radrād (al-Jabali) in Yemen are known through the historical references of the Yemenite geographer and metallurgist of the 10th century, al-Hamdānī, and have been identified through geological and archaeological surveys performed to document the ore deposit and the medieval landscape undertaken by French and German archaeologists and geologists (Cierny et al. 2004; al-Ganad 1994; Peli/Téreygeol 2007). Silver was found to be concentrated in sphalerite up to 3900 ppm, whereas the galena did not contain detectable amounts of silver (al-Ganad 1994, 50). Ströbele et al. (2010) refer to a similar situation in Wiesloch, in the area of Heidelberg, near the Rhine valley, where silver is concentrated in the sphalerite up to 0.05 percent and the galena is much poorer in silver. The Mississippi-Valley-Type lead-zinc deposit of Wiesloch has been mined at least since the Roman period, but there was an important mining phase in the 10th and 11th centuries AD (Ströbele et al. 2010). With that said, it is not clear if these silver-bearing zinc minerals were actually considered ‘ore’ in the medieval period; there may have been other silver-bearing minerals present in these deposits.

2.2.5 Comparison of Ore Quality: Texts versus Archaeology

The 10th century account of al-Hamdānī describes the grades of ore, clearly defined as the ore or the stone taken from the mine, ranging from 50 percent silver, being the highest and most profitable ore grade, down to 0.83 percent being the lowest grade (Toll 1968, 272-5). Ore that contains 50 percent silver is a true silver ore, possibly consisting of minerals like acanthite, cerargrite, stephanite, pyrargyrite, or native silver, and the lower grades are more consistent to lead-based ore described by Bachmann with a silver content around 1 percent, rarely up to 3 percent (Bachmann1993, 489). With reference to al-Hamdānī’s account, the question can be raised of whether galena with silver contents around 0.1 percent can be considered silver ore in the medieval period. Al-Hamdānī’s account is unquestionably in discord with the proposed silver production from argentiferous galena of Carolingian Melle which contains 0.15 percent silver. There is no easy solution to this problem, but it must also be stated that the quality of the ore itself is not the only factor determining whether it made economic sense to extract the silver or not.

As a deposit is mined the ore grades tend to decline with increasing depth and over time through the selective mining of veins, and the ore that was historically mined may not be what remains today. An historical example is given by Tylecote (1986, 69) who describes the declining silver content of ore from the Welsh mine of Cwmsymlog, in Dyfed. The earliest written record dates to 1604 and the silver content of the ore was 734 ppm, which was due to the mining of a particularly rich vein, but over the course of the following centuries the ore grade fell to 220 ppm, 122 ppm and finally, less than 80 ppm in 1845.[5] This is a clear reminder that veins of high quality ore and the upper part of the oxidation zone may have existed in the past and would have likely been completely exhausted before lower quality ore would

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[4] www.mindat.org, accessed 29.10.2013.

[5] This difference in ore quality may also reflect changes in the extraction methodology: naturally if miners were digging veins of richer silver ore by hand this ore would be better quality than bulk ore obtained by using explosives, etc.

have been sought. The veins of native silver from the Kongsberg deposit in Norway, first documented in 1623 (Tylecote 1987, 87), is a perfect example of how rich silver vein deposits could be. The problem is that it is often not possible to determine if and where such deposits existed. Mining archaeology and archaeometallurgy provide some methods for exploring questions concerning the selection and extraction of ore types.

2.3 Principles of Smelting Lead and Silver

Silver rarely occurs as native metal that could have been used in its natural state. More often, silver ore is a mixture of silver-bearing minerals, metal oxides, sulfides, silicates, and carbonates. Some of these unwanted impurities can be separated mechanically by crushing the ore and using water or wind to enrich the metalliferous minerals due to differences in density. In the case of copper, lead, and silver, the ore concentrate goes through high-temperature processes to separate impurities and to further enrich and concentrate the desired elements and bring them into a metallic state.

The principle of smelting impure lead, copper, and silver ore is simple to explain: ore containing impurities usually needs to be heated at temperatures in the range of 1100-1200 °C to melt the components so that the impurities divide from the metallic or sulfide melt in the liquid state. The slag is important as way to collect the impurities while the desired metallurgical products settle and collect under the slag due to their higher densities. Theoretically, a slag is not always needed; pure minerals such as malachite, galena, acanthite, and cerargrite can be smelted to produce metal without slag formation (Anguilano et al. 2010a), and high-grade silver minerals can be refined directly without smelting and would also be slagless (see **2.4.2**). An example of slagless silver smelting is given by Agricola (Bandy/Bandy 2004, 176). Where impurities like iron and zinc are present in the ore minerals, or if the gangue material cannot be separated from the ore through physical means, slag formation is required.

Iron and zinc-bearing minerals are regularly associated with deposits containing lead, copper, and silver minerals. Together with quartz, feldspar, calcite, fluorite, and barite, minerals containing iron and zinc are often found in the ore gangue. In the case of minerals like chalcopyrite, tetrahedrite, argentiferous sphalerite, or jarosite, chemical bonds exist between the elements in the crystal structure making manual, physical separation of impurities like iron and zinc impossible. At high temperatures, these chemical bonds can be broken and mineral structures can be altered or destroyed. Ideally, a highly reactive silicate melt is produced to draw out impurities. The oxides of iron, zinc, calcium, magnesium, and manganese have strong affinities to form silicates, stronger than lead oxide (Bachmann 1993, 491-2). Reducing conditions are needed to reduce Fe^{3+} to Fe^{2+}, which reacts readily with silica to create a fluid liquid solution at working temperatures between 1000 and 1200 ºC. Upon cooling, phases such as olivines,[6] clinopyroxenes,[7] melilites,[8] iron oxides,[9] and spinels[10] crystallize out of the liquid slag. Concerning the oxygen partial pressure, the reducing conditions required to form Fe^{2+} at 1150 ºC is too oxygen-poor for lead to be in its oxide form; therefore, lead will mostly be in a metallic state.[11] Therefore, for an effective smelt, temperatures in the range of 1100-1200 ºC and sufficiently reducing conditions are needed to insure that the reactions occur so that the oxides of iron, zinc, manganese, calcium, and magnesium form a liquid solution with silica and that most of the lead is reduced to metal.

Lead plays a very important role as the silver collector. At high temperatures lead and silver form a single solution, and lead metal, being the densest metallurgical product that could have been produced, settles to the bottom of the furnace under the silicate slag, taking with it nearly all of the silver (Bachmann 1993, 489). Therefore, it is important that as much of the lead as possible be separated in order to reduce the loss of silver in the slag. This lead-silver alloy could be further processed to separate the two metals (see **2.4**).

2.3.1 Lead and Lead-Silver Production

Lead-based ore was used to produce both common lead and argentiferous lead. The smelting of galena and cerussite to produce lead is a relatively straightforward process. Cerussite and galena can be easily reduced to metal without the need of a roasting step to reduce the sulfur content (Bachmann 1993, 490; Craddock 1995, 205-6).

For cerussite the reactions are:

$$2PbCO_3 = 2PbO+2CO_2$$
$$PbO+CO = Pb+CO_2$$

Carbon monoxide from the burning charcoal or wood reduce the lead oxide into metal.

Galena is slightly more complex requiring more oxygen and follows:

$$2PbS+3O_2 = 2PbO+2SO_2$$
$$2PbO+PbS = 3Pb+SO_2$$
$$2PbS+4O_2 = 2PbSO_4$$
$$PbS+ PbSO_4 = 2Pb+2SO_2$$

These reactions can take place at lower temperatures than needed for effective silver production. The lead ore could be reduced to metal in a hearth with a

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[6] Fayalite, willemite, kirschsteinite.
[7] Hedenbergite, augite, pigeonite.
[8] Sorosilicates, silicates containing $(Si_2O_7)^{6-}$.
[9] E.g. magnetite and wüstite.
[10] Magnetite, gahnite, franklinite, etc.
[11] See Ellingham diagram (Rosenqvist 1974, 517).

wood fire under mildly reducing conditions. The silicate slag produced in this process is generally high in lead, which means high lead loss, but due to the low temperatures the lead produced is relatively pure from hardening impurities like copper, arsenic, and antimony and is therefore called ‘soft’ lead. Soft lead was highly valued for its malleability, and was considered better than the harder varieties, which are by-products of silver production (Craddock 1995, 205-11; Willies 1993). The Westphalia process described by Agricola is similar to the lead smelting process used in medieval England where soft lead was produced in hearths or boles fueled by wood or charcoal (Craddock 1995, 208-9). Often hearths were positioned on the crests of hills to take advantage of the wind, which supplied oxygen for the fire and helped to dissipate the dangerous fumes (Craddock 1995, 208-9).

The production of argentiferous lead is a different process, which requires higher temperatures, in the range of 1100-1200 ºC to break down the silver-bearing minerals, and as mentioned previously the loss of lead is avoided. A fluid slag is produced in which phases like olivine and clinopyroxene crystalize upon cooling. The greater affinity of iron oxides and other base oxides to bond with silica in conjunction with the reducing conditions at high temperatures force out much of the lead from the slag (Bachmann 1993, 491-2). Al-Hamdānī describes the smelting of argentiferous lead in the 10th century from lead-based ore (Toll 1968, 268-75). Smelting was performed in a small furnace built with a tapping hole and furnished with one or two bellows. Charcoal from the acacia tree, as well as other types, is layered with grape-sized fragments of ore to the top of the furnace. The charge is lit and air is forced into the furnace. Charcoal is added as the charge descends so that the fire does not subside. Once finished, the lead is tapped to form an ingot. The furnace is broken after cooling so that any remaining lead can be collected. Al-Hamdānī goes further to mention that 400 furnaces operated simultaneously at the mining village at ar-Radrād in Yemen, and that flames and toxic fumes would kill overflying birds. Slag can be found at the site covering an area of more than 70 hectares (Peli/Téreygeol 2007, 192).

2.3.2 Complex Smelting: Jarosites and Polymetallic Ore

Silver is not only found in association with lead minerals, but can be bound in jarosites, copper sulfides, and fahlore. A number of researchers have worked on reconstructing complex smelting technologies, which were required to efficiently extract silver from these types of ore (Anguilano 2012; Asmus 2012, 248-51; Craddock 1995, 216-21; Keesmann 1993; Rehren et al. 1999).

Jarosites and fahlore can contain substantial amounts of arsenic, antimony, and bismuth, which can cause problems during smelting. Speiss is a metallurgical product that can form during the smelting of ore with Periodic Table Group 15 elements (As, Sb, and Bi), and it has been often documented in archaeological slags, particularly those associated with silver production from jarosites and fahlore minerals (Asmus 2012, 58, 273-4; Craddock 1995, 219-21; Kassianidou 1998; Keesmann 1993; Rehren et al. 1999). For the silver to be successfully and efficiently recovered, sufficient quantities of lead must be present to collect the silver during smelting and antimony and arsenic should be either oxidized and incorporated into the slag or drawn out through vaporization. If the antimony and arsenic are reduced they will bind with metallic copper, iron, nickel and precious metals to form speiss phases (Keesmann 1993, 114; Peterson/Twidwell 1985, 225; Rehren et al. 1999, 76-7). The silver that is trapped in the speiss is thought to have been unrecoverable to the smelter (Kassianidou 1998). Jarosite ores often lack the quantity of lead necessary to extract the silver during smelting, but this issue could be solved by adding imported lead during smelting. This has been shown to have taken place at Rio Tinto where the lead isotope analysis of the jarosite ore and the smelting slag have different isotope ratios, reflecting the addition of imported lead during the smelting process (Anguilano 2012, 236-68; Anguilano et al. 2010b; Craddock 1995, 217).

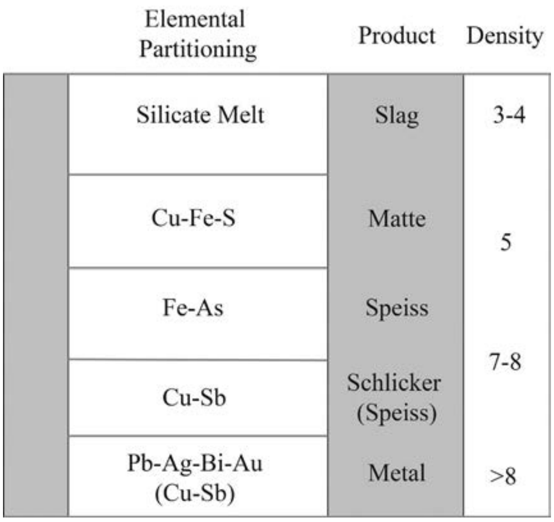

Figure 2.1 *Products of polymetallic smelting according to density (based on Keesmann 1993, 114). With multiple metal, sulfide, and speiss phases, the majority of these would separate out into different layers according to density. Lead is the densest (10.66 g/cm^3), then speiss (8.42 g/cm^3), sulfide matte (7.6 - 4.9 g/cm^3) and finally the slag (4 - 3 g/cm^3).*

The situation can be similar to the extraction of silver from fahlore or copper-silver ore. When the silver ore was not associated with lead, lead would have been required during smelting. This has been attested in the late medieval Erzgebirge where lead from the Harz was imported to extract the silver from fahlore (Bartels 2008, 30). The process of smelting silver-rich copper sulfides is more complex than smelting lead-based silver ore. The process requires multiple smelting steps. The smelting of Rammelsberg polymetallic ore in the medieval period has been studied by Asmus (2012) and the procedure generally follows the account of Theophilus the Presbyter, an ecclesiastic craftsman and metallurgist of the 11th/12th century AD (Hawthorne/Smith 1979, 139-40). The Rammelsberg ore is a fine-grained mixture of copper, iron, zinc, lead, and silver minerals with localized ore shoots of nearly pure chalcopyrite. A set of three furnaces were used to separate the copper from the argentiferous lead. During the first smelting of the primary sulfides, copper matte,[12] argentiferous lead, and speiss were produced. Due to immiscibility of the products they would separate according to their densities (Rosenqvist 2004, 295-6; Keesmann 1993, 114) as illustrated in **Figure 2.1**. If the matte contains lead sulfide and silver phases, it would need to be re-smelted to completely separate them from the copper sulfides. The argentiferous lead would be most efficiently separated from copper while the copper is still in sulfide form as a matte.[13] It is thought that liquidation, or the so-called Seiger process, to separate metallic lead from metallic copper was economically employed only in the 15th century AD in Central Europe (L'Héritier/Téreygeol 2010; Munro 1998, 39; Suhling 1994), and it is not known if the process of separating metallic lead from metallic copper was used on any significant scale in the early medieval period.[14]

2.4 Cupellation

The most important end-product of all of the mentioned silver smelting processes is the argentiferous lead. Argentiferous lead, or Werkblei, is where the silver from the smelting process is concentrated. This lead is further processed to produce the silver through the cupellation process. Cupellation as a process to separate lead from precious metals has been performed since the 4th millennium B.C. (Bachmann 1993, 493). The theory behind cupellation is that both gold and silver resist oxidation under the same conditions where base metals are oxidized, and this chemical property can be used to separate noble metals from base metals. Lead metal oxidizes into litharge, which is molten above 888 ºC, and while lead and silver form a single liquid phase at high temperature (**Figure 2.2**), litharge, and silver are immiscible. The litharge can be tapped, drawn off, or absorbed into an inert, unreactive material like bone ash, wood ash, or calcareous clay. Whereas the litharge is absorbed into the hearth material, due to the high surface tension of the metallic silver and/or gold, the precious metals remain on the surface of the hearth and form a metallic bead. At temperatures at 950-960 ºC and with an adequate supply of oxygen, nearly all of the lead will oxidize as will most base metals and separate from the silver.

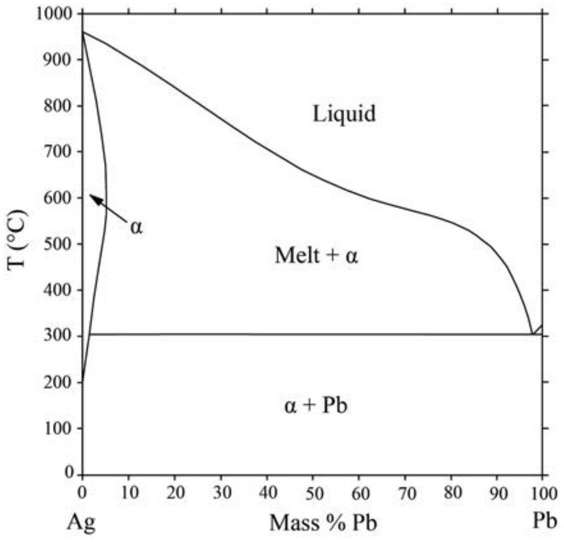

Figure 2.2 *Phase diagram of lead and silver showing that silver forms a liquid solution with lead and the melting point lowers with increasing amounts of lead. The eutectic forms at 305° C at 95.7 % lead (after Lee et al. 1994, 295).*

2.4.1 Cupellation and the Refining of Impure Silver

Cupellation is performed to recover the silver from freshly smelted argentiferous lead, but cupellation as a method of refining precious metals could be performed at any time. If a higher purity is required than the metal at hand then cupellation could be carried out to remove the impurities. Metallic lead and a suitable vessel or hearth are all that are required. Biringuccio, an Italian metallurgist of the 16th century, recommends the ratio three parts lead to one part of the material to be refined (Smith/Gnudi 1959, 164). Agricola mentioned that the more copper there is in the material to be cupelled or assayed, the more lead is required to carry out the process (Hoover/Hoover 1950, 251; Martinón-Torres et al. 2008, 62-3). When refining silver debased with copper, having enough lead is important to prevent the loss of

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[12] Metallurgical semi-finished product containing copper, iron and sulfur. Phases ranging from $CuFeS_2$, Cu_5FeS_4 to Cu_2S.

[13] In regard to the smelting of polymetallic ore, Theophilus the Presbyter (Hawthorne/Smith 1979, 140) says that the lead is released from the 'stone' in the first smelt. The lead is tapped, but the 'copper' remains in the furnace. The 'copper' is removed and put in a smelting furnace for a second smelt. The intermediate copper product only makes sense as copper matte. Why put copper back into the smelting furnace if it is already in a metallic state?

[14] The separation of lead from copper described by Theophilus (Hawthorne/Smith 1979, 144-5) relies on similar principles to cupellation. The lead is oxidized to litharge, which is combined with ash and skimmed from the surface of the copper melt. After cooling, the copper is then tested by hammering. If the copper contains lead it will crack (due to the build-up of lead at the grain boundaries - also known as hot shortness). This method of removing lead from copper by oxidizing and slagging-off the lead would rather concentrate the silver in the copper and cuprite phases. Unlike the Seiger process, little silver could be produced from the by-products of the process described by Theophilus.

silver in cuprite, which, unlike litharge, forms a solution with silver at high temperatures (Bayley/Eckstein 1997, 108); they point out that the Roman cupellation litharge analyzed contains more cuprite and more silver loss than the medieval Anglo-Saxon examples, implying that the Roman metallurgists were unaware of this problem.

2.4.2 Cupellation of High Grade Ore and Mercury Amalgamation

It must be noted that the cupellation of smelted argentiferous lead is not the only way of producing silver. It is possible to produce silver by adding high-grade silver ore to lead during cupellation. A present-day example is described by Cohen et al. (2010) in the Bolivian Andes. Galena was smelted to produce lead, which was only produced to be cupelled with high-grade silver ore to produce silver. This can only be done with silver ore that is relatively free of impurities, and only minerals in which all the components would be either vaporized or oxidized during the cupellation process could be used, but an advantage of the process is that no silver is lost in a smelting slag, meaning a higher and better controlled yield. It is thought that this type of process was used for the highest quality ore in the medieval period (Bartels 1992, 132-42; Bartels 1997, 32-3; Rehren et al. 1999, 80-1). According to Agricola, the highest-grade silver ore, meaning silver ore like native silver, acanthite, and cerargyrite were already separated from the low-grade ore in the mine, and rather than being smelted, it underwent cupellation to recover the silver (Hoover/Hoover 1950, 268-70).

Another important process to recover silver or gold that is present in a metallic state is by mercury amalgamation. Mercury can dissolve metallic gold and silver forming an amalgam and can be used to collect these metals in crushed ore or to recycle precious metals in a workshop setting. Once the mercury collects the precious metals, it can be evaporated or distilled by heating, leaving behind the gold and silver. Al-Hamdānī describes the use of mercury to extract raw gold from ore and to collect precious metals from dust, slag, and workshop debris (Craddock 1995, 215; Toll 1968, 136, 264-7). Although native silver could be extracted from ore by using a mercury amalgation, it is not thought that mercury was used to extract silver from ore on any significant scale prior to the invention of the Patio Process in the 16th century (Craddock 1995, 215-216).

2.4.3 Cupellation: Trace Element Fractionation

The cupellation process when performed to completion can produce silver that is 99 percent pure, but small amounts of impurities will always remain.[15] Two sets of experiments were undertaken to better understand the segregation of trace elements during the cupellation process (McKerrell/Stevenson 1972, 197-8; Pernicka/Bachmann 1983), and a summary of the results follows.

Lead

There is always a small amount of lead remaining in the precious metal. Medieval silver typically has a lead content in the range of 0.05 to 1.0 percent, which is normal for silver that has been cupelled. Silver that contains much less than 0.05 percent lead is unusual and may indicate that the silver did not go through metallurgical steps requiring lead (Meyers 2003, 274). Such is the case with some silver objects from the Early Bronze Age (Meyers 2003, 280-2). Native silver and silver that went through modern-day refining methods would have very little lead (McKerrell/Stevenson 1972, 198).

Bismuth

Bismuth, according to Pernicka and Bachmann (1983, 595), can only be oxidized and removed from the silver once the lead content is below 0.1 percent. Bismuth was found to be difficult to remove completely from the silver, and because of this, it can be a useful element in distinguishing silver sources. It should be mentioned that the exact, numerical ratio of bismuth to silver is not a reliable criteria for provenance studies because its behavior during cupellation is variable (Pernicka/Bachmann 1983, 595), but it is clear that silver containing bismuth likely came from silver ore that contained bismuth and vice-versa.

Copper

The copper content is substantially reduced in the cupellation process, but the results of the experimental studies are inconsistent. McKerrell and Stevenson (1972, 198) show that copper is removed to 0.5 percent, but Pernicka and Bachmann (1983, 595) show that 2.2 percent or more can remain in the cupelled silver. The ratio from copper to silver may be meaningful as a tracer for provenancing (Pernicka/Bachmann 1983, 596), but it cannot be ruled out that small amounts of copper were added to the metal after cupellation to improve the working properties (McKerrell/Stevenson 1972). The addition of copper, even small amounts, could bring in elements like antimony, arsenic, zinc and tin in levels that would otherwise be eliminated in the cupellation process. Like lead, the absence of copper in silver is particularly of interest because it may indicate a copper-free silver source.

Gold and other Noble Metals

Gold is one of the few elements that remain unchanged in the cupellation process. Gold resists oxida-

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[15] The coins from medieval Afghanistan are proof that cupellation was not always carried out to completion; several coins analyzed thus far have bismuth and lead contents above 10 percent (Cowell/Lowick 1988, 70; Ilisch et al. 2003, 78-85).

tion and is unaffected by the process (Pernicka/Bachmann 1983, 596). Other noble elements like platinum, palladium, ruthenium, and rhenium are expected to survive completely (McKerrell/Stevenson 1972, 198). The gold content in silver, usually fewer than two percent, was uneconomical to extract before the invention of strong mineral acids in the high medieval period (Craddock 1995, 231). The ratio of gold to silver thus is directly related to the ore used and can be used to distinguish different types of silver. A caveat is that when gilt silver objects are recycled, the gold content would be expected to increase, so ore-type may not be the only factor involved. But to the contrary, Theophilus mentions that when recycling gilded silver, the gold was scraped from the silver and refined separately (Hawthorne/Smith 1979, 147), so this may have been a possibility also in the Viking Age.

Antimony and Tin

The behavior of antimony and tin were observed by Pernicka and Bachmann (1983, 595). Antimony is easily oxidized and nearly all goes into the litharge. A small portion seems to remain constant and can only be oxidized under the conditions needed to remove bismuth. Tin behaves in a similar way. McKerrell and Stevenson reported that tin was easily removed to under 0.1 percent (1972, 198).

Zinc

Zinc is easily oxidized. Even concentrations around 5 percent posed no problem to remove (McKerrell/Stevenson 1972, 198). Therefore, the presence of zinc in silver cannot be argued as an artifact of the ore type and is better explained through the addition of brass after refining. Due the high zinc content of some Anglo-Saxon coins, McKerrell and Stevenson (1972, 201) argue that silver could be enriched with calamine[16] in the same way as it is used to produce brass, but this theory must be seen critically (see Gilmore/Metcalf 1980, 84). The selective corrosion of copper, lead and tin over zinc has been previously documented (Wadsak et al. 2000, 161), and the cleaning of corrosion products may superficially deplete these metals in relation to zinc.[17]

Mercury

Mercury is highly volatile, and at high temperatures it should be completely vaporized. The presence of mercury in silver must belong to a process that occurred after the initial cupellation. Traces of mercury can be evidence for fire-gilding / silvering or other types of surface treatments or contamination.

2.4.4 Cupellation Summary

As explained, cupellation is an essential metallurgical step used to extract silver from argentiferous lead or high grade silver ore. As the silver is concentrated from the ore to nearly pure silver in the final cupellation, it changes quite substantially as do the elements associated with the silver. Some elements follow the silver from beginning to end, like gold and platinum, but many are separated out, or are in reduced quantities. For the provenancing of silver and understanding the ore type used, the noble metals are the most significant. Next is bismuth due the difficulty of removing this element completely. Ores containing bismuth will produce silver containing bismuth, and, conversely, ore that has no bismuth will produce silver with no bismuth. Although copper is also difficult to remove, the addition of small amounts of copper cannot always be easily ruled out. When other elements like tin, zinc, arsenic, antimony, and mercury are found in concentrations higher than 0.1 percent, it is probable that they came from anthropogenic alteration of the alloy after cupellation.

2.5 Alloying, Recycling, and Metalworking

The extractive metallurgy of silver ends with the cupellation. The silver then goes through a number of changes before it is formed into an object. The recycling of silver is common, and changes to the alloy are to be expected. Finally, the burial environment, conservation treatments, and cleaning also impact the final appearance and composition of the silver. These post extraction processes as well as the testing of alloys and their working properties will be discussed in the following section.

2.5.1 Alloys, Impurities, and Working Properties

In the Viking Age, the silver cast bar-shaped ingot is an important and commonly used form for both exchange and metal working. Throughout much of history, the production of ingots is closely associated with the production site of the metal itself, but this is not necessarily true in the Viking Age. Ingots made from recycled precious metals and / or brass were produced at Hedeby as evidenced from the number of ceramic and stone ingot moulds uncovered at the site (Drescher 1983, 178-81). The dimensions can be quite different, and there seems to be regional variation in the ingot shape in England, and the North and Baltic Seas, but these morphological differences have never been explored in detail. Ingots from silver production sites are not known in the early medieval period, but they were likely pro-

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[16] In this case, a mixture of zinc oxide and zinc carbonate minerals that can be found in the oxidation zone of a zinc or lead-zinc deposit.

[17] See Mortimer 1986, 237-8, and see Chapter 5 (Section 5.2.5.) for further discussion on the problem of high zinc to copper ratios in silver.

Alloy	**Ag**	**Cu**	**Color**	**Brinell Hardness**	**Elongation**	**Density**	**Melting**
	(%)	**(%)**		**Annealed (HB)**	**(%)**	**(g/cm3)**	**(ºC)**
Fine Silver	100	0	White	24.5	50	10.49	960
-	97	3	White	c. 30	47	10.45	c. 940
Sterling Silver	92.5	7.5	White	c. 40-76	28-40	10.4	c. 900
-	90	10	White/Yellow	c. 50-79	25-35	10.3	c. 880
-	80	20	White/Yellow	c. 70-92	23-30	10.1	c. 820
Eutectic	72	28	Yellowish	c. 80-95	23-25	10.0	c. 800
-	50	50	Red	c. 75	c. 40	9.7	c. 860

***Table 2.1** The properties of binary silver-copper alloys as presented by Brehpol (2003, 47, Figure 1.23 and 49, Table 1.3). This table shows the differences of color, hardness, density, and melting temperature, which could have been used for testing for debasement but also for the alloy's application in metalworking.*

duced. In regard to Samanid Central Asia, one historical description written by al-Muqaddasi mentions that all silver ingots were transported to Bukhara, the capital of the Samanid state (Allan 1979, 15).[18] The bar ingot is the base form from which many types of objects could be produced. The majority of Viking-age silver objects could have been formed through the smithing of ingots, but cast silver objects also occur. The elongated shape of the bar ingot is well designed for division by cutting with a chisel and is ideal for forming objects like pins, rings, rods, wires, and coin blanks.

As mentioned in the previous section, silver could be used in its pure form, as pure as the limitations of cupellation allow, but it could also be intentionally alloyed with a number of metals. There are both economic and practical reasons for alloying. When metals like copper, lead and tin are more abundant than silver they can be used to debase the silver to stretch the supply. Alloying changes a number of physical properties such as the melting temperature, hardness, and color. Pure silver is very soft (24.5 HB[19] annealed[20]), but the addition of copper can greatly increase the hardness (up to 95 HB, annealed, at 28 percent Cu) (Brepohl 2003, 49). The alloy known as English Sterling silver, which has 7.5 percent copper, has a hardness of 60 HB annealed, and has nearly the color of fine silver. The addition of more copper already imparts a yellow/red hue to the silver (Brepohl 2003, 51). For massive castings such as amulets and brooches, the hardness of the alloy is not as significant as with fine smithing work. A silver alloy with 10 percent copper is about half as ductile as fine silver (**Table 2.1**). With increased hardness and brittleness, more care is needed during smithing, and annealing is more often required to prevent cracking.

In the early medieval period, silver was typically alloyed with brass, bronze, copper, or a mixture of copper alloys. The alloys used in the 9th and 10th century Baltic are quite pure and tend to be above 90 percent silver, but minor and trace elements are also present (Steuer 2003, 139-49). Gold forms a solid solution with silver and imparts no disadvantage, but lead, for instance, is detrimental for smithing work because it causes embrittlement even in small amounts, especially when the alloy needs to be re-heated or hot worked (Brepohl 2003, 52). Lead is usually kept below 1 percent and is most likely a remnant from the cupellation process. It is also possible that variable amounts could come from the addition of copper-based alloys. Tin, like lead, can cause a silver alloy to become fragile due to the formation of tin oxide at the grain boundaries during heating (Brepohl 2003, 52-3). Therefore, alloying tin bronze and silver negatively impacts the working properties.[21]

Bismuth is also disadvantageous because it causes the silver to become fragile. Experiments undertaken by Zwicker et al. (1991, 72-3) show that a bismuth content of 0.52 percent is already problematic, and silver with 1.4 percent bismuth shows widespread cracking. Due to the difficulty of removing bismuth through cupellation, silver high in bismuth could have been mixed with silver poor in this element to improve the working properties of the metal (Zwicker et al. 1991, 72-73). This strategy may have been important for the recycling of the high bismuth silver in the 10th century AD (see **7.5.2**).

An alloy with zinc through the addition of brass is advantageous in several ways. When comparing the alloy 80 Ag : 20 Cu to 80 Ag : 15 Cu : 5 Zn the alloy with zinc has superior castability, lower melting point, and is also more ductile and more resistant to corrosion (Brepohl 2003, 54). In light of the advantages recognized by Brepohl, the choice of brass over copper for debasement beginning with the Romans (Mortimer 1986) and in widespread use in the Carolingian (Metcalf/Northover 1989, 115; Sarah 2010, 233), Anglo-Saxon (Gilmore/Metcalf 1980; McKerrell/Stevenson 1972; Metcalf/Northover 1985, 161-2; Metcalf/Northover 1986, 47; Metcalf/Northover 1989) and other medieval coinages (Bompaire/Guerra 2000; Skaare 1976, 84-5) probably was not due to the unavail-

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[18] It is not indicated whether the ingots come from silver production sites or not.

[19] Brinells hardness scale (HB).

[20] To anneal is to heat the metal to the point that the metal can recrystallize, which releases the stress formed by deformation by hammering and compression.

[21] This is also mentioned by al-Hamdānī: Tin destroys gold and silver (Toll 1968, 318).

ability of pure copper or the ‘cheapness’ of brass, but for truly practical reasons.[22]

2.5.2 Testing of Purity

It is often difficult to separate our own biases based on our own understanding of money, purity, and value from various cultures and eras. Was the difference between 92 and 95 percent silver important in the financial system of the Viking Age? Could this have been precisely measured? Certainly from the high medieval period and onward, there is evidence for the precise calculation of silver contents through the analytical cupellation process (Rehren/Eckstein 2002), but how was silver tested earlier? There are a wide range of perspectives on the subject of testing and the understanding of purity in the Viking Age (see Archibald 1990; 2007; Gustafsson 2013, 106-109; Kilger 2006; 2008a; Söderberg 2011), but together the views show some conflict and need to be reconciled.

It is clear that many of the working properties of silver alloys were well-known to smiths and there are clear indications that many silver objects were tested. The questions are what were they looking for and what characteristics were they testing. The account of al-Hamdānī gives some clues as to which criteria were important in 10th century Yemen: the ductility of the metal, its facture texture, and its color (Toll 1968, 286). The testing of silver quality has clear economic implications, but it is also important to understand an alloy’s suitable metalworking applications.

Pecking, Bending, and Nicking

The most rudimentary ways of testing silver are by bending, pecking, and cutting the silver. Soft, fine silver bends without cracking while alloys higher in impurities crack upon bending (Toll 1968, 286). Pecking[23] and nicking,[24] two different techniques with their own history and cultural background[25] were most probably developed to look into the interior of the metal (for example see **Figure 2.3**). While it is suggested by some that these were methods of testing the metal’s hardness, pecking and nicking would reveal if surface enrichment techniques were used, which can cause debased silver to appear pure on the outside (compare Archibald 2007, 49; Graham-Campbell 1995, 33; Söderberg 2011, 22). It is difficult to say if the slight differences in hardness of higher-grade silver could be determined with these methods particularly when work hardening is considered,[26] but definitely imitations made of lead could be identified due to their softness.

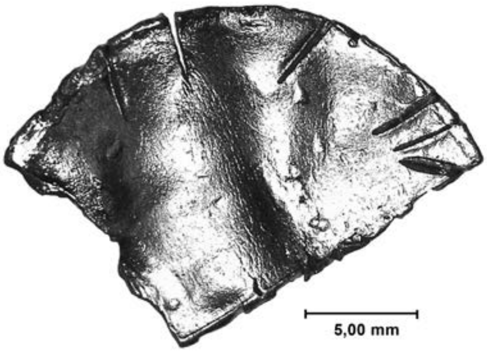

Figure 2.3 *Coin fragment with nicked edges found at Hedeby (Khazar dirham imitation,* ***Cat. 51****). Nicking was a simple method to test for debasement.*

The most obvious reason for pecking was to test for a debased core. Although the silver plating of base metal coins in its true sense may be quite rare, silver surface enrichment of debased alloys through depletion silvering was easily achievable and may have been common practice in parts of the early medieval world. The account of Evvind in the Heimskringla, thought to originate in the 10th century, states that fine silver was to be “white in the fracture” suggesting that plating or depletion silvering was a known problem in the Viking Age, or at least in the 14th century when the story was first written (Söderberg 2011, 6, 22). In al-Hamdānī’s account, he states that slight variations of hue and brightness can reveal the quality of the metal, and, importantly, he says to check the color in a fresh break (Toll 1968, 286), which also implies that the surface of the metal can be deceptive.

Touchstones

The use of touchstones has been attested at Hedeby (**Figure 2.4**) and other medieval sites, not to mention their reference in several historical accounts (see Armbruster 2010, 192; Levey 1967, 7; Oddy 1993). Touchstones typically are dark fine-grained stones so that the streak of the metal can clearly be seen. The streak’s color can be compared to the streak of known alloy compositions to estimate the composition of an unknown alloy. The use of touchstones is most associated with the testing of copper and silver in gold alloys (Oddy

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[22] Al-Hamdānī also notes that brass alloys well with silver (Toll 1968, 318).

[23] Defined as the mark made by a sharp point into the surface of a silver object (Kilger 2006, 456-457).

[24] Defined as a cut into the edge with a sharp knife (Blackburn 2008, 66-67).

[25] Duczko 2002 and Kilger 2006 for cultural perspectives on the use of pecking.

[26] An example is that ca. 98 percent silver, work-hardened, has a maximum hardness of 60 HB which is the same hardness of 85 percent silver directly after casting (Brepohl 2003, 47, Figure 1.23). A dirham with 98 percent silver could be as hard as a cast bar ingot with 85 percent silver. For this reason, hardness is not a reliable method for determining silver content, unless only like objects are compared or pecking is performed directly after heat treating and annealing. Naturally, other impurities like lead and bismuth also impact the hardness.

***Figure 2.4** Touchstone from Hedeby (Maixner 2010, Figure 30) 4.4 cm x 2.9 cm x 1.2 cm. Such stones were used to examine the streak of precious metals to interpret the composition.*

1983), but silver can also be tested to estimate the copper content (Ježek/Zavřel 2011; Wälchli 1981, 158). Touchstones are difficult to find in archaeological contexts, and their use leaves only superficial traces on the stone and the metal objects tested.

Specific Gravity

The density of gold (19.3 g / cm^3), silver (10.5 g / cm^3), and copper (8.9 g / cm^3) allow the alloys to be distinguished by their specific gravity. Archimedes, credited with discovering this method, used the weight of the metal in conjunction with the volume to determine if gold was debased (Oddy 1983, 55). Pure gold, being denser than all other available metals, is readily identified with this method, but in practice the usefulness of this technique is tied to the ability to produce accurate measurements. The differences in the density of silver alloys would require scales that could distinguish tenths of grams. The collapsible scale used in the 10th century Baltic was able to distinguish weight differences as little as 0.04 grams[27], and an earlier scale set dating from the 6th century after excavation and conservation still functioned to a similar result (Hershend 1989, 377). Weighing such small quantities does not seem to be the problem, only the calculation of the volume and its relationship to the weight may have posed a challenge. It is not known if the gold and silver smiths of Viking-age Scandinavia were masters of this technique. There are sporadic mentions in later medieval literature, but they refer mainly to gold alloys (Oddy 1983, 55). Distinguishing between the slight density variations of silver alloys may have been particularly difficult.

Fire Testing and Assaying

Testing by fire could mean two different processes. Alloys with high copper contents will oxidize at high temperatures and create a black film of tenorite and cuprite, whereas high purity alloys do not discolor or tarnish (Brepohl 2003, 188). Brepohl (2003, 188-189) states that 80-20 alloy of silver and copper most easily builds a black oxidation layer. This test may have been performed in conjunction with pecking as described by Söderberg (2011, 22) or may have been performed simply to test the bulk silver. Theophilus describes this process for detecting copper debasement in gold (Hawthorne/Smith 1979, 119), but clearly it could also have been used for silver.

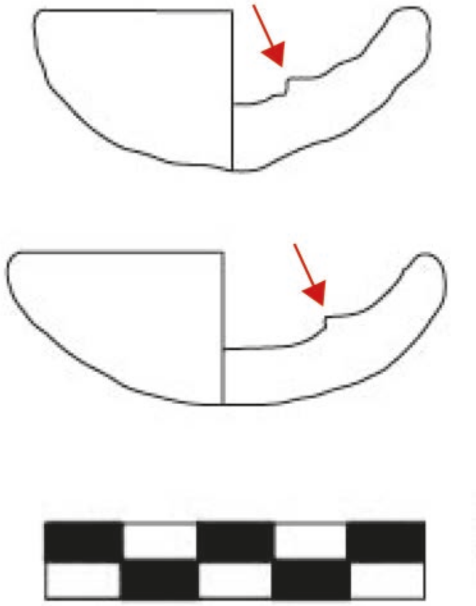

***Figure 2.5** Profiles of heating tray fragments from Hedeby (**Cat. 232** and **214**). The interior of the crucible contains a glassy lead-silicate slag as well as the impression left by the metal that was melted in it. The upper crucible was used to melt a gold-silver alloy and the lower crucible for silver. Scale bar is 5 cm.*

The other way in which silver can be tested by fire is through the cupellation process, or in other words, analytical cupellation. Analytical cupellation is a process where a sample of a precious metal alloy is tested by measuring the weight before and after the cupellation to calculate the difference, giving the precise fineness of the original alloy. Analytical cupellation is an analytical tool that has both metallurgical and economic applications. The question of whether the Vikings used this method to calculate the purity of silver has not been sufficiently answered. Small dishes, known as heating trays or ceramic cupels, were used to melt precious metals and there is often, if not always, a lead-rich slag on the interior and often there is a depression in the

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[27] Based on the scale set found in the Valsgärde 12 grave. The pivot was broken, but when fitted with a reconstructed pivot, the scale functioned.

center demarcating the metal melted (**Figure 2.5**). Such vessels have been found at Viborg Søndersø (Jouttijärvi/Andersen 2005, 358-60) and numerous other settlements covering much of the Viking world. It is thought that analytical cupellation was carried out in these ceramic dishes (see Bayley/Eckstein 1997, 109-11; Söderberg 2011) despite the fact that silica-rich ceramic material is less than ideal for this process.

The use of silica-rich ceramics for true cupellation is problematic due to the formation of glass. Litharge is highly reactive with silica and readily forms a lead-silicate glass at the temperatures required for cupellation. When silica-rich ceramic is used the litharge cannot be absorbed into the ceramic, rather it melts and destabilizes the ceramic. For the lead-silver alloy to be oxidized, it needs to be exposed to air. But in the process the metal would not only sink under the litharge, but would sink into the molten ceramic and is no longer able to be oxidized, halting the purification process. Not only is this a problem for the purification of the silver alloy, the structural stability of the ceramic is also problematic. For these reasons only very small amounts of lead could have been added to the silver to prevent an excessive build-up of glass and litharge which would hinder purification and destabilize the ceramic, and such amounts were likely insufficient to fully purify the metal (see **2.4.1**). It is likely that slag formation was the goal of the process, not the formation of litharge as cupellation requires, and not the complete separation of base metals from the gold or silver.[28]

It should be questioned that the intention behind the heating tray process was to test the purity of the metal by way of analytical cupellation. The refining process mentioned by Theophilus is not analytical cupellation. It is set in a workshop setting where fine alloys were needed for metalworking (see Hawthorne/Smith 1979, 96-7). Heating trays could have likely been used for the cleaning of workshop debris and scrap metal for reuse. Al-Hamdānī describes a similar process where a crucible slag is formed to clean the gold of non-metallic impurities, and it is in a workshop setting for the recycling of precious metals (see Toll 1968, 158-161). The role of heating trays in Viking society is an important topic and their use has both metallurgical and economic implications. It should also be noted that in the context of provenance studies the heating tray process would impact the elemental and isotopic composition of the gold or silver melted.

Summary and Conclusion

Although there are several ways in which the silver content could be measured, with the evidence at hand, it seems as if the color of the alloy, both inside and out, may have been the most important indicator of the silver content. Below ninety percent silver, the alloy begins to appear markedly different and perhaps slight differences in copper content could be ascertained even in the higher grades (see Söderberg 2011, 22). The hardness of a silver alloy is not as simple of a criterion as it seems. Small amounts of bismuth or lead can make silver hard and brittle as will manufacturing processes that build stress in the metal. The drawing of wire and the hammering of bars and sheets will drastically increase the hardness of the silver. We should thus take care to separate silver content from purity and hardness. An expert could probably distinguish annealed fine silver by its softness and malleability.

These various tests described above test for different properties. Bending may be testing for brittleness or to identify the presence of bismuth or other impurities in the silver although the silver content itself could be quite high. Pecking, on the other hand, may have been more focused on identifying a debased core. Fire testing and assaying could have been used to determine whether significant amounts of brass or copper were alloyed with the silver, but this could have been determined by other more practical methods.

The way in which silver was tested provides a glimpse into what criteria were important for silver dealers and metalworkers and the overall understanding of alloys and their purity in the Viking Age. There appear to be two types of resolution; one is perhaps economic in application, and the other with a metallurgical application. The testing for debasement by pecking, bending, and cutting give a resolution detectible by the eye, or somewhat by touch. Naturally, with experience slight nuances in color or hardness could have been detectable, and this factor may be easy to underestimate, but, in the end, these method lends themselves best to coarse sorting based on ‘good’ silver (white, perhaps soft, above 92 percent silver) and ‘bad’ silver (yellow, reddish, grayish in interior, perhaps harder, under 90 percent silver). The threshold of around 90 to 92 percent silver is where silver noticeably changes color and it may not be a coincidence that much of Viking-age Baltic silver before the 11th century is at this quality or better (Hårdh 1976; Steuer 2003).

The second type of resolution could belong to a separate sphere that may relate to more specialized applications. Touchstones can be very precise tools to measure gold and silver contents, but the application of this knowledge in the Viking world is most likely for metallurgical reasons. In the Viking Age, the use of touchstones, with their association to gold, may belong to a sphere beyond commercial exchange, as gold was a metal of restricted availability and use (Hårdh 1996, 132-4). In the hands of a skilled gold-silver smith, the information obtained by a touchstone could have been used to test and sort alloys for metallurgical applications, an example being the production of Terslev-style granulated ornamentation (**Figure 2.6**), which would require precise knowledge of the melting temperature for successful soldering and technical properties of the different components.

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[28] A technical study of cylindrical crucibles and heating trays can be found in **Appendix G**.

Figure 2.6 *Example of a Terslev-style brooch found at Hedeby (*M*AIXNER 2010, Figure 29) 3.9 cm x 3.7 cm.*

The fineness of silver alloys could have been tested empirically simply by its appearance in fracture and its working properties in the hands of an experienced metalworker or metal handler. The testing of alloys via analytical cupellation and its economic implications may actually be anachronistic; alone this theory is not supported by the finding of heating trays, which may have had a different function altogether.

2.5.3 Adjusting Silver Purity and Recycling Practices

As mentioned previously alloys can be altered to enhance the working characteristics of the metal in workshop settings and refining could have taken place on a small-scale for specific purposes as Theophilus describes (HAWTHORNE/SMITH 1979, 96-7). The theme of silver purity is inextricably tied to economics. The purity of silver is seen most often from an economic perspective due to its widespread use as an exchange medium. The work of generations of economic historians and especially numismatists has given a wealth of information concerning the fluctuations of the silver content of coinages. The political and economic motivations to maintain or alter the silver content of coins is indeed complex and will not be explored now, but, concerning the archaeometallurgy of silver, these changes have profound implications in understanding silver as an archaeological material. Two processes have been identified that have been used in the recycling of silver for coin making and other purposes. With a focus on minting, **Figure 2.7** shows two models of the *chaîne opératiore* for recycling silver that was in circulation.

Minting and Cupellation (Figure 2.7a)

It is well-known that Roman coinage was reminted by collecting old coins, and sometimes the coins were re-issued at a lower fineness, sometimes at a higher fineness (BURNETT 1987, 20-28), and PONTING et al. (2003, 592) go further to point out that the raising of the silver fineness is evidence for large-scale silver refining. The maintenance of the fineness of a coinage as well as debasement by adding base-metals does not necessarily require refining, but, to raise the silver standard of a coinage, the cupellation process must be carried out unless the change solely represents access to new silver resources.

In the early medieval period evidence of a large-scale refining campaign can be seen in the coinages of Charles the Bald in the 9th century (SARAH 2010, 232-3). The coinage produced under Charles the Bald can be separated into two chronologic groups. The coins dating from 840-864 AD are debased with brass, as indicated by the zinc to copper ratios, but after 864 the coins were brought to a high standard of fineness. The gold to silver ratios of the silver before and after 864 are in most cases similar and do not indicate a new silver source. It seems that the older silver coinage was in large part refined. This is also evidenced by the fact that the coins produced directly after 864 have higher zinc contents possibly representing a relic of the brass used in the earlier coinage (SARAH 2010, 234). Such events indicate the ability, politically, economically and technologically, to control the silver alloys over large geographic areas.

It is clear that large-scale cupellation campaigns occurred on occasion in the early medieval world. The question remains open of whether mints cupelled the silver and adjusted the alloy to a certain standard before every reminting. METCALF and NORTHOVER (1986; 2002, 218), for example, argue that cupellation and alloying occurred prior to the reminting of Anglo-Saxon coinage even when the standard remained constant. The reason for this hypothesis is that there appear to be long-lasting regional traditions of silver standards that would not exist if there were not close controls at the regional mints (METCALF/NORTHOVER 1986, 42); this however is difficult to confirm with the corpus of published analysis available. Other additional factors must also be considered that may influence the composition of the alloys. Such factors include the scale of minting, which may influence the homogeneity of the silver but also affects the profitability of slight debasement, the number of persons who had access to the silver having the capability and motivation to alter the alloy, and a low volume of extra-regional export / import of coins, which may help to reinforce regional differences.

Cupellation is a labor intensive process and probably was not performed unless it was necessary (see TOLL 1968, 274). One must be reminded of the skilled labor, the fuel costs, and the construction of hearths and furnaces for the processing of lead and litharge. Cupellation litharge from the refining of silver was found in several of the towns in Britain where minting occurred (BAYLEY/ECKSTEIN 1997, 109; TYLECOTE 1986, 119). Minting debris and litharge were found in the Coppergate excavation at York dating from the 10th century AD, and litharge was found in Late-Saxon contexts in Lincoln and Winchester (BAYLEY/ECKSTEIN 1997, 109). Cupellation certainly was carried out, but it must also be pos-

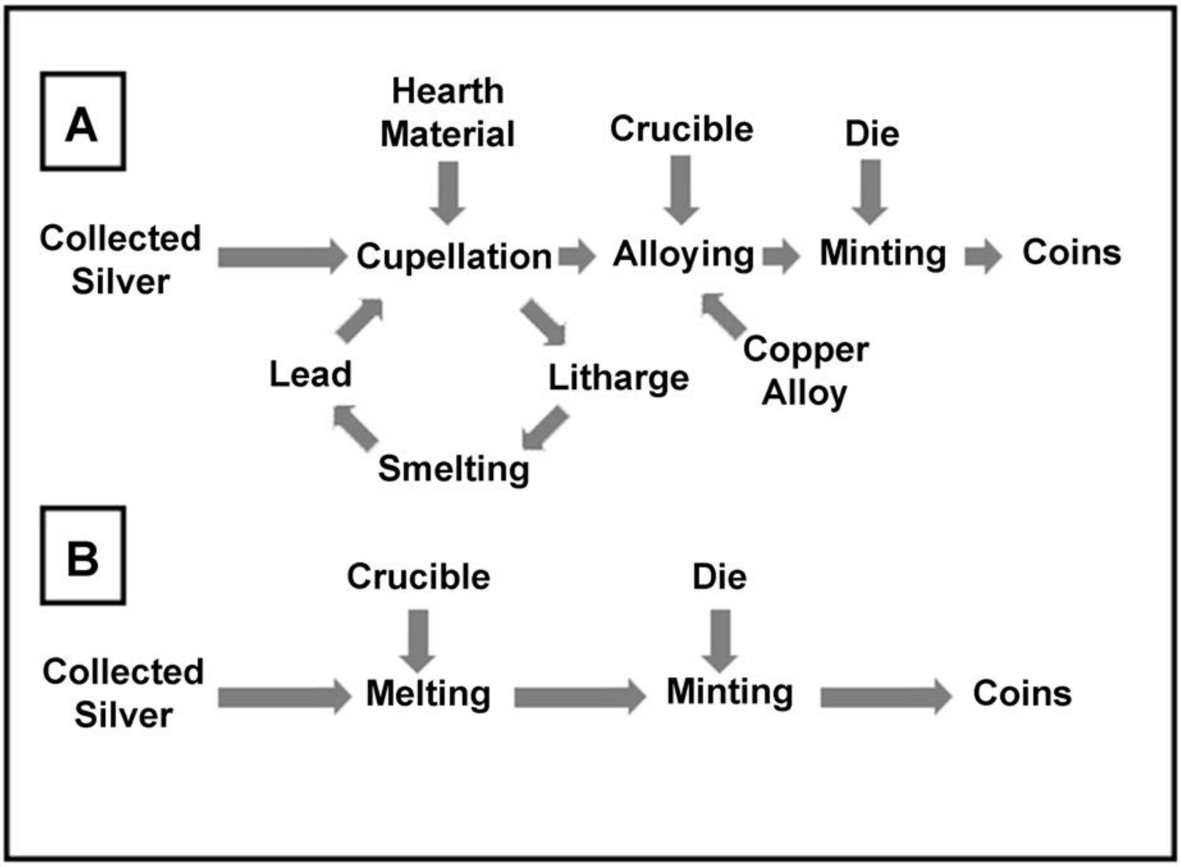

Figure 2.7 *Two metallurgical models for the making of coins from recycled silver. A: Minting with cupellation and B: Minting from re-melted silver. This diagram shows the difference in labor and complexity between the two methods.*

sible that only obviously debased silver was cupelled to raise it to an acceptable standard. The same level of control of the alloy standard may not have been achieved overall and the assumption that all silver at all mints was refined and re-alloyed at every re-minting may not be valid. This must be viewed as a multifaceted issue that is in need of further exploration and scientific analysis.

Minting Recycled Silver without Refining (Figure 2.7b)

It has been argued that in other regions, the silver was not always cupelled before minting. The coinage of the Isle of Man seems to be produced from unrefined silver (Bornholdt 1999, 206). The fluctuation of silver content and trace elements even among die-linked coins is interpreted as the use of different batches of recycled silver scrap. Similar to the Manx coinage, in Denmark it is also thought that minting in the 11th century was not so advanced that silver was refined and adjusted to a standard fineness; instead, it is thought that good quality silver was simply recycled without refining (Elfver 2007, 214). Although cupellation may not have been important in the minting of Danish coins, true cupellation is known in Scandinavian contexts. Cupellation hearth remains and litharge impregnated bone-ash have been found on Gotland at Fröjel dating from the 10th to the 12th century (Söderberg/Gustafsson 2006, 29-30). The workshop where the cupellation was carried out also contained mould fragments for Viking-age Gotlandic-style arm rings; these may have been considered a type of primitive money (Söderberg/Gustafsson 2006, 30).

At Hedeby where a mint was sporadically maintained, there is evidence for the recycling of silver. Silver was melted in ceramic crucibles of local and non-local manufacture. Two crucible forms are common, and they represent two different technologies with important implications for the understanding of recycling at Hedeby. The two main crucible forms are the cylindrical crucible and the dish-shaped open crucible. A more detailed discussion of the recycling at Hedeby will be provided in **Appendix G**, but at this point it is necessary to mention that a type of small-scale silver refining at Hedeby was undertaken. The dish-shaped crucibles, known as heating trays, were used to clean silver from impurities with the formation of a lead-silicate slag. As far as true cupellation is concerned only one object has been identified which may have been connected to the process. A crucible fragment[29] has been found to contain a 1-2 mm

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[29] **Cat. 247** for the analysis and discussion see **Appendix H**

thick layer of a white, powdery substance consisting of primarily lead carbonate and may be the remains of a cupellation lining inside a ceramic crucible.

Implications of Recycling Technology in Archaeometallurgy

Not only do these types of recycling technology tell us about the organization behind production and the consciousness of the economic impacts of alloy composition, from the archaeometallurgical perspective, the use of cupellation, recycling by re-melting, or alloying affect the composition in different ways. Cupellation, as discussed previously, can be used to make pure silver when carefully carried out. Lead isotope analysis is an important method in studying the provenance of metals like silver, but due to the addition of significant quantities of lead during the cupellation process, the result of lead isotope analysis will reflect the lead used during this process. Recycling by re-melting, on the other hand, will create an alloy that is a mixture of its constituents. If present, there may be some loss of zinc and mercury due to evaporation, but generally the melting down of silver objects homogenizes the metal both elementally and isotopically. Alloying after cupellation or to debase the silver will impart elements that typically do not survive the cupellation process in amounts above 0.1 percent, such as arsenic, antimony, zinc, and tin. The addition of a copper alloy can occasionally be identified due to increased amounts of zinc or tin. The ratio of zinc to copper may indicate whether freshly made brass was added to the silver. Lead may also enter with any copper alloy added but the amount of which depends on the original concentration in the copper alloy and in what proportion the copper alloy was added to the silver.

2.5.4 Surface Treatments – Intentional and Unintentional Implications

Once an alloy is produced the surface could have been altered in the past and in the present both naturally and intentionally. Surface treatments were used for multiple purposes: to improve the appearance or corrosion resistance or to deceitfully conceal debasement. Treatments like fire-gilding using mercury were well-known and were used in the Viking Age (Steuer et al. 2002, 159). This method could theoretically be used for silvering copper-alloy objects, but very few examples have been identified (La Niece 1993, 230). It is known that mercury was used particularly in Islamic mints such as in North Africa and silver dirhams are enriched with mercury on their surfaces (Heidemann 2011, 457; Ilisch et al. 2003, 110-111; Kaczmarczyk et al. 1977, 168-169), but the reasoning behind this is not altogether clear. Werner and Cowell (1975, 124) suggest that mercury contamination may not be intentional because silver readily absorbs mercury from the atmosphere. If silver-mercury amalgams were processed in the mint then this may leave traces of mercury on the coins.

Perhaps the most important surface treatment historically and presently is the superficial enrichment of silver from a debased alloy. The discovery of the technical processes used to make Tumbaga[30] and its dissemination in academic circles has raised awareness of chemical techniques to enrich the surface of precious-metal objects (see Lechtman 1971). The technology of surface enrichment has survived to the modern age (see Brepohl 2003, 189; Grimwade 1999; Hiorns 1907, 265), but its application in the medieval and earlier periods is only now being explored (Arles 2009, 461-503; Ingo et al. 2007). Particularly important is the use of depletion silvering in the making of medieval coins. A debased silver alloy can be enriched to sterling quality silver on the surface only by heating, oxidizing and using weak acids such as vinegar to remove copper. [31] The polishing of the remaining porous surface or the compression through the striking of coins helps to seal the debased core from environment, in effect, helping to increase the corrosion resistance of the object. Therefore, we may not simply assume that such tactics were meant to deceive, but may have had a practical function when such alloys had to have been used for economic reasons.

In regard to the testing of silver by pecking, the surface enrichment of silver using the simple techniques described above could have been used anywhere, at any time, and by anyone. Therefore, for every transaction the old peck marks could not be used as a reliable indicator of the internal composition of the object. New pecks are required if the true color is to be seen, and this is a reason to retest objects at every subsequent transaction (compare Kilger 2006, 456-65).

Lastly, it should be mentioned that the modern conservation and cleaning of archaeological silver objects might generate a surface enrichment of silver. Elements like copper, lead, and tin corrode readily in most burial environments, and the corrosion products build in the porosity and on the surface of the object. The cleaning of these corrosion products, commonly with acids like nitric acid, will superficially remove these elements from the surface. What remains is silver of high purity. This obviously can lead to misinterpretation when the objects are analyzed with non-destructive techniques such as those that analyze only the surface of the object (see Sándor et al. 2000). The problems of surface enrichment in regard to material science analysis will be discussed in further detail in **Chapter 6**.

Section 3.

[30] An alloy of gold, silver, and copper, which has a surface of high-grade gold due to surface enrichment techniques.

[31] There is a note that medieval Islamic minters (Egypt, 13th century) were using lemon juice and salt to brighten the surface of debased silver coins (Levey 1967, 9-11).

2.6 Closing

A number of changes can be observed as silver is transformed from ore to the finished products. In this chapter the major metallurgical process regarding extraction and recycling of silver have been discussed. None of the factors influencing the composition of silver objects remain constant, but can change and vary due to the production technologies, metalworking techniques, recycling practices and conservation methods. Care must be taken to thoroughly examine all the contributing factors, and only in this way can the intentional, cognitive processes carried out in the past be identified, the possible continuities from ore minerals to finished products be detected, and the relationship between objects and the movement of goods and people be perceived.

In this chapter an effort was made to recognize what factors were known and actively manipulated by the metallurgists and silver smiths in the early medieval period, and this was achieved through a synthesis of the physical / working properties of silver alloys with metallurgical processes and the procedures for testing silver purity.

In this chapter, a list of the factors and an interpretational framework of the application of material science analysis of early medieval silver were outlined. In regard to the provenancing of silver objects, the path is not straight-forward. A number of complications exist that can be difficult to surmount. Some of the major problems stem from the refining and recycling of silver, which not only affect the isotope ratios of lead, an important provenance tracer, but alter the other elements alloyed with the silver in various ways.

3. Chapter
Hedeby and the Silver Economy of the Viking Age

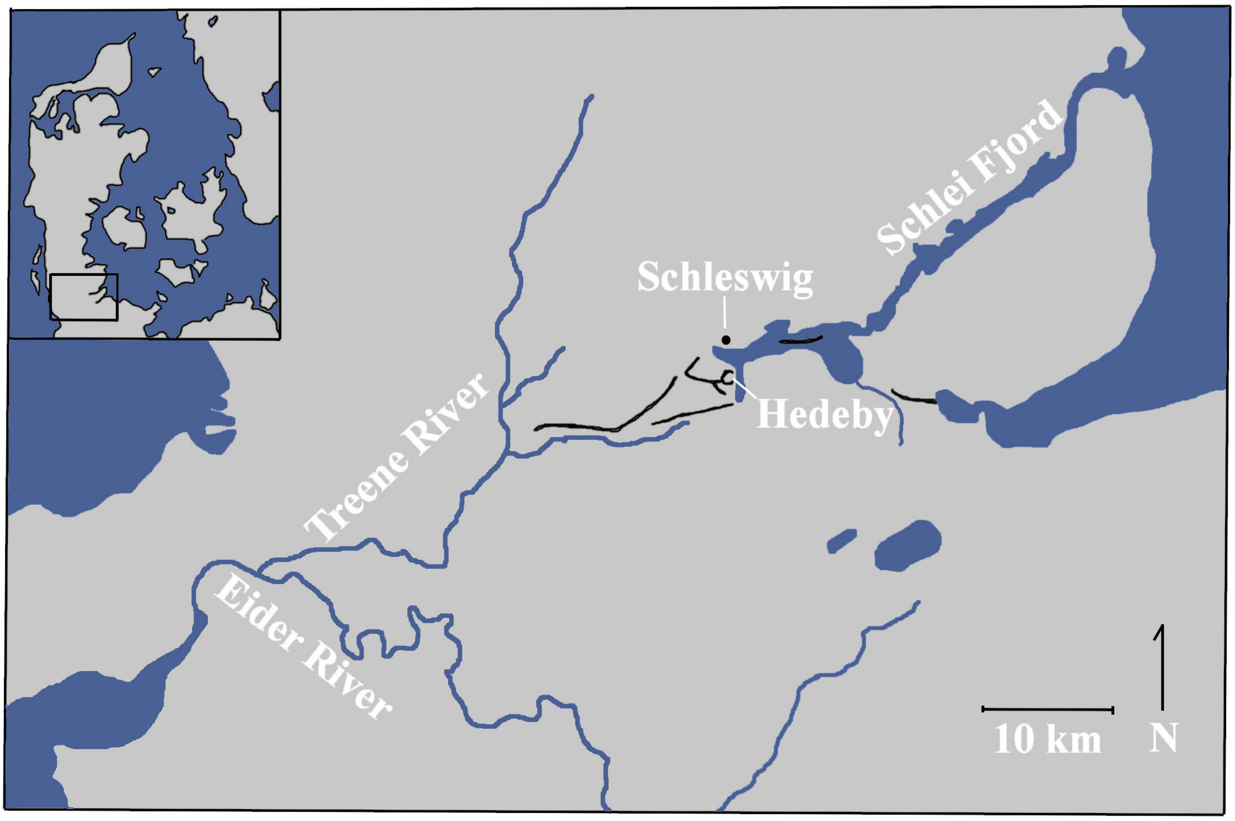

Figure 3.1 *Map showing the Danish border region. Hedeby can be accessed by water from the Baltic via the Schlei Fjord. The region between the Schlei and the Treene River is fortified by the Danevirke, a system of earthen/timber walls (Black lines). The Treene River offers access to the North Sea. Map redrawn by S. Merkel from* Dobat *(2008, Figure 1).*

3.1 Introduction

Understanding the role of silver in the economy of Hedeby is a central focus of this work. With more than one hundred years of archaeological investigations (Hilberg 2009, 84-7), it is clear that Hedeby was an economic center of paramount importance in the Viking Age as both a generator and conductor of long-distance trade. Silver is the most significant feature in the famous hoards of the Vikings, and silver along with the tools of measurement can be found in the trading centers of Scandinavia. It clearly played an important role in the exchange practices of the Vikings and for the economic and political development of Scandinavia. The theme of this chapter is the introduction of Hedeby and the development and functioning of silver in the economy in the Viking Age.

3.2 Hedeby

Hedeby was an important Viking-age settlement in the 9th to the 11th centuries AD. The role of Hedeby to the Danish kings was strategic in both military and trade. Its position on the sheltered shore of the Haddebyer Noor allowed direct access to the Baltic Sea via the Schlei Fjord, but most importantly, the settlement was built at the narrowest point of the Jutland Peninsula, which also formed the border between the Danish lands and the Frankish and later German kingdoms. Hedeby was built at the cross road of the east-west trade route across the peninsula, by-passing the long and difficult passage through the straits between North and Baltic Seas, and it is located near the Ox Road, the north-south road that runs the length of Denmark and south into the Saxon and Slavonic lands (Kalmring 2010, 27-40).

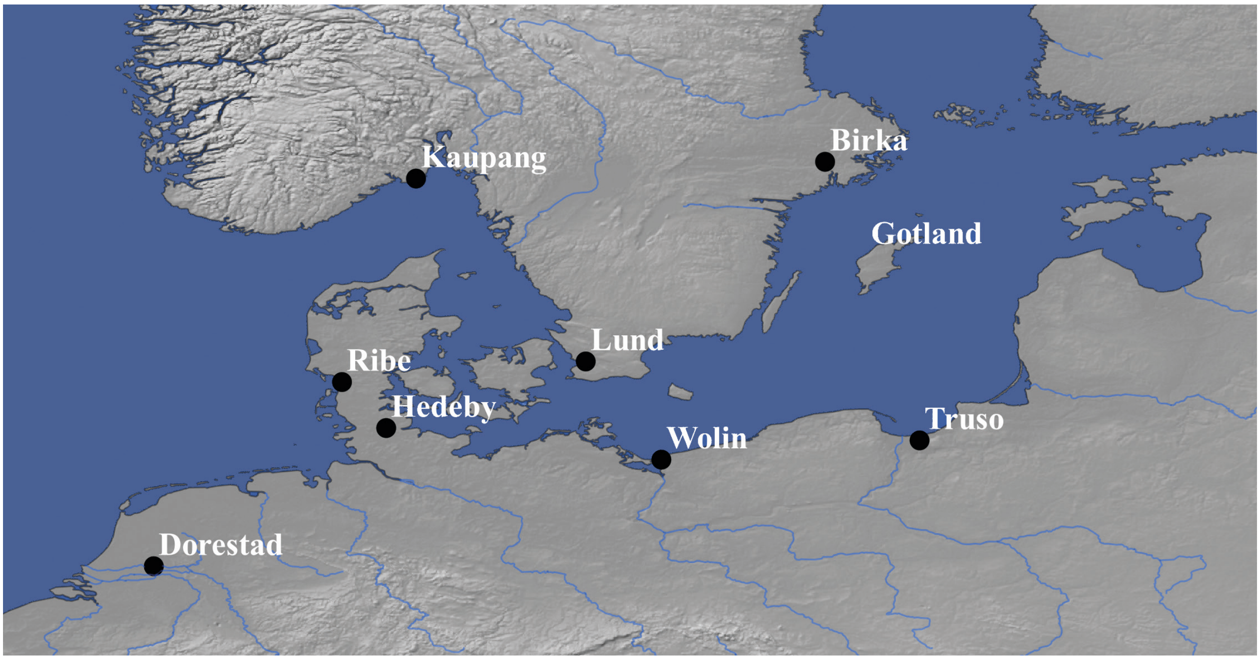

Figure 3.2 *Map showing the location of several major maritime trading centers. Hedeby is located at the narrowest point of the Jutland Peninsula and facilitated traffic of goods between the North and Baltic Seas.*

The origin of Hedeby is found in the mid to late 8th century, and already at that time the harbor beach was in use (Kalmring 2010, 111-112, 457-8). Hedeby's rise to prominence as an emporium is marked by the historical account of Gotfred's militarization of the Danish border and the relocation of merchants and possibly craft workers from the Slavic trading settlement of Reric around the year 808 AD (Hilberg 2009, 79; Schlesinger 1972, 77). At the beginning of the 9th century, Hedeby, respectively the Sliesthorp from the written records, was the place where king Gotfred gathered his fleet and may have been something like a royal manor (Hilberg 2009, 79). There is a clear rise in the number of archaeological finds from the early 9th century (Jöns 2000, 93). In the second quarter of the 9th century there is archaeological evidence for the first dock construction (Kalmring 2010, 458), which is contemporary to an important construction phase in the main settlement area dated by dendrochronology (Schultze 2008, 248-9).

The duel role of Hedeby as an economic and military center is re-enforced by its association with the Danevirke, the earthen and timber fortification marking the southern Danish border and protecting the route connecting Hedeby to the North Sea (**Figure 3.1**). Hedeby was fully incorporated into the Danevirke defense structure in the middle of the 10th century with the construction of the semi-circular town wall (Dobat 2008, 41-2). It is argued that the development of Hedeby, its harbor, and the Danevirke may have been directly linked, all stemming from the 8th century (Dobat 2008, 46-7; Müller-Wille 2007, 163).

Since the royal involvement of the Danish kings at the settlement, it seems that the affluence brought from long-distance trade and manufacturing was of primary interest. As Schlesinger (1972, 77-8) discusses, the relocation of merchants from Reric to Hedeby was a way to better secure income acquired by trade. Not only was it of economic interest to the Danes, but also to other groups like the Saxons, Norwegians, Swedes and the Slavs[1] who all carried out military excursions to varying levels of success (Schlesinger 1972). Though raids to the settlement brought temporary rewards, the control of Hedeby brought duties or tribute, which must have been in significant amounts.

Hedeby was an emporium developed to control the movement of goods traveling between the Baltic and North Seas as well as an entry point into the lands of the Danes (**Figure 3.2**). The funneling of trade through this one location produced wealth, as can be attested by finds from the settlement and harbor as well as the lavish burials of rulers and merchants (Hägg 2002; Müller-Wille 1976). It was a magnet for ships bearing cargo, bringing raw materials, foodstuff, and finished products from near and far. Harbor settlements and beach landing sites were not uncommon in Viking-age Scandinavia, and served as nodes of exchange and transport of local products and agricultural surplus, but Hedeby, like Birka, belonged to an exclusive group of Viking settlements with a focus on 'international' trade (Ulriksen 2009, 141, also see discussion by Sindbæk 2008). In reference to the account of Ohthere's voyage from Norway to Hedeby, one of the few historical references of maritime travel and commerce in 9th century Scandinavia, Ulriksen (2009, 141) states:

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[1] Abodrites.

> *The restricted number of long-distance trading sites in 9th-century Scandinavia is no coincidence. Society had no need for competitive sites in the modern sense of the word, and these emporia were situated in convenient contact zones. It is noteworthy that Ohthere obviously was very focused in his travel behaviour. He did not refer to any incidents of trade or exchange in connections with his numerous stops from northern Norway to the western Baltic. Only Skiringssal[2] and Hedeby were important. They were the focal points in the communication system of the time, and where Ohthere could exchange his cargo of raw materials for what he required.*

The archaeological remains indicate that a wide variety of raw materials were brought to Hedeby to be further processed, for example stone (Müller-Wille 2007, 158-9; Schön 1995, 34-5), amber (Ulbricht 1990), fur-bearing animals (Reichstein 1991, 104-7; Schmölcke 2006, 209-10; Steuer 2009, 303), antler (Gerds 2001; Ulbricht 1978), glass (Dekówna 1990), and metals like gold, silver, brass, lead and tin (Ansprach 2010; Armbruster 2002; Sindbæk 2001; Steuer 2004). Through the maritime connections raw materials were acquired with which the craft workers of Hedeby fashioned numerous products. Numerous types of finished goods were also imported for local consumption or for further exportation, examples being weapons, jewelry, silver coins, ceramics (Steuer 1987a), and textiles (Hägg 2002).

Archaeologists tend to focus on, or perhaps overemphasize the role of goods that leave clear physical traces. Ephemeral goods like salt, grain, and notably slaves, are often difficult to detect in the archaeological record (see Hilberg 2009, 91; Steuer 2009, 302-303). An historical account recorded by Rimbert about the visit of the missionary Ansgar to Hedeby described the thriving slave market (Klindt-Jensen 1970, 168). Slaves were a lucrative commodity and were traded over long distances to markets ranging from Spain to Central Asia in the medieval period (Henning 1992; Noonan 2001). Slaves were primarily important as an export good to markets in the Byzantine and the Islamic Empires, but the role of slaves and their use in Scandinavia is more difficult to describe.[3] The capture and selling of slaves was an economic engine that helped to power long-distance trade and the slave market at Hedeby may have greatly contributed to the wealth and success of the settlement.

The trade of goods, be it slaves, furs, raw materials, or finished products, was concentrated at Hedeby. Hedeby was a truly international settlement used by the Frisians, Slavs, Danes, Swedes, Norwegians, Saxons, Anglo-Saxons, Balts, and Finns, among others (Marold 2001). The complex trading network that connected Hedeby to the rest of the known world could not have functioned without some centralized control and without protection of the settlement, the overland route, and the trading vessels that met there. Sindbaek (2008, 154-5) points out that the organization of trade in Scandinavia was multi-layered: social interdependence, norms, tradition, and material culture helped to regulate exchange at a certain level, but, at another level, centralized control is reflected, such is seen with the development of specialized trading ships requiring protection (Crumlin-Pedersen 2002, 75) and with the fortification of trading settlements in the 10th century. The history of Hedeby is one intertwined with royal power. The rulers of Hedeby provided protection to the settlement and the transport route across the peninsula and secured the rights of merchants from a number of lands and cultures (Dobat 2008; Schlesinger 1972, 77-9). The goods brought by the long-distance exchange network helped to reinforce the status of the elite, but also trading centers like Hedeby brought income that could be used to further exert economic and political influence elsewhere. In this environment trade and exchange flourished.

3.3 Money, Exchange, and the Role of Silver in the Viking Age

It goes without saying that where there is trade, there is also a system of valuation. The process of exchange at Hedeby has left abundant archaeological evidence, and the exchange system was probably diverse relying on the use of commodity-money,[4] barter, and true money.[5] It is widely accepted that the lead and copper-alloy weights and scales sets found in Viking contexts should be related to the weighing of silver for trading purposes (Brather 2010, 143; Gustin 1997, 163; Steuer 2009, 294), and scales sets and a variety of weights have been found in large numbers at Hedeby particularly from the 10th and 11th centuries (Hilberg 2011, 217; Steuer 2009). The finding of hacksilver, ingots, and foreign and locally-made silver coins attest to the commercial exchange of goods in which silver was an accepted exchange media (Hilberg 2011).

Goods can be valued in various ways and exchanged by direct comparison, i.e. barter / commodity exchange, or goods can be valued against a weight

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[2] Skiringssal: name of a Norwegian central-place complex of which Kaupang is a part (Pilø/Skre 2008, 24).

[3] One could ask if the metalworkers of Hedeby were themselves slaves or if they were legally free to move about (compare Callmer 2002; Gustafsson 2013, 73-5). Brink (2008) describes the complexity of the social structure and legal status of slaves in Scandinavia and advises against a simple definition of slavery and the direct comparison to earlier and later eras. There are very few ways to explore these questions further, and it is unfortunate that the archaeological record is nearly silent on the subject. Gustafsson (Forthcoming) may have found a way to identify the remains of metalworkers, and thus enabling the exploration of their social status, though this status may not be directly comparable with legal status as a slave (Brink 2008, 55).

[4] Commodity-money is an exchange medium where the value stems from the value of the material of which it is made.

[5] Money is defined as a token that has a socially accepted value that is separate from its value as a material (see Innes 2004 [1913]).

standard or monetary unit. The economy of the Viking Age was in constant transition and witnessed the change from an economy based on bartering and commodity exchange to the production of local coinages, i.e. monetization (Steuer et al. 2002), but although the development seems linear it is not straight-forward and multiple systems may have been used simultaneously. The transition period is complex and was dependent on both external and internal forces. The use of silver as a medium of exchange in Scandinavia and the rise of small-scale and national coinages of Viking-age Denmark are themes of vast social, political, and economic importance.

3.3.1 Why Silver?

The hoarding of silver is a widespread phenomenon in Scandinavia in the Viking period. Of the largest known, the two Spilling hoards found on the island of Gotland in the Baltic contained 67 kg of silver in the form of jewelry, rings, ingots, and coins (Östergren 2011). Silver, a rare natural resource in Scandinavia, was in widespread use in the Viking world and performed a number of functions, although its economic function as commodity-money and money seems to overshadow all others. In some cultures, textiles fulfilled the role of exchange medium (Gustafsson 2013, 42; Kilger 2008a, 296; Spufford 1988, 71-2). Textiles are valuable products due to the skillful and time-intensive manufacture, and they are a product that can typically be produced from local raw materials.[6] Silver is a product that was not locally produced in Viking-age Scandinavia, and was solely imported from silver-using and silver-producing regions. Textiles are made to be consumed (clothing, etc.), and silver can also be consumable (jewelry, funerary goods, etc.), but it has other advantageous qualities as an exchange medium.

It is accepted that the source of real wealth in the medieval period was the ownership of agricultural land and livestock, but to support the ever-growing complexity and necessity of commerce in and outside Scandinavia, a universal transaction medium was required (Skre 2011). As Sindbæk (2011) points out, silver fulfills the most important criteria for this purpose: Silver is widely accessible via long-distance trade, it is divisible, compact, and transportable, it stores value, and its purity can be verified and regulated.

3.3.2 The Development of an Exchange Medium

Skre (2011) describes in theory how the need for a medium of exchange could have come to be. As the complexity of trade grew, the use of a common exchange medium eased the problem of finding willing trading partners. Bartering only works well when both trading partners accept the goods of the other, and this requires a prior knowledge of the trading partner’s preference for goods. Silver, as a proxy for value, allows transactions to take place when the partner’s preferences are not known, or when the goods desired are not what the partner can offer in return.

The connection between the cost of finding an exchange partner and the use of commodity-money was described by Adam Smith in the 18th century, but Innes (2004[1913], 29) argues that the true utility of an exchange medium is when there is no trust in the trading partner to pay debts, i.e. where there is no credit. The economic situation in rural Scandinavia can hardly be described as having a lack of trust, and as emphasized by Skre (2011), silver had little use in many of the rural areas of Scandinavia. The development of a medium of exchange is rooted in the long-distance trading networks and strengthened by the contacts with the West developed during Vikings’ military campaigns. The development of an exchange medium can be tied to trading not only with persons having unknown preferences or preference to silver, but also with persons that may not be known or trusted.

Following the concepts of North (1977; 1984), the use of silver as an exchange medium lowers the overall cost of exchange because it is a way to reduce the uncertainty and fear of economic loss as the number and variety of goods, services and trading partners rise. There is a cost of obtaining silver, and there is an added cost of performing two transactions (goods-silver, silver-goods) as opposed to one transaction (goods-goods), but the cost of finding the right trading partner who offers exactly what is desired must have significantly out-weighed these factors.

Although market-based theories of the development of commodity-money are often used to describe the development of the Viking silver economy, it must be considered that public institutions may have played an influential role in the origin of silver as a commodity-money. Public institutions like governments, trade organizations, or religious organizations in other regions and at other time periods are thought to have been important in the selection, implementation, and enforcement of measurement standards and the medium of exchange. For example Hudson (2004) argues that the development of the silver unit of account in Mesopotamia was a way for the governmental bodies to better manage accounts and to regulate credit/debt. Henry (2004) also bases the development of commodity-money in ancient Egypt on the requirements of the emerging state to collect and manage taxes. The extent to which the public institutions of the Vikings influenced or benefitted from the use of silver is uncertain and a question in need of further exploration. Whereas Hudson (2004, 119) states that commodity exchange between individuals acting on their own account played little role in the development of commodity-money (in this case silver), it is unclear if this can

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[6] Access to dyes and raw materials like silk, linen, or certain types of wool may certainly have been restricted or required importation.

also be said for the development of the silver economy of the Viking Age. It is thought that the commodity exchange of silver used in Viking-age Scandinavia emerged in the absence of powerful centralized states (Hårdh 1996, 27). The role of the state, the trading centers, and supra-regional trade organizations in the exchange practices in Viking-age Scandinavia is anything but understood, and in truth the agreement on silver as the exchange medium may have been influenced by both public institutions and the individuals in constant contact with silver-using and monetized regions.

The finding of silver fragments, silver coins, ingots, weights, and scales at the major trading centers of Scandinavia indicate how pervasively and intensively silver was used as an exchange medium (see Hårdh 1996; Hårdh 2011; Hilberg 2011). The rise of the silver economy in Scandinavia in the early Viking Age was a significant economic innovation with wide-reaching consequences. A balanced perspective must be maintained; however important the use of silver as an exchange medium for commercial transactions was for the early medieval economy, it was only one facet of the wider economy in which there were other methods of exchange, i.e. bartering or gift exchange (see Hillebrandt 2009, 93-4; Naismith 2012, 260-7), which may be more difficult to see in the archaeological record. Additionally, the use of a unit of account, such as weights of silver, coins, or a good cow, hardly means that all transactions were realized with these media: They could be substituted for the equivalent value in other commodities (for example see Skre 2011, 73-5). With what is known about the medieval economic system, it was likely flexible, dynamic, and situation dependent.

3.4 Coins, Rings, Ingots, and Hacksilver

Can it be said that form follows function? Silver can be found in many forms, and these forms must provide some indication of how the silver was used. Years of research by scholars of the Viking Period have revealed differences of silver use and form (Hårdh 1996; Kilger 2008a; Steuer et al. 2002; Wiechmann 1996; Williams 2007). Silver use is not uniform and varies regionally and chronologically (Hårdh 1996), but there are three major trends in the form of silver intended for commercial transactions: coins, ring-money / ingots, and hacksilver.

Coins indicate a central authority and a standardization of form, weight, and purity, but this standardization can vary depending on the accepted minting policy. Coins are stamped with texts or images that are culturally and politically significant. Weight-adjusted rings and ingots are also units of a standard form, weight, and purity, and are a type of money that fit into a supra-regional exchange network. Hacksilver is a specially defined term meaning fragments of silver that have been cut or otherwise physically altered with disregard to its original form or function, and reflects a radical economic transition in the control and use of silver (see Kilger 2008a, 320-1).

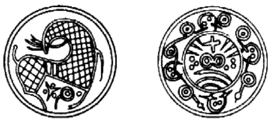
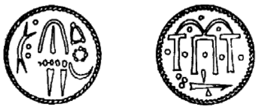
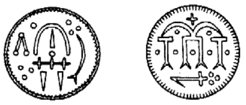
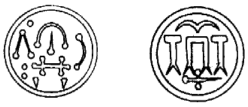
As long as all three types of silver (ring-money / ingots, hacksilver, and coins) are of a similar purity, measuring silver by weight is the least common denominator, but, in essence, each of these three systems relies on different, even conflicting, ideologies of calculating value (Kilger 2008a). Despite this, the three systems are not mutually exclusive and could have co-existed to some degree (Williams 2007, 181-5). In the following sections the relationships between the three valuation systems will be discussed along with their chronology.

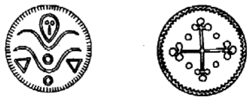
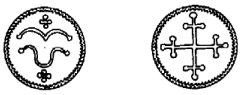
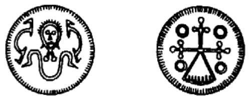
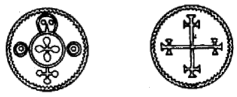
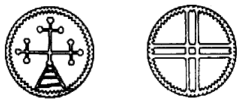
3.4.1 The Development of Coinage in Southern Scandinavia

Because of the ease in which imported silver coins could fit into a weight-based economic system, this section will focus only on the indigenous minting in Scandinavia. The minting of coins at Hedeby indicates that there was an understanding of the benefits of coin making, but also that a level of economic and political organization existed that could have allowed minting to make economic sense for both the merchants and the central authority.

The conceptual boundary between commodity-money and true money is not firm, but can fluctuate back and forth depending on the social or political situation. Coins of precious metal have a commodity value, but they also have a social value that is propagated by institutions. It may be argued that the value of a coin is tied to the royal assurance of its purity and weight, or in other words, its material value, but others argue that coins when used within the political / economic sphere for which they were made have a monetary value that is not directly connected to their material value (Ingham 2004, 212-214; Innes 2004[1913]; Wray 2004). When coins are exported or used outside the realm of the political or economic sphere of influence, they may lose their monetary function and are valued by their material. There are certainly good reasons for institutions to produce stable and good quality coins: Firstly, it potentially makes counterfeiting less profitable, and secondly, it is advantageous when conducting business or military campaigns in areas outside the political or economic sphere of influence of the minting authority (see Wray 2004, 253).

In contrast to theories forwarded in economics (Samuelson/Nordhaus 2007, 717-9), it can be argued that the primary function of money, or coins, was to fulfill the financial needs of the state and religious organizations as a means of taxation, wealth transfer, and the settling of accounts (Ingham 2004, 190). Moesgaard (2012, 128-131) argues that the coins produced at Hedeby are the work of a king, town government, or merchant organization. It cannot be assumed that the

Group	Type	Mint	Date Range	State
	Old Carolingian and Picture Types			
KG 1		West Europe	768-793/4	
KG 2		Northwest Germany	Before 800	
KG 3		Hedeby	ca. 825	Denmark
KG 4		Hedeby	ca. 825	
KG 5		Ribe	After ca. 825	
KG 6		Ribe	ca. 840-860	
	Younger Carolingian Type (Half-Bracteate)			Ottonian Empire / Denmark?
KG 7		Hedeby	ca. 900-920	
KG 8		Hedeby	After ca. 950	
KG 9a		Hedeby	After ca. 965	
KG 9b		Hedeby	After ca. 975	
KG 9c		Hedeby	After ca. 975	
KG 9d		Hedeby	After ca. 980	

	Cross Type			
KG 10a		Lund / Hedeby?	975-980	Denmark
KG 10b		Lund / Hedeby?	975-980	
KG 10c		Lund / Hedeby?	ca. 985	
KG 11		Lund / Hedeby?	975-980	
KG 12		Lund / Hedeby?	After ca. 985	
KG 13		Lund / Hedeby?	995	
	11th Century Types			
Årstad 95		Hedeby?	1015-1035	Denmark
Årstad 96		Hedeby?	1015-1035	
Hauberg 50		Hedeby	1035-1042	
Hauberg 72		Hedeby	1048-1074	

Figures 3.3 and 3.4 These figures show the stylistic development of the Malmer combination group (KG series) coinage from the Carolus/Dorestad types to Danish types of the 11th century. In several cases the mint has not been firmly identified. The figure is based on Wiechmann *(2007, Figures 1a-1b) with some modification. The Årstad coins are redrawn from* Wiechmann *(2013), and some examples of the coins of Harthecnut and Sven Estridsen are redrawn from* Hauberg *(1900).*

making of coins at Hedeby or elsewhere in the early medieval world was solely performed to ease or facilitate commercial transactions, however legitimate this argument appears to be on the surface. The idea of minting is to control access to the means of exchange in order for an institution to regulate and benefit from economic exchange. Coins in a monetized society had an inflated value compared to their weight in metal, and this value was regulated and maintained by a central authority, such as a king. The minting at Hedeby may be linked to the raising of funds for public construction works, for military funding, or for duties or tribute to the ruling authority (see Bendixen 1981, 407; Williams 2007, 188). The development of coinage in Scandinavia cannot be separated from the centralization of governments and the streamlining of tax collection. In the absence of contemporary written works on the financial system of early medieval Europe, much must be extrapolated from incomplete archaeological and numismatic evidence. In the following section an introduction to the monetary history of Hedeby and early medieval Denmark will be provided.

3.4.1.1 Frisians and Sceattes

With the end of the Roman Empire, the tradition of minting in western and southern Continental Europe continued. There was a break in the making and circulation of coins in Britain, but Scandinavia was outside direct Roman influence and had no tradition of minting. Beginning in the 7th century AD, there is evidence of the circulation of coinage in the North Sea region (Spufford 1988, 28-32). The use of silver coins named sceattes linked the economies of southeast England with the Frisians, who inhabited the mouth of the Rhine and the south and southeast coasts of the North Sea (Grierson/Blackburn 2007, 164-8). The source of the silver itself is thought to stem from the Frankish Empire, who switched from a gold coinage standard to silver in the 7th century (Spufford 1988, 27-32; Téreygeol 2013). The growth of maritime trade by the Frisians can be seen in earlier times, but with the distribution of sceattes the role of the Frisians becomes increasingly clear. The finding of numerous sceattes of the Wodan / Monster type at the settlement of Ribe in modern-day Denmark indicates a direct connection to the Frisian North Sea trading network and the beginning of coin use already in the early 8th century and may reflect the first minting of coinage in Scandinavia (Feveile 2008).

3.4.1.2 The Beginning of Scandinavian Minting

The Frisians maintained a dominate role in transport and exchange in the North Sea even as it was incorporated into the kingdom of the Franks. In the later 8th century, the settlement of Dorestad on the Frisian lower Rhine appears to have been the most prolific mint of the Frankish kingdom, and it grew into a powerful trading center in the emerging Carolingian Empire (Coupland 2010a). The influence of Frisians and Carolingian Dorestad is distinctly seen in some of the earliest coins of Scandinavian manufacture. The first coins to be minted at Hedeby used a Frisian imitation of a Carolus / Dorestad coin as a model (**Figures 3.3** and **3.4**): the Malmer KG 3 (Malmer 2002, 121; Steuer et al. 2002; Wiechmann 2007). Stylistic and archaeological evidence points to a date around 825 AD for the first minting of the Combination Group 3 (KG3) at Hedeby (Malmer 2002). It is unclear who was responsible for the minting at Hedeby. Godfred, Harald Klak or Godfred's son Horek were kings of Hedeby during the 820s, and all had contacts with the Franks (Williams 2007, 188-9). The distribution of coins of the KG4-6 type may point to minting in Ribe (Malmer 2007, 20), but this is altogether unclear. There may have been some connection with the minting at Hedeby (Malmer 2007, 22-4). The limited number of coin finds of the 9th century do not allow a firm reconstruction of the mint locations, distributions, and date range of these coinages. The proportionally large number of dies used to make the KG3-6 coins shows that production must have been much larger than that represented by the coin finds themselves (Malmer 2007, 20).

3.4.1.3 The 10th Century: Carolus / Dorestad and Cross Coinage

Around the turn of the 10th century minting was resumed at Hedeby with the KG7 coinage. The motif of this coin type is based on the earlier KG3 and is a further abstraction of the Carolus / Dorestad type (Malmer 2002, 122-5). Whereas the 9th century coinages (KG3-6) are tied to the Carolingian weight standard, i.e. Obol or half-penny (Malmer 2007, 19-20), the KG7 weighs notably less (Malmer 1966, Plate 51). The KG7 is described as a half-bracteate because it is minted on thin metal so that both die imprints appear on both sides of the coin. These thin coins are thought by Wiechmann (2007) to be part of a regional currency area that connected Hedeby to its agricultural hinterland in Angeln and Schwansen and were the only accepted coinage. This argument was based on the fact that so few hacksilver fragments and ingots were found at Hedeby, but the new metal detected finds from the settlement have slightly changed this picture and demonstrate that silver in various forms was traded at Hedeby (Hilberg 2011, 218-20). The following KG8 and KG9 coins of the third quarter of the 10th century are even lighter, and may indicate an economic decline (Malmer 2002, 124-5), but this may be more related to a shift in the general usage of silver in this period (Hårdh 1996, 86; Malmer et al. 1991, 43). The making of thinner and lighter coins in the second half of the 10th century has parallels in hacksilver, the weights of which also decline in this period (Hårdh 1996, 24, 128-9). As Steuer (2009, 305) suggests, the smaller units of this period may reflect a switch from a focus on long-distance trading to local 'market' type trading.

It is thought that the coinages of the Carolus / Dorestad type were produced by the town government or a type of pre-Hanseatic merchant organization because the conservative nature of the coins motif throughout the tumultuous political conditions at Hedeby in the 10th century (Moesgaard 2012, 128-9).[7] The final quarter of the 10th century marks a change with the emergence of a new type of Danish coinage. This is the so-called cross coinage, and their minting is associated with the king Harald Bluetooth. The political control of Hedeby during the 10th century is uncertain despite the written records. It is thought that Hedeby was recaptured by the Danes in the year 983 after Hedeby had been under Ottonian control[8] for about forty years (Malmer 2002, 125; Schlesinger 1972, 81-5), but this theory is contested by Moesgaard (2012, 130-1) who finds the historical evidence unconvincing. There have been a number of opinions of where the cross coins were minted. Malmer (1966, 229-38) rejected the idea that the cross coinage

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[7] Although it may be the case that minting was carried out by a local official or trade group, taxes from minting may have been levied by the current king / emperor, who perhaps granted the right to mint.

[8] The form of this control is uncertain. It may have been direct military occupation or indirectly controlled through a requirement to pay tribute.

was made at Hedeby and argued for a northern source like Lund because of the lack of examples found at Hedeby, but with the recent metal detecting and excavations the number of cross coins has greatly risen (Hilberg 2011, 214; Hilberg/Moesgaard 2010). Moesgaard attributes the minting of the cross coinage to Hedeby, which represented a coinage reform of Harald Bluetooth to revamp the coin production at Hedeby and increase the circulation of his coins in the rest of Denmark (Moesgaard 2012). The system collapsed after the death of King Harald in 987 AD at which time the minting in Denmark ceased and the circulation of foreign coins, particularly German coins, dominated (Moesgaard 2012, 131-2).

3.4.1.4 Hedeby and Danish Minting in the 11th Century

The last decade of the 10th and first decades of the 11th century witnessed a substantial influx of coins from Anglo-Saxon England and Germany into Scandinavia (Blackburn/Jonsson 1981; Ilisch 1981). At this time there was a break in the minting at Hedeby only to begin again in the second decade of the 10th century. The distribution and chronology of the Årstad 95/96 coinages also seem to indicate that Hedeby was minting between 1015 and 1035 AD and typologically represent the transition in Denmark between the earlier half-bracteate and the later penny type coinage (Wiechmann 2013). The motif and style of the Årstad coinages reflects primarily Anglo-Saxon stylistic influence in combination with Byzantine and Saxon features (Wiechmann 2013, 149-53). In the 1030s the style of coinage in Denmark radically changed taking a more nationalistic character with mints having individual symbols (Malmer 2002, 129). Under the reigns of Hardeknut (1035–1042), Magnus (1042–1047), and Sven Estridsen (1042–1074) coins were minted at Hedeby and other Danish towns (Gullbekk 2000; Hauberg 1900; Jonsson 1994, 223–7), but minting under Cnut the Holy (1075–1086) is more obscure.

The coinage of Sven Estridsen (1047-1074) has been the focus of a few studies because of suspected debasement. Gullbekk (2000, 111-29) argued for the debasement of the Danish coinages of the second half of the 11th century marking a shift in monetary policy to a policy of recoinage and restricted circulation of foreign coinage. Elfver (2007), on the other hand, contests this debasement arguing that Cnut the Holy (1080-1086) was the first to debase the coinage. Both of these studies used archaeometric analysis of coins as the basis of their argumentation. The analyses performed as a part of this doctoral thesis supports the position of Gullbekk (2000) that the coinage of Sven Estridsen is debased. Further explanation and possible reasons for the analytical discrepancy between Elfver and Gullbekk will be discussed in **Section 5.3.5**. [9]

3.4.1.5 Conclusion

The inception of coinage in Scandinavia was influenced by the Frisian North Sea trade and contact to the Carolingians in the 9th century. Hedeby played a central role in the numismatic history of Denmark. Minting was sporadic at first and appears to have been small scale, but during the course of the 10th and 11th centuries a number of changes occurred eventually leading to an enforced national Danish currency. Parallel to the development of a coin-based economy between the 9th and 11th centuries, other competing methods of using and trading silver were also in a phase of transition.

3.4.2 The Aurar System, Hacksilver, and the Bullion Economy

Not only is the valuation of silver by weight in ideological conflict with the use of indigenously produced coins, the development of hacksilver denotes a fundamental change from the use of standardized ingots and rings. The development of the ring money and bullion economy is complex and the focus of a number of books and scholarly articles (Coupland 2007; Hårdh 1996; 2007; 2008; Kilger 2008a; Kruse 2007; Steuer et al. 2002; Wiechmann 1996), and in this section a summary of the major points will be presented.

3.4.2.1 Ring Money and Ingots

An important theme of the discussion is whether the form or completeness of a silver object has some influence on its value (Kilger 2008a). Naturally, if weight was the only consideration, than the form of the silver is unimportant. In the early Viking Age, particularly in the 9th century, there is evidence that the form was significant because objects were typically used in their complete form as ingots or rings of standardized weight. The respect of form denotes a system of valuation that is a socially or culturally-enforced detachment from the material/commodity value. Although these rings and ingots are weight adjusted, emphasizing their bullion value, the respect to their form emphasizes their use as money in its abstract form.

The development of the system of exchange using weight-adjusted rings and ingots of gold and silver known as the ‘Aurar system’ is connected to the weight system of the eyrir or the øre, and the system of measurement was probably based on the Roman ounce (Kilger 2008a, 279-88). The early eyrir weighed 26.4 grams and was the standard of measurement in Scandinavia during the Merovingian and early Viking period before the introduc-

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[9] A story from the Morkinskinna saga relates that the king Harald Hardada of Norway (1047-1066) minted coins that were 50% silver and these coins were refused by mercenaries who wanted to be paid in good silver (Williams 2007, 178-9). It is argued by Skaare (1976, 9-10) that the story preserves a genuinely early oral tradition, and from what is known about the coins of Sven Estridsen the coins in Denmark may have been equally debased during this period.

tion of the Islamic weight system in the 10th century based on 24 grams; the two weight systems were use in parallel from the 10th century at least until the late Viking Age (Kilger 2008a, 280).

Concerning silver, two groups of objects were standardized in this system: the ingot and the ring. The most common ingot type (type 1 after Wiechmann 1996, 65-7) are formed in an oblong bar shape usually with a d-shaped cross-section and rounded ends (**Figure 3.5**). They are adjusted to multiples of the øre unit (24-26 grams) and are frequently found at weights of 1, 2, 4, and 8 øre (Hårdh 2008, 107; Kruse 1988). They were cast in moulds of soapstone or clay, and more than a hundred examples of such moulds for the making of silver bar ingots were found at Hedeby and numerous examples can be found at Kaupang (Hårdh 2008, 104; Resi 1979). This type of bar ingot is concentrated in southern Scandinavia in the formerly Danish areas, but examples are commonly found on Gotland and there is a scattering in eastern Ireland (Hårdh 2008, 104; Wiechmann 1996, 620, Map 76).

Figure 3.5 *Cast silver bar ingot found while metal detecting at Hedeby (**Cat. 174**), (Photo: V. Hilberg).*

As mentioned in the previous chapter (**2.5.1**), the cast bar ingot is the base form from which many objects could be made. Some types of arm rings and neck rings could have been made from bar ingots, but all are typically adjusted to the øre weight standard (24-26 grams) which is a unit of the Scandinavian mark (ca. 200 g) and is associated with the Russian pound (ca. 400 g) (Hårdh 1996, 137).[10] There are various types of rings found with different distributions. Most notably, the twisted spiral rings form two groups; one probably originates in what is now Russia and the other is of Scandinavian, probably Danish manufacture. The so-called ‘Permian Spiral Ring’ (**Figure 3.6**) are large neck rings typically adjusted to units around 100, 200, 300, or 400 grams and finds are concentrated in Russia west of the Urals where more than 100 examples have been found (Hårdh 1996, 137-40; Hårdh 2007). The largest examples are found in Russia, but complete examples can be found on Gotland, Öland and in southern Jutland (Hårdh 2008, 108). There is a group of weight-adjusted spiral rings probably of Danish manufacture. They are smaller than their Russian counterparts weighing 50 or 100 grams, paralleling the silver bar ingots, which are most concentrated in Schleswig-Holstein (Hårdh 2008, 111). It is clear that ‘Permian’ spiral rings are datable to the 9th and the beginning of the 10th century, but fragments of rings and twisted rods can be found throughout the 10th century (Hårdh 1996, 140-1; Hårdh 2008, 111).

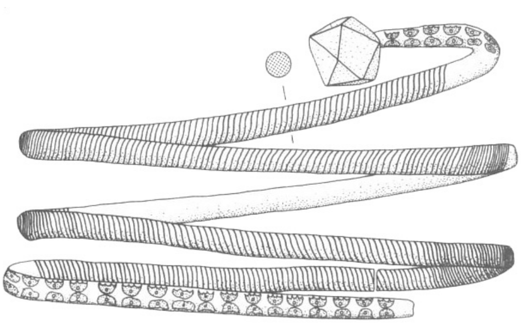

Figure 3.6 *Permian spiral ring from the Sylt hoard (Wiechmann 1996, 669, Plate 19, Cat. Nr. 41 A 1). Image not to scale.*

Some special evidence for weight-adjusted arm ring manufacture has been found in a workshop on the island of Gotland. Söderberg (2011, 25-6) likens the making of these rings as a form of minting because there is evidence for the control of purity via cupellation in the same workshop where casting moulds for arm rings were found. These arm rings often have distinguishing marks on them that are suggestive of hallmarking and may indicate a stamp of quality (Söderberg 2011, 25). We can therefore conclude that these rings were a form of money, though the boundary between utility as jewelry and valuation by its weight in silver may be diffuse.

Particularly in the eastern Baltic, the large weight-adjusted objects seem to indicate that trading was organized by relatively few people using large units of measurements (Hårdh 1996, 166, 179). Hårdh (2007, 144-6) later argues that the Permian type ring was standardized and executed with such high craftsmanship that it could be equaled to coinage, but states that the rings were not used as money and were not circulated in Russia or in Scandinavia. It is clear that the rings were not traded and circulated as a coin would be traded, but to say they were not a form of money seems erroneous and to state that they did not circulate is equally incorrect. How then did they get to Scandinavia if they were not traded? The fact that they fit into the weight system used in Scandinavia for the exchange of rings and ingots at least ideologically links them to the Aurar system of reckoning value.

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[10] An interesting question is whether the rings that were made from ingots have the same value as the ingot despite the labor of producing the ring.

One could ask how such a weight system was maintained. Both Hårdh (1996, 167) and Steuer (1987b, 490) argue that there may have been a supra-regional trade organization that directly controlled the weight standards, and this may have been formalized at the major trading centers of Scandinavia like Hedeby, Birka and Kaupang. It cannot be known if the standards developed simply as a trading convention or if there were political motives behind their development. In any case, these weight-adjusted objects of Scandinavian and Russian manufacture were certainly made at special locations from recycled silver, and probably a large portion of this silver originated as coins minted in the monetized regions of the Islamic and Christian world. The custom of making and trading with weight-adjusted rings and ingots may be partially responsible for the low quantity of coin finds from the 9th century in southern Scandinavia (Coupland 2007, XV 15–20; Kilger 2008a, 323-4).

3.4.2.2 Hacksilver

The weight-adjusted rings and ingots have functions comparable to the concept of money; however, hacksilver is not money. Hacksilver is a form of commodity-money, a pure exchange medium where the value is not manipulated but is solely a reflection of the value of the material from which silver objects were made (**Figure 3.7**). The origin of hacksilver use is a difficult research topic. Some of the oldest hacksilver hoards date from the early to mid 9th century[11] and have a strong presence of Carolingian silver; however, the hacksilver hoards with *terminus post quem* dates in the second half of the 9th tend to contain Islamic dirhams, some examples being the Westerklief II hoard (t.p.q. 871, Coupland 2011, 122) and the Rantum I hoard (t.p.q. 874, Wiechmann 1996, 425). In the 9th century Islamic dirhams begin to flow into the Baltic region via eastern trade routes; a discussion of the chronology and origin of dirham silver will be provided in the following chapter, but what is important to mention at this point is that the dirham finds in Scandinavia indicate a rapidly growing import of silver from the Islamic world between 850 and 950 AD, particularly in the last decade of the 9th century. With this growth in dirham import, a new weight system was introduced (see Gustin 1997, 164; Kilger 2008b, 241; Steuer 1987b; Steuer 2002, 137-140).

***Figure 3.7** Fragments of hacksilver found while metal detecting at Hedeby (Photos: V. Hilberg). Image not to scale.*

***Figure 3.8** Oblate-spheroid weights found at Hedeby (Maixer 2011, 184 Figure 209). Image not to scale.*

***Figure 3.9** Cubo-octahedral weight found at Hedeby (Photo: Landesmuseen Schloss Gottorf). Image not to scale.*

There seems to be a relationship between the use of hacksilver and the use of pseudo-Islamic oblate spheroid weights and the cubo-octahedral weights (**Figures 3.8** and **3.9**). There is evidence that the øre (ca. 24 g) was subdivided into units such as the ertog (ca. 8 g) and the half ertog (ca. 4 g) in the 9th century, and this can be seen in the lead weights from Kaupang (Pedersen 2008, 148). While the oblate spheroid weights seem to fit into the øre system, the cubo-octahedral weights generally fit into a system based on a unit of 0.35 grams and seem to represent a weight system based on the weight of a dirham between 3 and 3.5 grams (Pedersen 2008, 148; Sperber 1996, 55, 64; Steuer 1987b, 463, 477). Despite hints of two separate weight systems op-

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[11] Some of the earliest examples of hacksilver hoards are the Krinkberg hoard, ca. 800 AD (Hatz 1985, 125), and the Westerklief I hoard, ca. 850 AD (Coupland 2011, 120).

erating simultaneously at the end of the 9th century, the evidence is not simple to interpret; there are overlaps in the different types of weights and inconsistencies in the units that weaken the argument of two distinct closely controlled systems (Pedersen 2008, 137; Kilger 2008a, 312-5).

A number of factors link the normalized weight system with an eastern influence (Gustin 1997 and references; Steuer 2002, 137). The finely-tuned weight system for measuring small amounts of silver is seemingly based on the weight of a dirham. The form of the cubo-octahedral weights are mirrored in the terminal ends of the Permian spiral rings thought to originate in Russia (**Figure 3.10**) (Hårdh 2007, 140), and the oblate spheroid weights often have pseudo-Arabic inscriptions (Kilger 2008a, 307-9). Lastly, the dissemination of this weight system coincides with an increase in the scale of importation of Islamic silver into the Baltic area evidenced by the dirham finds.

*Figure 3.10 Permian spiral ring terminal end (**Cat. 176**), (Photo: V. Hilberg).*

As Kilger (2008a, 325) points out, the change from trading whole ‘Aurar’ objects to the hacksilver economy of the 10th century is in fact a revolution in the way silver was valued. The hacksilver economy broke the idea that value is based on objects that embodied individual units, but that value is determined by its relation to a unit of weight. The transition from objects valued as physical units to objects valued in association to a weight unit does not seem radical, but it denotes a change of who was in control of defining and determining value. The adoption of the hacksilver system was an economic reorganization, which may also represent a socio-political reorganization (see Kilger 2008a, 325).

The use of hacksilver in southern Scandinavia is dynamic and changes over the course of the 10th century. The Rantum I hoard (t.p.q. 874, Wiechmann 1996, 423-5) is an example of a mixed hoard with Aurar objects and hacksilver, whereas hoards of the mid- to late 10th century like the Waterneversdorf hoard (t.p.q. 976, Wiechmann 1996, 489-90) are highly fragmented consisting of hacked coin and jewelry pieces. Hårdh (1996, 84-9) explains that there is a general tendency for the increase in hacksilver fragmentation over the 10th century. The use of small pieces of silver, as small as a tenth of a gram, seem to indicate that silver was expensive, but it also means that a wider segment of the population had access to silver and that it was used in small everyday transactions (Hårdh, 1996, 24, 86; Kilger 2008a, 320-1).

Mentioned in **Section 3.3.3**, the development of commodity-money likely reflects a situation where trading partners did not know each other, or trust one another, and, therefore, it is no surprise that the tradition of pecking by the Viking expands at the end of the 9th century (Moesgaard 2011, 297). Although there is relatively little evidence of pecking in the Baltic region in the first half of the 10th century (Moesgaard 2011), it must be pointed out that the process of cutting or breaking the silver is in itself a method of testing or proving the silver purity. Pecking is only necessary if an object is not to be fragmented in the exchange. As the economy shifted into a monetized economy, the testing of silver declined. From the mid-10th century onwards, there is a gradual decline in the use of hacksilver and a growth in minting and the use of coins in southern Scandinavia (Hårdh 1996, 161). Hacksilver is gradually replaced by foreign coins, and eventually by coins of local manufacture.

3.4.2.3 The Relationship of the Methods of Payment

Kilger (2011, 265) writes that, “Researchers have normally interpreted the Viking-age bullion economy (Gewichtsgeldwirtschaft) and the coin-based economy as representing two different currency systems.” Two difficulties in the study of the Viking silver economy are the ease to which objects slide between theoretical categories and that there is not a standard terminology for discussing monetization and forms of exchange. Coins can fit perfectly into the bullion economy as long as they are of standard quality. Coins become something distinct when they are tied to an official, socially accepted unit of value that is not solely dependent on its weight or material; or in short, when they functioned as money. Thus, the process of monetization is a construction of social relationships whether it is a relationship between the state and the governed or a relationship among equals.

Both the development of the Aurar system and the indigenous Scandinavian coinage are forms of monetization and denote a separation of units of value, its social value from the commodity value. The hacksilver system can be defined simply as the exchange of commodity-money. The difference between the Aurar system and minting coinage is the size of the unit, and reflect two different types of user. Hacksilver economy of the 10th century denotes a period of economic transition: it represents the breakdown of the former system of trade where few had access to silver and, through the reorganization of the economy, opened the way for the expansion of coin use by the wider population in the 11th century.

3.5 Closing

At Hedeby all three systems were used: coinage, ring money / ingots, and hacksilver. Ingot moulds provided evidence that weight adjusted ingots were probably produced there. Many of the early Scandinavian coinages are thought to originate there. Hacksilver was traded, and the oblate-spheroid weights for weighing hacksilver were made there. It is apparent that the merchants and rulers of Hedeby were readily able to adapt to the wider changes to the economy, if they were not already instigators and initiators of these innovations.

Hedeby was a settlement designed to make profit through craft production and control over the access to trade goods. As a hub of long-distance trade, materials and products were brought from much of the known world. Goods varying from the most expensive commodities like gold, cloth, and slaves to mundane materials like lead could be found and traded there. The income brought by the control of access to these materials and products was certainly of paramount importance to the kings and rulers of Hedeby. Though precious metals are only one aspect of the economy, the finding of silver and gold is one of the most significant indicators of economic and political power. Silver as a medium of exchange is deeply intertwined with the politics of money making, just as Hedeby itself.

4. Chapter
Silver Mining and the Trade of Silver in the Early Medieval Period

4.1 Introduction

The last two chapters dealt with questions concerning how silver was produced in the early medieval period and how silver could have been used. Now it is time to look more closely at the sources of silver in the Viking Age and how the silver came to Scandinavia, and more specifically, to Hedeby. In order to investigate these questions, background knowledge is required concerning the locations, chronologies, and scales of production of silver mining regions and the minting of coins. It can be argued that most of the silver produced in the Viking Age was produced in coin-using regions of the world. Some mines went through boom phases where they produced silver in quantities for export; some seem to have been exploited for centuries based on archaeological and historical evidence, yet other mines remain unstudied and await investigation.

There are four strands of evidence for silver production: 1. Archaeological traces of mining, 2. Historical accounts, 3. The large-scale exportation of silver coinage and bullion, and 4. The elemental and isotopic characterization of silver artifacts, ore deposits, and production remains.

Care must be taken in all instances because each has its limitations and problems. The archaeological evidence is never complete; the historical accounts are few and incomplete and may not accurately represent physical reality. It is rational to assume that when there is a large export of silver from one region to another, it reflects a surplus due to active mining in that region, but this relationship is not always direct. The fourth strand of evidence for mining, the archaeometric approach, employs methods of material science to identify distinguishing elemental and isotopic characteristics that can be used to relate metal objects to each other and potential sources; this will be the focus of **Chapter 5**.

The aim of the present chapter is to discuss the archaeological, historical, and numismatic evidence of mining and how this relates to the long-distance trade of silver in the Viking Age. The archaeometric approach must have a foundation firmly based in the realm of archaeological and historical possibility, and this chapter presents the archaeological and historical basis for early medieval mining and silver export and is a further development of the research questions at the core of this thesis.

4.2 Survey of Mining Regions

It can be argued that the traditions of mining in the medieval period have their roots in the Roman and Sassanian mining traditions. In the literature, Roman mining operations are often described as well organized and large-scale as we know from the silver mines in Huelva or Cartagena in Spain (Anguilano 2012, 11-7; Jones 1974, 115) and the Balkans (Merkel 2007), or for example, the copper mines of Faynan (Mattingly 2011), but there was also small-scale production in many parts of the Roman world (see Matschke 2002, 115). Many changes occurred following the collapse of the Roman administrative structure, and it is thought that these changes greatly affected the way mining was structured. As Edmondson (1989) discusses, in many of the former Roman territories mining did not cease after the fall of Rome, it changed forms in the absence of powerful central authorities to an increase in smaller scale operations. An amount of organization and protection is required for the operation of large mining districts, but also there must be a strong demand for the metal and an infrastructure for distribution. Some argue that a collapse of extractive metallurgy occurred after the fall of Rome brought about an economy based on recycling and scavenging Roman objects into the medieval period (see Fleming 2012 for examples from medieval Britain).

Mining technologies did not notably change between the late Roman and the early medieval period, which makes the chronological transition difficult to study. If we exclude the few large Roman mining districts, it is hard to quantify a difference in the small-scale mining of the late Roman and early medieval periods. There is an obvious and justifiable tendency to focus attention on the large-scale mining areas because of their economic importance and their visibility in the archaeological/historical record. Small-scale and defuse mining operations are typically less studied and less mentioned. It is possible that many go unnoticed or unstudied, and, in all cases, mining traces could have been destroyed through more recent workings. It is difficult to see to which extent this bias on the large-scale mining operations influences our understanding of the history of mining and the continuity of mining between the Roman and early medieval period.

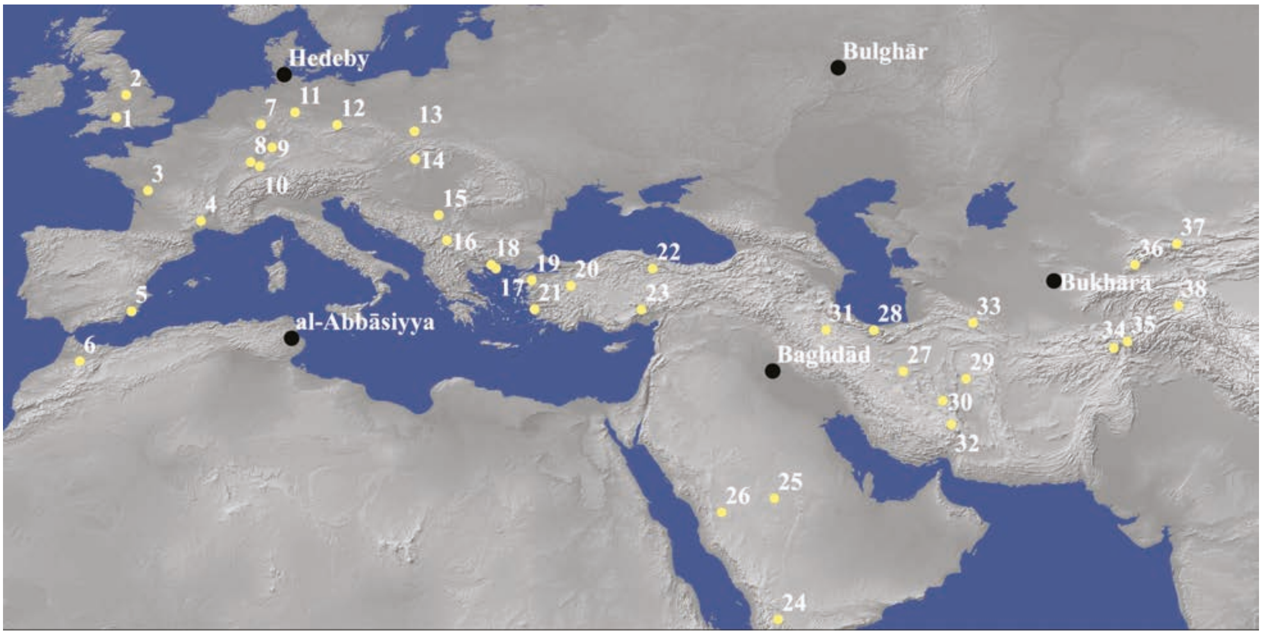

Figure 4.1 *Map showing a selection of mints (black circles) and mining regions mentioned in the text: 1. Mendips, 2. Derbyshire, 3. Melle, 4. Mont-Lozère/Cevenne, 5. Tudmir/Mazarrón, 6. Unspecified Moroccan mines near Fes (Fornin 1990, 73, Fig.1), 7. Sauerland/Siegerland/Bergisches Land, 8. Sainte Marie-aux-Mine, 9. Wiesloch, 10. Breisgau, 11. Harz, 12. Erzgebirge, 13. Tarnowskie Góry, 14. Banská Štiavnica, 15. Kosmaj, 16. Ulpiana, 17. Thasos, 18. Pangaion, 19. Karaaydin/Kalkım, 20. Gümüşköy/ Kütahya, 21. Söke/Gümüş-Dağ, 22. Gümüş/Amasya, 23. Gümüşköy/Bolkardağ, 24. al-Radrād/Jabali, 25. Shaman/Najd (location not certain), 26. Mahd al-Dhahab, 27. Nakhlak, 28. Duna, 29. Seh Changi/Naybānd, 30. Chubanan/Tars, 31. Anguran/Zanjan, 32. Jīroft/Kirmān, 33. Tūs/Nishāpūr, 34. Farinjal, 35. Panjihīr, 36. Shāsh-Īlāq, 37.Talas Valley, 38. Bazardara/Pamir.*

Not only did the Romans take control of active mines in the lands that they occupied, the Roman prospectors probably sought traces of older mining and reopened mines with origins in the distant past,[1] and the same may be applicable to the miners of later periods. The mines of the Romans were often revisited and mining resumed in the medieval and modern eras.[2] Therefore, a good start for the search for medieval mines requires background knowledge of Roman and earlier mining. Additionally, ‘new’ mining areas were opened as changes in the political/economic structure and technological advancements allowed ore deposits that were previously considered unprofitable, or only of regional significance, to become lucrative and important on a supra-regional scale.

The survey of mining areas presented as part of this study is by no means exhaustive. There is great variability in the historical and economic importance of mining areas and the amount of information available on each specific mining area. The mining areas known to be important for the export of silver during the period of focus (9th-11th centuries AD) will be given special emphasis, but there will be an attempt to balance this bias with a well-rounded discussion of other, smaller, or regionally important mining areas (**Figure 4.1**). Much work is still needed to fill the gaps in the archaeological record, and it is good to reiterate, as is often repeated in archaeology, that a lack of evidence is not necessarily evidence of absence.

4.2.1 Mining in the Islamic West, in Eastern Europe and in Western Asia

4.2.1.1 Lead and Silver Mining in Morocco and Spain

In the 8th century AD there appears to have been a mining boom in North Africa that supplied the silver for the dirhams of al-’Abbāsiyya (Kairouan, Tunisia) and Ifriquiya (Tudgha, Morocco). During the reign of the Abbasid governor Yazid bin-Hatim (771-787 AD) dirhams were produced on such a scale that they were exported to the eastern Mediterranean and further exported to Scandinavia via Russia (Fomin 1990). There is historical and numismatic evidence that silver was mined around Sijilmasa, Fes, and Tahert in northern Morocco at the end of the 8th century (Fomin 1990, 72-4). During the course of the 9th century AD, it appears that silver ceased

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[1] An example for this is the state of the lead industry in Britain shortly after the Roman invasion. Within six years of occupation inscribed lead ingots indicate that lead was being produced for export (Tylecote 1986, 61). This means that either the Romans inherited a pre-existing industry (Nriagu 1983, 105), or that they knew exactly what to look for with their prospections. Another example from Britain is the mine of Engine Vein at Alderley Edge in Cheshire where there is evidence of small workings during the Roman period next to traces of early Bronze-age mining and mining of the 17th and 18th centuries (Timberlake/King 2005; Timberlake/Kidd 2005, 92-3).

[2] See Groer (2008, 14) on Agricola’s description of reworking of ancient spoil and slag heaps. For an archaeological example for medieval reworking of Roman mines see Körlin (2010, 106-9).

to be used in North Africa in favor of gold-based currency (Blanchard 2001, 527; Fomin 1990, 74).

Spain in the 9th and 10th centuries AD was part of the Umayyad Caliphate, and was autonomous from the eastern Abbasid Caliphate. Although Spain was a well-known producer of silver in the Phoenician and Roman periods, by the medieval period there is little physical evidence that this mining was sustained. This may be due to the lack of archaeological research in the Islamic period. Ibn Hauqal (Ouseley 1800, 27) mentions some mining areas in Andalusia where gold and silver were found, but unfortunately he is not specific which deposits produced which metals, nor their locations.[3]

The numismatic evidence during the early medieval period shows that the supply of silver in Spain was unstable. A peak of silver minting occurred around 853 AD with a decline and collapse in the end of the 9th century. This collapse in minting lasted approximately 50 years until large scale minting resumed in the decade of 940-950 AD (Noonan 2000, 256-9). Blanchard (2001, 527) does not paint such a dreary picture of the silver production in medieval Spain, stating that the old Roman mines reopened such as Tudmir (Carthagena / Mazarrón) and that other deposits near Cordova were exploited. At the exact moment when Noonan describes a cessation of dirham minting in Spain and a silver shortage, Blanchard describes a surplus of silver between the years 850 and 950 AD, enough to export to the neighboring Frankish Empire. This is contradictory and problematic; it is symptomatic of the lack of research on mining and the economy of early medieval Spain.

4.2.1.2 Silver Mining in the Balkans

The Slavic lands of southeast Europe formed a border region between the Frankish and Byzantine spheres of political influence. The expansion of the Frankish Empire under Charlemagne brought the Franks into direct contact with Byzantium in Dalmatia, in modern-day Croatia (Budak 2008, 231). Evidence of the mining of lead and silver in the regions of Serbia, Kosovo, and Croatia during the Roman period is significant and widespread (Gassmann et al. 2011; Merkel 2007; Nriagu 1983, 141-6; Škego 1998), and it is thought that mining in this region was of special importance to the early Byzantine state (Matschke 2002, 116). There are sporadic accounts of medieval silver mines in this region, for example in the hypogene lead-silver deposit of the lower Drina valley (Škego 1998, 46), which appears to be a continuation of the Roman workings (Škego 1998, 92-3). The Roman lead-silver mines in the area of Kosmaj in Serbia were of an exceptionally large scale and were reworked in the medieval period (Bogosavljević/Vuković 1993, 421; Merkel 2007). Near the Roman city of Ulpiana in modern-day Kosovo, there are substantial mining traces of polymetallic ore containing silver-bearing fahlore from both the Roman and medieval periods (Gassmann et al. 2011). Several Serbian medieval silver mines are known, dating to the high medieval period (Bogosavljević/Vuković 1993), but dating of archaeological sites based on the first mention in medieval texts is problematic. Mining may have well been undertaken in earlier periods, and without archaeological surveys, their chronologies are impossible to reconstruct. These details would be best acquired in a regional study looking closely at the continuation of Roman mining into the medieval period. Such a study is needed to evaluate the importance for this silver supply to the economies of the Carolingian and the Byzantine Empires.

4.2.1.3 Lead and Silver Mining in Anatolia and Greece

The mining of silver and lead in Anatolia is ancient, perhaps with origins in the Neolithic (Meier 1995, 112-3). Many lead-silver deposits were mined in the Roman period, which are not only mentioned in historical texts, but are also evidenced by archaeological mining traces and metallurgical remains (Meier 1995, 112-24). There are no texts indicating the continuation of Byzantine silver mining in Anatolia after the 7th century AD (Bryer 1982, 140). There are several mines with archaeological evidence of Byzantine period extraction, such as Karaaydin (near Kalkım) and Gümüşköy (near Kütahya), and there is indirect evidence of Byzantine production at Söke (Gümüş-Dağ). Smelting of lead-silver ore was identified at Isik Dağ (80 km north of Ankara) dating from the 8th to the 10th century (Meier 1995, 116-7). The rich lead-zinc-silver deposit of Gümüş (58 km northwest of Amasya) was worked for millennia, and radiocarbon and ceramic evidence support a medieval production phase (Meier 1995, 116). A survey in the Bolkardağ region has identified a number of silver mines, most of which were small workings, but indicate that mining was carried out in the region at least until the 8th century AD (Matschke 2002, 118; Yener/Toydemir 1992). In the Bolkardağ region, Gümüşköy is of particular importance because of the amount of slag found there (600,000 tons) and diagnostic artifacts and coins dating from the medieval period, which indicate a long continuity (Yener/Toydemir 1992, 158). There is some indication or speculation that a new silver source was found in Armenia in the 8th century AD, which caused tensions between the Byzantines and the Caliphate in this region (Spufford 1988, 39), and elsewhere in the southern Caucasus there have been mines of silver in the medieval period (Noonan 2001, 157), but these remain unexplored.

In Greece, there is some evidence that the silver mines of Laurion, famous for their importance in the Classical era (Conophagos 1980), were worked into the 5th and 6th centuries AD (Mussche 1998, 65), but there is little evidence that Laurion was worked on any signif-

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[3] It is not known if the place names following this statement refer to mining areas: near Cordova at a place named Koules, and there are two districts called Sarrah and Marsafa (Ouseley 1800, 27).

icant scale later on in the medieval period. On the Island of Thasos there was a long continuity of silver production based on argentiferous lead ores from prehistory through the Byzantine period (Hauptmann et al. 1988, 109; Matschke 2002, 118-9). In eastern Macedonia at the site of Pangaion, the mining of silver is attested with the final abandonment of mining operations between the 8th and 11th century AD (Unger 1987, 110). The ore exploited at Pangaion is sulfidic, consisting of galena, arsenopyrite, silver-bearing fahlore, and gold (Unger 1987, 98). There are numerous references to gold mining in Macedonia, Moesia, Thrace, and other provinces in the core of the Byzantine Empire (Matschke 2002, 116). Gold is typically found as an alloy with silver in various proportions, known as electrum. The technology for the metallurgical separation of gold and silver existed for more than a millennium, and therefore the production of gold could indicate silver production. But alas, this is dependent on the quantity of silver in the gold and whether it was economically viable to extract.

4.2.1.4 Lead, Silver, and Gold Mining in the Arabian Peninsula

Some of the silver mines in the Arabian Peninsula were connected to the Sasanians, who expanded and intensified mining activities in the 6th century (Morony 2004, 167,184). According to al-Hamdānī, the two most famous silver mines in Arabia and Yemen were worked by Persian miners. The mine of al-Radrād in Yemen was particularly productive although ruinous since 883 AD, and it was operated by Persian miners who arrived in the pre-Islamic, Umayyad, and Abbasid eras (**Figure 4.2**). The silver-copper mine of Shaman in Najd was described as less productive. The description of fire temples indicates the presence of Persian Zoroastrians. The Shaman mine was worked in the pre- and early Islamic times, but was abandoned by the time al-Hamdānī wrote his account in the 10th century (Dunlop 1957, 40).

Figure 4.2 *Medieval mine gallery from a lead-zinc-silver mine at al-Radrād (al-Jabali) in Yemen. (Photo: G. Steffens).*

A large number of gold-silver and polymetallic deposits of Saudi Arabia were mined in pre-Islamic, Umayyad, and Abbasid periods. A survey of mining areas with textual and/or archaeological evidence for early medieval activity is presented by Heck (1999). One of the most important is the gold-silver mine of Mahd al-Dhahab, which was exploited from the 1st millennium BC into the Abbasid period (Heck 1999, 381), but there were several other prominent silver and gold mines with exceptionally large outputs (Heck 1999, 378-9).

4.2.2 Silver Mines of Iran, Afghanistan, and Central Asia

4.2.2.1 Lead and Silver Mining in Iran

Iran is known for its rich lead-zinc-silver deposits as well as the antiquity of its extractive metallurgical tradition (Nriagu 1983, 158-63). Medieval accounts from the 10th century[4] describe silver mining regions within modern-day Iran, but they do not have the fame of those of medieval Transoxania and Afghanistan. There are mentions of ancient lead-silver mining in Kerman, Jibal and Fars areas, which are known as silver producing regions in recent history (Ladame 1945, 276-89 via Allan 1979, 14).

Ibn Hauqal, a 10th century Kurdish geographer, describes silver ore as being scarce in Persia and that there are silver mines in a region called Mānein, between Kerman and Iṣfahān (Ouseley 1800, 110, 134), which has been interpreted as the region of Aranak-Nakhlak (Wertime 1968, 929). The cerussite and galena of Nakhlak are argentiferous (Stöllner et al. 2004a, 82), and the mines were active during the Sassanian and early Islamic period (**Figure 4.3**). The fortress protecting the mining area contains Zoroastrian fire temples and argues for a pre-Islamic date, but although Zoroastrianism stems from the Sassanian period, its practice in regions of Iran is historically documented and goes well into the Abbasid era (9th-10th centuries AD) (Hallier 1972, 302). Archaeological evidence of the underground and alluvial mining of silver-bearing cerussite and galena and smelting has been attested at the site of Nakhlak, and this dates mostly from the first millennium AD (Stöllner 2004, 51; Stöllner et al. 2004a).

In the hills north of Tehrān there are the lead-zinc deposits of Duna and Elikah. Sassanian and early Islamic mining has been confirmed by radiocarbon dating and a datable oil lamp found in a mine (Stöllner 2004, 53). Other lead-zinc-silver mines dating from this period can be found in the area of Seh Changi near Nayband (Sīstān), Chubanan near Tars to the north of Kirmān, and Anguran to the west of Zanjan (Momenzadeh et al. 2004, 15, Figure 5; Stöllner 2004, 53). In the account

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[4] After al-Hamdānī (Dunlop 1957, 40-41; Toll 1968) and Ibn Hauqal (Ouseley 1800).

Figure 4.3 *Sassanian-early Islamic gallery at Nakhlak, Iran, with a vein of lead-zinc minerals (Photo: T. Stöllner).*

of Ibn Hauqal there is a further description of a mountainous area in Kirmān having silver mines located about 30 miles[5] (one Merhileh) from Jiroft (Ouseley 1800, 141, 144).[6]

The silver mines near Iṣfahān were abandoned prior to the 10th century and are thought to have been important in the 8th century (Allan 1979, 15 via Ibn Rusta, ca. 900 AD). In the 10th century AD, al-Hamdānī says that most of the silver mines were in Khurāsān mentioning Andarāba and Samarqand but also that Tūs and Nishāpūr had silver mines (Dunlop 1957, 41).[7] In general, it seems that the medieval mining in Iran is associated with the continuation of Sassanian silver production, and that the major medieval mining phase in most parts of Iran occurred before the 10th century AD. There is substantial evidence for medieval lead-silver production in Iran, but a systematic synthesis is lacking, and many more deposits could be explored for mining traces (see Momenzadeh et al. 2004, 15, Figure 5).

.2.2.2 Mining in Afghanistan: Panjhīr and Farinjal

The mining region of Panjhīr is near the town of Andarāba in northern Afghanistan and is thought to have been an important supplier of silver to the Abbasids and later Samanid Empire (Allan 1979, 14; Cowell/Lowick 1988; Noonan 2001, 153). Andarāba is located near the Khāwak Pass to the Panjhīr valley on the trade route that crosses the Hindu Kush south to Kābul and India. The lack of archaeological investigations produces confusion over the chronology and productivity of silver mining in the region. While Blanchard (2001, 246) argues for an early peak of production in the Panjhīr Valley in the pre-Islamic and again in the Abbasid period with the exhaustion of the deposits by the time of the Samanids, other authors, like Allan (1979, 13-14), Noonan (2001, 153), and Weisgerber (2004, 202-205), contend that silver production was strong in the 10th century AD based on several historical records. The 10th century geographies give accounts to the prosperity of the mining activities at Andarāba and Panjhīr. An account from the geographer Ibn Hauqal describes the large mining settlements of Panjhīr and Jārīāba and states, for instance, that the economy of Jārīāba was based solely on metal production and was entirely void of agriculture (Ouseley 1800, 225). Minting of silver coins was undertaken at Andarāba and Panjhīr from 872 to 1035 AD and 871 to 940 AD respectively, but it is also thought that silver was delivered to Balkh, the nearest major city, for minting from the Umayyad times onward (Allan 1979, 14).

The mining and metallurgical site of Farinjal, west of Chardeh in the Ghorband Valley in northern Afghanistan, was connected to the working of lead-bearing ore from the 3rd century BC to the 13th century AD (Nriagu 1983, 165). Among the industrial waste, litharge was found. Modern analyses of the galena show low silver concentrations and hence the litharge is interpreted as production waste from the smelting of oxidic ores and not from cupellation for silver recovery (Nriagu 1983, 165; Tylecote 1968a, 1-2; Weisgerber 2004, 200). It is problematic that the ore analyzed, forming the basis for this argument, is copper-free galena and does not match the ore type indicated by the analysis of the slag. The slag investigated was primarily fayalite, magnetic, and had inclusions of lead and copper phases (Tylecote 1968b), and this indicates that polymetallic ore was smelted. Although Tylecote does not think the production at Farinjal had anything to do with silver production, perhaps a closer look at the slag might reveal that argentiferous fahlores in addition to galena were smelted.

4.2.2.3 Silver Mines of Transoxania

Transoxania, in present-day Uzbekistan was the heartland of the Samanid Empire. The silver production of Samanid Central Asia is of primary importance in the export of silver over large expanses of the early medi-

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[5] Equals one Merhileh.

[6] There are no documented silver mines in the region around Jiroft (Momenzadeh et al. 2004, 15, Figure 5)

[7] Also probably polymetallic: compare to Ibn Hauqal who says the mountains of Tūs and Nīshāpūr have turquoise with no mention of silver (Ouseley 1800, 215).

eval world. The dirhams from Central Asia are commonly found in Scandinavia over the course of the 10th century AD (Kilger 2008b, 235-240). Of the Samanid mints al-Shāsh was the most productive followed by Samarqand (Kovalev 2003, 50), and both are located in Transoxania. These mints were likely supplied with silver coming from rich polymetallic deposits of the Tien Shan Mountain Range (see **Appendix I** with maps included). It is thought that the regions of Shāsh, Ferghāna and Talas came to be under direct control by the Samanids in the year 893 AD providing direct access to the important silver mining regions and minting of silver dirhams sharply increased (Koralev 2003, 61-2). In the 1960s and 1970s, Buryakov (1965; et al. 1973; 1974) has documented mining sites in Shāsh describing mines in Īlāq and a number of mines in the Chatkal valley; the mines of the Īlāq were primarily for polymetallic copper-lead-silver or gold ore, but the mines of the Chatkal valley are less well studied and may have supplied a diverse array of raw materials (Sverchkov 2009, 145-6).

There is a high concentration of medieval polymetallic silver mines in the Shāsh Īlāq, which is located in the Kurama Mountain Range and in the Ahangaran valley in Uzbekistan. Lashkerek, in the Īlāq region, is one of the largest documented medieval silver mines in Central Asia and was exploited between the 7th and 10th centuries AD. Approximately 9,000 tons of slag containing 20 percent lead has been found in near the mine, and according to geological research the ore deposit is classified as polymetallic with veins of native silver and primary sulfides such as fahlore (tetrahedrite), galena, sphalerite, chalcopyrite, and bornite (Buryakov 1965, 288; Eniosova/Mitoyan 2011, 583). The element bismuth seems to be associated with the galena[8] and increases in quantity with depth. During the 10th century the mine reached depths of approximately 300 m and it may have been abandoned technical reasons (Buryakov 1965, 283; Eniosova/Mitoyan 2011, 582). Despite the fact that it is the largest mine in Īlāq, it was one of no less than fourteen documented medieval silver mining areas located in the region (Buryakov 1974, 18-23, 110-1, 127).[9] Many of the medieval silver mines exploited polymetallic ores with varying amounts of gold, silver, and copper, and semi-precious stones like turquoise may have been found (Pruger 1971). Archaeological traces of mining begin in the 8th century AD over much of the Īlāq region, and the period of highest intensity was in the 9th to the12th century AD (Pruger 1971).

Mining in the area around Samarqand is less studied. The medieval mining of polymetallic ore (Au-Ag-Cu-Pb) has been attested in the Nuratau Mountains at the site of Sentjab, to the north of Samarqand, but research into the mining history of the Samarqand area in general is unsatisfactory (Sverchkov 2009, 155). In the Zeravshan River Valley in the upper Nignot drainage in the Hissar Mountains, there are ancient mines of silver-lead ores; the largest mine is called Koni-Nukra (Sverchkov 2009, 150).

4.2.2.4 The Pamir and Talas Regions

Both the Pamir and Talas regions were at the periphery of the Samanid Empire in present day Kazakhstan and Kyrgyzstan, but there is archaeological evidence of medieval silver production and they may have been supplying silver to Samanids (893-999 AD) and Karakhanids (992-1212 AD). Traces of mining, smelting, and medieval mining settlements have been found in the Pamir Mountains, in modern-day Tajikistan. The archaeological evidence points to a production peak in the 11th century AD and gradually took over for lost production in the Īlāq region (Blanchard 2001; Bubnova 2001). Several silver ore deposits in the eastern Pamir have been worked from the 9th to the 11th centuries AD at Sasyk[10] and at Bazar-Dara (Bazardara deposit), but mining in the western Pamir (Tokuzbulak deposit) seems to date slightly earlier (Bubnova 2001, 177-8). The geology of the silver-antimony ore district of the Pamir has been analyzed, and remains an important supplier of silver today (Pavlova/Borisenko 2009, 171-3).

In the upper courses of the Talas valley, there is evidence of a mining boom dating from the late 10th into the 11th century AD under the Karakhanids. This region was semi-autonomous, controlled by powerful Turkish rulers and may not have been a major supplier for the Samanids (Kovalev 2003, 62-3). This area has been researched by Bubnova (1963) and is summarized by Blanchard (2001, 229-70). The mines are described as being decentralized small-scale workings, and production in this region helped to fill the economic void of caused by the collapse of the silver industry in the Īlāq in the middle of the 10th century AD (Blanchard 2001, 245-7).

4.2.3 Silver and Lead Mining in Christian Western Europe

4.2.3.1 Melle and the Cevennes

The mines of Melle, in the region of Poitou-Charentes in Aquitaine, were perhaps the most important silver mines under the control of the Merovingian and later Carolingian emperors. Mining at Melle began before the end of the Roman Empire in the 5th century AD. A massive increase in the scale of production occurred in the last quarter of the 7th century AD, which may be closely associated with the switch to a silver-based coinage in the Merovingian Empire (Téreygeol 2007, 125;

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[8] This is probably not metallic bismuth, but bismuth replacing lead in galena or as bismuthinite.

[9] Buryakov (1974) mentions the names Kansai, Takel', Altyntopkana, Karatashkutan, Kanimansur (Kalmakyr), Kaandzhola, Aktashkan, Chokadambulak, Karatiub-Miskan, Almalyk, Saukbulak, Pangaza, and Gudas.

[10] May match with the Kaltatur ore cluster described by Pavlova and Borisenko (2009, 171, Figure 5).

2013, 82). The coinage of Melle and of Aquitaine (8th-10th centuries AD) are found over a broad geographic area from Spain to eastern Europe (Téreygeol 2007, 132), and a number of examples are known from Scandinavian contexts (Coupland 2011, 113).

The abandonment of the mine at the end of the 10th century AD and absence of subsequent reworking of the deposit has helped to preserve traces of medieval mining. Fire-setting was one of the major techniques for extracting the argentiferous galena from the mines and the process has left abundant remains of charcoal. This charcoal helps to reconstruct the chronology of mining through radiocarbon dating but also the evolution and degradation of the forest cover (Téreygeol 2013). This evidence supports the argument that mining was actively pursued between the last quarter of the 7th century AD until the end of the 9th century AD, and production declined in the 10th century AD in part because of the deterioration of the wood supply that made mining no longer economical (Téreygeol 2013).

Lead and polymetallic deposits in the south of France were mined in the pre-Roman and Roman periods. There is evidence for the mining and smelting of lead, copper, and silver between the 2nd century BC and the 1st century AD (Meier 1995, 64-6). Medieval mining of galena, possibly argentiferous, is attested by smelting sites in the Central Massif with radiocarbon dates ranging from the late 10th century AD to the 13th century AD (Baron et al. 2006), but there seems to be a concentration of the radiocarbon dates from the first half of the 12th century AD (Ploquin et al. 2003). Lead-rich slag was found at 70 sites in the Mont-Lozère region dating from this period (Baron et al. 2006, 241). They conclude from the lead isotope analysis of ore and slag from the region that galena from the mines of Montmirat and Les Bondons was the most likely ore smelted, although these mines are not the nearest to the slag heaps. It is thought that the ore was brought to the smelting sites because of the available wood supply or for political reasons (Baron et al. 2006, 250-1). The dating of the lead-silver production might indicate that this region took over as mining operations at Melle ceased at the end of the 10th century AD. Outside these regions, a number of Roman mines documented in France that exploited polymetallic or lead-silver deposits to various extents. Summaries are given by Nriagu (1983, 109-13) and Bode (2008, 83-7).

4.2.3.2 Silver Mining in England and Ireland

There is little physical evidence that silver was produced on the British Isles during the 9th and 10th centuries AD. There are records that come from later periods documenting silver production such as at the mines in Alston, Cumberland, which produced silver between 1100 and 1307 AD, and the bishop obtained the rights by the king to retain the silver for the mint of Durham (Tylecote 1986, 71). Bere Ferres / Bere Alston in Devon produced silver from during the 13th and 14th centuries AD (Claughton/Smart 2010) and is known for its argentiferous galena (Bevins 2010, 26).

There is much more evidence for lead production in Anglo-Saxon England. In the medieval period lead production was concentrated in Derbyshire and in Sommerset (Mendips) (Tylecote 1986, 70-1). There were several mines in Derbyshire, one of which is Wirksworth leased to an ealdorman by the Abbess of Repton in 835 AD (Tylecote 1986, 70). The Domesday Book (1086 AD) only identifies a few lead mines primarily in Derbyshire (Hill 1981, 111; Tylecote 1986, 70).[11] In the Roman period it is thought that the lead produced in Derbyshire had too little silver to extract, but lead from the Mendips and from Devon and Cornwall may have been more promising (Tylecote 1986, 69). Tylecote (1986, 54-5) indicates that large deposits of cerussite were exploited in the Mendips and the ore from this region can have higher quantities of silver than many of the other mining regions in England. Galena has typically low silver contents in England, but other types of ores could have been exploited. A fragment of cerussite ore[12] was discovered at a Roman Villa in southern Wales context containing 0.52% silver making it one of the richest archaeological silver ores found in United Kingdom (Craddock1995, 213-4; Tylecote 1964, 28; Tylecote 1986, 54).

As it is true with the Romans, silver probably was not produced from galena in Anglo-Saxon England. In addition to cerussite ore extracted by the Romans in the Mendips, argentiferous polymetallic ore possibly from Devon and Cornwall may have been smelted in the pre-Roman and Roman Iron Age (Tylecote 1986, 58-60), but there is no archaeological evidence for Anglo-Saxon silver production in Devon and Cornwall. At Alderley Edge, near Chester, there is a polymetallic ore deposit known to produce silver in early modern times (Williams et al. 2014), and there is evidence for small-scale Roman lead production and Bronze Age mining (Timberlake et al. 2014), but there is no direct evidence for Anglo-Saxon mining or production (Timberlake/Prag 2005).[13] In recent times, the mine of Herodsfoot in Cornwall has deposits of tetrahedrite that have been worked to produce silver.[14] Mines such as the Wheal Herland mine in western Cornwall first documented in 1717 AD had veins of native silver and other silver minerals associated with copper, lead, and antimony ore.[15] In Dorset at the site of Hengistbury Head smelting and cupellation debris was found dating to the Late Iron Age to

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[11] But care should be taken as the Domesday Book might only describe the properties that were not under direct ownership of the king.

[12] It is not known where this ore fragment came from - perhaps the Mendips, which are located across the Bristol Channel.

[13] There is a suspicion that the mint of Chester, which is near Alderley Edge, may have been supplied by nearby mines or silver mines in Wales, but there is little archaeological evidence to support this (Metcalf 1986, 143).

[14] http://www.herodsfoot-online.co.uk/History.htm accessed 18.07.2013.

[15] http://www.mindat.org/loc-950.html accessed 10.03.2014.

the early Roman period (Salter/Northover 1993). The finding of copper matte with lead and silver inclusions at Hengistbury Head indicates that polymetallic ore was smelted, and it is suggested that the argentiferous polymetallic ore came from deposits in southwest England (Salter/Northover 1993, 656).

Elsewhere on the British Isles, such as in Wales, Scotland and Ireland, there is also little evidence for silver production in the early medieval period. Evidence of early medieval lead production has been found in the Leadhills of southern Scotland, and in Cumbria dating from the 10th and 11th centuries AD (Pickin 2010). The lead-copper polymetallic deposit of Copa Hill in Wales contains minor amounts of silver and was worked in the Bronze Age (Bevins 2010, 21; Ixer/Budd 1998, 30), but there is no evidence of extraction in the early medieval period (Andrews 1994, 14). There are several lead-copper and lead-zinc deposits in the Central Wales Orefield, which have traces of silver and gold (Rust/Mason 1994; Ixer/Budd 1998, 30), but their role in the medieval period is not clear. Ross Island in Ireland has deposits of copper-lead-zinc-silver ore, which have been worked since the Bronze Age, and there appears to be evidence for early medieval metallurgy (Ixer/Budd 1998, 32). Although the copper matte found in copper slag dated to the 9th century AD contains amounts of silver, it remains unknown how much silver could have been produced at Ross Island or whether it was produced at all (Meyerdirks et al. 2004, 655, 662).

According to Tylecote, “Britain was mainly a silver importer at all times,” and he goes further to argue that the silver associated with Anglo-Saxon lead production cannot be compared with the substantial amounts produced by the Ottonian and Salians during the 10th and 11th centuries AD (Tylecote 1986, 70-1). The cerussite and polymetallic ore deposits of the southwest of England (Mendips, and those in Devon and Cornwall) may have supported silver production, but their importance in the Anglo-Saxon period is an area in need of consideration and further investigation.

4.2.4 Silver and Lead Mining in Central Europe

4.2.4.1 Silver Mining in the Rhenish Massif

The Rhenish Massif is host to a number of mineralizations containing lead, zinc, copper, and silver (see **Figure 4.4**). In the region spanning from Liege to Aachen, Trier, Cologne and Dortmund there are several mines dating from the Roman and earlier periods, but mining in the early medieval period has proved difficult to detect. Historical records indicate that silver mining was active in the Rhine area at least in the 12th century and later. Medieval documents from the 12th and 13th centuries mention mines at Mechernich near Aachen, Lüderich (east of Cologne), Altenberg in Siegerland (Bartels/Klappauf 2012, 169-74), and Bad Ems / Holzappel.[16]

Many ore deposits were worked by the Romans and mining either continued or was resumed in the medieval period under the governance of the Carolingian / Ottonian / Salian kings or the Archbishops of Cologne or Trier. There is evidence for mining at some localities in the Carolingian and Ottonian periods, but it is sporadic and often indirect. Unfortunately, there is yet to be a synthesis of the evidence of mining in this period. A comprehensive study of medieval mining in the Rhenish Massif is out of the scope of this thesis, but a few examples will be given.

Just to the east of Cologne there is a region called Bergisches Land where several ore deposits can be found. The lead-silver deposit of Lüderich has traces of the Roman mining and silver production (Bode 2008, 189-93; Körlin 2006). With the end of the Roman occupation, the mining industry collapsed but restarted in the medieval period. There are some hints that in the Carolingian period (9th century) mining and production of non-ferrous metals resumed (Gechter 2001, 41-2). Evidence[17] suggestive of early medieval extraction of polymetallic copper-lead-silver ore was found in the area of Gruben Anacker and Gruben Penny,[18] and this fits with the fact that the Archbishop of Cologne Dietrich I (1208-1212 / 1215) confirmed the toll privileges for the trade and production of metal in this region, privileges that were claimed to be rooted in the Carolingian period (Gechter 2001, 41-2).

In Sauerland, the mountainous region south of Dortmund, the counts from Werl / Arnsberg ruled the Ramsbeck area in the Carolingian and Ottonian periods (Strassburger 2006, 59-60). The nobility had their origins in Meschede, but transferred their center of rule to Werl in the first half of the 10th century, probably to gain economic advantages from the trade and production of salt where they built a fortress and founded a church in conjunction (Strassburger 2006, 59). Meschede remained an important hub for long-distance trade despite not being located along the Hellweg, a road connecting Paderborn, Soest, Dortmund and Essen to the Rhine at Duisburg. The importance of this settlement is verified by the giving of ecclesiastical, toll, and market privileges by Otto the Great in the year 958, and puts it on the same level as places like Corvey (Strassburger 2006, 75-6).

Meschede is about 15 km from the Ramsbeck mining area. There is evidence that medieval lead-copper-silver mining began at Ramsbeck in the 10th or 11th century AD, though the first historical mention of the mine is in the 14th century (Strassburger 2007, 182).

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[16] In 1158 AD, the mines of Bad Ems were mentioned in a text written by Emperor Frederick Barbarossa to the Archbishop of Trier to loan him the rights to the silver mines. http:/www.emser-bergbaumuseum.de/ accessed 11.03.2014.

[17] What this entails is not explicitly mentioned, nor how it was dated.

[18] In Bergisches Land, Rösrath and Neunkirchen-Seelscheid, respectively.

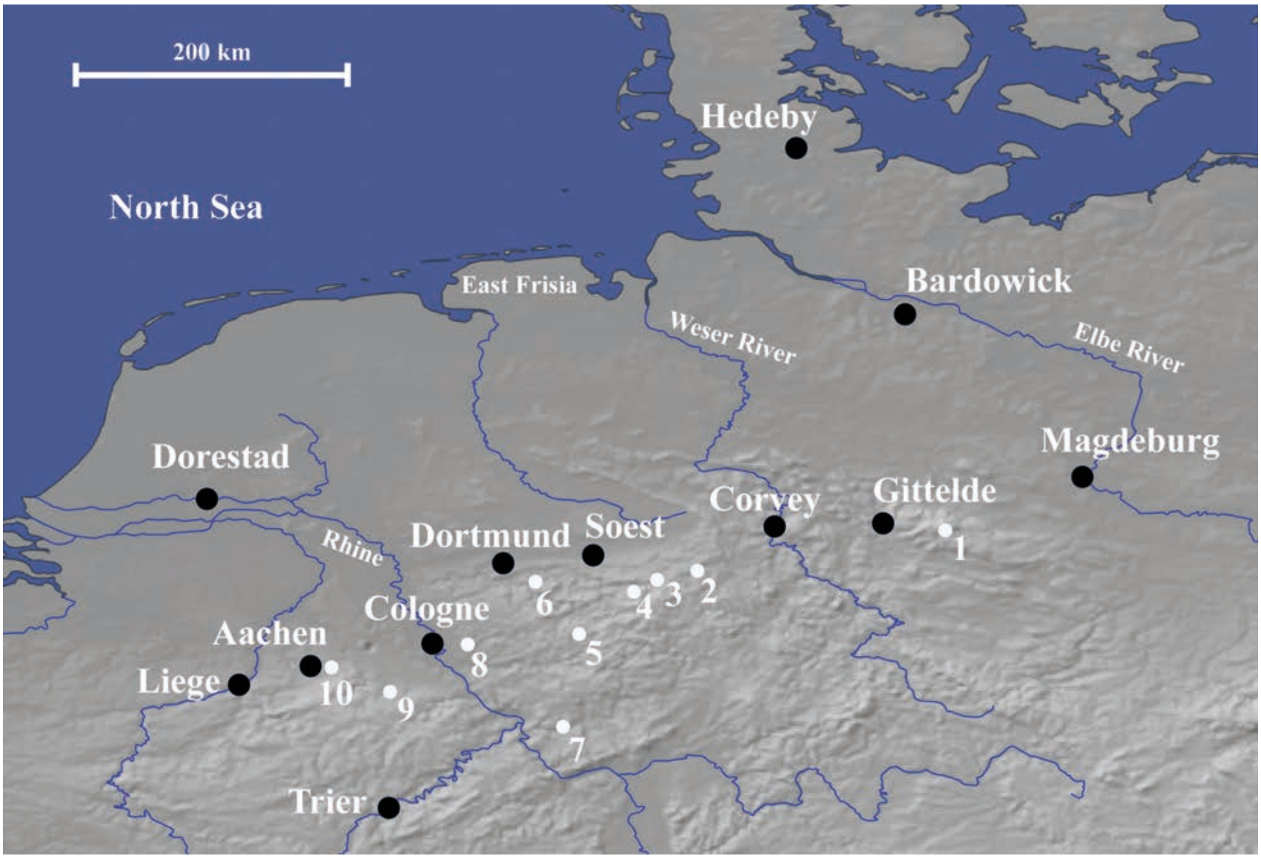

***Figure 4.4** Detail map showing Saxony, Lower Lotharingia and southern Denmark with selected trading and/or production centers (black) and mining areas mentioned in the text (white). Mining areas: 1. Harz Mountains (Cu-Fe-Pb-Zn-Ag), 2. Marsberg (Cu), 3. Brilon (Pb-Zn), 4. Ramsbeck (Pb-Zn-Cu-Ag-Fe), 5. Altenberg Siegerland (Pb-Zn-Cu-Ag), 6. Iserlohn (Pb-Zn), 7. Bad Ems/Holzappel (Pb-Zn-Cu-Ag), 8. Lüderich Bergisches Land (Pb-Zn-Cu-Ag), 9. Mechernich (Pb-Zn), 10. Aachen-Stolberg (Pb-Zn).*

A number of collapsed mineshafts have been found on the Bastenberg with evidence for 11th to 13th century occupation. Amounts of slag, evidence of iron smithing, and medieval pottery sherds were found in the area around the mines. Under the ceramics of the 12th and 13th centuries were Pingsdorfer jar sherds, and charcoal from the site date from the 11th to the 12th century.

Miners sought ore-bearing veins in the Venetianer Gallery at Ramsbeck in the medieval period. Within the mine itself, medieval ceramics were found nearby charcoal dating from the 10th to the 12th century.[19] In an excavated area above the Venetianer Gallery, another charcoal sample dates from the 10th to the 12th century (Strassburger 2007, 185-8). Silver, copper, and lead could have been produced from ore consisting mostly of sphalerite, galena, and chalcopyrite, but isolated deposits of silver-rich minerals and fahlore can also be found in the Ramsbeck area.[20] Traces of smelting can only be found in the form of black, glassy, lead slag which can be found near the Venetianer Gallery and in the slag heaps below the mines, but the heaps are unfortunately undated (Strassburger 2006, 69, 73).

There is substantial evidence for the wide-spread lead production during the Roman period like the North Eifel (Mechernich), Aachen (Stolberg), Sauerland (Brilon), Siegerland and Bergisches Land (Bode 2008, 52-79). Many of these deposits have galena with low silver contents, and were extracted primarily to obtain lead (Bode 2008, 144). Mining became important again in the medieval period. An example is given in the case of Brilon, which has indirect evidence of Roman period lead production (Bode 2008, 71-4), but, according to a document from 1103 AD, Brilon was supplying lead to the Monastery of Corvey and suggests mining was active in the 11th century or earlier (Jülich 2006, 56).

At this point, though not directly related to lead-silver production, the mining of calamine and the importance of brass production in the early medieval period must be mentioned. Brass, an alloy of copper and zinc, was made by heating calamine or zinc oxide with copper in crucibles, or furnaces, before the discovery of metallic zinc in the post-medieval period (Craddock et al. 1990). Significant lead-free calamine deposits can be found stretching from the Meuse valley (Liége) to Aachen and south into the Eifel. These deposits are of particularly high quality, and calamine extracted from these

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[19] The charcoal dating to 980 AD was from fire-setting remains in a medieval section of the mine that was cross-cut by more modern workings. The traces of medieval mining were found 200 meters underground, indicating that mining had been carried out for at least a century (Christoph Bartels pers. comm. 13.03.2014).

[20] Christoph Bartels pers. comm. 13.03.2014 and Thomas Kirnbauer pers. comm. 19.03.2013.

deposits likely formed the basis of a brass industry in the 10th century and perhaps earlier (Day 1998, 133-4). Additionally, in the area around Dortmund, in Westphalia, there is some indication that brass was being produced. In Soest (Plettenberg), Kückshausen, and in the medieval city of Dortmund, large amounts of crucibles were found and those tested contain high amounts of zinc and droplets of brass; the scale of production reflects a developed industry (Capelle 1974, 301; Krabath et al. 1999; Rehren et al. 1993; Sicherl 2011). The source of calamine for the brass production of Westphalia may have been regionally available (Krabath et al. 1999, 435); one such deposit is near Iserlohn, but, to date, no archaeological investigations have been performed in this mining area.[21]

4.2.4.2 Silver Mining in the Harz

There are hints that mining in the Harz Mountains occurred in the 3rd century AD, perhaps earlier (Klappauf 1989). Copper, lead, and silver were produced in the following centuries with an increase in production starting in the 9th century. This change is attributed to the organization brought by royal control of the resources first with the Carolingians, which continued under the Ottonians (Klappauf et al. 1990). The first historical mentions of silver mining comes from the History of the Saxons written by Widukind von Corvey in 968 stating that in the land of the Saxons veins of silver were opened (Steuer 2004, 133-4). Later, Thietmar of Merseburg in the early 11th century wrote that under the reign of Otto the Great (reigned 936-973 AD), the first silver mine was established in the land of the Saxons (Steuer 2004, 134). These accounts are undoubtedly referring to the mining activities in the Harz Mountains. As Steuer (2004, 134) and Asmus (2012, 115) explain, these accounts of silver mining in the Harz have often been associated with the Rammelsberg deposit, which is primarily a copper deposit, and recent research has shown that ore deposits of the Upper Harz and western Harz were probably more important for medieval silver production (Klappauf 2011; Klappauf et al. 2008).

The two major ore mineralizations in the Harz Mountains are the Rammelsberg, which is characterized by banded fine-grained intergrowth of pyrite, chalcopyrite, galena, sphalerite, and fahlore (tetrahedrite), and the Upper Harz (Oberharz), which is characterized by hydrothermal veins with large crystal growths of galena, sphalerite, pyrite, chalcopyrite and fahlore (Asmus 2012, 37-51). The two deposits formed under very different conditions and are of different geologic ages. The Rammelsberg deposit is older, stemming from the Carboniferous age during the formation of the Variscan orogeny. The vein deposits of the Upper Harz are notably younger and formed during the Triassic age (post-Variscan). Both types of deposits have silver, but the Upper Harz deposits are on average richer and can be better beneficiated, and also pockets and veins containing argentiferous tetrahedrite and high-grade silver ore can be found (Asmus 2012, 47-50; Stedingk 2012).

Archaeological evidence in the Upper Harz indicates that copper, lead, and silver were being produced already in the 9th century (Alper 2003, 19–25, 353). The sharp increase of silver mining in the 10th century may have been a result of the combined efforts of church and state. The Ottonian emperors and the ecclesiastic administration in Magdeburg may have played important roles in the expansion of silver production in the Harz region, for example the development of places like Gittelde and Badenhausen at the foot of the Harz. The historical connection between Gittelde and Magdeburg began in 953 AD with a document indicating that Otto the Great gave the royal property of Gittelde to Magdeburg's Mauritius Monastery (Reissner 1988, 48). Between 965 and 968 the Archbishop of Magdeburg, in addition to having gained minting privileges, gained control of Gittelde, which is near to the silver production site of Badenhausen (Alper 2003, 22–23; Mehl 2011, 30; Reissner 1988, 48). In the settlement of Badenhausen, smelting and cupellation remains were found dating to the 9th or 10th century (Brockner et al. 1989; Klappauf 1993, 254). Although, the silver production associated with the Upper Harz was perhaps of highest economic significance, the Rammelsberg was also mined and was an important supplier of copper, lead, and silver, and smelting sites for Rammelsberg copper ore can be found in a number of locations in the Harz region (see Klappauf/Linke 2004; Reissner 1988, 65-7).

4.2.4.3 The Upper Rhine Valley and Neighboring Regions

In the vicinity of Wiesloch, south of Heidelberg, a number of mines, ore-beneficiation sites, and smelting sites have been discovered dating to the 9th and 10th century AD (Hildebrandt 1993). The Mississippi-Valley-Type lead-zinc-silver deposit of Wiesloch was exploited by the Romans, and it is thought that the medieval production is connected to the monastery of Lorsch (Kötz et al. 2009, 165; Hildebrandt 1993, 256). In the past it was thought that the medieval production focused on the extraction of lead and zinc sulfides (Hildebrandt 1993, 255), but more recent research indicates that the oxidized lead-zinc deposits containing calamine were probably more important for silver production (Kötz et al. 2009, 171; Ströbele et al. 2010, 221), and, additionally, calamine could have also been used to make brass. Investigation of the galena has shown that they are typically silver-poor and could not have been the basis for silver production in the medieval period; instead a notable silver content is found in the sphalerite and other zinc minerals, which can be as high as 5000 ppm (Kötz et al. 2009, 168).[22] At Wiesloch fayalite slags containing

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[21] Christoph Bartels, pers.comm. 13.03.2014.

[22] Although this is described as the first instance that such silver-bearing sphalerite has been discovered worldwide, a

high amounts of zinc have been found and are thought to have been produced during the smelting of argentiferous calamine and galena (Ströbele et al. 2010).

In the Black Forest region, a document from Konrad II from 1028 AD mentions the silver mines south of Freiburg, giving the mines and the mineral deposit to the bishop's church in Basel. There is evidence of Roman production of lead and silver in this region, such as at Sulzburg, and mining was resumed in the Carolingian period (Steuer 1993, 76). Archaeological evidence for production is in the form of mining remains and radiocarbon dates ranging from the 10th to the 12th centuries AD (Steuer 1993, 79). In the Vosges in the east of France, the silver mines of Sainte-Marie-aux-Mines were first mentioned in a document from Emperor Otto III in 984 AD to the Bishop of Toul (Zotz 1993, 194), but despite its long history of production (Téreygeol 2013, 83), archaeological research on this site is only recently beginning to be published (Gauthier et al. 2015).

4.2.4.4 *Eastern Central Europe*

The Saxonian Erzgebirge, or Ore Mountains, is famous for its rich silver deposits, which were mined in the High and Late Middle Ages. The first historical mentions of silver ore at Freiberg date to around the year 1168 AD (Herrmann 1953, 13; Schwabenicky 2011, 29) and started an era of intensive colonization in the region, a colonization that is intertwined with the development of mining laws (Asrih 2013). Archaeology in the Erzgebirge region seems to confirm that large scale silver mining did not occur before the 12th century: prior to the mid-12th century the region was connected by roads assumed to be used for the purposes of interregional trade, and settlements found in the lower reaches of the mountains may have used the forests as a source of wood. It was not until the second half of the 12th century that rapid economic and industrial development can be seen (Kenzler 2009; Kenzler 2012, 42-3). Archaeological evidence for silver metallurgy is attested in the Erzgebirge in the 13th and 14th centuries AD (Eckstein et al. 1994).

In the Łosień - Strzemieszyce region of Poland there is archaeometallurgical and environmental evidence for lead smelting in the second half of the 11th century AD. Lead-silver ore can be found in the area of Tarnowskie Góry, and there is historical documentation of silver production near Bytom dating from 1136 AD (Boroń/Roszmus 2015, 94; Rozmus et al. 2014, 204-5). The Łosień - Strzemieszyce region is known for their lead glazed ceramics which were exported to many parts of Poland (Rozmus et al. 2014, 207), and the access to lead might have been directly tied to the production of lead and silver. A number of large kilns were found in this region for processing lead and / or lead ore (Boroń/Roszmus 2014), and although archaeologists maintain that silver was at the center of production, it is difficult to prove if the metallurgical finds are truly connected with silver metallurgy and not simply lead smelting. Cupellation hearths or the detailed analysis of the mines, ore fragments, and slag would help to confirm that silver could have been produced. Archaeological research focused on understanding the development and scale of lead and silver industry in Upper Silesia and Lesser Poland in the High Middle Ages is just in the early stages.

Mining of silver in Slovakian Erzgebirge may have begun in the Early Middle Ages. In the High Middle Ages the ore deposits in the region of Banská Štiavnica were particularly important, possibly making up 50 percent of all metal produced in Hungary (Zámora et al. 2008, 17). Silver mining in this region may have had its roots in the 10th century AD due to an account in the Nestor Chronicles written in 969 AD. Following the translation of Cross and Sherbowitz-Wetzor (1953, 86):

> *I do not care to remain in Kiev, but should prefer to live in Pereyaslavets on the Danube, since that is the centre of my realm, where all riches are concentrated; gold, silks, wine, and various fruits from Greece, silver and horses from Hungary and Bohemia, and from Rus' furs, wax, honey, and slaves.*

Both lead-silver and gold-silver ore can be found in the Banská Štiavnica. Records from around 1930 describe the gold-silver ores as being 5-8 grams per ton gold and 60-90 grams per ton silver and the base metal ores consisting of 3-5% lead, 3.5-6.5% zinc, 0.5% copper, 0.2-1 gram per ton gold and 30-70 grams per ton silver (Zámora et al. 2008, 157). Based on the analyses of the ore of Banská Štiavnica, silver with a significant gold content (ca. 1 percent) may have been produced in the Middle Ages, and the historical account suggests that silver was produced in quantities large enough for export, at least in Danube-Dnieper river systems.

4.2.5 Closing

With the use of historical documents and archaeological surveys of mining areas it is possible to make a rudimentary, if not crude, reconstruction of mining in the medieval period. The fragmentary nature of the evidence, such as the loss of mining areas to more recent mining, the recycling or reworking of slag and tailings, and the limited amount of archaeological investigations and historical accounts, gives only a coarse resolution to the history of mining in the early medieval period. It remains difficult, if not impossible, to quantify the

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similar example is described at Jabali Pb-Zn-Ag deposit, in Yemen, by al-Ganad (1991, 133-4, Table 9; al-Ganad et al. 1994, 44, 50). In the Jabali ore deposit, the silver content of the hypogene ore is correlated to the sphalerite with contents up to 3900 ppm and there is no relationship with the galena, which has much less silver. Despite this, the medieval miners of Jabali probably exploited the much richer oxidized ore where acanthite and native silver could be found, and the silver-bearing sphalerite possibly played little role in the medieval silver production.

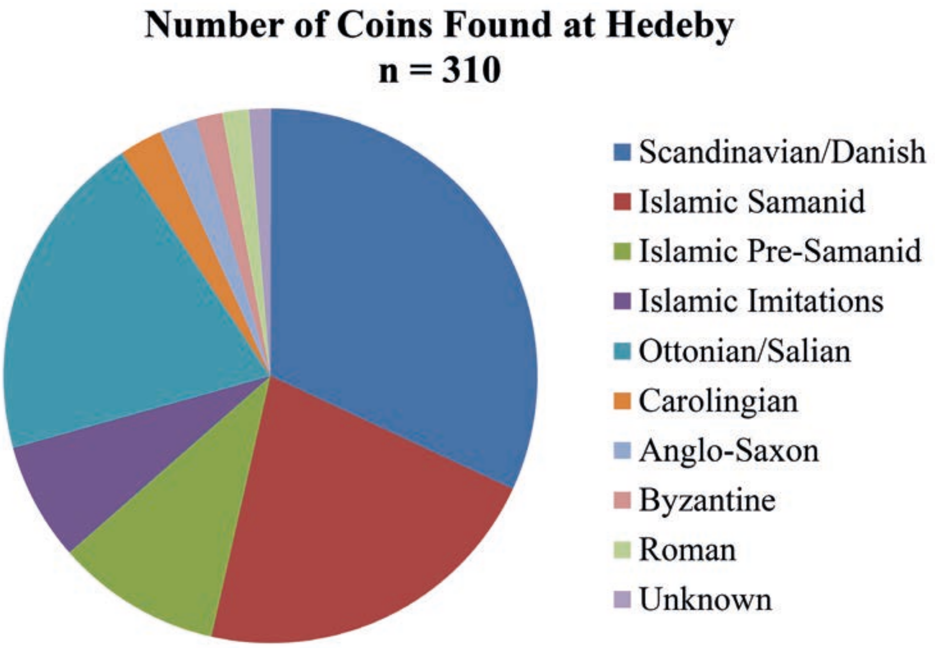

***Figure 4.5** Numbers of coins and coin fragments found at Hedeby by region/type (Hilberg 2011; Wiechmann 2007; and unpublished coin finds identified by L. Ilisch, V. Hilberg and J.C. Moesgaard). The pre-Samanid group consists of dirhams from the Umayyad, Abbasid, and Saffarid dynasties. The Islamic imitations consist of Khazar and Volga-Bulghar coins, but also include tin-lead imitations possibly made in Scandinavia (Wiechmann 2007, 199-200).*

amounts of metals produced and the chronology of exploitation based on historical records and mining archaeology. Slag heaps, shafts, and galleries might give an idea of scale of production, but, unless carefully dated and combined with extensive excavations and surveys, cannot inform about the chronology or duration of mining, and archaeological evidence can easily disappear.

4.3 Coins, Trade Routes, and Chronology

Other strands of evidence can help to strengthen our understanding of mining and its economic and cultural impact; one example is through the identification of surpluses, the export of metals. The reconstruction of trade routes in pre/protohistory and the movement of material culture are at the foundation of archaeological research and can be best achieved through the analysis of archaeological find material. In the case of medieval silver, the study of numismatics is an important methodological approach to look at surplus and trade, and, to a limited extent, it can give an impression of the scale of production and its chronology.

Patterson (1972, 151) gives a rough estimate of the 'half-life' of a coinage in the Roman-medieval period as being between a quarter-century to a century, depending on how active the exchange was. Silver in circulation gradually disappears, and without an influx of new silver resources, the minting of silver coinage would quickly collapse. It logically follows that to maintain a level of minting, fresh supplies of metal must be available to the same level as the rate of coinage loss. Growth in minting must mean an increase in metal production or an increased access, but minting based solely on the recycling of old metal in the absence of new supplies can only lead to a shrinking in minting, debasement, or weight cuts. This theory may seem simplistic, but, in practice, the combination of medieval numismatic history and the study of mines can help to identify the chronology of production phases and gives some indication of scale.

The silver used in Viking-age Scandinavia likely arrived in the form of silver coinage imported from the East and West (Coupland 2007, XV 16). The production and distribution of coinage is dependent on the scale and chronology of primary silver production, along with political, economic, and cultural factors. Primarily focusing on the major silver exporters of the Viking Age, the chronology of minting will be discussed in conjunction with the evidence of silver production to develop a better understanding of the silver supply. The coin finds from Hedeby (**Figure 4.5**) provide a physical basis to begin the discussion of coin importation at the site. The most commonly found coins, besides those of Scandinavian manufacture, come from the Islamic world and from Central Europe, and these major silver exporters

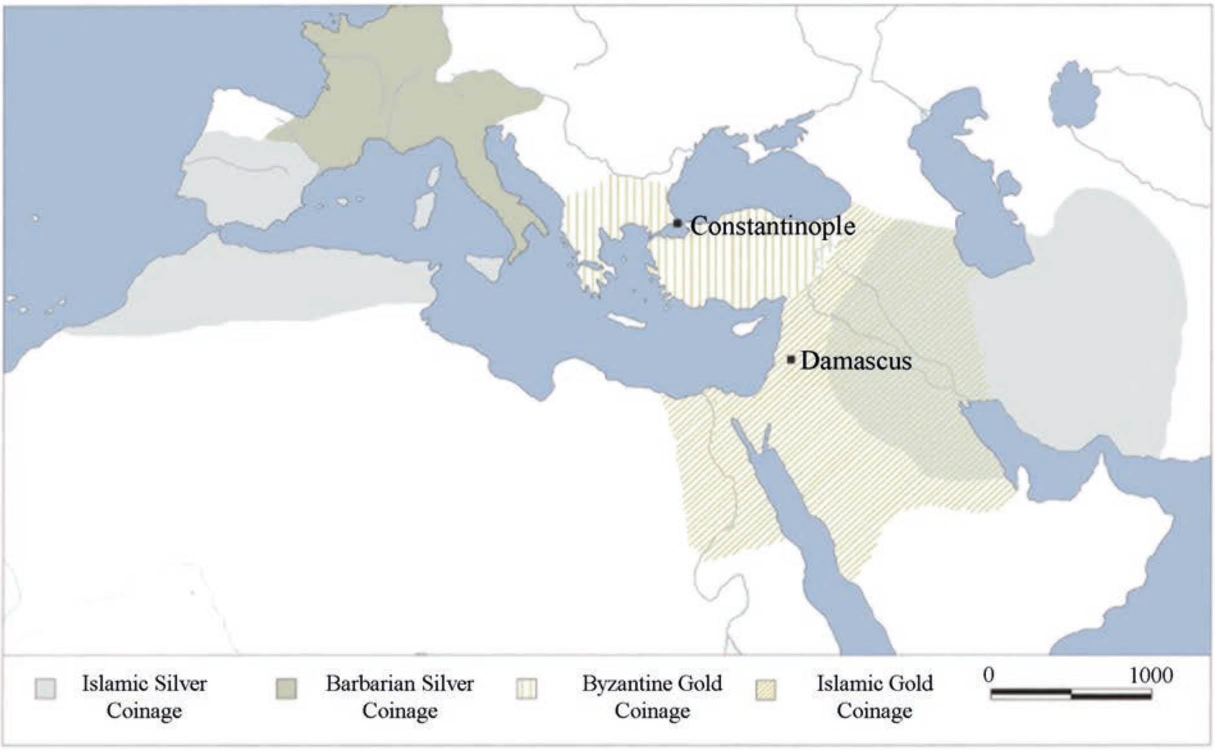

Figure 4.6 *Map of regions using gold or silver coinage, c. 700 AD. (Redrawn from map of E. Naumann in Kilger 2008a, 304 Figure 8.17, based on Spufford 1988, Map 3).*

will be the central focus of the following study on silver coin production and circulation.

4.3.1 Medieval Silver Circulation prior to the 10th Century

There are some important points to discuss before examining the focus period of the 9th through the 11th century. The traditions of the Romans, Byzantines, Sassanians, and early Islam influenced the way precious metals were used and how they circulated. The use of silver and gold as metals for coinage has a complex history; to begin with, one implicit, yet concrete and tangible factor to consider is that the use of a monetary system based on gold or silver is dependent on the availability of these metals. Naturally, if there was no way to obtain the metals through direct control of ore deposits or through trade, then there could have been no coinage based in these metals.

The traditional use of silver for the coinage of the Sassanians is probably due to the availability of local silver resources, and this tradition of silver use continued in the early Islamic period in the eastern part of the Caliphate (see **4.2.1.4** and **4.2.2.1**).[23] In many lands, coinages of silver and gold were coexistent, but there seems to be one metal that is more preferred. Under the reign of Harun ar-Rashid, this division was documented: Iran, Khurāsān, and North Africa paid taxes in silver and the lands of Arabia, the Levant, and Syria paid in gold (Fomin 1990, 71). In the Byzantine Empire, gold had always been the preferred metal for coinage, but silver coins were also sporadically produced. The Merovingians turned to a silver standard at the end of the 7th century AD as the gold reserves dwindled due to insufficient production or to an unfavorable trade balance with the eastern Mediterranean (Spufford 1988, 18-9). The map (**Figure 4.6**) gives an impression of the division of gold and silver currencies in the 8th century AD. The map illustrates that already in the 8th century AD there were two major spheres of silver coinage circulation: one in the east and one in the west. The two spheres are divided by the region of the eastern Mediterranean, but as we shall see, this was not necessarily a barrier to the trade of silver.

4.3.1.1 Circulation of Silver in the 9th Century: The Carolingians

At the start of the 9th century, three territories produced silver in quantities to export: the Carolingian West, North Africa, and the eastern lands of the Caliphate. In the west, the Carolingians were using silver for their coinage, as were the Frisians and Anglo-Saxons. Beginning in the 8th century, commerce in Lotharingia and

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[23] The coins of Central Asia were tied to the Sasanian drachm until the early 9th century. Finds of Abbasid-issued drachms are associated with the fortress of Samarqand, Afrasiab (Noonan 1980, 435).

Frisia was rapidly developing. The port town of Dorestad on the lower Rhine controlled trade and benefitted from the movement of merchants and their goods, and not only grew into one of the most important commercial centers of the Carolingian Empire, but was perhaps its most prolific mint (Spufford 1988, 28-30). The supply of silver for the coinage of Dorestad is not known, but it is suspected that the source is in the Frankish Empire, the most well-known being the Carolingian mine of Melle (Spufford 1988, 32). The circulation of silver deniers in the 8th century in the Frankish Empire seemed primarily to reflect use on a local scale, as opposed to long-distance trade (Spufford 1988, 33), but in the first half of the 9th century there is an increase in coin-use and commerce most concentrated in the regions of Frisia, Lotharingia, and the Frankish heartland (Spufford 1988, 48). The intensive increase in trade activities, and probably also mining, resulted in an economic boom in the Carolingian Empire in the 820s and 830s (Coupland 2010b, 302).

Close connections to the Carolingians via the Frisian trading network can be seen at Hedeby through the evidence of trade goods and the material culture (Hilberg 2009, 91-2; Steuer 1987a, 134-72, 183-97). Gravimetrically and stylistically, the early coinage from Hedeby, the Malmer KG3, is related to that of Carolingian Dorestad. It is evident that the economy of 9th century Hedeby was influenced by the Carolingians, but did the silver from the Carolingians reach Scandinavia to any significant scale? It is curious how rare finds of Carolingian coins and other Carolingian silver objects are in southern Scandinavia in the 9th century AD (Coupland 2007, XV 11-14; Garipzanov 2008; Wiechmann 1996, 80–1). Except for a few hoards and stray finds from settlements, very few examples exist. Half of the Carolingian silver objects found in Denmark were refashioned into new object types, nearly all were found in contexts dating to the 10th century or later, and it seems that Carolingian silver of the 9th century was perceived and used differently compared to other types of silver (Baastrup 2013). The problem is the same for 9th century Anglo-Saxon coinage, which is remarkably rare at Hedeby and elsewhere in Schleswig-Holstein (Hatz 1983, 208; Hilberg 2011, 206-7; Wiechmann 1996, 87-8; Wiechmann 2007, 205-15). There are some parallels between the 9th century coinage of Anglo-Saxons and the Carolingians; the debasement of the coinages roughly falls in line (Blackburn 1993, 44) and the fact that both used fresh brass in the debasement may not only reflect a level of economic interdependence, but might indicate that similar sources of metal were involved (see Metcalf/Northover 1989, 120).

There are three theories of why there are so few Carolingian and Anglo-Saxon coins found in Denmark in the 9th century AD: that Carolingian silver was re-exported back to western Europe (Metcalf 1981, 81), Carolingian silver was melted down to make the ingots and rings that commonly found in Viking hoards (Coupland 2007, XV 14-7), or that Carolingian silver was not imported to Scandinavia on any significant scale (Sawyer 1990, 285). In truth, all are possibilities and do not exclude, nor entirely contradict the other, but each possibility has wide-reaching repercussions on our understanding of the Viking-age economy.

4.3.1.2 Circulation of Silver in the 9th Century: The Eastern Route

In the early 9th century, silver dirhams began trickling into Scandinavia in increasing numbers (Kilger 2008b, 213). A pathway was opened, which accessed the Black and Caspian Seas via the Russian river systems. The rivers Dnieper, Don, and the Volga became major arteries of trade connecting the Baltic with the economies of Byzantium and the Islamic world.[24] The Russian coin hoards of the early 9th century give the best look into what types of coins were being traded and where they were minted (Noonan 1980). The earliest trade seems to originate in the Caucasus, and the coin hoards indicate that the silver traded reflected what was circulating in the Caucasus region at that time (Noonan 1980, 413) and consisted of old out-of-date coin types from the Sassanians[25] and the Umayyads mixed with current coins from the Abbasids. On a note of interest, North African coins from the late 8th century are often found in the hoards of the early 9th century in the Caucasus and in Iraq (Heidemann 2011; Noonan 1980, 415, 420-3). North African dirhams were slightly lighter than the dirhams in western Asia (Syria and Iraq), and together with the apparent surplus of silver from mining in North Africa, these dirhams penetrated the markets in the core of the Abbasid Empire (Heidemann 2011; Noonan 1980, 434). Although it might seem more rational to assume that the dirhams from North Africa came to Scandinavia via a sea route from the west, the archaeological evidence, and, chiefly, the finding of large quantities of North African dirhams together with Umayyad and Abbasid dirhams in Russia, points predominantly to an eastern route (Lieber 1981, 20; Kilger 2008b, 216-7, 221).

The beginning of dirham traffic through Russia was of a restricted nature, as opposed to diffuse *en masse* exportation (Kilger 2008b, 221). The island of Gotland appears to be one of the most important beneficiaries of the early silver trade, evidenced by a small number of hoards containing large proportions of North African dirhams found dating to the early 9th century AD (Kilger 2008b, 220-1). It perhaps took time for the silver to become dispersed in the Baltic Region, but this chronology is difficult to quantify. The excavations of Truso in

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[24] The origin of the trade route from upper Volga may be much older than the Viking period. Sassanian and Byzantine metal vessels and silverware have been found in high concentration in this region dating from the third to the sixth century (Grierson 1993, 143; Noonan 1981, 53).

[25] Sassanian drachm also circulated in Syria in the Abbasid period (Heidemann 2011, 454; Noonan 1980, 438).

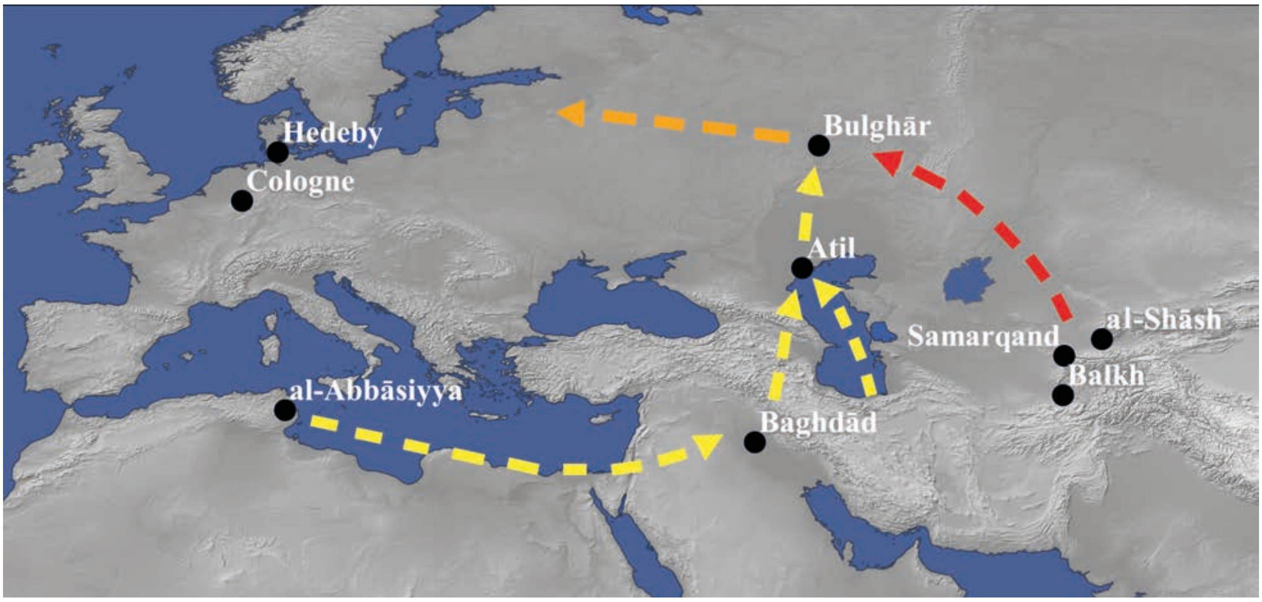

Figure 4.7 *Silver trade routes reconstructed from the scale of dirham hoards (Based on Spufford 1988, 66, Map 7). A switch in trade routes occurred around the turn of the 10th century from a route controlled by the Khazars (at Atil) to a route directly from Central Asia to Volga Bulgharia (at Bulghār).*

Poland expand upon what is known of this early importation of coins from the western Asia. Sasanian drachms as well as Umayyad dirhams were found (Bogucki 2010, 352-4) showing that Truso was probably connected to the silver trade in the early 9th century. At Hedeby, no Sasanian coins have been found, but there are three from hoards in Schleswig-Holstein (Wiechmann 1996, 76-7).

The silver trade gradually evolved over the course of the 9th century. A general growing trend can be seen in the access to Islamic silver in the Baltic, but this was fueled by periodic waves of dirham importation (Bogucki 2010, 355; Kilger 2008b, 232-5). The waves of dirham imports brought newly minted dirhams together with older dirhams, and these older dirhams do not necessarily reflect the date of the export but the peaks of minting in the Abbasid caliphate (Kilger 2008b, 222-33; Noonan 1986). In addition to the dirhams produced within the Abbasid caliphate, imitations of Abbasid dirhams were made in the Khazar kingdom, which is located in the region covering parts of modern-day Kazakhstan, Ukraine, Russia, and the Caucasus. There was a peak of Khazar coin production around 837 AD, and the coins are most often found in contemporary hoards in Russia, but it took a quarter of a century for them to reach their highest intensity in Scandinavia, though in relatively subdued numbers (Kilger 2008b, 224-5).

The source of silver for the minting of the Khazar dirham imitations may be from the recycling of dirhams of the Islamic world. It is suggested that the dirhams of North Africa were supplied by mines in Morocco, or perhaps southern Spain. The major mints of Iraq, such as Baghdād, Wāsiṭ, and al-Baṣra, are far from silver resources and must have imported silver. Allan (1979, 16) suggests that mines of Iran were suppliers, as they probably supplied the silver for the production of the Sassanian drachms. Other sources may have been in the Taurus Mountains, a contested border region between the Abbasid and Byzantine Empires in the 8th and 9th centuries AD (Kennedy 2006, 113-4), the Caucasus, the Arabian Peninsula, or the silver mines of Afghanistan or Central Asia. In the 9th century AD, there is a presence of the mints of Iran in the hoards of Scandinavia,[26] which may reflect coin production based on local silver resources. The mints of Jayy/Iṣfahān, Nīshāpūr, Kirmān, and al-Muhammadiyya[27] are all in regions that may have had active silver mining at this time. Al-Muhammadiyya, an especially prolific mint of the early Abbasid period (Kennedy 2006, 168; Noonan 1986, 140), is located near the mining areas like Duna and nearby Elikah in the Alborz Mountains north of modern-day Tehrān.

4.3.2 Circulation of Silver Coinage in the 10th and 11th Centuries

The late 9th and early 10th century brought about two major shifts of economic power: the rise of the Samanid Empire in Central Asia at the end of the 9th century and economic expansion of the Ottonian Empire in Central Europe in the second quarter of the 10th century. Both empires had access to rich silver deposits and aggressively pursued mining. During the 10th and 11th centuries thousands, if not millions, of silver dirhams from Central Asia and coins from mints in Germany and England poured into the Baltic. This section will discuss the

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[26] Examples are Spillings Hoard II (Waugh 2011, 168) and Rantum I (Wiechmann 1996, 425).

[27] Also known as Rayy, and is located near modern-day Tehrān.

minting of the Samanids, Ottonians, and Anglo-Saxons in relation to the trade routes in the east and west and how this impacted the flow of silver into the Viking world.

4.3.2.1 Changes to the Eastern Trade Route

Towards the end of the 9th century there were a number of changes to the trade routes in the east, which reflect the emerging economic power of the Samanids in Central Asia (**Figure 4.7**). There is an observable switch in the origins of the dirhams found in the hoards of the Baltic between the end of the 9th and beginning of the 10th century AD from primarily Abbasid dirhams from Iraq / Iran to Samanid dirhams produced in Central Asia and Afghanistan, and this switch is directly connected to the development of a new trade route (Noonan 2001, 147-51). Khazaria, the main avenue of dirham traffic in the 9th century, lost its central role at the end of the century; the causes for this development are not altogether certain, but the wars with the Byzantines and groups from the Russian steppes may have caused a financial drain or created economic instability in the region (Noonan 2001, 151-2). Another explanation is that silver production faltered in Iran and in the Abbasid Caliphate, but this needs to be proved. The new trade route went overland from Transoxania to Volga Bulgharia, bypassing the Khazar kingdom. Volga Bulgharia, already a power in the 9th century overtook the bulk of the trade as intermediary between the Rus merchants and the merchants of Central Asia (Noonan 2001, 152-8). This trade between the Volga Bulghars and the lands of northern Russia and the Baltic is thought to have been primarily based on the exchange of slaves and furs for the freshly mined silver of the Samanids and other trade goods like textiles and glass (Noonan 2001, 167-94).

Hundreds of thousands of Samanid dirhams have been found in northern Europe, which is a testament of the massive scale of the silver trade, but to keep a balanced perspective, Kovalev (2003, 47-8) states that even when considering global estimates in the millions, the yearly trade with northern Europe may have been less than 3 percent of the annual Samanid administrative budget. The millions / billions of dirhams produced in the Samanid heartland chiefly stem from two mints: al-Shāsh and Samarqand and the highest intensities of production were in the first two decades of the 10th century (Kovalev 2003, 54, 56-7). The Volga Bulghars produced coins imitating dirhams, like the Khazar, but whereas the Khazar imitations are mostly from the 9th century, the Volga-Bulghar imitations are from the 10th (Rispling 2004, 125; 2005, 175) and many examples are found in hoards around the Baltic (Kropotkin 1990, 198, Figure 1).

Samanid coin production and silver export are indisputably tied to the indigenous production of silver within the empire. The mines of Panjhīr and of the Īlāq are repeatedly mentioned in the literature and are specifically mentioned in historical accounts of the period (Kovalev 2003, 61, 65-6; Noonan 2001, 153-5; see **4.2.2.2-4.2.2.3**). The mint of al-Shāsh is often attributed to the administrative capital of the al-Shāsh province, Tashkent or Binket (see Ilisch et al. 2003, 62), but based on the account of Ibn Hauqal (Ouseley 1800, 267-8) the mint of al-Shāsh may be located at Deinket, which according to the location indicated in the account might be the city of Tunket, a major city and metallurgical center in the Īlāq (see Buryakov et al. 1973, 93). Ibn Hauqal's 10th century account states that in all of Transoxania there are no mints but at Samarqand and at Deinket (Ouseley 1800, 268); this is significant because evidence for silver metallurgy has been found at Tunket (Buryakov 1974, 50-53, also **Appendix I**). The mining in the Īlāq was vital to the silver supply of the Samanids, but the role of other deposits such as in the Pamir Mountains or at Panjhīr is less clear. They did not produce coinage in similar quantities as the mints of Transoxania, but the archaeological evidence and historical records indicate silver production from this period. These questions are important and are further investigated in the following chapter (**Chapter 5**) using archaeometry and archaeometallurgy and will be further discussed in **Chapter 7** and **Appendix I**.

The trade route connecting Samanid Central Asia to the Baltic Sea closed in the later 10th century AD (Lieber 1981, 24-6; Noonan 2001, 215-7). Debasement plagues the second half of the century (Steuer 2004, 132), and there is a general declining trend in the number of the Samanid coins produced over the course of the 10th century (Kovalev 2003).[28] The degeneration of the eastern silver trade in the second half of the 10th century AD coincides with the rise of minting and silver production in Central Europe.

4.3.2.2 Silver of the West: The Harz and Beyond

Until the beginning of the 10th century there is little evidence for minting in the Carolingian Empire east of the Rhine,[29] but this quickly changed over the course of the 10th century (Spufford 1988, 75). During the reign of Otto I (reigned 936-973), after a stagnation of minting in the Rhine Valley, mints were reopened, and a new mint in Magdeburg in Lower Saxony was opened, which is the supposed origin of the Sachsenpfennig (Kluge 2005, 11-5). The mint name was not inscribed on the coins, but they are widely thought to have been made in Magdeburg, a burgeoning market town and focal point of the Ottonians (Kluge 2005, 13-4). As described in section **4.2.4.2**, Magdeburg had a documented relationship with the Harz Mountains around the middle of the

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[28] Since these numbers are based on the coin finds in Scandinavia, the debasement of the coinage may also be responsible for the decline in number because they may not have been readily accepted as payment outside the Samanid Empire.

[29] There is historical evidence from Corvey, but there is no numismatic evidence for minting before Otto I. However, there is numismatic evidence for minting in Würzburg and Regensburg in Bavaria in the early 10th century (Kluge 1991, 23-7).

10th century, but Magdeburg was also a major trading settlement, which controlled a crucial east-west road and acted as an entry point into the Ottonian Empire from the Slavic lands to the east (Spufford 1988, 76). Magdeburg may have had a slave market (Henning 1992, 404), but also goods from the east may have been funneled through this point (Ludowici 2010, 336). It is believed that silver entered the Carolingian and Ottonian Empire through trade and tribute from the Slavs (Lübke 2008, 199), and in the 10th century AD this silver may have been the source of the early Sachsenpfennig thought to have been made there (Kluge 2005, 13). The first mention of minting in Magdeburg is in 942 AD with a letter from Otto I to the Mauritius Monastery that they can use the profits from minting, but, later on, towards the end of Otto's reign, there may have been two mints in Magdeburg, one for the Archbishop and one for the king (Kluge 2005, 14).

The Otto-Adelheid-pfennig is one of the most prominent coinages of the late 10th and early 11th century and is the foremost single German coin-type found in Scandinavia in the Viking Age with 12,000 coins found in the hoards of Sweden alone (Hatz 1974, 43). The precise dating of the first minting is not known, but it is thought that minting began in the years between 983-996 AD, during the transition period before the reign of Otto III, and more probably around the year 991 AD when Empress Adelheid became regent (Kluge 2005, 37-40). The last decade of the 10th century brought about an intensification of minting in the Harz region evidenced by the verification of minting rights by a number of settlements in this region and this coincides with the start of the Otto-Adelheid-pfennig (Kluge 1990, 170). The production of the Otto-Adelheid-pfennig is thought to be linked with the silver production in the Harz (Kluge 1990, 170; Kraume 1961, 3), but it seems that they did not originate from a single mint. There is no mention of the mint of Goslar before 1093 AD; instead, the seemingly parallel minting of several types of Otto-Adelheid-pfennig indicates that multiple mints may have been active, and mints such as at Gittelde, Seligenstadt/Osterwieck, Gandersheim, Harzgerode, Halberstadt, Quedlinburg, and Rottleberode all surround the Harz Mountains and are historically mentioned in the last decade of the 10th century AD (Kluge 1990, 170; contra Kraume 1961, 3). The mints of Gittelde, Seligenstadt/Osterwieck, and Harzgerode were specifically given the right to produce "moneta publica," a term normally associated with royal minting, and in this case the term is interpreted as the Otto-Adelheid-pfennig (Kluge 1990, 170).

The extent of mining in Central Europe at the beginning of the 10th century is poorly understood, but by the end of the century, some mines are documented historically and archaeologically. Most important, is the silver production of the Harz Mountains. Silver is thought to have been taken from the Harz to Cologne via the Hellweg, the major east-west route through the Ottonian Empire linking Magdeburg to the Rhine (Spufford 1988, 85); but, also in the later 10th century, silver may have also been produced in regions closer to the Rhine Valley. The mint of Cologne came to prominence and was one of the most prolific mints in the Ottonian Empire, and other mints in Lotharingia and along the Rhine were revived with new supplies of silver (Spufford 1988, 85). The minting under the Archbishop of Cologne around the year 1000 AD was large, with mint locations along the Rhine and in western Westphalia (Ilisch 2010, 290-1)[30]; and in the 11th century the Colonia pfennig was imitated by mints in Westphalia (Ilisch 2005a) and by Frisians (Ilisch 2007, 151-2). Of the German coins found in the silver hoards of Sweden, the number of coins of the Colonia type is second only to the Otto-Adelheid-pfennig (Hatz 1974, 43, 46).

The coin finds and hoards of Scandinavia indicate an impressive growth in the import of coins from Central Europe and Anglo-Saxon England at the end of the 10th century and into the 11th century (Steuer 2004, 136). The import of Anglo-Saxon and German coins was apparently connected, as there has yet to be a major hoard found in Scandinavia that only consists of one or the other, which indicates that the coins were mixed prior to arrival (Jonnson 1990, 142), although the List hoard in Schleswig-Holstein contradicts this statement (Wiechmann 1996, 276-306). Jonsson (1994, 206) later argues that the theory that the English coins found in Scandinavia came mostly from the export of the Danegeld is not as likely as the coins being used in trade. There also seems to be a relationship in the volume of minting in England under Æthelred II and in northern Germany under Otto III (Blackburn 1993, 44; Blackburn/Jonsson 1981, 154-7). Under the reign of Cnut (1017-1035 AD), ruler of England, Denmark, and Norway, the mint output declined (Jonsson 1994, 230). It is assumed, based on the number of coins found in the Swedish hoards, that the import of coinage from Germany to Scandinavia was about double the amount from England (Jonsson 1994, 215), and, in addition, the large-scale export of German silver coins occurs before that of England and ends a decade or so afterwards (Blackburn/Jonsson 1981, 154-7). These facts point to the conclusion that a common source, or sources, of silver were in use and that mines in Germany may have been the supplier, but this has yet to be proven conclusively.

The peak of export of Central European coinages to Scandinavia occurred in the first half of the 11th century (Hatz 1974, 50). The two rivers, the Rhine and the Elbe, were the major arteries that brought German silver in the form of coins (Colonia, Sachsen, and Otto-Adelheid-pfennig) to the north (Jonsson 1990, 142). It is unclear where the German coins mixed with the Anglo-Saxon coins, but this probably occurred in the trading centers in Frisia or in Scandinavia (Jonsson 1990, 142; Metcalf 2006, 366, 382-383). Whereas the Colonia and Otto-Adelheid-pfennig had important roles in the export market, beginning already in the 10th century there

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[30] Bonn and Soest are examples given.

was a growing trend for the German coinages to become regionalized with restricted areas of circulation (Blackburn 1993, 45). The production of the Otto-Adelheid-pfennig, the most important German coinage in the Viking-age hoards of Scandinavia, seems to end around 1050 AD or short thereafter (Hatz 1974, 43; Ilisch 2005b, 53; Rundberg 2000, 17). The use of the German pfennig in foreign trade declines in the second half of the 11th into the 12th century (Jonsson 1990, 143), or perhaps the trade of silver simply becomes more difficult to see. The development of national coinages in Denmark and Norway, and the growing strength of the monarchies to enforce their currencies, may have helped to eradicate traces of foreign coins through reminting.

4.4 Closing

The mining and export of silver are intimately connected. The archaeology and history of mining in combination with the study of numismatics help to reconstruct the production cycles of silver, trade routes, and the direction of trade in the Viking period. The Vikings, though not producing silver themselves, were able to acquire silver from a number of sources via long-distance trade routes. The coin finds from the hoards and settlements illustrate a picture of wide-ranging trade connections and economic resilience in spite of changing conditions.

While the coin finds of Scandinavia give substantial information about the scale and chronology of silver importation, there are limitations to the use of coinage in this way. The number of coin finds may be an indication of the amount of trade or the intensity of coin use, but silver is a material that is easily recycled, and the survival of coins may be just as heavily influenced by the recycling practices as any trading practice. Were types of silver or coins more prone to recycling than others? Is the absence of Carolingian coins in southern Scandinavia due to a lack of trade, or were the coins melted down by the Vikings to make ingots and jewelry? It has been suggested that rather than being the receivers of Carolingian silver, the Vikings were intermediaries charged with transferring Islamic silver to the Carolingians in the second half of the 9th century (Gustin 2004, 96; see Kilger 2008b, 230). The coinage of Anglo-Saxon England is thought to have relied on the silver sources of Continental Europe, but the physical evidence, the Carolingian and Ottonian coins, no longer exist in their original form. The coinages of Hedeby are examples of recycled silver. Where the objects no longer exist, but the material does, archaeometry may be applied to gain information stored. Elemental and isotopic differences and relationships in silver can be used to distinguish silver types and to group silver with potentially shared origins. **Chapter 5** builds upon the evidence of silver production and the chronology of coin production and trade, but with a focus on the archaeometric analysis of Viking-age silver.

5. Chapter
Archaeometry and Viking-Age Silver

5.1 Introduction

An introduction into the history of mining, minting, and the long-distance trade of silver in the Viking Age based on historical evidence and archaeological traces of metal production was provided in **Chapter 4**. Due to the incomplete nature of the historical/archaeological record and the limited extent to which mines and metallurgical sites have been investigated, there are a number of questions that remain elusive. The material science analysis of the silver itself can help to acquire missing information to bridge this gap of knowledge. A number of studies have been carried out to explore elemental differences in various types of Viking-age silver, but the use of lead isotope analysis has been rarely used to study silver of the 9th-11th centuries. **Chapter 5** will provide a survey of the application of material science analysis to explore archaeological questions concerning early medieval silver, and methods that have yet to be applied to Viking silver will be explored. In this context, the goal of this chapter is to develop the methodological framework and theoretical direction of the present analytical investigation of the silver from Hedeby.

5.2 Theory of the Material Science Analysis of Archaeological Silver

There are several reasons that archaeological metals are analyzed with methods of material science. Analysis for the application of the study of trade seeks to identify meaningful classifications composed of distinctive characteristics that enable metals from different sources, geographic areas, or cultures to be distinguished. Traditionally, elemental analysis has been used for this purpose in the field of medieval archaeology, but the analysis of the isotopes of lead, when aptly applied, is an additional tool towards this goal. As has been discussed in **Chapter 2**, the elemental and isotopic composition of silver is partially a product of the ore from which it came, but it is also a product of the extractive technology, the alloying and recycling processes, use practices, and the post-excavation treatment. All of these material and technological aspects influence the composition of the object and can consequently influence their interpretation. Additionally, the method of analysis also contributes to the interpretation and dictates the extent to which the data can be reliably used.

5.2.1 Elemental Analysis

Though the determination of the elemental composition of coinage has its roots in the 19th century (REHREN/PERNICKA 2008, 240), elemental analysis of medieval silver began for all intents and purposes in the 1960s and early 1970s (CHARLES/LEAKE 1972; FORBES/DALLADAY 1960; GORDUS 1972; KRAUME 1961; KRAUME/HATZ 1967; MCKERRELL/STEVENSON 1972; METCALF 1972). A wide variety of methods has been used to determine elemental compositions of silver objects ranging from non-destructive nuclear methods like neutron activation analysis (NAA) to X-ray techniques like X-ray fluorescence spectroscopy (XRF), energy dispersive spectroscopy (EDS), microprobe analysis (EPMA), and particle-induced X-ray emission (PIXE), but destructive sampling of silver coins for atomic absorption spectrophotometry (AAS) and inductively-coupled plasma mass spectrometry (ICP-MS) has also been performed. These different analytical methods exploit variations in electromagnetic properties, mass differences, and/or irradiation behavior of the elements to quantify the proportion of each element in a material.

A major divide exists between the non-destructive analytical methods that measure the surface of an object, and those methods, both destructive and non-destructive, that measure the bulk composition of the object interior. Because the surface of objects can be contaminated by corrosion, other metal objects, or the burial environment, and because surface cleaning and surface enrichment/depletion techniques can all influence the analytical results, these data must be handled with particular care. Some instruments are more precise and accurate than others, and the terms qualitative, semi-quantitative, and quantitative are used to describe the types of data produced. Each analytical method is different, and although much work is directed toward improving the comparablity of analytical results, there will always be dissimilarities between them. Even interlaboratory comparability between similar instruments is a potential issue. In all cases, the reliability of the data can only by assessed with the measurements of known standards materials, which are not always performed nor presented. For this reason, the direct numeral comparability of data sets should not be assumed. The direct comparability of data requires argumentation and evidence, but in the absence of proof, each data set must be assessed independently; however, data trends and correlations between data sets form an important basis for argumentation and the development of theories.

In the analysis of silver objects, the elements of silver and copper typically form the major and minor elemental constituents. The trace elements that completely or partially survive the cupellation process, namely gold and bismuth, are the most important elemental tracers of silver sources. Although there are instances when the elemental link between ore and metal are compromised by either recycling or alloying, momentarily speaking, gold and bismuth are the only elements that can be used to indicate silver sources with any degree of confidence (McKerrell/Stevenson 1972, 198; Pernicka/Bachmann 1983, 596) and are, therefore, the primary focus of most provenance studies of silver using elemental analysis. Other elements give important information such as zinc, tin, arsenic, and antimony, which reflect the copper alloy used to harden the silver or may come from contamination with other metals during recycling. These elements in quantities above 0.1 percent likely do not reflect the source of the metal, but rather give information about the copper alloy used and the technological traditions of alloying and recycling.

5.2.2 Lead Isotope Analysis

Not mentioned above, lead is another element that survives the cupellation process in minor or trace amounts, but unlike bismuth, its concentration in medieval silver is rarely distinctive enough to provide information about the source; however, the isotopic composition of the lead can be distinctive and has been successfully used in provenance studies, The isotopes of lead can be measured by mass spectrometry, which utilizes the differences in mass among the isotopes to measure the relative abundances of each isotope producing isotope ratios. Thermal ionization mass spectrometry (TIMS) was the most used method in the 1980s and 1990s, but the use of the multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) overtook TIMS in popularity due to the simplification of sample preparation procedures and to its high analytical accuracy and precision (Niederschlag et al. 2003, 64-5). The isotopes of lead are ideally suited for provenance studies because the isotopes do not fractionate during metallurgical processes (Gale/Stos-Gale 2000, 525-528). This means that the silver produced from the smelting and cupellation of lead-bearing ore will have lead isotope ratios that reflect the ore used (Brill/Shields 1972, 279; Stos-Gale/Gale 2009, 198-201).

The isotopes of lead provide another dimension to the study of provenance. They are able to relate information about the geologic age of ore formation based on the radioactive decay of uranium and thorium and about the geologic origin of the lead due to differing abundances of uranium and thorium at different levels of the earths crust (Albarède et al. 2012; Chiaradia et al. 2006, 416-419; Zartman/Doe 1981). They are a product of the geologic processes surrounding the formation of an ore deposit, and although they can at times be distinctive, ore deposits can form in different parts of the world that have similar geologic ages and form from similar types of crustal or mantle reservoirs creating overlap of isotope signatures (Brill/Shields 1972, 280; Gale/Stos-Gale 2000). Because of the problem of overlap, the use of lead isotope analysis can only be used confidently to exclude deposits from which the lead could not have originated.

Naturally, the more factors and variables involved, the more complex the task of provenancing artifacts becomes. It must be emphasized that the isotopes of lead only give information about the lead in the silver, and mixing, alloying and refining may all impact the lead isotope composition. The small amount of lead in the silver may have become mixed during recycling (Gale/Stos-Gale 2000, 531-533; Stos-Gale 2001) or may reflect an altogether different source if the silver was refined through the cupellation process or if complex silver ore was smelted with imported lead (see **2.3.2**). In **Figure 5.1** the two important recycling practices are shown with their effect on the lead isotope ratio of the silver product. The fact that cupellation can completely alter the lead isotope ratio of the silver means that lead isotope analysis alone is not a firm basis for the provenancing of silver. Even if it could be proven that the type of lead contained in a silver object is isotopically distinct, the source of the silver itself cannot be substantiated without the support of other forms of evidence. Other variables must also be considered, such as the gold and bismuth content and trace elements that may indicate alloying or mixing. Lastly, the archaeological and historical evidence for silver production and trade must be taken into account; no provenance study of silver can be undertaken without consideration of the archaeological realm of possibility. Together, elemental analysis and lead isotope analysis, used with the support of archaeological/historical evidence, can produce a positive confirmation of provenance (see Baron et al. 2014), but like all archaeological interpretations, the degree of certainty is only as strong as the strength of the evidence.

5.3 Themes of Archaeometric Research Regarding Early Medieval Silver

One of the first questions that comes to mind concerning Viking silver is its source or sources. Since silver can change form, available silver objects can be transformed into locally-made products. Where did the Vikings

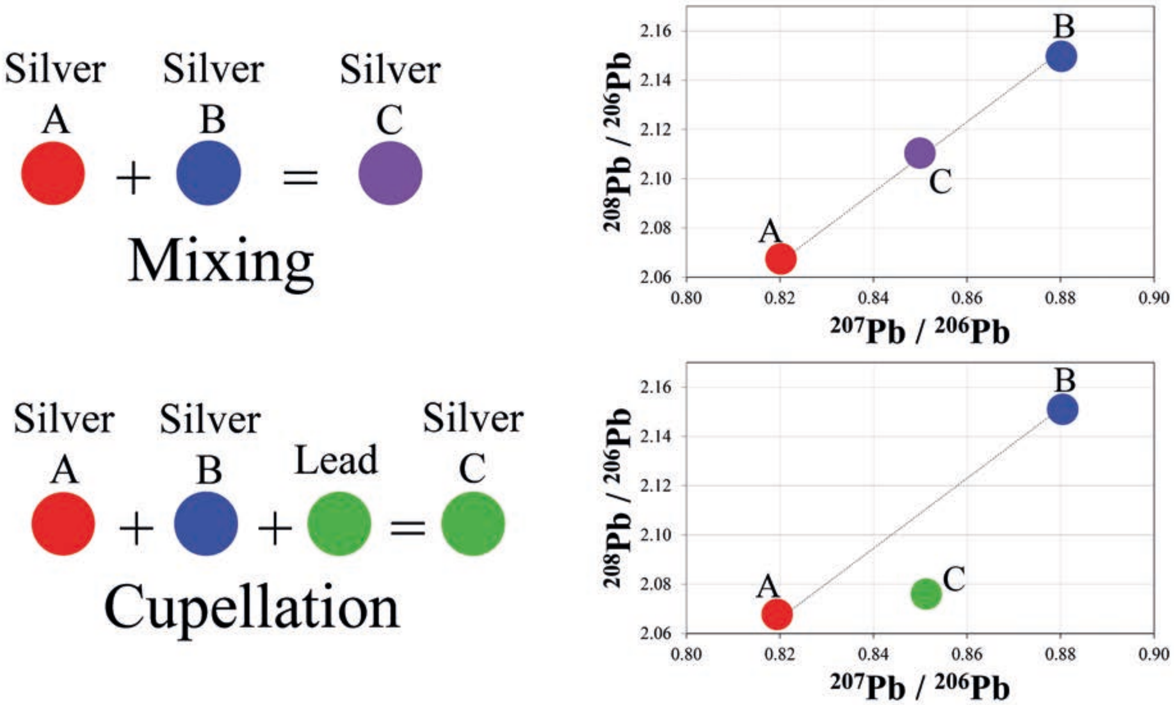

Figure 5.1 *This figure theoretically models the relationship of two recycling methods and the lead isotope ratio of the outcome. Mixing of Silver A and Silver B will create a silver (C), which is an average of the two and must fall between A and B. In contrast to mixing, the cupellation process requires the addition of lead to refine the silver. Cupellation breaks the relationship between Silver A and Silver B. Instead the isotope ratio of Silver C reflects the isotope ratio of the lead used during cupellation.*

get the silver used for their jewelry, ingots, and indigenous coinages? Not only are there questions regarding the source of Viking silver, the source of silver for the making of the Anglo-Saxon pennies is an ongoing mystery (Lieber 1981, 18; McKerrell/Stevenson 1972; Metcalf 1986). What was the impact of the recycling of Kufic dirhams (Eniosova/Mitoyan 2011; Ilisch et al. 2003; McKerrell/Stevenson 1972) or mining in the Harz on the silver supply of northern and western Europe (Kraume/Hatz 1967; Metcalf 1972, 409-10)? Already in the 1960s and 1970s, a number of studies were published with these goals in mind. The methods and approach to the archaeometry of Viking-age silver has gradually evolved and remains a current topic of active debate. In this section, a synthesis of these studies will be given and their conclusions will be discussed as well as new research directions which develop from these studies.

5.3.1 Characterization of Carolingian Silver

Regarding the Carolingians, the word silver is often associated with the mine of Melle in Poitou, which was one of the most prolific mints during the reigns of Charlemagne and Charles the Bald (Sarah 2010, 261). The argentiferous galena from the mines of Melle has been characterized by lead isotope analysis (Téreygeol et al. 2005) in addition to coins from Melle and other Carolingian mints (Barrandon/Dumas 1990; Téreygeol 2007; Téreygeol et al. 2005), and it is clear that the coins of Melle typically match isotopically with the galena from Melle, but coins from other mints do not always match indicating that Melle was not the only silver supplier during the Carolingian period (Barrandon/Dumas 1990; Téreygeol 2007).

The ground breaking study of Sarah (2010) has shed light on the fact that the alloy of Carolingian (Carolus) silver coins form chronological compositional groups mostly based on the copper, zinc, and gold contents determined by laser ablation mass spectrometry. The use of silver-brass alloys in the coinage has been documented (Metcalf/Northover 1988, 110-1; Metcalf/Northover 1989, 116-9; Sarah 2010, 233), and brass was often used in the debasement during the reign of Charles the Bald before the Edict of Pîtres in 864 AD, an edict which brought the coinage back to a high silver standard (Metcalf/Northover 1988, 99). Alloying is thus responsible for the changes to the zinc contents, but differences in the gold content likely reflect silver of different origins, but it cannot be ruled out that the recycling of fire-gilt silver, e.g. such as in the form of jewelry or fittings, is responsible for the higher gold contents. The freshly-made silver from the argentiferous galena from Melle is low in gold, bismuth, and other trace elements, well under 1000 ppm (Sarah 2010, 284-5; Guillaume Sarah pers. comm. 01.05.2014). If there is an alternate source for of the silver with higher contents of gold, often much greater than 1000 ppm, it is not momentarily known. Carolingian silver from the Cuerdale Hoard (Metcalf/Northover 1988, 110-1) is relatively homog-

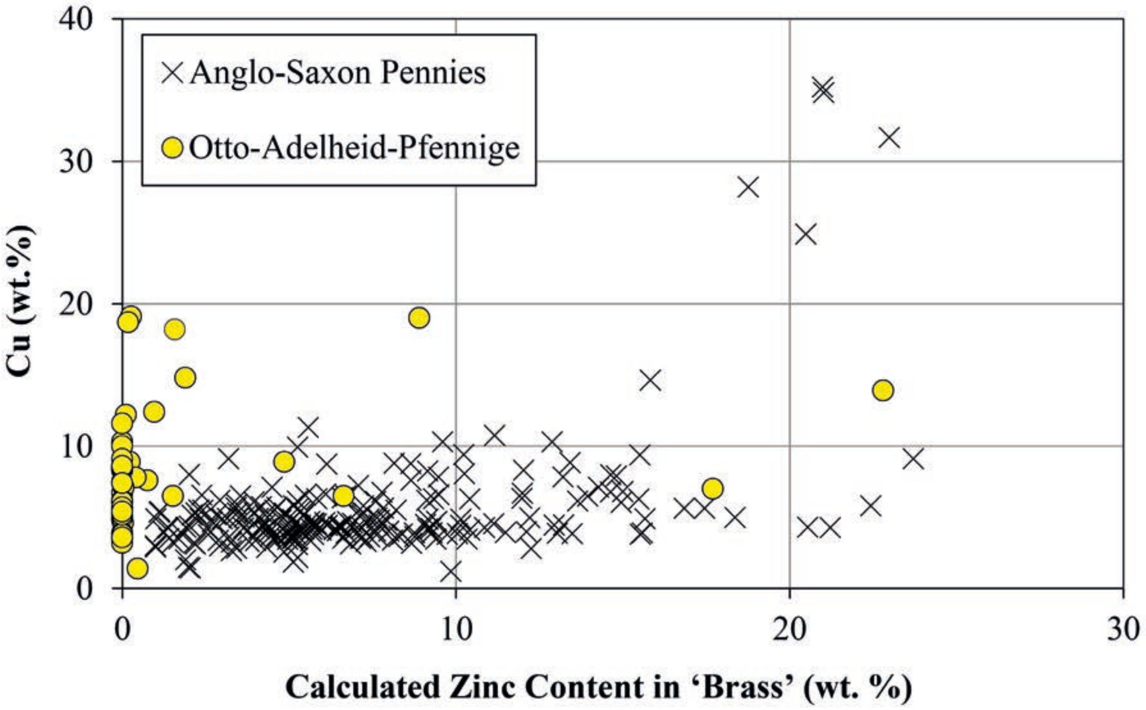

Figure 5.2 *Detectable amounts of zinc were found in all Anglo-Saxon coins dating from 974 to 1035 AD. The brass used in minting was with a maximum of 24 wt. % zinc, but the average brass contains around 7.4 wt. % zinc. A total of 227 Anglo-Saxon and Hiberno-Norse coins are represented from mints in London, Lincoln, Canterbury, Lincoln, Chester, Winchester, Exeter, Oxford, and York. In contrast, the Otto-Adelheid-pfennige (991-1050 AD) rarely were alloyed with brass. Five examples from a sample of 46 coins were alloyed with a brass containing more than 2 wt. % zinc. The data are from published microprobe and XRF analyses (METCALF/NORTHOVER 1986; ILISCH et al. 2003). The difference in zinc content between the pfennige and pennies is not an artifact of the analytics because ILISCH et al. (2003) measured both coin types and confirm the difference in zinc.*

enous with an average gold content of 0.8 percent. In the analyses of coins from the reigns of Charlemagne and Charles the Bald, gold contents range from under 1000 ppm to around 1 percent (METCALF/NORTHOVER 1989, 116-9; SARAH 2010, 278-85). SARAH (2010, 234, Fig. 3) documents a clear division of low and high gold contents in the coinage of Charles the Bald after 864 AD, even from the coins of Melle (SARAH 2010, 284-5), and this seems to indicate that either two sources were available to the mint or that one type is newly produced silver and the other is recycled silver, which is contaminated by gilding, etc. The bismuth contents of the Carolingian coins analysed by SARAH (2010) are low, typically well under 1000 ppm, with the exception of the debased issues of Charles the Bald at Toulouse, which have up to 2700 ppm. To add to the complexity, Carolingian coins from the last quarter of the 8th century AD analyzed by STEUER (2003), including coins from Dorestad, have very heterogeneous silver, gold, zinc, and tin contents, but are all relatively low in bismuth (< 1600 ppm).

5.3.2 The Alloy of Anglo-Saxon Coinages and Irish Silver

From the beginning of elemental analysis of Anglo-Saxon coinage in the 1970s, the question of the source was of central importance (MCKERRELL/STEVENSON 1972; METCALF 1972), and the source of silver in Anglo-Saxon England has since been under continual debate. The supposition that Anglo-Saxon England had no prolific silver mines led the search for the source of Anglo-Saxon silver abroad, to the Carolingians, Ottonians/Salians, and the Islamic world. MCKERRELL and STEVENSON (1972) were able to demonstrate that the alloys of the Anglo-Saxon coins are distinct and unrelated to the silver produced in the Islamic world, in this case represented by the silver of the Samanids; the gold content of the Anglo-Saxon coinage is high, at least higher than has been found in dirhams of the late Abbasids and Samanids analyzed in the study (MCKERRELL/STEVENSON 1972).

The gold content of Anglo-Saxon silver from the 9th and 10th centuries is characteristically higher than that found elsewhere, the one exception being the Carolingian Empire (see **Section 5.3.1**). In the second half of the 9th century it is often in the range of 0.6 to 1.2 percent (FORBES/DALLADAY 1960, 85; MCKERRELL/STEVENSON 1972, 205; METCALF/NORTHOVER 1985, 170-5). METCALF (1986, 145) maintains that around 947 AD there is a general decline in gold content, but it still remains relatively high, between 0.3 and 1.0 percent (FORBES/DALLADAY 1960, 85; MCKERRELL/STEVENSON 1972, 205-8). During the reign of Æthelred II and to the middle of the

11th century the gold content is in lesser quantities, typically in the range of 0.15 to 0.5 percent (Forbes/Dalladay 1960, 85; Metcalf/Northover 1986, 52-63). It has been suggested that the decline in gold to silver ratio during the reign of Æthelred II marks the importation of silver from the continent (Metcalf 1986, 145), perhaps from the Harz (Metcalf/Northover 1986, 47). Over the course of the 9th to the 11th century, bismuth contents are not constant, but fluctuate between amounts less than 1000 ppm to over 1 percent, and this occurs particularly during the period of 976-1035 AD under Edward, Æthelred II and Cnut (Metcalf/Northover 1986, 52-63).

It has been suggested that in the Irish Sea area there may have been a silver source that was supplying the mint of Chester with silver (Metcalf 1986, 143), but this remains to be proven. As to date there are no analytical studies that identify a different source of silver for the coins of the Irish Sea region from elsewhere in the British Isles. The coins produced on the Isle of Man in the late 10th and early 11th century seem to be made of recycled silver without a standardized elemental composition (Bornholdt 1999, 206) and are similar to contemporary English coins (compare Metcalf/Northover 1986). Lead isotope analysis of silver ingots from Viking hoards (ca. 900AD) in Ireland (Ryan et al. 1984, 361) suggest that the Vikings took silver with them to Ireland; the isotope ratios of the silver objects do not match any known Irish lead or lead-silver deposit, but they do have isotope ratios consistent with deposits elsewhere, for example in England (compare Northover et al. 2001; Rohl 1996).

Another important characteristic of Anglo-Saxon silver is the quantity of zinc in the alloy. As opposed to alloying the silver with pure copper, the Anglo-Saxons preferred brass, bronze, or a mixture of brass and copper. This preference has been documented from the 9th century through the 11th century (Forbes/Dalladay 1960, 84-5; McKerrell/Stevenson 1972, 200-1; Metcalf/Northover 1985; 1986; 1989; 2002). There are fluctuations in the zinc and tin contents over time indicating changes in minting practices or perhaps the availability of base metal alloys; brass was used in alloying around the 840s, contemporaneous with the debasement of Charles the Bald (Metcalf/Northover 1989, 116-20), and in the second half of the 9th century a brass-bronze mixture was more common for the severely debased coinage of southern England (Metcalf/Northover 1985, 170-5). In the late 10th and 11th centuries brass was again used in the coinage of Anglo-Saxon England (Metcalf/Northover 1986; 2002). Hiberno-Norse Dublin (Heslip/Northover 1990, 110-1), and the Isle of Man (Bornholdt 1999, 217). As evidenced by the analyses of the Otto-Adelheid-pfennige (**Figure 5.2.**), the tradition of using a brass-silver alloy for coinage is relatively uncommon in the Ottonian Empire, although they were supposedly the supplier of brass in the 10th and 11th centuries (Day 1998).

5.3.3 Silver of the Ottonians

Silver production in Central Europe, particularly in the Harz mountains, is thought to be of great importance to the silver supply of northern Europe in the 10th and 11th centuries. Characterizing the silver of the Harz in order to track its movement in northern and western Europe has been the focus of a number of studies. As mentioned in the previous chapter (**4.2.4.2**) the Harz mountains contain numerous mineralizations, but for the sake of simplicity, the two important sources of silver were the Rammelsberg and the Upper Harz deposits. Much of the discussion in the literature is about the silver of the Rammelsberg, but confusion arrises in that the Rammelsberg is one deposit type in the Harz, though the term is often loosely used synonymously with the Harz in general. The state of archaeological research of mining in the Harz region prior to the 1980s is partially responsible for this confusion. The subsequent archaeological fieldwork lead by Lothar Klappauf has greatly advanced ths area of research in this regard.

Early analyses of silver from several ore deposits in Central Europe have revealed differences in the gold and bismuth contents (Kraume 1961, 9). Silver of the Rammelsberg is defined as being high in both gold and bismuth (Bode 1928, 148; Kraume 1961, 9; Zwicker et al. 1991, 59-60). A notable gold content is not mentioned in association with any other silver ore in the Harz mountains, but bismuth may be present in silver ore near Hasserode (Bode 1928, 148-52). The Lower Harz is low in gold and bismuth (Kraume 1961, 9), but the Upper Harz was not discussed because at this time it was thought that this deposit type was not mined in the 10th century (Kraume 1961, 5-6). It is now quite clear that Upper Harz deposits were mined by the Ottonians, and were important sources of silver (Alper 2004, 188; Brockner et al. 1989, 193; Klappauf 2011).

Analyses of Otto-Adelheid-pfennige show that gold and bismuth are often correlated and both silver with gold and bismuth greater than 0.15 percent and silver with low gold/low bismuth (<0.1%) were used (Ilisch et al. 2003, 161; Hatz et al. 1991, 79). It has yet to be proven, but the low gold / low bismuth type used for the Otto-Adelheid-pfennige may stem from the Upper Harz deposit. Perhaps lead isotope analysis could help to differentiate the origins of the silver because there is a distinct difference in the lead isotope signature of the Upper Harz and the Rammelsberg deposits. The lead isotope analyses of Otto-Adelheid-pfennige performed by Hatz et al. (1991) indicate that both the Upper Harz and the Rammelsberg may have been sources of the silver, but the elemental analyses of the coins were not done in coordination with the lead isotope analyses, so any relationships between the two datasets are not visible. Furthermore, the most recent analyses of Otto-Adelheid-pfennige are without lead isotope ratios and no bismuth contents are given (Lehmann 2011, Table VI.8) and are, therefore, unhelpful in resolving this issue.

Discussions about the source of Anglo-Saxon silver at the end of the 10th century have been affected by the interpretation that Rammelsberg silver with its high gold/ high bismuth content is representative of the silver of the Harz. This has lead some scholars (Härdh 1976, 117-8; Metcalf 1972, 409; Metcalf/Northover 1986, 47, 50; Söderberg 2011, 9-10) to speculate whether the Rammelsberg signature can be seen in coins of England or the silver of Scandinavia. It is now clear that the problem is much more complex, and that Rammelsberg silver, with its distinctive trace elemental pattern, is not the only type of silver available in the Ottonian Empire.

Outside the Harz area, there were other Ottonian mines producing silver, but there are few published studies and the ore deposits are much more complex than can easily be summerized. The raw silver from deposits in the entire Eifel region (Lahn/Rhine/Moselle/Aachen) is thought to have low contents of gold and bismuth (Kraume 1961, 9, Table 2; Zwicker et al. 1991, 71), and mines in this region may have supplied silver for the coins of Ottonian Cologne (Kraume/Hatz 1967, 36-7). but little is known about the raw silver of the Sauerland/ Siegerland/Bergisches Land area. In the Black Forest, the silver is thought to have higher bismuth contents (500-1000 ppm) with lesser amounts of gold (100-600 ppm) (Kraume 1961, 9, Table 2; Zwicker et al. 1991, 71), but native silver can have exceptionally low gold and bismuth and can be found in the Black Forest (Zwicker et al. 1991, 71), Siegerland (Schneider 1998), and other deposits in Central Europe and beyond. In contrast, the silver from the oxidized deposits of Wiesloch can have notable amounts of gold and bismuth (Kraume 1961, 9; Zwicker et al. 1991, 71). Many types of silver may have been accessible to the Rhine River Valley, and because of its role as a major waterway and transport route one would expect that the silver used in mints along the Rhine would be a mixture of newly mined silver and silver obtained through commerce and tolls.

As for the lead isotope characteristics, the deposits of the Black Forest and the Wiesloch area are geologically much younger than the deposits of the Rhenish Massif and can be distinguished from the Harz, Eifel, Sauerland, Siegerland and Bergisches Land (Hatz et al. 1991, 141-4). The Harz Mountains formed at the same time as much of the Rhenish Massif and there are overlaps between individual deposits (Lehmann 2011, 119-36; Hatz et al. 1991, 141-4), but within the Harz/Rhenish Massif a distinction should be made between deposits of Pre-Variscan age, such as the Rammelsberg, and deposits of Post-Variscan age, like the Upper Harz. The lead isotope ratios of these two types of deposits can be readily distinguished from each other (Lehmann 2011, 119-36).

5.3.4 Sassanian and Islamic Silver

There have been very few archaeometric studies looking at the sources of silver in the Sassanian and Islamic period and this is in large part due to the lack of analytical studies of ore and slag associated with primary production during this period. There are insufficient investigations of mines dated to the Islamic period outside the mines of Central Asia. In the absence of archaeological research on actual mines, archaeometric research was to be focused on the silver coins themselves in order to identify possible silver producing regions and to describe and interpret the changes to the silver stock over time.

The dominance of silver in the mints of the eastern Islamic world has its roots in the Sassanian tradition. The Sassanians sought out and extracted silver resources in the Arabian Peninsula, the Caucasus, and in the core of the Sassanian Empire, Iran, and many of these mines continued to operate in the early Islamic period. The first large-scale study of Sassanian drachms and Umayyad dirhams was the neutron activation analyses of Gordus (1972), and the gold contents of numerous coins were measured, but unfortunately there is no discussion of bismuth. The analyses show that the Sassanians primarily used silver with high gold contents, often in the range of 1 percent, and Gordus (1972, 138) proposed that there was a source of high-gold silver in the Caucasus. Other studies have confirmed the high quantity of gold found in Sassanian silver, but it should also be mentioned that there is no systematic difference in Sassanian silver from that used in the late Roman Empire (Hughes/Hall 1979, 334). This relationship has yet to be explored in detail.

The Umayyads continued to use high-gold silver, but there seems to be a new silver source low in gold in western Central Iran[1] that supplied the mints of Hamadān, Māhī, and al-Taymara in the 8th century AD (Gordus 1972, 138-9). A shift can be seen in the coins of Wāsiṭ, Iraq, in the 8th century AD to the use of low-gold silver (Gordus 1972, 141, Table 12). The transition to low-gold silver described by Gordus is thought to be evidence for a technological transition in the Islamic world from relying on oxidized lead-silver ore to primary sulfide ore like galena (Meyers 2003, 276), but this argument is in need of further supportive evidence particularly from mines and production sites dated to this period.

Archaeological evidence supports that deposits of Iran were mined by the Sassanians (See **4.2.2.1**), but also lead isotope analysis points to this conclusion. Meyers (1998, 246, Table 6) also reports high gold contents of Sassanian silver objects ranging between 0.4 and 0.7 percent, and lead isotope ratios measured are consistant with lead ore from several deposits in Iran and Turkey.[2] The lead isotope ratios of Sassanian silver artifacts presented by Stos-Gale (2001), Brill and

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[1] Jibal region / possibly in Iṣfahān or Qom provence.

[2] Closest matches are galena from Khaneh Sormeh (Iṣfahān), and Herzarabad (Arak) and lead slag, litharge, and cerussite from Nakhlak (Central Iran) (Pernicka et al. 2011; Stos-Gale 2001; Stos-Gale 2004) and galena from the Taurus 2a group (Yener et al. 1991).

	Nr. of Coins	Au	Bi
		%	%
Baghdād	26	0.22	0.05
Caucasus	11	0.05	0.21
al-Muhammadīyya	16	0.06	0.12
Iṣfahān	10	0.24	0.20
Merv	47	0.12	0.23
Bukhārā	17	0.22	0.15
Nishāpūr	43	0.10	0.22
al-Shāsh	87	0.07	0.30
Samarqand	122	0.26	0.42
Balkh	62	0.07	0.17
Khazar Imitations	2	0.45	0.07
Iranian Imitations	10	0.59	0.26

***Table 5.1** Gold and bismuth contents of dirhams / imitations from important mints of the 9th century (800-900 AD). Gold contents are highest in the imitation coinages, but generally the gold and bismuth content of dirhams of the 9th century are around 0.2 percent or lower. The mints with the highest bismuth content are those of Transoxania, but the lower gold and bismuth contents of the coins of Balkh are more similar to mints in Khurāsān. XRF spectral analyses (Ilisch et al. 2003).*

	Nr. of Coins	Au	Bi
		%	%
al-Shāsh	68	0.17	1.38
Samarqand	67	0.34	1.16
Balkh	66	0.15	3.57
Andarāba	50	0.09	3.91
Volga-Bulghar Imitations	38	0.24	0.71

Table 5.2 Gold and bismuth contents of Samanid dirhams (893-961 AD) and contemporary Volga-Bulghar dirham imitations. The bismuth contents from the major mints in Central Asia (al-Shāsh / Samarqand) and northern Afghanistan (Andarāba / Balkh) are above one percent on average, although the bismuth content of the Volga-Bulghar dirhams is lower, it is still higher than that found in the dirhams of the 9th century. XRF spectral analyses (Ilisch et al. 2003).

Shield (1972), and Meyers (1998) all show a similar range of compositions, and seem to reflect the use of Iranian lead-silver ores (Stos-Gale 2001, 64). A single Umayyad dirham from Damascus was analysed (Brill/Shield 1972) and has lead isotope ratios analogous with ore, slag, and litharge from the lead-silver mine of Nakhlak, in Iran (compare Pernicka et al. 2011; Stos-Gale 2004).

There is a limited number of published analyses of Umayyad and Abbasid dirhams. The analyses of Gondonneau and Guerra (2002) confirm the analyses of Gordus (1972) in that during the Umayyad Dynasty new low-gold silver became available; compared to the consistently high-gold contents of the Sassanian drachme, the Umayyad dirhams range from high to low gold contents and the Abbasid dirhams have overall less gold, in a range of less than 0.1 percent to as much as 0.5 percent. The decrease in gold content of silver dirhams seems to be a pan-Islamic phenomenon as it is seen in both the coins of Iraq and in North Africa (Gondonneau/Guerra 2002, 583). No bismuth contents are reported by Gordus (1972), Meyers (1998), or Gondonneau and Guerra (2002).

According to the analyses of Ilisch et al. (2003), the coins of Baghdād have higher gold contents in the 8th century (0.1 - 1.5%) than in the 9th and 10th centuries (0.1 - 0.3%), and prior to the 10th century bismuth contents are minimal (< 0.1%).[3] The differences in the silver used in mints in the eastern Islamic world in the 9th century AD is illustrated in **Table 5.1**. The highest bismuth contents are found in Transoxanian mints like Samarqand and al-Shāsh, and this possibly comes from the extraction of local silver resources in the Īlāq region. The mints of Iraq and Iran have notably less bismuth and have average gold concentrations between 0.05 and 0.22 percent. The fact that the imitations of dirhams probably produced outside the Caliphate have higher gold contents than the official dirhams seems to indicate that a silver stock of slightly older age was used in these regions perhaps reflecting traces of Sassanian and Umayyad silver.

Samanid dirhams have been analysed by McKerrell and Stevenson (1972), Cowell and Lowick (1988), Ilisch et al. (2003), and Eniosova and Mitoyan (2011), and it is clear that the silver of the Samanids is distinctive due to its typical high bismuth and low gold content. This is most visible in the coins from northern Afghanistan, which can have very high quantities of bismuth with almost no gold. Cowell and Lowick (1988, Figure 2) have shown that the distribution of high bismuth / low gold silver is most concentrated in the Panjhīr/Andarāba region and show that this signature is not found in contemporary mints in Iran and Iraq, but there is too little data for a comprehensive picture. The high bismuth concentrations found in the silver of northern Afghanistan are thought to be characteristic of the silver from the mines of Panjhīr, but mints in Transoxania also used bismuth-containing silver, which may have been supplied by local mines (**Table 5.2** and **Figure 5.3**).

Due to lax production standards, the silver of Panjhīr/Andarāba is frequently improperly refined and can contain several percent of bismuth, which would make the silver hard and brittle (**Figure 5.4** and **Figure 5.5**). In regards to recycling, silver with such high bismuth contents would be inappropriate for the making of objects requiring cold working techniques, but the working prop-

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[3] However, the bismuth contents rise notably in the 10th century dirhams from Baghdād (Ilisch et al. 2003). This increase in bismuth in the 10th century dirhams of Iran and Iraq was first documented by Werner and Cowell (1975, 123) and it is possible that Samanid silver particularly from Transoxania was recycled in the Abbasid Empire (Lowick 1975, 122-3).

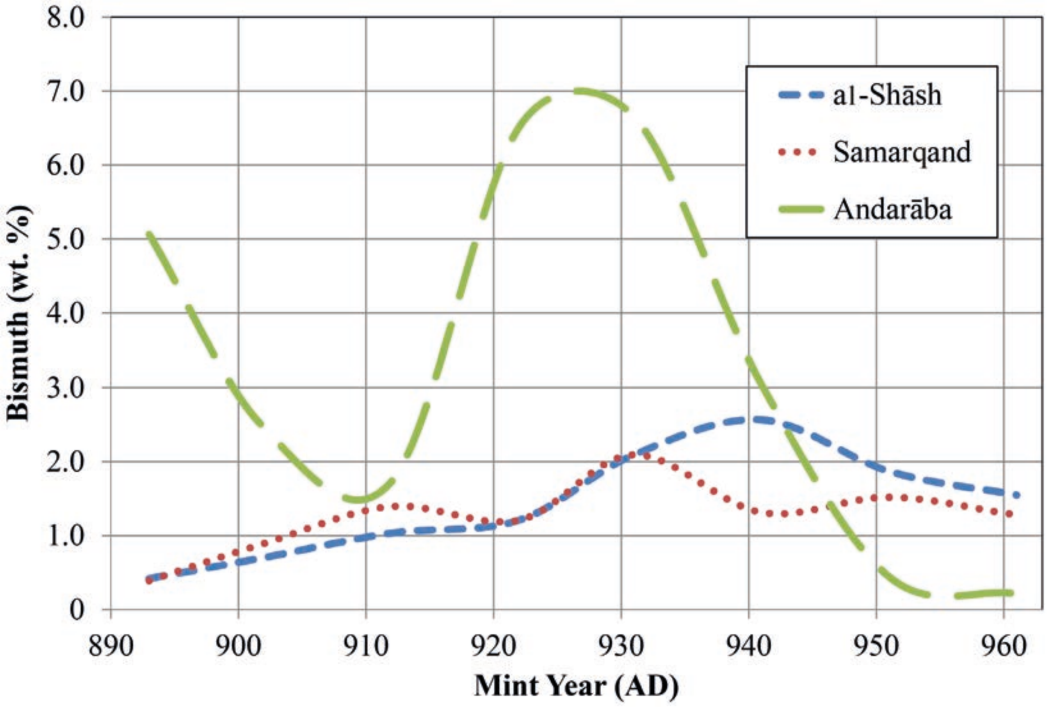

***Figure* 5.3** *This graph illustrates the fluctuations of average bismuth contents of dirhams from three major mints of the Samanids between the years 893 to 961 AD (280-350 AH). The content of bismuth between the mints of Samarqand and al-Shāsh are relatively similar, but the dirhams from Andarāba often have high percentages of bismuth reflecting silver that was poorly refined. Data based on the XRF analyses of 185 dirhams (ILISCH et al. 2003).*

***Figures* 5.4** *and* **5.5** *Samanid double dirham minted at Panjhīr, Aghanistan under Nuh I. ibn Nasr, 942-954 AD (331-343 AH) (STÖLLNER et al. 2004, 804, Cat. 536). This dirham exhibits cracking due to the brittleness of the silver, and this is characteristic of high bismuth silver. The composition of the coin is recorded as 87% silver, 2.5% copper, and the remaining 10.5% probably consists of bismuth and lead: the values were not provided.*

erties could be improved by careful and repeated refining or by dilution with silver free of bismuth. The coins of Volga Bulgharia are imitations of Samanid dirhams, but they typically have less bismuth than the dirhams they imitate. This could be explained by mixing Samanid silver with an earlier stock of silver, which had less bismuth, although there is the less likely possibility that silver from other, unrelated sources was circulated.

A decline in the export of dirhams to Volga Bulgharia and to the Baltic occurred in the second half of the 10th century, and this is contemporaneous with the faltering silver standard of the dirhams produced in the Samanid Empire. The analyses of Samanid dirhams (ILISCH et al. 2003; STEUER et al. 2002, 153, Figure 12) markedly show that shortly after 940 AD (330 AH) Samanid dirhams begin to fall to below 90 percent silver and in the following two decades can reach as low as 50 percent silver. Copper was the primary metal used for debasement, but high quantities of bismuth and lead can be found in some of the coins (Ilisch et al. 2003, 78-85) indicating the use of poorly refined silver.

5.3.5 Viking Silver

The silver used in Scandinavia is undoubtedly imported, and several analytical studies were performed to look at the elemental composition of Viking silver with the aim of identifying its source. The question of whether the Vikings primarily used Islamic, German, Frankish, or Anglo-Saxon silver is not new. The first study specifically looking at the source of Viking silver was by Arrhenius et al. (1973). This study investigated silver rings and hacksilver from Birka and from one Gotlandic hoard with atomic absorbtion spectroscopy (AAS) and compared them with known compositions of Islamic and western European silver coins. It was determined that the silver rings from Birka are most similar to Abbasid dirhams, whereas the silver of the Gotlandic hoard had much higher zinc contents and is unrelated to Islamic silver (Arrhenius et al. 1973, 160). As a result of this study, the idea was first put forth that there may be chronological differences in the composition of Viking silver; differences that are in need of further study (Arrhenius et al. 1973, 160).

As a continuation upon this theme, Hårdh (1976) presented analyses of Viking silver from 10th to 12th century hoards. Scandinavian neck rings, arm rings and granulated/filigree objects were sampled and analyzed by AAS. One important result is that it can be shown that the silver smiths consciously selected the alloys to best exploit their material properties. The granulated and filigree objects have consistently higher silver contents than the rings (Hårdh 1976, 115). Following the argumentation of Mecking (2010, 53-4), there are technical benefits to the use of high quality silver for granulation and filigree and, due to the higher melting temperature of pure silver, there is a wider thermal tolerance during soldering. Towards the question of provenance, the results show greater similarities to coins of German origin rather than Anglo-Saxon because of the low quantities of zinc and gold, but unfortunately there are methodological problems that limit the use of the trace elemental data. Firstly, bismuth was not consistently measured (Hårdh 1976, 113), and, secondly, the use of nitric acid (Hårdh 1976, 113) for the sample preparation excludes the gold from the sample solution. Gold can only be dissolved by aqua regia, a mixture of hydrochloric and nitric acid. This can explain why gold was below the detection limit for all the samples analyzed.

The next major study to be performed on Viking silver is the XRF spectral analysis of unminted silver from the British Isles (Kruse/Tate 1992). The hoarded ingots and hacksilver objects on the British Isles are thought to be products of the Vikings, and objects from several hoards over the 9th to 11th centuries were analyzed to gain information about their potential source. It is evident from the analyses that the provenance of silver by elemental analysis is not simple nor straightforward. In some instances, there are similarities to the coinages of Anglo-Saxon England, and others seem more similar to Islamic dirhams (Kruse/Tate 1992, 323), whereas German silver is not similar to the Viking bullion due to the German coins' lower gold content (Kruse/Tate 1992, 318). Lead isotope analysis is recommended as a method to better discern the sources of the silver (Kruse/Tate 1992, 324).

A large scale study was performed using non-destructive XRF to identify the alloys used in a wide range of medieval coins and Viking silver objects (Ilisch et al. 2003). Part of this study was to look at the composition of Scandinavian unminted silver objects from several hoards from the 9th to the 11th century AD in addition to coins produced at Hedeby and coins from important mints of the 8th to the 11th century (Steuer et al. 2002; Steuer 2003). The results of the XRF study are significant and provide a rich data set for comparison. The data collected has been published, but unfortunately there is little interpretation of the data set. The discussion on the origin of the silver for the coinage of Hedeby presented by Steuer et al. (2002, 147-54) falls short because it greatly underestimates the temporal dimension. It cannot be assumed that the Hedeby coins made over the course of a 150 year period (825-975 AD, Malmer KG3-KG9) can be put in a single group and compared to coins groups of yet a larger time span (770-1050 AD) and achieve a successful result. It is clear that the alloys used in all regions were not static but instead were highly sensitive to temporal changes. A selective approach may be more informative, comparing coins in smaller chronological groups that more realistically represent the archaeological situation. However, it must be stated that many of the Hedeby coins analyzed in this study are of the Malmer KG7 type (900-920 AD), and their apparent relationship to the Volga-Bulghar dirham imitations (Steuer et al. 2002, 152-3) seems to be chronologically valid and is worthy of further consideration.

In a recent study of silver from 10th century hoards in Gnezdovo, Russia (Eniosova/Mitoyan 2011), the compositions of Samanid dirhams are compared with various Slavonic and Scandinavian jewelry objects. This study confirms the results of Hårdh (1976) showing a clear difference in silver purity between the filigree/granulated objects and cast/smithed objects (Eniosova/Mitoyan 2011, 583). The most significant result is the presence of high quantities of bismuth in many of the Slavonic and Scandinavian objects, and this is interpreted as evidence for the recycling of Samanid dirhams; however, the bismuth contents of these objects are consistently lower than the dirhams, and indicate that either refining occurred or that the silver was of mixed source.

The source of silver is not the only focus of archaeometric research of early Scandinavian coinage. The identification of debasement in coinage and its economic and political implications is also a topic that requires the use of analytical methods. Concerning the debasement of Danish and Norwegian coinages of the 11th century, a number of analytical techniques have been used to varying results. Touchstone estimates, neutron activation analysis (NAA), and XRF surface analyses have been used to answer the question of whether the debasement of the Danish coinage occurred under the reigns of Sven Estridsen (1047-1074 AD) or Cnut the Holy (1080-1086 AD). The NAA results presented by Gullbekk (2000)[4] indicate a clear debasement during the reign of Sven Estridsen, whereas Elfver (2007) argues for a high silver standard during the same period. The extreme variation in the results may be more of a methological and/or source critical issue. NAA is a method that analyzes a complete object, but XRF analyzes only a thin layer on the surface. Surface enrichment and cleaning may result in significantly higher silver contents on the surface of an object, and this may explain the difference in the analytical results.[5] The coinage of Harald Hardrada, king of Norway (1046-1066 AD), seems to parallel the Danish coins of Sven Estridsen in that debasement is present towards the end of their reigns. Interestingly, brass was used in the debasement of the coinage of Harald Hardrada, and there is speculation that several unminted objects sharing the same range of compositions may have been made out of debased coins (Skaare 1976, 84-5).

5.3.6 Conclusions

What can be learned from the published analytical work on early medieval silver is that alloys vary regionally and have a significant temporal dimension. Concerning Viking silver, some themes have been touched upon: specific alloys are used for specific functions, there are visible changes in the compositions of silver over time, and there may be correlations in the isotopic/elemental composition of imported silver and the silver used in Scandinavia. It is clear that any attempt to track these correlations in Viking silver would require a nuanced approach that takes into account the temporal nature of the alloys being imported. While chronological trends are difficult to see in German coinage; the alloys of Carolingian, Anglo-Saxon, and Islamic silver all show important shifts in composition over time. These temporal and regional differences in silver composition are dependent on cultural, technological, and geochemical factors; factors that can be untangled to reveal information about the medieval economy and the movement of silver.

Though gold and bismuth contents provide significant information about the potential source of silver and the identification of changes to the silver stock, it is clear that they provide only a limited resolution for understanding the chronologic changes to silver compositions. Lead isotope analysis has not yet been systematically applied to investigated Viking silver, and it has been used sparingly to study silver of the early medieval period. Due to the lack of isotopic data from medieval silver mines in much of the Islamic world, it is unknown if lead isotope analysis will be useful in distinguishing Islamic silver from silver of European origin. Lead isotope analysis shows promise in several regards: firstly, it provides more variables useful in distinguishing groups of silver, secondly it can help to answer the question of whether silver was commonly refined or not, and thirdly, with the combination of ore, slag and metal, lead isotope analysis can be used to build arguments concerning provenance.

5.4 Development of Sampling Strategy and Analytical Approach

The goal of this thesis is to better understand the changes to the silver composition in Scandinavia, with special emphasis on Hedeby, during the 10th and 11th centuries. It has been demonstrated that changes in composition reflect both technological developments and changes in the origin of the silver. The use of lead isotope analysis and elemental analysis, together, to characterize Viking silver has yet to be performed. Additionally, there is little available information about the isotopic composition of silver from the various regions from which the Vikings likely drew their supply. The methodological approach, thus, centers on two problems: understanding the chronological changes to Viking silver compositions and broadening the basis for comparison. A systematic approach to the study of the silver of Hedeby with a combination of lead isotope and elemental analysis may provide a new perspective to the problem of silver source and can help to characterize the changes to the silver stock in the 10th and 11th centuries.

5.4.1 Chronological Framework – Hedeby and Danish Coins

A chronological structure is needed to see the changes to the composition of silver over time. The 10th century Hedeby coins of the Malmer combination group series (KG 7-11) and 11th century Hedeby/Danish coins form the chronologic frame of the study. Each coin type has a rough date range from when they were in production and in use. These coins provide a window into the alloys used at Hedeby and other mints in Denmark at different segments of time during the period of focus.

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[4] Refered to the methods of Skaare (1976, 79-85).

[5] Even though one coin could be analyzed in cross section due to an accidental breakage (Elfver 2007, 214), it is not known if the fragility of the coin was due to porosity caused by the leaching of base metals, or it may have represented a coin of Sven Estridsen that was not debased.

The coins involved in this study come primarily from the metal detection and excavation campaigns at Hedeby, but additional 10th century coins from the Steinfeld hoard (Wiechmann 1996, 436-9) and a West Slavonic hoard[6] were selected, as well as 11th century coins from the excavations of Schleswig harbor. In all, forty-one Hedeby/Danish coins were selected for analysis (**Cat. 114-154**).[7] The coins were divided into chronologic groups each covering a span of time of less than fifty years: Malmer KG7 (900-920 AD), Malmer KG8-11 (950-985 AD), the Årstad 95-96 and Harthacnut coins (1015-1042 AD), and the coins of Sven Estridsen and coins attributed to the reign of Cnut the Holy (1047-1086 AD).

5.4.2 Comparison Material – Coins, Unminted Silver, and Base Metals

The analysis of imported silver coins is key for the study of the silver trade. Imported coins may have been the chief source of silver for the Vikings, and coins are among the most informative object type. The major silver producing regions of the early medieval world were all controlled by coin-using societies; therefore, coins from silver producing regions may provide the clearest signal for freshly produced metal. Coins from active mining regions will give the most information about the characteristics of the newly produced silver, whereas coins from commercial centers and unminted objects are more likely to be mixtures of circulating silver. Besides silver, the analysis of lead and cupellation waste is also vital for answering questions regarding refining at Hedeby and the role it may have played.

The material selected for comparison is of a broad nature, and reflects the fact that little is known about the relationships of lead isotope and elemental composition in the types of silver available at Hedeby and the wider southern Scandinavia region in the 10th and 11th centuries. All objects analyzed in this study are presented in the catalogue (**Appendix A**). Most of the material comes from the settlement of Hedeby, but to augment the numbers of some coin and jewelry types, a small number of objects were taken from hoards found in Schleswig-Holstein[8] and a West Slavonic hoard. Imported coins form the central focus, with a special emphasis on the two coin groups most commonly found at Hedeby: Kufic dirhams and coins of the Ottonian Empire. Due to the large number of Samanid dirhams found in the the Baltic sea region during the 10th century, thirty-seven dirhams were chosen, but earlier Abbasid and Saffarid dirhams were also selected. Forty coins from Westphalia, Frisia and Lower Saxony form the second major coin group. Smaller numbers of Hiberno-Norse, Anglo-Saxon, and Byzantine coins were selected. Unminted wires, ingots, bar fragments, and jewelry pieces found at Hedeby and nearby hoards in Schleswig-Holstein were selected for comparison. Many of the unminted objects from Hedeby were found by metal-detecting, a category of objects that were previously not known from the former excavations, but unfortunately that means that they lack secure archaeological contexts. Some objects can be stylistically dated but most cannot and are thought to come mostly from the second half of the 9th century to the 11th century. Base-metal alloys were also sampled for analysis. A small number of copper alloy objects were mistaken for silver and were sampled. Lead and lead-tin alloy fragments from both metal-detection and excavation were selected. This group of lead-tin objects consists of counterfeit coins, ingots, ingot fragments, weights and scrap metal.

5.4.3 Recycling and Refining at Hedeby and the Lead and Tin Finds

To look at the question of recycling and refining, a collection of technical ceramics from the excavations at Hedeby were gathered for analysis. This assortment primarily consists of cylindrical crucibles and dish-shaped crucibles called heating trays. At the center of this investigation is the better understanding of the function of the heating tray. Samples of refining slag from heating trays were sampled for lead isotope analysis to compare with the lead and silver found at Hedeby. The sampling of crucible fragments also enable a discussion about the types of refractories used and the alloys melted. The results of the study of technical ceramics can be found in **Appendix G**.

Lead and tin objects were sampled for analysis to charaterize their elemental and lead isotope ratios and to compare these finds with the silver objects and a small number of heating tray refining slags. A further crucible that may be related to cupellation (**Cat. 247**) was sampled and analyzed. These results are found in **Appendix H**.

5.4.4 Ore and Slag from the Islamic World

To broaden our knowledge of silver production in the Islamic world, material from two silver production regions were selected for analysis. In the heart of the Samanid Empire, the mines of Transoxania may have been some of the greatest suppliers of silver in the 10th century. Polymetallic slag from production sites at Tunket and near Lashkerek and ore fragments from the medieval mine of Lashkerek and ore deposits in the region of Samarkand have been collected to provide a

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[6] Unpublished West Slavonic hacksilver hoard dating before 985 AD. Forschungsstelle für Islamische Numismatik, Universität Tübingen, inventory number 91-29.

[7] As discussed in **Chapter 3** (**3.4.1.3-3.4.1.4**), the precise location of the mints of many of the Danish coins of the late 10th and 11th century are not firmly established. It is thought that the KG 10-11 could be produced at either Hedeby or Lund. Additionally, 11th century coins from the mints of Viborg, Hedeby, and unidentified Danish mints are represented in this study. The most likely mint of the individual coins analyzed is found in the catalogue (**Appendix A**).

[8] Giekau Hoard, t.p.q. 921 AD (Wiechmann 1996, 238-56); Waterneverstorf hoard I, t.p.q. 976 AD (Wiechmann 1996, 488-505); List hoard, t.p.q. ca. 1000/1003 AD (Wiechmann 1996, 276-306), and an isolated non-hoard find from the settlement of Füsing (**Cat. 159**).

comparison to the dirhams produced in the Samanid Empire. This material has enabled an investigation into the production technology of silver and provides some indication of what type of ore was extracted (**Appendix I**).

The lead-silver mine of al-Radrād, or al-Jabali, in Yemen was in operation during the Sassanian to the Abbasid period and is described by the 10th century writer al-Hamdānī. The mines of al-Radrād may have been an important silver supplier to the early Islamic world. Slag, furnace fragments, and ore from the medieval mines were collected for analysis. This material gives a glimpse into the ore-type extracted and provides a basis for the reconstruction of the smelting technology and the characterization of the lead isotope signature for provenance studies (Merkel et al. 2016).

5.5 Closing

Much work has been performed over the last 50 years to understand the changes to the alloys of silver in the early medieval world. Archaeometry has been applied to the study of early medieval silver for several reasons. Concerning provenance studies, several analytical methods are available. Traditionally, gold and bismuth contents were used to distinguish silver groups, but lead isotope analysis can add a new dimension that potentially provides information about the source of the silver. Lead isotope analysis has been used sparingly in the provenance studies of early medieval silver, primarily because it is expensive and requires destructive sampling. Non-destructive elemental analysis is much more popular for obvious reasons, and although the elemental results form an important dataset and are useful in answering particular archaeological questions, the elemental results often lack the resolution required to provenance silver. Advancements in mass spectrometry, and more specifically, laser ablation techniques are helping to alleviate the problems surrounding destructive sampling.

The sampling strategy and analytical approach for this thesis were developed to systematically characterize the alloys of Hedeby and Danish coins of a two-hundred-year period beginning in the 10th and ending in the 11th century. These coinages produced in southern Scandinavia form a chronological and geographical anchor, and a wide range of coins and objects have been selected for comparison. The sampling strategy is dynamic and broadly representative of the material found at Hedeby, however many types of objects are represented by only few examples. The small sample size of many types of objects is problematic, and, regarding the lead isotope analysis of early medieval silver, the objectives of this study must remain exploratory. Few objects of the Viking Age have been analyzed by lead isotope analysis, and before the technique can be validated it must be first applied.

6. Chapter
Material Analysis
Methods, Procedures and Data Quality

6.1 Introduction

In the previous chapter, the set of archaeological problems was discussed, and the scientific approach and sampling strategy were developed; in this chapter, the acquisition of the analytical data will be explained in detail. This is important so that the quality and reliability of the data can be independently assessed, that the methodological biases can be identified, and that the methods can be reproduced in future studies.

The development of the sampling strategy is made complex by the physical limitations of analytical techniques, but also the variable availability and accessibility of archaeological material for sampling. All archaeological material is finite and irreplaceable, and, due to the intellectual and cultural value of many rare archaeological finds, non-destructive techniques are the only acceptable option. On one extreme, there is the Viking-period coinage from Hedeby with few intact examples worldwide, and on the other extreme, there is the waste of industrial processes at silver smelting sites, which can leave amounts weighing thousands of tons. The methodology for sampling and analysis must weigh the cost of analysis, both in cultural and financial senses, against the information accessed through destructive, semi-destructive, and non-destructive analysis.

Optical microscopy, X-ray techniques like X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopy (SEM-EDS), and various methods of mass spectrometry were used to analyze the archaeological material and geological specimens. Each of these techniques relies on different technological principles to explore facets of material properties and chemistry and each reveal material characteristics relevant to the archaeological discussion. The combination of multiple types of analysis is imperative because each analytical method has its own strengths and weaknesses, but together they provide a firmer foundation to build and support archaeological theories.

This chapter is divided into three parts: 1. A description of the qualitative and semi-quantitative analytical methods; 2. An account of the quantitative methods involving mass spectrometry; 3. A broader discussion of how the methods relate to each other and the inter-laboratory compatibility.

6.2 Qualitative / Semi-Quantitative Analysis: Microscopy and X-ray Techniques

A number of techniques will be discussed in this section relating to imaging and the understanding of materials through their interaction with X-rays. These techniques range from fully destructive to non-destructive and can aid in the identification of metals, phases, minerals, and chemistry to obtain information about technological processes, raw materials, and changes caused by corrosion and burial processes. Regarding imaging techniques, both optical and scanning electron microscopy were used to analyze industrial waste from Hedeby and from Uzbekistan. Although many techniques exist for analyzing such archaeological material, image-based techniques provide unique perspectives to differentiate intentional technological processes from features of decay and corrosion (Rehren 2009). The scanning electron microscope is a versatile instrument that is image-based, but when coupled with energy dispersive spectroscopy it allows for semi-quantitative elemental analysis of metals, minerals, phases, and glasses. Portable X-ray fluorescence spectrometry (pXRF) is a quick, non-invasive technique to gather elemental compositions of some types of objects, but this is not without limitations. Finally, X-ray diffraction (XRD) is a technique that solely provides information related to the crystal structure of phases and minerals.

6.2.1 Optical Microscopy

Reflected and transmitted light microscopy were performed on a Zeiss Galaxy Axiophot microscope (**Figure 6.1**) with the capability of 2.5 to 40 times magnification. The microscope is equipped with a polarizer and cross polarizer to aid in the identification of phases and minerals. The microscope is connected to a digital camera, which is operated through a software program for image processing. Sections of crucibles, geological samples, and slag were analyzed and were prepared at the Deutsches Bergbau-Museum Bochum by mounting in epoxy resin or as surface-polished thin-sections with a thickness of approximately 30 µm.

Figure 6.1 *Polarized light microscope, Deutsches Bergbau-Museum Bochum (Photo: S. Merkel 2012).*

Figure 6.2 *Scanning electron microscope with energy dispersive spectroscopy capabilities at the Deutsches Bergbau-Museum Bochum (Photo: S. Merkel 2012).*

6.2.2 Scanning Electron Microscopy

The scanning electron microscope (SEM) is an instrument that employs a concentrated electron beam to obtain high-resolution imaging and, when coupled with an energy dispersive spectrometer (EDS), can collect element-characteristic energy spectra that can be used for semi-quantitative elemental analysis (**Figure 6.2**).

A Zeiss Gemini SEM with a Thermo UltraDry Silicon Drift X-ray Detector (EDS) was used because of its capability to obtain elemental data on the phases and minerals as well as its imaging. The working distance was 10 mm, and the energy was set at 20 kV so that all peaks of 0.1 to 15 keV were visible (GOLDSTEIN et al. 2003, 357), and this is beneficial for exploratory analysis. The EDS uses the NSS (Noran System Seven) software system to quantify the results.

Ideally, for the best analytical results on metals, ceramics, glasses, and slag, polished sections of the objects should be used. The sectioning and polishing of objects gives access to the interior of the object that is typically the least effected by corrosion and contamination. In addition, the polished surface allows the structure of phases and minerals to be seen clearly and provides the best surface and geometric angle for the EDS. Due to their unique nature, certain objects, such as the goldsmithing crucibles from Hedeby, were not destructively sampled but were analyzed only on the surface.

An added factor to consider is the atmosphere within the SEM. To dissipate the build-up of electrons on the surface of the sample, which makes imaging difficult under high vacuum conditions, samples can be coated with a conductive medium. The prepared samples and the non-destructively analyzed objects were left uncoated[1] in order to limit the impact to the samples, but also to allow the samples to be analyzed by optical techniques. Electron charging, especially with the non-conductive samples, was overcome with a low vacuum using nitrogen gas (50-60 Pascal), although this is not ideal for the analytical results due to interaction between the gas and the electron beam. For metallic objects, conductive carbon tape and a high vacuum (under 0.5 Pascal) were used for the best analytical results.

The results of the EDS, particularly on prills and phases below 20 µm in size, can be greatly impacted by the surrounding matrix. The EDS obtains X-rays not only of the direct surface, but also a volume under the surface impacted by the electron beam. The size of the interaction volume is dependent on the energy of the electron beam and the density of the material analyzed. With elements of higher atomic numbers (Pb, Au, etc.), the interaction volume is smaller, and the lower the atomic number (Al, Si, Ca, etc.), the larger the interaction volume. At 20 kV the interaction depth can range from sub-micron to about 5 µm for the light elements (GOLDSTEIN et al. 2003). A certain amount of interaction is expected in the results of the SEM-EDS.

Peak overlap is a known problem with SEM-EDS analysis. This occurs when two or more elements produce similar X-ray frequencies, and in some cases they are difficult to separate from one another. The greatest problems occurred due to peak overlap between lead (Pb Lα) and arsenic (As Kα) and magnesium (Mg Kα) and arsenic (As Lα1). The separation of the peaks should be possible (WARD 1987), but the EDS software could not reliably do this. The presence of arsenic was checked with the Kβ1 peak, which has no overlap with

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[1] Conductive coatings of carbon or gold may be applied to discharge electron build-up.

any other peaks. When the peak was not visible above the background, the arsenic content was not calculated. Therefore, discussion of the arsenic content in phases is unfortunately limited. The peak overlap between sulfur (Kα/β) and lead (Mα) did not pose a problem for the software, as lead sulfide and lead were consistently distinguishable.

The NSS software is run without standards and relies on "Fitted Standard" calibration. This method gives values of approximately ± 2 percent on a polished section in a vacuum. Greater variation can be expected on samples with no preparation because of surface roughness and irregular measurement angles (GOLDSTEIN et al. 2003, 431, 476-80). The peak overlap, interaction volume, low vacuum, standardless quantification, and irregular sample geometry all lower the resolution and the analytical results. For these reasons, the results should be viewed as semi-quantitative. All results were normalized to 100 percent, and oxides were always calculated stoichiometrically.

Imaging based on the backscatter of electrons, as opposed to secondary electron imaging, was primarily used during the analysis of the archaeological material. Secondary electron imaging gives more information about the surface morphology, but the backscatter imaging method is best to determine differences in the density of the phases and minerals and greatly aids in their differentiation and identification.

6.2.3 Portable X-Ray Fluorescence

Being a method that is quick and inexpensive to perform and lacks complex sample preparation, portable X-ray fluorescence spectrometry (pXRF) is the ideal technique to screen for traces of non-ferrous metals in ore, ceramics and slag as well as determining major, minor and occasionally trace element concentrations of silver, lead, tin and uncorroded copper alloy objects. A Thermo Scientific, NITON XL3t Analyzer pXRF device was used at the Deutsches Bergbau-Museum Bochum (**Figure 6.3**). This method was used successfully to quickly classify alloys prior to mass spectrometry because of the alloy-dependent sample preparation procedures. In four instances the pXRF values for major elements were used for lead-tin alloys due to difficulties with sample dissolution and low analytical totals (**Appendix C**, **Table 5**, **Cat. 199**, **202**, **204**, and **207**).

An Innov X systems pXRF device was used to determine the major and minor elements of silver coins and objects as a control for the laser ablation inductively coupled plasma quadropole mass spectrometry measurements at the Leibniz Universität Hannover Institut für Anorganische Chemie. The methodology used is described in the thesis of LEHMANN (2011, 75-76, Anhang II). All silver objects measured in Hannover were analyzed by pXRF as a cross-check for major elements measured by mass spectrometry. Five of the objects measured had unusual compositions that could not be properly quantified by mass spectrometry; in these instances, the pXRF values for the major elements were used (**Appendix C**, **Table 1**, **Cat. 47** and **155-158**).

Figure 6.3 *Portable X-ray fluorescence device docked to a protective sample chamber, Deutsches Bergbau-Museum Bochum (Photo: S. Merkel 2012).*

6.2.4 Effects of surface enrichment

An important analytical problem must be mentioned regarding the methods that only measure the surface of objects, and it is that of surface enrichment. This applies to non-destructive analytical methods such as SEM-EDS and PIXE (partically induced X-ray emission), but in this context the emphasis is on XRF analysis. Intentional surface treatments performed in the past, the build-up of corrosion products or the cleaning of the objects can all influence the results of these techniques, and they will briefly be described below.

Copper and silver alloys behave differently during manufacturing processes and corrosion and therefore have very different surface enrichment characteristics. For copper alloys, tin and lead seem to be most mobile and corrode into carbonates, sulfates and chlorides that build up on the surface. Simply performing surface analyses of corrosion or patina of copper alloy objects will typically give overvaluation for the lead and tin content compared to the core of the object, and zinc, on the other hand, seems more resistant to corrosion and is less mobile (WADSAK et al. 2000, 161).

As opposed to copper, silver is a noble metal and is resistant to oxidation, which is a characteristic that is important in both manufacturing processes and in the corrosion of silver alloy objects. In the manufacture of silver coins, for instance, copper can be removed from the surface of the coin blank through oxidation and pickling with weak acid (Arles 2009, 461-503). The result of this process is a surface enrichment of silver. This can also happen when objects are cleaned after excavation. When corrosion is removed by cleaning with acids, the corrosion products, which are mostly copper based, are removed leaving behind a porous silver-rich surface. Beck et al. (2004) describes silver enrichment processes, both intentional and unintentional, which can lead to errors in calculating the silver content by surface analysis. The experimental work of Beck et al. (2004) proves that microstructure of the alloys can greatly influence the results.

As for the high zinc to copper ratios of archaeological silver, Mortimer (1986) discusses this topic in depth. A number of authors have run into interpretive problems because of high zinc contents in silver with surface analysis. There are even reports that there are higher copper to zinc ratios than technologically possible with the brass-making methods available in the early medieval period. McKerrell and Stevenson (1972, 201) argue for a previously unknown metallurgical process where calamine was used to directly enrich silver with zinc, but this is very unlikely because the poor uptake of zinc in silver (Mortimer 1986). The zinc content cannot be a relic of the ore, as Ströbele et al. (2010, 211) suggest, because smelting and cupellation remove zinc almost completely (McKerrell/Stevenson 1972; Pernicka/Bachmann 1983). The zinc content undoubtedly comes from brass used in alloying, and the problem with high ratios of zinc probably is due to the depletion of copper during corrosion and cleaning. Where non-destructive surface analyses like SEM-EDS and XRF are used, questions regarding the cleaning of the objects, corrosion, and analytical bias must be first answered before archaeological theories can be developed.

In both copper and silver alloys, the analysis of the surface can be misleading. Methods that penetrate deeper than 10µm may be sufficient to reach the unaltered core of silver alloys (Arles 2009, 489), but depending on the depth of corrosion, the depletion of copper, lead, tin, and other metals may reach 60-250µm (Arles 2009, 50; Lehmann 2011, 96). With copper alloy objects, corrosion layers can be quite thick, and analysis of surfaces from which the corrosion was removed may reflect a depletion of tin and lead which had been leached out into the corrosion. Drilling, cutting, or ablating objects seem to be the best methods to overcome the effects of corrosion.

6.2.5 X-Ray Diffraction

X-ray diffraction (XRD) uses X-rays to determine the crystal structure of a given sample, and is therefore only useful in identifying crystalline phases and minerals. Ore, slag, ceramics, and precipitates/un-dissolved residues from the metallic samples were measured with this technique. The analyses were carried out in the Forschungsstelle Archäologie und Materialwissenschaften at the Deutsches Bergbau-Museum Bochum. Powdered samples were run using a PAN alytical X'Pert instrument (PRO MPD) with X'Celerator detector and High Score Plus-software for analytical interpretation. The analysis requires about 100 mg of powdered sample (< 0.063 mm fraction size), and the samples were analyzed with ADS (automatic divergence slit) Cu-Kα-radiation of 1.54178 Å at 45 kV (40 mA) with angle array set to 5-70° 2-theta at a rate of 0.017°/10 sec. The data obtained by XRD are presented in the appendices (**Appendix H, Figure 3**; **Appendix I, Tables 3** and **4**).

6.2.6 XRF Artifact Scanning

At the Leibniz Universität Hannover an EDAX Eagle µ-Probe II micro X-ray fluorescence analyzer was used to gather more information about the composition and surface treatments on specific objects. The micro analyzer is able to provide elemental maps of entire objects as well as semi-quantitative elemental compositions. The instrument was operated using EDAX Eagle Probe Vision 32 software. Elemental composition scans of select objects are presented in **Appendix F**.

6.3 Quantitative Analysis: Mass Spectrometry – Elemental Analysis

Two mass spectrometers were used to analyze elemental concentrations in the archaeological and geological specimens. Specimens, which could be destructively sampled, were prepared and measured at the Deutsches Bergbau-Museum Bochum by single collector inductively coupled plasma mass spectrometry (SC-ICP-MS). These objects consisted of hacksilver, ingots, lead, and crucibles found at Hedeby, and ore and slag from various mining and smelting areas. Due to the rarity and high informative value, the silver coins and silver jewelry specimens were analyzed by laser ablation at the Leibniz Universität Hannover Institut für Anorganische Chemie. The methods of sampling and analysis for both laboratories are described below.

6.3.1 SC-ICP-MS

At the Forschungsstelle Archäologie und Materialwissenschaften at the Deutsches Bergbau-Museum Bochum, a Thermo Scientific Element XR SC-ICP-MS was used to measure major, minor, and trace element concentrations of a variety of materials. Analyses were performed with liquid solutions. A sample size of 10-100 mg is recommended to get a representative result. The bulk chemistry should be known prior to the dissolution of the samples because the acid or acid mixture needed is dependent on the objects composition. For this reason SEM, pXRF, and/or XRD were first used to better understand the chemistry and phase composition of the samples.

6.3.1.1 Sampling Methods

The samples taken for wet chemical analysis were taken by destructive means. Metallic objects were cut with pliers (scrubbed and cleaned with isopropyl alcohol) or were sampled by drilling either with a hand-held device or with a portable drill press (**Figure 6.4**) using stainless-steel drill bits[2] ranging from 1 mm to 2 mm wide. The drill bits were cleaned in isopropyl alcohol prior to use and were discarded after each use to prevent cross-contamination. The contamination from the drill bits themselves is minimal and below the level of detection (Prange 2001, 42). The drillings were collected on clean wax paper and placed in individually labeled glass or plastic vials. Ore samples, crucible fragments, and slag samples were cut using a circular table saw or were broken into smaller fragments. The lead-rich crucible slag and powdery residues from cupellation/refining dishes were scraped or hand-selected from crushed fragments. All slag, ceramic, and glass samples were crushed using steel implements and milled using agate ball-mills, which were cleaned with a solution of five percent hydrochloric acid in distilled water and through the crushing of quartz sand.

***Figure 6.4** Taking samples of metallic objects with portable drill press at Schloss Gottorf (Photo: V. Hilberg 2013).*

6.3.1.2 Chemical Digestion

Samples of 10-25 mg of silver were dissolved using dilute nitric acid (2 ml H_2O : 1 ml 14.5N HNO_3). Samples were left to dissolve for 1-3 days. For copper alloys, about 25-50 mg of each had been dissolved in a mixed hydrochloric and nitric acid (2 ml H_2O : 1 ml 14.5N HNO_3 : 1 ml 7.8N HCl). The lead samples, 50-100 mg, were dissolved in dilute nitric acid (5 ml H_2O : 3 ml 14.5N HNO_3), but with mixtures of lead and tin, the tin forms insoluble hydroxide compounds in concentrated nitric acid and requires a second digestion with dilute HCl to dissolve the tin for a complete measurement. Depending on the original sample size, the silver, copper, and lead solution concentrates were then filled up to 10, 25, 50, or 100 ml with ultra-pure water in order to produce a solution of approximately 1000 ppm for the ICP-MS.

Quantifying gold in metals is problematic without aqua regia digestion. In order to measure the gold content of the silver objects, a minimum of 10 mg of sample material was mixed with aqua regia (3 ml 7.8N HCl : 1 ml 14.5N HNO_3). Since the HCl of the aqua regia reacts with both silver and lead to form insoluble chlorides which greatly slows the dissolution process, the samples were first dissolved in dilute nitric acid (2 ml H_2O : 1 ml 14.5N HNO_3) followed by evaporation. Concentrated 14.5N HNO_3 was added to break up the precipitates and then quickly mixed with 7.8N HCl to make the ratio of aqua regia. The Teflon beakers containing the solutions were heated overnight at 105 ˚C to extract as much gold as possible into the solution.

The digestions of silica-bearing samples (ore, slag, and crucibles) had been carried out with a µPREP-A microwave[3] using concentrated acids. The sample size was 100 mg of pulverized material. When lead was not a major or minor element, the sample material was digested in PTFE pressure vessels with a mixture of concentrated acids (6 ml HCl : 1.75 ml HF : 4.8 ml HNO_3) for forty minutes at 250 °C. Lead-based samples had been mixed with 1.75 ml HF and 11 ml HNO_3. In a second step, 10 ml of boric acid (50 g/l) were added and the samples were then heated to 200 °C for twenty minutes to avoid the precipitation of calcium fluoride and aluminum fluoride. Finally, digestions were diluted with ultra-pure water up to 100 ml.

6.3.1.3 Analysis and Quantification

Elemental analyses were performed with a Thermo Scientific ELEMENT XR ICP-MS. For main element analysis, sample solutions had been diluted 1:100, for traces 1:10 with 5 percent HNO_3 solution. The analyses were carried out with a FAST SC-system, ST 5532 PFA µ-FLOW nebulizer, Peltier-cooled PFA spray chamber and 1.8 mm sapphire injector in triple detector mode at all three different mass resolutions ($m / \Delta m$) depending on the elements of interest. Measurements were calibrated with standards for silver[4], copper[5], bronze[6], tin[7], lead[8], ceramic[9] and mineral samples.[10] A total of sixteen elements were measured for the silver and copper alloy artifacts (Ag, Cu, Au, Bi, Zn, Sn, Pb, Fe, Co, Ni, As, Sb, Se, Cd, Te, and Hg) and for the lead objects phosphorous

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[2] Type DIN HSS-E 338 Co, 5 percent cobalt.

[3] MLS GmbH.

[4] RAgP6 (Rand Refinery Ltd., MBH Reference Materials).

[5] BAM-376 (Bundesanstalt für Materialforschung und –prüfung).

[6] Bronze C (British Chemical Standards).

[7] NF-54/1 (Brammer Standard Reference Material).

[8] PG1 to PG6 (Institute of Non-Ferrous Metals, Poland).

[9] GBW 07107 (Brammer Standard, MC Certified Reference Material).

[10] FER-2 (Canadian Certified Reference Materials Project) and GF-1 (Bergakademie Freiberg, BAF).

was also analyzed. For the ore and slag, twenty-four elements were measured (Na, Mg, Al, Si, P, K, Ca, Ti, Mn, Fe, Zn, Ba, S, Pb, Cu, Ag, Sb, Te, Bi, Sn, Co, Ni, As, and Se).

Depending on the type of material analyzed, the results are presented in either metallic or in oxide form. The major and minor elements of the ore and slag were manually calculated to oxides through stoichiometry. Particularly regarding the slag, the transition metal iron is often present in both ferrous (FeO) and ferric (Fe_2O_3) form. No effort was made to quantify the proportion of each form, and they are presented in their ferric form, which is reflected in the analytical totals. The results are presented in **Appendix C, Tables 3-8**.

6.3.2 Laser Ablation ICP-QMS

At the Leibniz Universität Hannover Institut für Anorganische Chemie, an inductively coupled quadrupole mass spectrometer coupled with a nanosecond laser ablation system (ns-LA-ICP-QMS) was used to measure the major, minor and trace elements of selected silver coins and jewelry. The New-Wave nanosecond laser ablation system[11] was used because of the wide range of elements that could be analyzed. Lehmann (2011, 40-51, 93-98) describes the laser system, quadropole mass spectrometer, and the methodology in detail. The coins and objects were placed in a clear plastic sample chamber that was under a low vacuum, and a helium gas stream was used to carry the ablated particles into the plasma torch. A laser beam size of approximately 100 µm was used to ablate the sample. After ablation, the coins and objects were cleaned with isopropyl alcohol to remove the superficial traces of ablation.

Each object was analyzed for 340 seconds and sixty-eight elements were measured simultaneously. A NIST 612 glass standard, two micro-homogenized silver standards[12] produced to emulate historic and archaeological silver (Lehmann 2011, 70-4 for methodology) and an industrial silver certified reference material (Fluxana 721) were measured in order to calibrate the results and to ensure the quality of the measurements. A confidence interval of ninety-five percent probability was calculated for nearly all elements measured which takes into account the standard deviation and the number of measurement cycles.

Approximately 10 percent of the analyses were problematic due to poor signals, heterogeneity, or extensive corrosion. These analyses were quantified and are signified in the list of results.[13] Lehmann (2011, 49) lists the detection limits for the various elements, but an effort was made to identify the level of reliability by taking into consideration the ninty-five percent confidence intervals, the measurement resolution, and the presence of negative elemental values. The elements most important for the study of silver and copper (Ag, Cu, Ag, Zn, Sn, As, Bi, Pb, Sb, Co, Ni, and Hg) and some selected trace elements (Pt, Se, Cd, Pd, In, Tl)[14] are presented in **Appendix C**, **Tables 1** and **2**.

For many of the other measured elements, concentrations were too low to detect or to properly calibrate and will be left out of the discussion. Other elements either appear random in their distribution or show little variation and are otherwise not useful in differentiating objects from one another. A summary of all the elements measured is listed in **Table 6.1**.

6.4 Quantitative Analysis: Mass Spectrometry - Lead Isotope Analysis

Two laboratories performed the lead isotope analysis involved in this study. Multi-collector ICP-MS was used because of the high precision and accuracy obtainable (Baron et al. 2014; Klein 2007; Niederschlag et al. 2003).The archaeological samples were dealt with differently depending on the availability of sample material. Destructively sampled objects were analyzed at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften as liquid solution, and coins and jewelry objects were analyzed by laser ablation at the Leibniz Universität Hannover Institut für Mineralogie. The sampling and analytical methodology will be described in the following section.

6.4.1 Lead Isotope Analysis with Multi-Collector ICP-MS

The lead isotope ratios were determined with a Thermo Scientific Neptune inductively coupled plasma multi-collector mass spectrometer at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften. Some information concerning the analytical methodology can be found in Klein et al. (2009, 62-4). This method required liquid solutions of the lead, and, therefore, destructive sampling and dissolution.[15] Sample solutions containing higher than 0.7 weight percentage lead were diluted and analyzed without further preparation steps. For samples with lead concentrations under 0.7 weight percent, elemental lead was chemically separated from the matrix to mitigate the impact of matrix elements like copper on the mass spectrometer measurements.

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[11] Nd: YAG-Laser 213 nm.

[12] The silver standards are named NA1 and NA2 and were tested at the Norddeutsche Kupferraffinerie in Hamburg (Lehmann 2011, 93).

[13] **Appendix C, Tables 1** and **2**.

[14] These elements were selected because they show significant variation that may be meaningful. The resolution of platinum is poor, but the presence appears to be related to gold and may be a useful provenance indicator.

[15] See section **6.3.2.1** and **6.3.2.2.**

Atomic Mass	Element	Highest Value	Lowest Value	Detection Limit
24	Mg	LOD	LOD	100
27	Al	800	LOD	100
45	Sc	300	LOD	100
47	Ti	130	LOD	10
51	V	30	LOD	0.2
52	Cr	80	LOD	12
55	Mn	130	LOD	0.7
56	Fe	10000	LOD	1000
59	Co	50	LOD	0.1
60	Ni	200	LOD	0.1
65	Cu	>10000	10	1
66	Zn	>10000	LOD	1
69	Ga	15	LOD	0.1
72	Ge	4	LOD	1
75	As	1600	0.1	0.1
82	Se	75	LOD	6
85	Rb	1	LOD	0.1
88	Sr	25	LOD	0.02
89	Y	1	LOD	0.01
90	Zr	1	LOD	0.02
93	Nb	1	LOD	0.3
95	Mo	1	LOD	0.2
101	Ru	0.1	LOD	0.08
103	Rh	4	0.1	0.05
105	Pd	15	LOD	0.3
107	Ag	>10000	-	1
111	Cd	10	LOD	0.8
115	In	0.6	LOD	0.1
118	Sn	>10000	LOD	1
121	Sb	2300	0.2	0.1
125	Te	Disrupted	Disrupted	-
133	Cs	4	LOD	0.01
137	Ba	55	LOD	0.3
139	La	0.5	LOD	0.01
140	Ce	0.3	LOD	0.01
141	Pr	0.7	LOD	0.01
146	Nd	0.3	LOD	0.04
147	Sm	Disrupted	Disrupted	-
152	Sm	0.3	LOD	0.1
153	Eu	0.6	LOD	0.1
157	Gd	2	LOD	0.6
159	Tb	0.2	LOD	0.1
163	Dy	0.4	LOD	0.2
165	Ho	0.05	LOD	0.01
166	Er	LOD	LOD	0.01
169	Tm	LOD	LOD	0.01
172	Yb	LOD	LOD	0.01
175	Lu	LOD	LOD	0.01
178	Hf	LOD	LOD.	0.01
181	Ta	LOD	LOD	0.01
182	W	750	LOD	0.3
185	Re	LOD	LOD	0.01
189	Os	0.8	LOD	0.1
193	Ir	0.4	LOD	0.04
195	Pt	1.6	LOD	0.1
197	Au	9000	LOD.	1
200/202	Hg	500	LOD	5
205	Tl	140	LOD	0.1
204/206/207/208	Pb	>10000	7	0.01
209	Bi	>10000	8	0.1
232	Th	0.08	LOD	0.05
238	U	0.2	LOD	0.01

Table 6.1 *Table showing a summary of the range of results obtained by the ns-LA-ICP-QMS. The elements measured are listed with the highest and lowest values measured and the detection limits in parts per million (ppm). The elements Te and Sm were not possible to quantify. 'LOD' means at or below the limit of detection. The estimated detection limit is a combination of the detection limits presented by* LEHMANN *(2011, 49) and the observed trends in the quality of the dataset.*

6.4.1.1 Lead Separation from Ores and Metals

Sample preparation took place in the Clean-Air Laboratory at the Deutsches Bergbau-Museum Bochum. Rock and metallic samples with trace amounts of lead (Pb) and the silver alloys underwent column-chromatography with anion-exchange resin.[16] Rock samples (~80 mg initial weight for samples with about 100 ppm Pb concentration) had been dissolved in 5 ml concentrated acid (5 ml:1 ml, HF:HNO_3) and the silver alloys were dissolved in dilute nitric acid (2 ml:1 ml, H_2O:HNO_3) in Teflon beakers at 100 °C. The solutions were evaporated at 105°C, remixed with 1 ml 7N HBr and 6 ml ultra-pure water and centrifuged for ten minutes. The anion exchange resin was placed in 1 ml quartz columns, cleaned with several runs of 1.5 resin volumes (RV) 6N HCl and 3 RV ultra-pure water, and then conditioned with 3 RV 1N HBr before addition of the dissolved samples. Before elution of Pb with 4.5 RV 6N HCl into Teflon beakers and evaporation, resin was again conditioned with 2 RV 1N HBr and 2 RV 2N HCl.

6.4.1.2 Measurement, Data Processing and Quality

At Frankfurt am Main, the samples were measured in several sessions. The solutions were run for twenty to sixty cycles. SRM 981 Pb and SRM 997 Tl isotope

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[16] BIO-RAD Laboratories, AG®1-X8 Resin.

standards were used to correct mass fractionation and instrumental bias/drift.

A ^{203}Tl/^{205}Tl (SRM 997 Tl) standard solution was run together with every analysis to correct for mass fractionation; the computer software automatically corrected the results. The interference of ^{204}Hg with the ^{204}Pb isotope was checked by measuring the ^{202}Hg signal for the sample and was automatically corrected. When in small amounts, mercury is easy to correct because the ratio of ^{202}Hg to ^{204}Hg is always constant, but uncorrectable error can occur when mercury is present in higher amounts, which unfortunately influences the lead isotope ratios containing ^{204}Pb.

The mass bias/instrumental drift was corrected using the measurements of the SRM 981 Pb isotope standard. The SRM 981 Pb was measured every six to fourteen runs. In reference to Baron et al. (2014), the values obtained by the SRM 981 Pb were used to normalize the data to values obtained with the double spike technique presented by Todt et al. (1996).[17] This was performed to better insure comparability between the measurements over long periods of time and between laboratories. The SRM 981 Pb measurements were used to bracket the samples and the nearest SRM 981 Pb was used for normalization. The values obtained for SRM 981 Pb are presented in **Appendix D**, **Table 8.**

Measurement spikes, or anomalous peaks, were rarely present, but when identified, peaks of greater than 3σ standard deviation were rejected by the software up to a maximum of ten percent of the total cycles. The isotope data is presented in **Appendix D**, **Tables 3**-**7**.

6.4.2 Lead Isotope Analysis with Laser Ablation

A Thermo Scientific Neptune multi-collector inductively coupled plasma mass spectrometer coupled with a femtosecond laser was used to obtain lead isotope abundances at the Leibniz Universität Hannover Institut für Mineralogie. Lehmann (2011, 51-3 and 79-92) gives information about the instrument and methods of analysis in detail and the department website provides additional information.[18] Briefly summarized, the mass spectrometer has nine Faraday detectors, a secondary electron multiplier and two compact discrete dynode secondary electron multipliers for isotopes with very low signal intensities (<10^6 cps; attached to the L4 and H4 Faraday detector, respectively). One amplifier with a 10^{12} Ω feedback resistor can be selected for a low signal intensity (typically <$5*10^{-13}$ A≡50 mV), and nine amplifiers with 10^{11} Ω resistors are installed enabling measurement of signals of up to <$5*10^{-10}$ (A≡50 mV). The Neptune uses a stable introduction system (SIS) quartz glass spray chamber combined with nebulizers, and to measure the metal samples a femtosecond laser ablation system was used. The objects were placed in a sealed sample holder under low vacuum conditions and streams of helium gas functioned as a carrying medium. The sample material entered the plasma torch chamber as an aerosol produced by the femtosecond laser. The isotopes ^{202}Hg, ^{203}Th, ^{204}Pb, ^{205}Th, ^{206}Pb, ^{207}Pb, and ^{208}Pb were measured simultaneously.

6.4.2.1 *Data Quality and Correction of Isotope Data*

Three measuring days were used to analyze the material, and 182 individual objects were tested with 208 ablations. The data quality produced by the mass spectrometer was checked against the SRM 981 Pb before, during and after each measurement session. Standards were measured for 120-500 cycles, and the ablation of objects lasted for 100 to 120 cycles. Instrumental bias was corrected manually by normalizing to the SRM 981 Pb values published by Todt et al. (1996) with the methods described above (**6.4.1.2**). A problem occurred on one measurement day (29th of Sept. 2012) in that the standard measurements were poor, probably due to over stimulation of the ^{208}Pb detector during the measurement of the SRM 981 Pb. The high errors associated with the ^{208}Pb are only found in the standard measurements and not in the artifact measurements. For this reason, the correction to the values of the ^{208}Pb standard measurements would impart an artificial error. All ratios besides the ^{208}Pb ratios were corrected using the standard measurements, and, with no other viable alternative, the ^{208}Pb ratios were corrected to the values obtained in the previous session. Mass fractionation was corrected with the SRM 997 Tl isotope standard. A ^{203}Tl/^{205}Tl (SRM 997 Tl) standard solution was run together with every analysis to correct for mass fractionation and the data produced was automatically corrected by the computer software following the values obtained by Begley and Sharp (1997) and following the formula given by Faure (1986). The analyses of the isotope standards are presented in **Appendix D**, **Table 8**. The ^{202}Hg content was measured and the interference of ^{204}Hg with ^{204}Pb was automatically corrected to the extent possible (Lehmann 2011, 80, 87-8).

Due to the heterogeneous nature of the sample material obtained by laser ablation, some added quality control measures were applied. Abnormal peaks or spikes were marked by the software and were excluded from the sum (peaks with greater than 3σ standard deviation and up to 10 percent of the total cycles). To assess the homogeneity of the data, the data quality was visually checked by graphing the ratios and isotope abundance. Sections of unstable signals and additional erroneous peaks not removed by the software could be clearly seen. In a homogeneous sample, a line forms, but in heterogeneous samples there are strong fluctuations in the isotope ratios. The stability of the current

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[17] The formula used to create a correction coefficient is as follows: $((R_{true}-R_{meas})/R_{meas})$ +1.

[18] www.mineralogie.uni-hannover.de/min_neptune.html#1143 accessed 07.04.2014.

was also checked to make sure there was no disruption in the ion stream.

The corrected isotope data are presented in **Appendix D**, **Tables 1** and **2**. For normal homogeneous data, which was the majority, the anomalous peaks identified by the software were taken out and re-averaged and the standard deviation was automatically recalculated. The problematic data with high standard deviations are summarized below. Several objects were analyzed twice or three times and give an impression of the homogeneity of the isotope ratios.

Causes of Uncorrectable Errors

- **Poor Measurement of ^{204}Pb**
  There may be several causes for the poor measurement of ^{204}Pb because it is the scarcest of the four stable isotopes of lead. This makes it the most affected by low lead concentrations. For the coins with low lead concentrations (<1000 ppm) or otherwise poorly measured ^{204}Pb ratios a higher frequency laser beam was necessary (see Lehmann 2011, 83) and eleven coins were re-analyzed on February 3rd 2012 (Analyses #241 - #251). Despite the use of a stronger beam, high standard deviations were obtained for the ^{204}Pb ratios of these coins. The ratios containing the ^{204}Pb values have high error, but the other isotope ratios have standard deviations at the usual level.

- **Corroded or Mixed Silver**
  Five analyses were exceptionally heterogeneous. Analyses #68, #69, and #74 are of semi-melted clumps of hacksilver and coins, and it is not surprising that they are extremely heterogeneous and that a clear signal was unobtainable. Analysis #244 is definite corrosion, whereas for analysis #221 it is not clear if corrosion or heterogeneity is the cause for the high standard deviation. All of these analyses showed too much variability to be further corrected.

- **Mercury Contamination**
  Two analyses, #157 and #190, both coins from North Africa, show unusual ^{204}Pb abundances, and these values likely come from mercury contamination. Mercury coatings on coins from Maghreb mints have been documented in several instances (Heidemann 2011, 457; Ilisch et al. 2003, 110-1; Kaczmarczyk et al. 1977). The mercury coating of the two coins (**Cat. 3** and **4**) can be seen in the counts of the first milliseconds of the Laser Ablation ICP-MS, but afterwards it has much lower concentrations. Two of the four coins from North Africa did not have the same problem and the ^{204}Pb values are much more homogenous (**Cat. 1** and **2**). The analyses may have been in areas where the coating has been worn away, or the coins may not have had mercury surface enrichments.

Manual Correction

- **Measurement Segments Cut**
  The standard deviations of several analyses were abnormally high and the data was inspected to find the source of the error. Due to corrosion or perhaps due to irregular surface morphology, segments of the data showed very heterogeneous results. In these cases the stable segments were taken. One analysis was only stable for 35 cycles, but in general, 50 or more continuous cycles were taken. Eleven analyses were corrected in this way.[19]

- **Outliers**
  Analyses #214, #217, #266 and #272 show instable signals. Therefore, an additional correction was applied. Automatically, the cycles with the highest deviations were excluded by the software, but to exclude more outliers the standard deviation was recalculated a second time and the points with greater standard deviations than 3σ were rejected with a maximum rejection of 10 percent of all measured cycles.

6.5 Control Points and Data Compatibility

Multiple laboratories and instruments were used to generate the analytical data presented in this thesis. The various instruments and laboratories have different procedures and rely on different physical and chemical principles, and, therefore, differences in the results are to be expected. To illustrate these differences, two hacksilver samples (**Cat. 180** and **187**) were analyzed by all methods.

6.5.1 Compatibility of Elemental Analysis

Four methods were used to determine the elemental composition of artifacts: LA-ICP-QMS, ICP-MS, pXRF and SEM-EDS. The two hacksilver samples were measured with each of these instruments and the data are presented in **Table 6.2**. The quantitative mass spectrometry results are relatively similar. Major differences are observed in the copper and silver contents. There appears to be a general tendency for the Hannover analyses to have lower copper contents. It is not clear if this is related to the effects of surface enrichment of silver from the LA-ICP-MS measurements as opposed to the ICP-MS analyzes, which measure the bulk concentration. This may also be due to methodological or instrumental differences, but what is clear is that the difference in copper concentrations may be as high as 3 to 4 weight percent. Silver concentrations are lower by ICP-MS than by laser ablation in Hannover. This is partially due to the

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[19] These are analysis numbers 169,174, 196, 205, 212, 215, 220, 241, 264, 266, and 269.

Cat. Nr.	Method	Analyses	Location	Ag	Au	Cu	Zn	Sn	Sb	Hg	Bi	Pb	Co	Ni	Se	Cd	Fe	Sum
				%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	%	%
180	LA-ICP-MS	x1	Hannover	96.7	0.42	2.8	0.05	0.02	0.001	0.001	0.016	0.49	0.3	1.8	8.6	<1	<0.4	100.5
180	ICP-MS	x1	DBM	91.0	0.35	4.2	0.03	0.01	<0.001	<0.001	0.014	0.52	0.1	1.8	6.7	10	0.01	95.8
180	pXRF	x2	DBM	94.1	0.54	2.7	0.07	-	-	-	0.03	0.43	-	-	-	-	0.31	97.9
180	SEM-EDS	x3	DBM	95.0	-	3.1	-	-	-	-	-	-	-	-	-	-	-	100

Cat. Nr.	Method	Analyses	Location	Ag	Au	Cu	Zn	Sn	Sb	Hg	Bi	Pb	Co	Ni	Se	Cd	Fe	Sum
				%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	%	%
187	LA-ICP-MS	x1	Hannover	96.1	0.17	3.4	0.35	0.024	0.005	0.001	0.063	0.94	1.1	2.6	<6	<1	<0.4	101.0
187	ICP-MS	x1	DBM	90.2	0.20	6.8	0.44	0.023	0.008	<0.001	0.066	1.18	1.2	15	<5	10	0.01	98.7
187	pXRF	x2	DBM	91.4	0.21	6.0	0.45	-	-	-	0.08	1.3	-	-	-	-	0.15	99.5
187	SEM-EDS	x3	DBM	94.3	-	3.4	0.4	-	-	-	-	-	-	-	-	-	-	100

Table 6.2 *Two silver objects analyzed with the various types of elemental analysis used in this study. The primary difference between the mass spectrometry at Hannover and in Bochum is that the copper contents are slightly lower in the Hannover analyses. The various methods measure in very different ways. The ICP-MS analyses represent homogenized, dissolved samples whereas the laser ablation represents a single 100 µm diameter area of the sample. The pXRF and the SEM-EDS are non-destructive surface analyses with higher detection limits for many elements. For the mass spectrometer measurements below the detection limit, the limits of detection are shown. The "-" means below the detection limit for the pXRF and SEM-EDS analyses.*

Cat. Nr.	Measuring Place (Date)	^{206}Pb/^{204}Pb	2σ	^{207}Pb/^{204}Pb	2σ	^{208}Pb/^{204}Pb	2σ	^{207}Pb/^{206}Pb	2σ	^{208}Pb/^{206}Pb	2σ
180	Frankfurt/Main (15.10.12)	18.452	0.004	15.639	0.004	38.48	0.02	0.8475	0.0001	2.0855	0.0004
180	Hannover (2.2.12)	18.457	0.017	15.643	0.016	38.49	0.04	0.8475	0.0004	2.0855	0.0011
187	Frankfurt/Main (15.10.12)	18.533	0.006	15.66	0.006	38.65	0.01	0.8449	0.0001	2.0854	0.0003
187	Hannover (2.2.12)	18.535	0.004	15.662	0.004	38.66	0.01	0.8449	0.0001	2.0856	0.0003

Table 6.3 *Two silver objects found at Hedeby were tested by laser ablation and as liquid sample at the laboratories in Hannover and Frankfurt am Main to demonstrate compatibility between the two data sets. The analyses from Frankfurt am Main represent homogenized bulk samples while the laser ablation represents only a small region measured by spot analysis.*

loss of silver chloride corrosion in the analytical totals of the ICP-MS, but the difference between bulk and near-surface analysis may also be an important factor.

The gold, zinc, tin, bismuth, lead, antimony, lead, cobalt, and selenium contents show good conformity between the mass spectrometers, but nickel and cadmium are less reliable. The pXRF accurately measured gold and zinc and, to some extent, bismuth and lead as well. Copper and silver measured with the SEM-EDS fit within the range of the two mass spectrometers and the pXRF, but most trace elements could not be quantified by this technique.

6.5.2 Compatibility of Lead Isotope Analysis

The lead isotope ratios determined by fs-LA-MC-ICP-MS and MC-ICP-MS show excellent conformity, despite the very different sampling methods (**Table 6.3**). The laser ablation was capable in both cases to measure the isotope ratios within two standard deviations of the values collected by liquid solution. In these two cases, the microscopic ablation area was able to capture the heterogeneity of the silver and is directly comparable to the values produced from a homogenized bulk solution. With this said, care must still be taken because the objects may have different levels of homogeneity. This is clear from the few duplicate and triplicate analyses, such as the variation between the three analyses of **Cat. 106**. There seems to be a small discrepancy in ^{204}Pb ratios between the analyses from the two laboratories, but the difference is still smaller than two standard deviations and are, therefore, negligible.

6.6 Closing

Detailed descriptions of the analytical methods, procedures and the data quality are important for the evaluation of the data, and, in the end, are imperative for the reliability of archaeological evidence and theories developed upon their foundation. The various analytical approaches used in this study were developed to consider the limitations surrounding the archaeological material but also the financial limitations and the analytical capabilities of the instruments available. The use of multiple instruments and laboratories makes the evaluation and application of the data complex and tedious; however, the use of various laboratories and instruments establishes a clearer picture of the comparability of data produced under various circumstances and attests to their consistency. Quantitative and qualitative analyses provide information regarding medieval technologies, such as mining, smelting and recycling, and the characterization and trade of metals, themes that will be developed in the coming chapters.

7. Chapter
Analytical Results and Discussion

7.1 Introduction

A wide range of materials were analyzed, and although they were analyzed to answer questions concerning the overarching theme of silver and silver metallurgy, the different objects were sampled to look at specific facets. In order to present the results of this study in an intelligible way, the materials have been divided into groups. The main questions of this thesis regard the chronological changes to the silver composition at Hedeby, and the structure of results and discussion chapter reflects this focus.[1] In this chapter the results of the mass spectrometry of silver objects will be presented in reference to the chronologic groups of Hedeby / Danish coins outlined in **Chapter 5** (**5.4.1**). The discussion of the origins of the silver at Hedeby will be, thus, in terms of the most comparable material and their chronological and archaeological feasibility. First, general interpretations of the dataset will be presented, followed by the characterization and interpretation of the silver in terms of the four chronological Hedeby / Danish coin groupings.

7.2 General Data Trends

7.2.1 Trends in Elemental Composition

As outlined in previous chapters, the composition of silver stems from both anthropological and geological factors. The gold content of early medieval silver, which is typically under one percent, is thought to come from the silver ore, although there may be some contribution from the recycling of gilded silver. The presence of copper can reflect residual copper that remains in the silver after cupellation or it can be an intentional addition to the alloy. Due to differences in the production process, refined silver has low amounts of elements like cobalt, nickel, arsenic, and antimony; however, metallic copper can be associated with these elements in more significant amounts. In the objects analyzed, the presence of elevated amounts of arsenic, antimony, cobalt, and nickel (**Figures 7.1 a-d**) is related to the copper content. Such as in the graphs of cobalt and nickel, copper must not be associated with higher amounts of these elements. The elemental variation may reflect different sources of copper or copper alloys.

Zinc and tin are also effectively removed during the refining of silver, and the presence of elevated quantities of zinc and tin likely reflects mixing with copper alloys after the refining of the silver. **Figures 7.1e-f** show that, although there is a clear correlation of zinc to copper (meaning brass), the tin content has a weaker correlation, and the ratio is typically lower than the composition of bronze. Some objects with low quantities of copper have elevated tin contents, and, in these cases, metallic tin may have become incorporated into the silver rather than in the form of tin bronze.

Bismuth is an important element in the provenancing of silver because it can be present in distinctive amounts and is problematic to remove completely from silver with cupellation. Bismuth can also be found in copper and copper alloys in trace amounts, however **Figure 7.1g** indicates that the high quantity of bismuth found in many silver objects is inversely proportional to the copper content. Any argument that alloying is responsible for the high amounts of bismuth content in the silver is improbable. Lead also seems to be very weakly correlated to the copper content. Irrelevant to the copper content, most silver objects have less than one percent lead. Silver debased with copper-alloys can have as high as 2.5 percent lead, but improperly refined silver from Afghanistan, for instance, can have low copper contents yet still have lead contents in the percentage range. Therefore, the relationship of copper to lead is more complex and must be discussed on a case-by-case basis.

The gold content is entirely independent from the copper content, but there is a visible relationship between the gold and platinum content. Like gold, platinum is a noble metal and survives the cupellation process completely. As gold can be used as a distinctive element for the provenancing of silver, platinum has not been explored. It seems from **Figure 7.1h** that platinum and gold are generally correlated, but the differences in the platinum to gold ratios have yet to be systematically investigated to determine if they are relevant for provenance studies of silver.

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[1] The results of the analysis of technical ceramics from Hedeby, lead and tin objects, and the material from the production sites in Central Asia will be dealt with in the appendices (**Appendices G-I**), and the conclusions formed from these studies will be synthesized in **Chapter 8.**

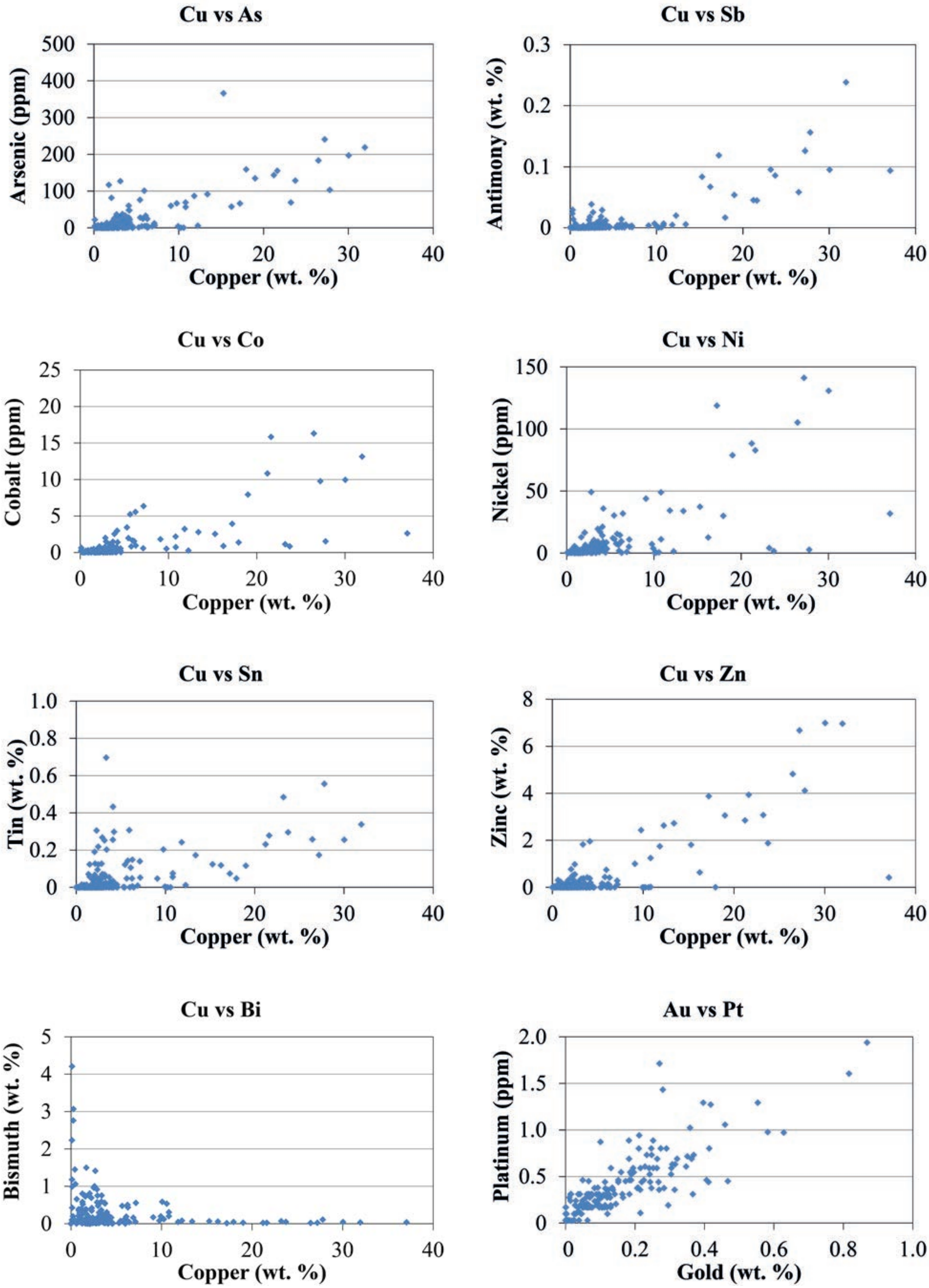

Figure 7.1 (a-h) *These graphs show the relationships between element pairs in the analysis of all silver objects analyzed by ns-LA-ICP-QMS. Arsenic, antimony, nickel, cobalt, tin, and zinc are positively related to the copper content, but bismuth is inversely related. Platinum and gold are correlated.*

Groups	Coin Types	Years (AD)	(n=)	Ag	Cu	Au	Bi	Zn	Sn	Pb
				%	%	ppm	ppm	ppm	ppm	ppm
Group 1	KG 7	900-920	x9	96.7	2.8	2900	990	980	1300	5000
				± 1.4	± 1.3	± 710	± 400	± 730	± 920	± 1300
Group 2	KG 8-11	950-980	x9	92.1	7.4	1900	2900	100	120	4000
				± 3.6	± 3.5	± 1000	± 1800	± 170	± 220	± 2700
*Outlier 1	KG 10a	975-980	x1	93.4	3.4	8100	5900	18000	7000	24000
*Outlier 2	KG 10a	975-980	x1	96.3	3.7	6	180	1	2	2500
Group 3	Årstadt-Harthacnut	1015-1035	x6	96.6	3.0	1200	630	2200	900	4500
				± 1.4	± 1.3	± 350	± 200	± 1600	± 840	± 2700
Group 4	Sven E.-Cnut the Holy	1047-1086	x13	74.0	21.9	930	420	40000	2500	9300
				± 9.1	± 7.6	± 310	± 260	± 18000	± 1400	± 5200

Table 7.1 *Average elemental compositions of the Hedeby/Danish coin groups determined by laser ablation ICP-QMS. Two outliers from Group 2 are presented separately because they deviate greatly from the average composition of this coin group. The standard deviations (1σ) are given so that the homogeneity of the compositions can be evaluated.*

7.2.2 Lead Isotope Composition Representation and Trends

There are four stable isotopes of lead and to visually represent all isotopes three isotope ratios are needed. Typically in archaeology the isotope ratios ^{208}Pb/^{206}Pb, ^{207}Pb/^{206}Pb, and ^{204}Pb/^{206}Pb are used whereas in geological applications the ratios are in respect to ^{204}Pb (Gale/Stos-Gale 2000, 507). **Figures 7.2**-**7.5** are lead isotope diagrams of the silver objects analyzed in this study. The graph with the ratio pairs ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb have standard deviations smaller than the symbols, but all graphs with ^{204}Pb have notably higher average standard deviations and the data are influenced more heavily by mercury contamination and the quantity of lead in the sample.

The ratios to ^{204}Pb gives important information about the geologic origin of the ore used to create the metal, but these ratios were difficult to measure in the past and were often with high errors. It has been recently argued that all isotope diagrams should be in relation to ^{204}Pb (Baron et al. 2014), but concerning the present dataset, the ratios of ^{204}Pb can only be used with objects having a stable and clear ^{204}Pb reading. Without the sixteen objects with abnormally high standard deviations for ^{204}Pb, meaning greater than double the average 2σ for the dataset, the 2σ is often smaller than the symbols (**Figures 7.4** and **7.5**), although, this is dependent on the scale of the diagram. So that all objects analyzed can be included in the interpretation and to conform to the convention used in archaeology, the ^{207}Pb/^{206}Pb to ^{208}Pb/^{206}Pb representation will be one of the primary diagrams used to interpret the lead isotope data. Much of the isotope variation can be found in the ^{207}Pb/^{206}Pb to ^{208}Pb/^{206}Pb representation and the high precision measurement of these isotopes can be more clearly visualized in this form. Rather than the traditional ^{207}Pb/^{206}Pb to ^{204}Pb/^{206}Pb diagram, which provides little interpretive value for this dataset, ^{204}Pb will be presented in the diagram ^{206}Pb/^{204}Pb to ^{208}Pb/^{204}Pb. The relatively small standard deviations for this diagram provide a better basis for interpretation than the ^{206}Pb/^{204}Pb to ^{207}Pb/^{204}Pb diagram.

In **Figures 7.2-7.5** some of the major lead isotope trends can be seen. Isotope ratios are diverse, ranging from geologically young to geologically old, and demonstrate diverse origins of the lead reservoir (see Chiaradia et al. 2006, 416-8). In **Figure 7.2** the differing elevations along the Y-axis and the differing slopes are due variations in the ^{208}Pb content, which are controlled by the quantity of thorogenic lead acquired during ore formation. These differences in slope are archaeologically and geologically meaningful and will be explored in this chapter.

7.3 Characterization of the Hedeby/Danish Coin Groups

Forty-one coins minted at Hedeby and other Danish mints were analyzed by laser ablation. The coins were divided into four chronological groups and the elemental compositions of the coin groups are summarized in **Table 7.1**. The standard deviations are presented to give an impression of the homogeneity between the coin alloys. Group 1, consisting of the Malmer KG 7, coinage is distinguished by its slightly higher average gold content and has minimal bismuth, zinc, and tin. The alloys of Group 2, the Malmer KG 8-11, are much more heterogeneous but generally have less gold and more bis-

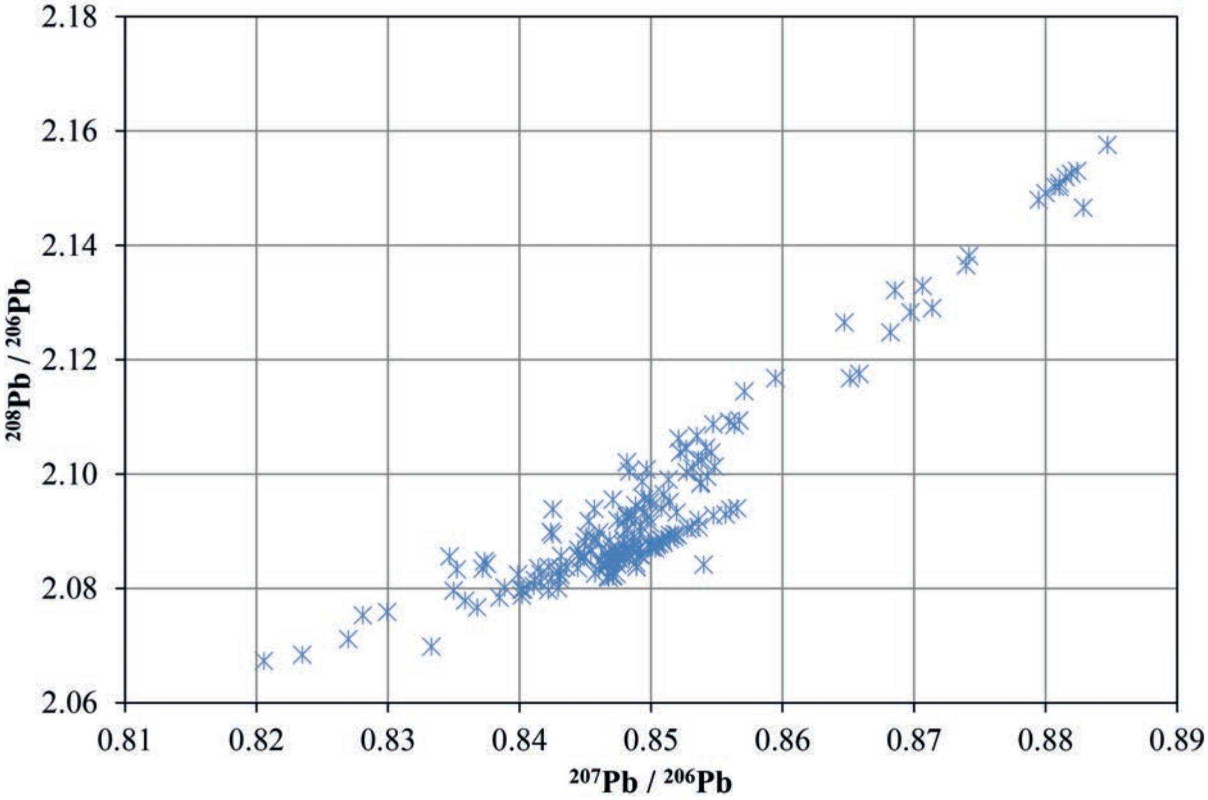

Figure 7.2 *This graph shows the isotope ratios of all silver objects analyzed in this study. 2σ is smaller than the symbol.*

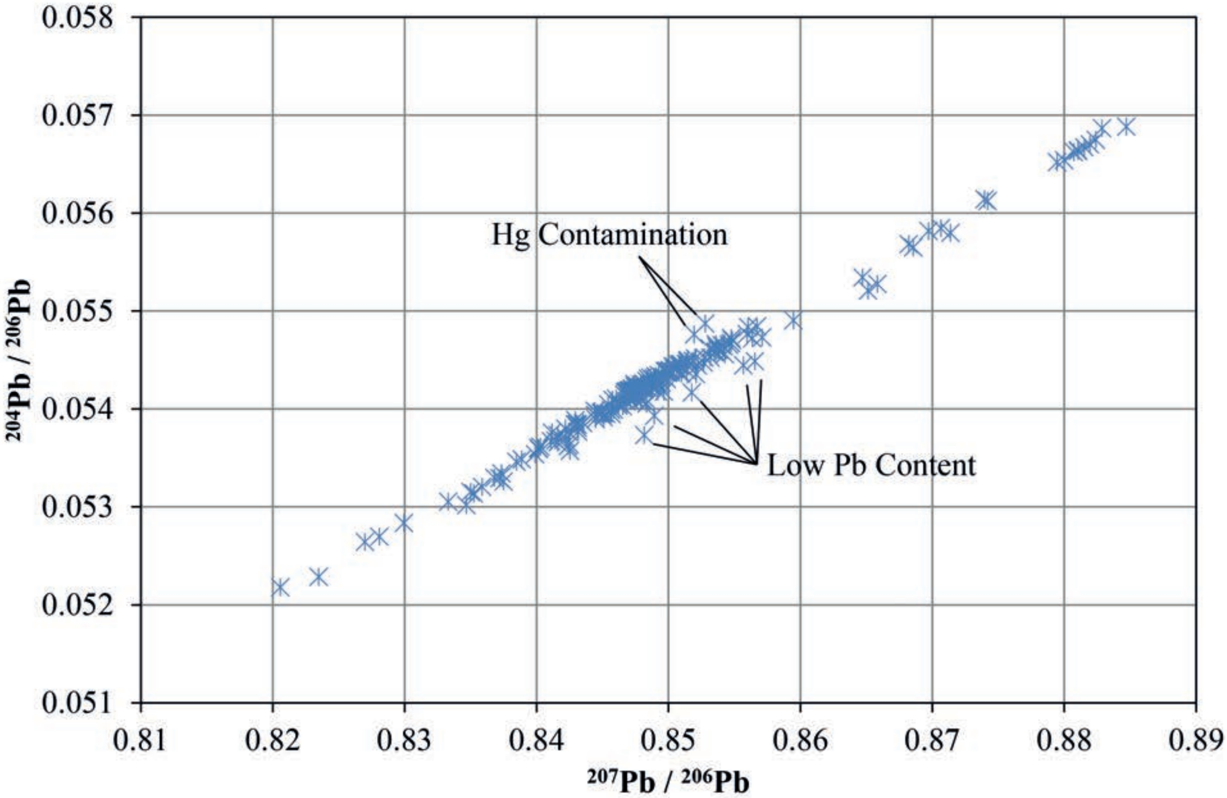

Figure 7.3 *The lead isotope diagram containing the ^{204}Pb/^{206}Pb ratio primary falls in a straight line with little deviation from the slope. The objects that fall under the line all have low lead contents and above are contaminated with mercury. Both of these problems cause high errors in the 204Pb ratios, which affects 16 objects in all; otherwise 2σ is smaller than the symbol.*

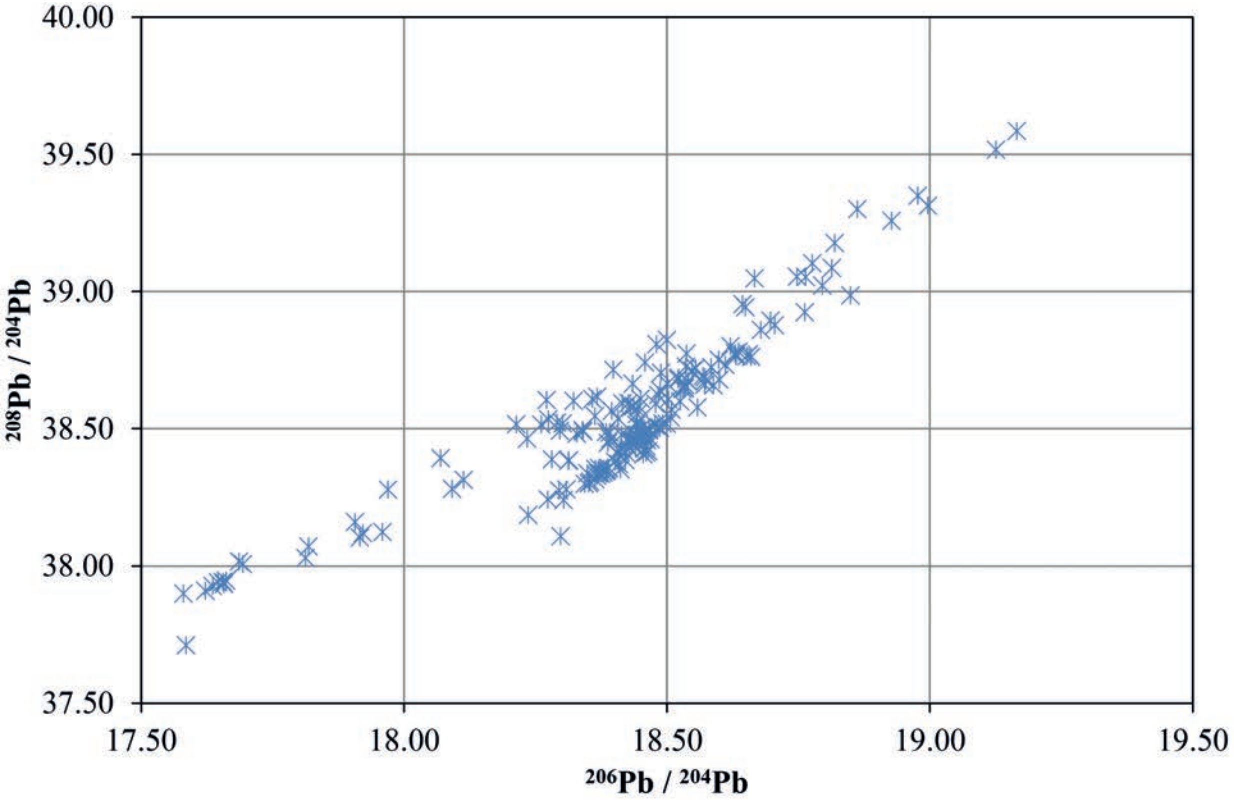

Figure 7.4 *Lead isotope diagram of all silver objects (with exclusion of the 16 objects with above average standard deviations for ^{204}Pb). 2σ is smaller than the symbol.*

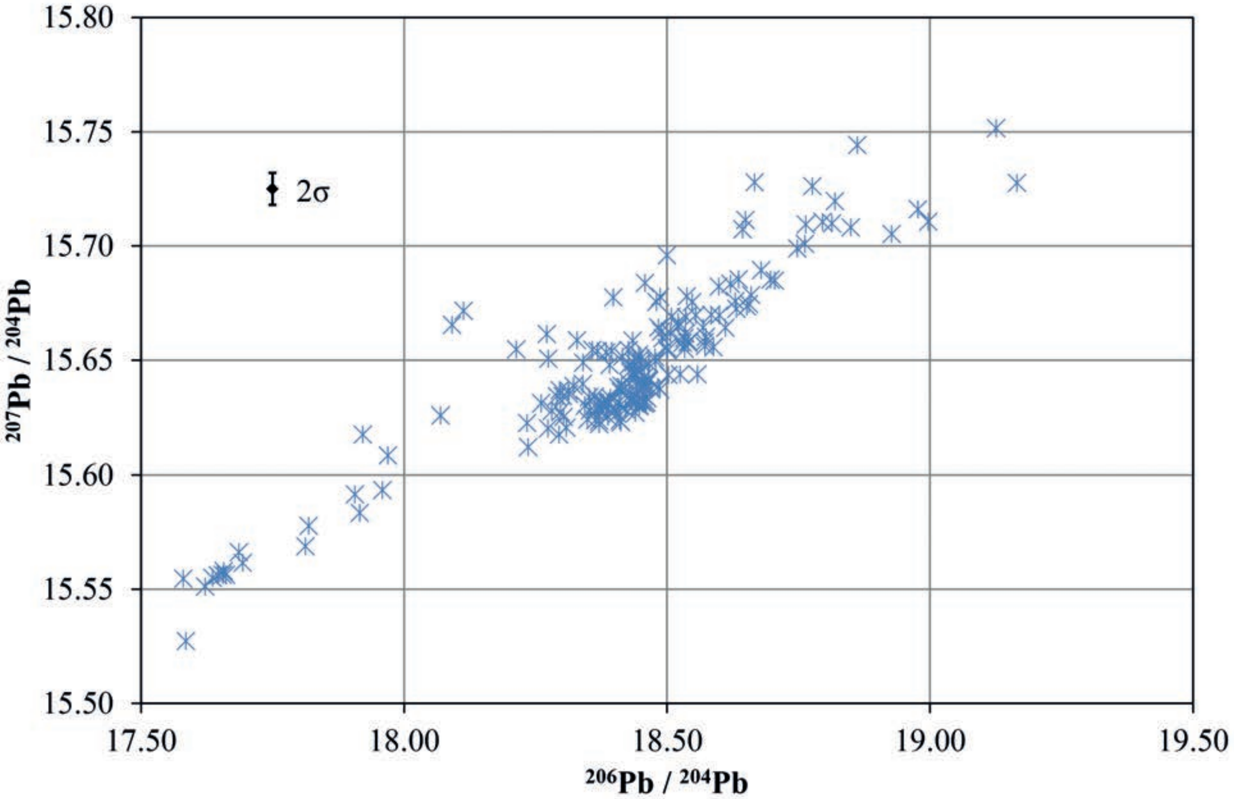

Figure 7.5 *Lead isotope diagram of all silver objects with exclusion of the 16 objects with above average standard deviations for ^{204}Pb.*

muth than Group 1. Two outliers were excluded from the Group 2 average because they greatly varied from the norm. The first coin (Outlier 1), at one extreme, has very high gold, bismuth, zinc, tin, and lead, but the second coin (Outlier 2) is at the other extreme and is very pure. These alloys undoubtedly have different origins based on their elemental composition alone. Group 3 is characterized as having less gold and bismuth than the previous two groups. Lastly, Group 4 is debased with brass. It has gold and bismuth contents proportional to Group 3 and the silver may be of similar origins. The addition of brass, containing an average content of fifteen percent zinc with small amounts of tin and lead, can be seen in the alloy composition.

It is clear from the elemental compositions that there are changes to the silver stock over the course of the 10th and 11th centuries. Until the middle of the 11th century, the silver standard for the Hedeby / Danish coinages was above 90 percent. There are fluctuations in the gold and bismuth contents, which mean that there were at least three types of silver circulating at Hedeby during the period of focus.

The lead isotope diagrams of the Hedeby / Danish coin groups are presented in **Figures 7.6-7.7**. Despite the higher standard deviations in the ^{204}Pb diagrams,[2] the isotope ratios form clusters and indicate that the lead isotope composition in the silver coins changes over time. Both the elemental and lead isotope compositions confirm that there is an evolution of the silver stock over the 10th and 11th centuries. These changes will be discussed in the following sections in chronologic order.

7.4 Malmer KG 7 (900-920 AD) and Related Silver

7.4.1 Introduction

Ten Malmer KG 7 coins were analyzed and form the first chronological group. As presented in **Table 7.1**, the average elemental composition of the KG 7 coins is higher in gold than the other groups and has a low bismuth level.[3] The KG 7 coins have gold contents between 1900 ppm and 4100 ppm and bismuth contents less than 1700 ppm. The zinc content can be as high as 2400 ppm and the tin content 3000 ppm. The analyses of KG 7 coins by Steuer (2003, 147-148) have both higher amounts of gold and bismuth than the analyses presented here, but the trend that the KG 7 have higher gold than bismuth is confirmed. The silver, copper, zinc, and lead contents are all similar to the results presented by Steuer (2003).

7.4.2 Malmer KG 7 and Contemporary Western Silver

The question that surrounds the KG 7 is whether they are made of western or eastern silver. As Steuer et al. (2002, 152-3) propose, the elemental composition of the KG 7 is most similar to coins of Anglo-Saxon and Volga-Bulghar origin. The Anglo-Saxon coins compared by Steuer et al. (see Steuer 2003) are dated to the last quarter of the 10th century or early 11th century, and as we know from the analyses of McKerrell and Stevenson (1972) and others, the alloy of Anglo-Saxon coins at the end of the 9th and early 10th century is quite different than what is found later. The Anglo-Saxon coins contemporary to the KG 7 have substantially more gold than the Anglo-Saxon coins from the late 10th century. The alloy used for the Carolingian and Anglo-Norse coins of the Cuerdale hoard (T.P.Q. 905 AD) (Metcalf/Northover 1988, 110-3) is similar to the Anglo-Saxon coin compositions provided by McKerrell and Stevenson (1972) for the late 9th century, and nearly all have gold contents close to one percent. Therefore, the composition of the KG 7 is dissimilar to the contemporary Anglo-Saxon, Anglo-Norse, and Carolingian coinages. The distinctively high gold contents of these coinages exclude them as major sources for the silver used to make the Malmer KG 7.

The lead isotope data provides an additional angle to the discussion. The only known silver mine active in the Carolingian Empire in the 9th century is Melle. Galena from the mine of Melle do not match the KG 7 (compare Téreygeol et al. 2005, 50),[4] and the KG 7 coins have higher ^{208}Pb / ^{206}Pb to ^{207}Pb / ^{206}Pb ratios than are typically found in the lead deposits of the British Isles (compare Rohl 1996).[5] Unfortunately, the elemental composition of the one coin (**Cat. 117**) that has the most similar isotope ratios to the galena from Melle and British galena cannot be compared because of the poor condition of the coin. One Carolingian gilt silver fitting analyzed (**Cat. 165**) matches the range of elemental composition and nearly matches the isotopic compositions found in Group 1; however, it is dated to the first half of the 9th century, 50 years prior to the proposed start of minting of the KG 7 at Hedeby around the year 900 AD. It does not match with the ore from Melle, and therefore, probably has a different source. The second Carolingian fitting (**Cat. 166**) is debased with brass, paralleling the composition of the debased coinage of Charles the Bald (compare Sarah 2010), and is starkly different from the KG 7 elemental composition. The lead isotope composition of the silver-brass alloy fitting plots within the Group 1 field, but the isotopic composition of this object may actually reflect the brass alloyed with

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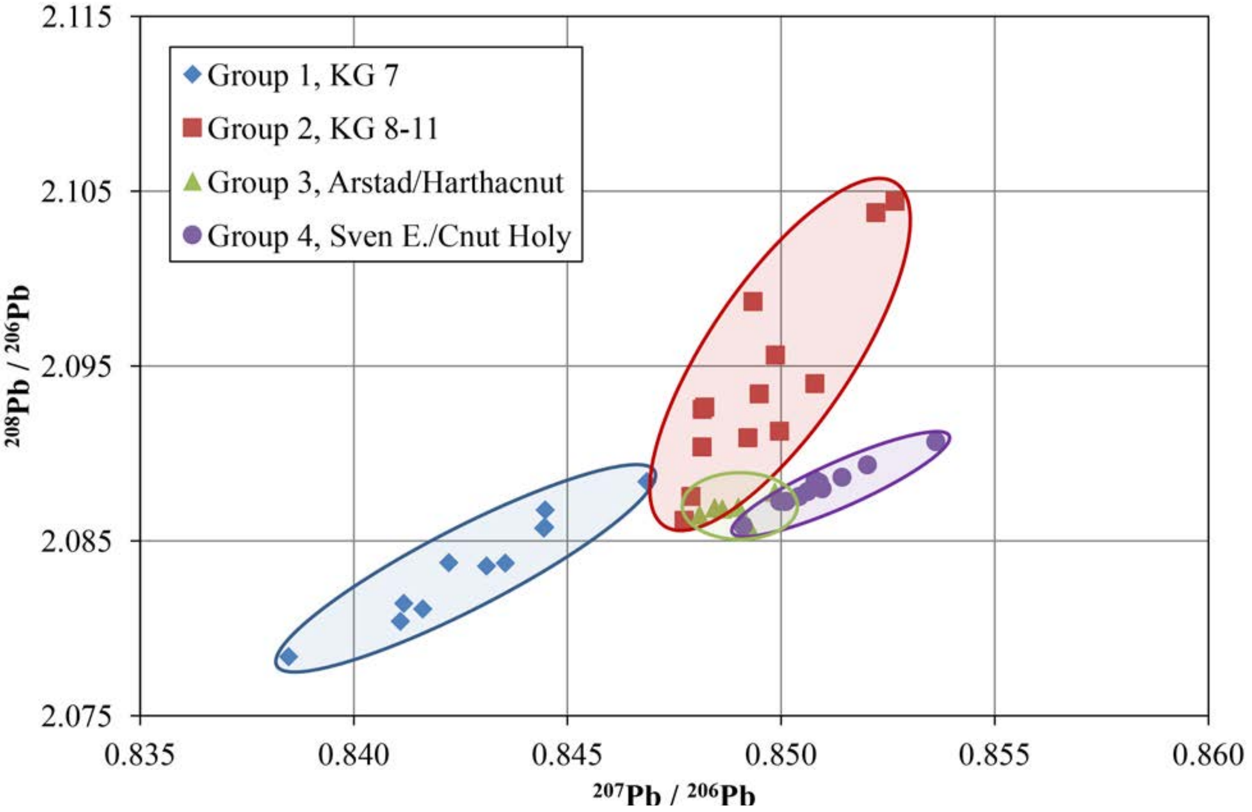
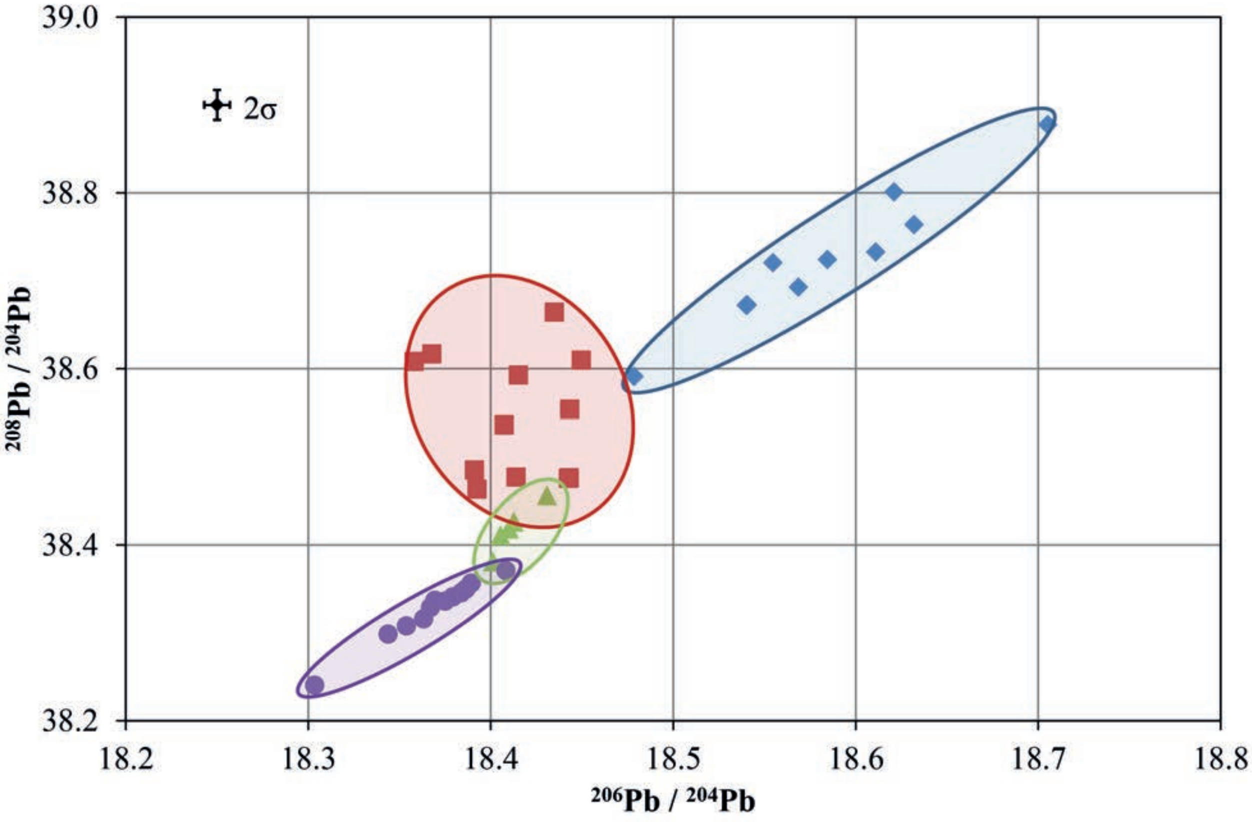
[2] Three coins are omitted from the ^{204}Pb diagrams due to the poor measurement of this isotope.

[3] The elemental composition of one KG 7 coin could not be obtained (**Cat. 117**) due to corrosion.

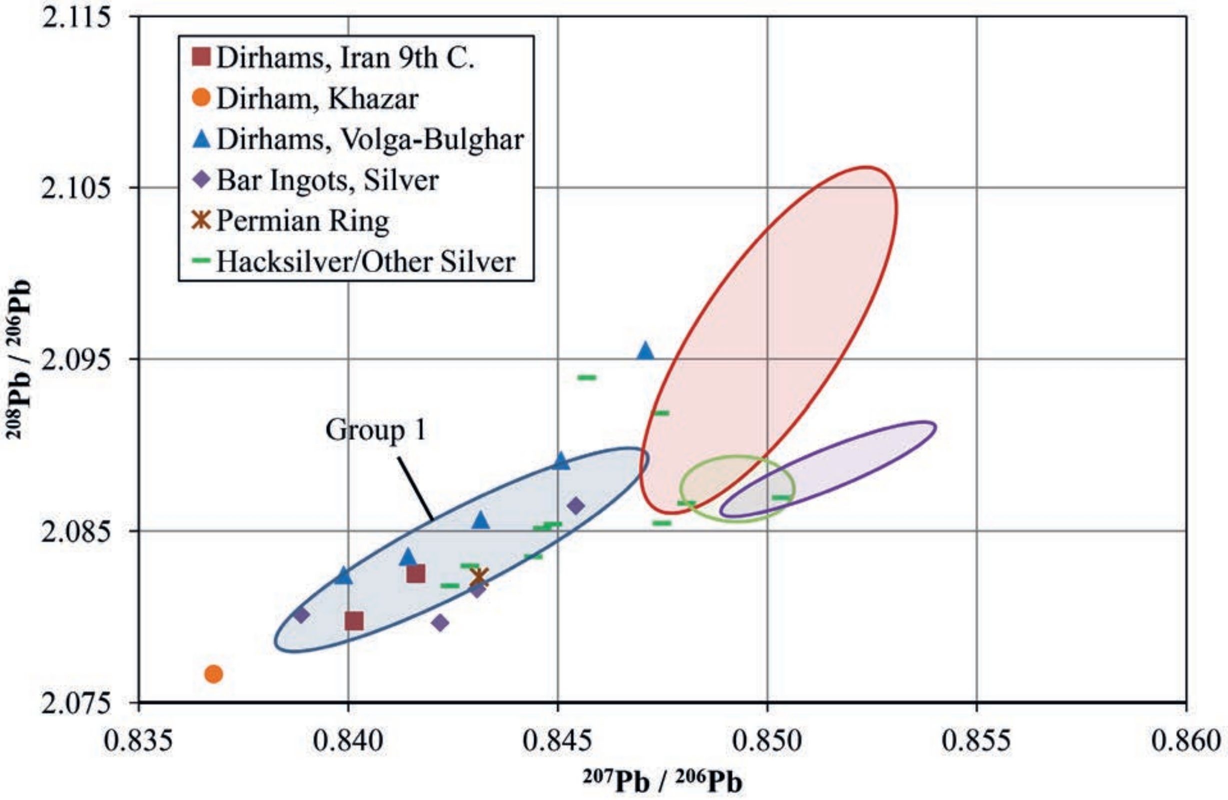
[4] The galena from Melle do not match with the KG 7 in the ^{207}Pb / ^{206}Pb to ^{208}Pb / ^{206}Pb diagram, although the ore do match with one KG 7 coin in the graphs with ^{204}Pb.

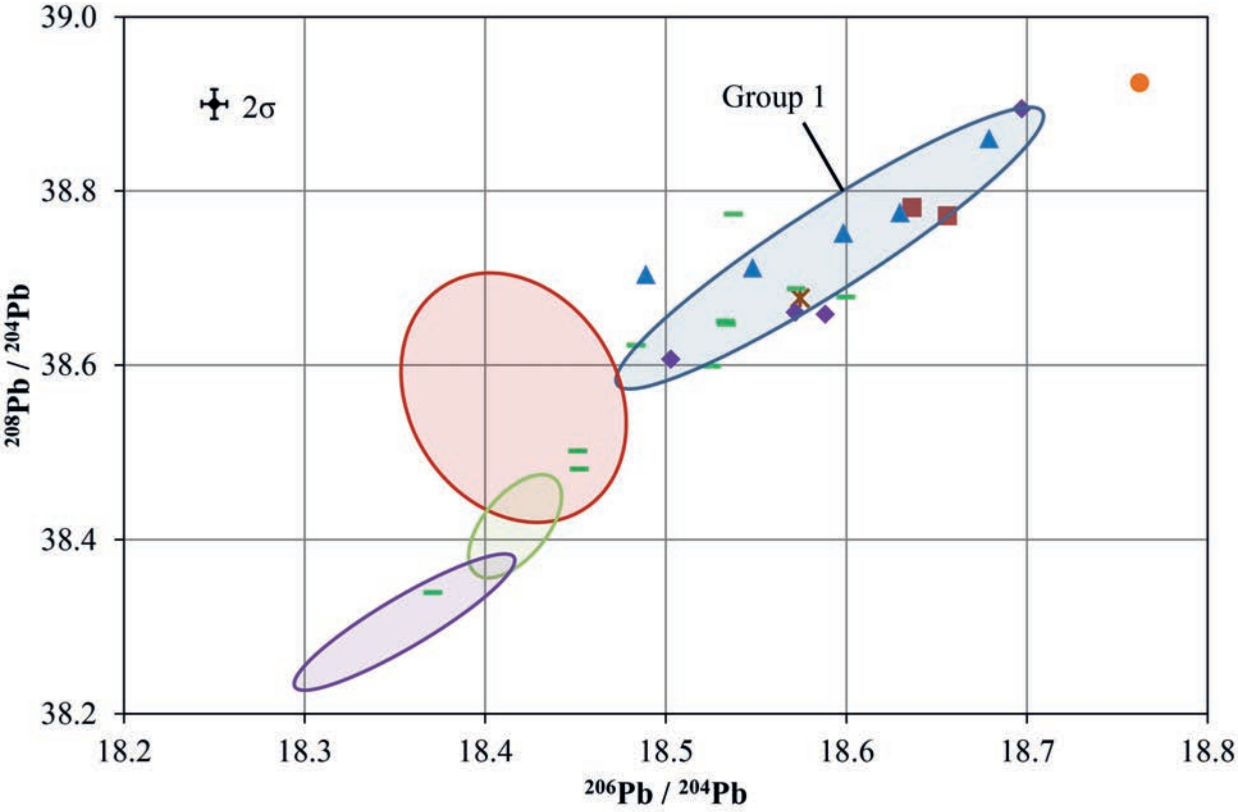
[5] With exception of one galena from Durham (Alston, Nenthead) and one galena from Cumbria (Keswick, West) (Rohl 1996).





Figures 7.6 and 7.7 *Lead isotope diagram of the four Hedeby/Danish coin groups in chronologic order. Group 1: Malmer KG7, ca. 900-920 AD; Group 2: Malmer KG8-11, ca. 950-980; Group 3: Årstad and Harthacnut types, ca. 1015-1035 AD; Group 4: the coins of Sven Estridsen and Cnut the Holy, ca. 1047-1086. 2σ is smaller than the symbol unless otherwise specified.*





Figures 7.8 and 7.9 *Lead isotope diagram showing the silver objects that are most similar to the Malmer KG 7 coins from Hedeby (Group 1). Only a portion of the Volga-Bulghar dirhams are shown, the coins with bismuth contents under 0.3 percent, and hacksilver and jewellery objects with less than 0.25 percent bismuth. 2σ is smaller than the symbol unless otherwise specified.*

the silver, as the attached brass needle has nearly an identical lead isotope composition.

7.4.3 Eastern Origins of the Malmer KG 7

Several objects of comparable composition to the KG 7 group are plotted in **Figures 7.8-7.9**. The coins of Group 1 are distinctly different from the Samanid dirhams in elemental composition (compare **Table 5.2** and **Appendix C**) and isotope ratios (**Appendix D**), particularly from the coins of al-Shāsh; however, there are similarities to the silver available in the Islamic world and Russia prior to the 10th century. The mints of Iran and Iraq were very active in the 9th century, and coins from these regions are relatively common in Scandinavia, an example being the 67 kg silver hoard found at Spillings on Gotland (Östergren 2011, 328; Waugh 2011, 165-9), and Abbasid dirhams dominate the Islamic coins found in the Cuerdale hoard (Lowick 1976), which with a terminus post quem of 905 AD, also contained one Hedeby KG 7 specimen (Archibald 1985; Malmer 2002, 124). The gold and bismuth contents of Abbasid coins (**Table 5.1**) seem to be more similar to the composition of the KG 7 than contemporary coins of western Europe and Samanid Central Asia. The eastern silver was not traded directly to the Scandinavians, but arrived through intermediaries in the Khazar kingdom and Volga Bulgharia. The Volga-Bulghar dirham imitations divide into two groups based on their bismuth contents. The low bismuth coins (< 0.3 % Bi) are most similar to the Hedeby KG 7 in both elemental and lead isotope composition. As Steuer et al. (2002, 152-3) first identified, there are similarities with the coins of Volga Bulgharia, and this is now confirmed by lead isotope analysis performed in this study.

Unfortunately, few dirhams dating to the 9th century were analyzed in this study because they are not as often found as the later Samanid dirhams of the 10th century. One Saffarid dirham from Iran dating to the last quarter of the 9th century has matching elemental and lead isotope compositions to the Hedeby KG 7, and another earlier dirham from Iran matches isotopically. The range of lead isotope compositions of the KG 7, though different from many western European ore deposits, has close parallels to the ore deposits of Iran and Turkey, deposits like at Nakhlak, Khaneh Sormeh (Isfahan), Hezarabad (northeast of Arak) (compare Pernicka et al. 2011, 670, Table 12; Stos-Gale 2001, 56, Table 4.1) and Taurus Group 2a (Yener et al. 1991). Published analyses of Sasanian silver also show a similar range of isotope compositions (Meyers 1998, 246, Table 6; Stos-Gale 2001, 65, Figure 4.4); however, the high gold concentrations in Sasanian silver preclude that the exact same silver resources or ore types were in use during the Abbasid and Saffarid periods.

Two dirhams from Iraq from the 9th century (**Cat. 9** and **10**) do not plot within the KG 7 field. They both have low bismuth contents and the coin from Samarra has a notable gold content. The lead isotope composition of the coin from Baghdād plots between the Taurus 1b and 2b fields (Yener et al. 1991) and have similarities to a deposit at Larassam near Tehrān (Stos-Gale 2001), but a positive identification of the source is not possible at this time. The lead isotope composition of the dirham from Samarra is distinct and has no known parallels to ore deposits in Taurus Mountains or Iran, but many deposits in these regions as well as in the Caucasus have not been systematically investigated. The only similar lead isotope ratios found in the published literature are lead-bearing glasses and lead from the city of Nimrod in Mesopotamia in the 9th century BC (Dayton/Dayton 1986, 26), although the source of this lead has yet to be identified.

The four North African dirhams of the late 8th century do not match with the isotopic field of the KG 7 and are remarkably pure, with practically no gold, bismuth, zinc, or tin. So far, ore deposits from which the silver could have originated have not been identified. North African silver is unlikely to have been important in the early 10th century because of its relatively short-lived minting, and the archaeological evidence of coin finds indicates that they circulated most widely in the first half of the 9th century (See **4.2.1.1** and **4.3.1.2**).

7.4.4 Malmer KG 7 and Related Ingots, Hacksilver, and Jewelry

There are similarities between the Hedeby KG 7 and a group of unminted Scandinavian silver objects like ingots and jewelry fragments. Four silver bar ingots (type 1 after Wiechmann 1996, 65-7) were analyzed, which have similar ranges of silver, gold, bismuth and zinc contents to the KG 7, and in the lead isotope diagrams three of the four ingots fit within the field of Group 1. Two of the ingots have notably higher tin contents than is normally found in Group 1. The one complete ingot is weight adjusted to 74 grams, fitting into the øre unit/Aurar system (see **3.4.2.1**), and has an analogous elemental and lead isotope composition to the Hedeby KG 7 group, which may reflect silver of similar date and origin.

A number of hacksilver objects, arm ring fragments, bars and wires, are comparable to the KG 7 group in both elemental composition and lead isotope ratios.[6] Two of the hacksilver objects are probably of eastern origin. **Cat. 168** is a fragment of a Volga-Bulghar style silver ornament and the analyses show that it is both elementally and isotopically similar to the KG 7. A further indication of an eastern source is the similarity of a faceted knob-shaped terminal of Permian spiral ring to the KG 7 group. The faceted knob terminal (**Cat. 176**) weighs 50 grams and likely belongs to the larger variety of Permian rings originally weighing 200 grams or more, a type most frequently found in Russia and the eastern Baltic (see Hårdh 1996, 137-140; Hårdh 2007). Based on the chronology, a relationship is plausible as the complete

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[6] **Cat. 176**, **177**, **181**, **187**, **190**, and **168**.

Permian rings are mostly dated to the 9th or early 10th century.

7.4.5 Summary and Conclusions

The closest parallels to the KG 7 can be found in: 1. Volga-Bulghar dirham imitations, 2. Ingots, unminted, and jewelry, some of which possibly of Russian manufacture, 3. A Saffarid and an Abbasid dirham from 9th century Iran. It must be stated, though, that the KG 7 group is most probably a mixture of silver from different sources and reflects perhaps several homogenization events. As the Volga-Bulghar dirham imitations themselves are likely to be mixtures of the Islamic silver available in Russia, the KG 7 are a mixture of the silver available in the western Baltic at the turn of the 10th century. The alloy of the contemporary Carolingian and Anglo-Saxon coinage seems to be unrelated to the KG 7, but if this silver was diluted with silver of eastern origin these differences would be more difficult to detect.

However, the fact that the lead isotope field of the KG 7 seems to be most comparable to silver of non-European origin, it can be argued that the primary source of the silver came from the east. It likely reflects a blend of silver from the Abbasids and Saffarids, some of which has been homogenized in Russia (as coins and rings) and in the Baltic as ingots and jewelry objects. The few analyses available for comparison limit the certainty of this conclusion, and more analyses are required to better characterize Abbasid and Volga-Bulghar silver and contemporary silver from western Europe. The conclusions presented here must therefore be regarded as tentative.

7.5 Malmer KG 8-11 (950-980 AD) and Related Silver

7.5.1 Introduction

The silver of the KG 8-11 group is a group with heterogeneous compositions, and it is evident that several distinctive types of silver were circulating in the second half of the 10th century. The lead isotope field for the KG 8-11 group is distinct from the previous KG 7 group indicating access to new types of silver. With a sample size of thirteen coins, little can be said about time-based differences within the group itself, but rather, the goal is to get a sense of the diversity of compositions and identify possible sources of silver used during this thirty-year period. Based on the archaeological evidence, two major types of coins may best represent the sources of silver at this time: they are Central Asian / Afghan dirhams from the Samanid Empire, which are ubiquitous in hoards in the Baltic dated to the 10th century, and Ottonian Sachsenpfennige, which were probably minted in Magdeburg and are possibly connected with silver production in the Harz Mountains. Though silver from these two coinage types may be the most important comparison material for the KG 8-11 coins, not all the variation in the compositions of KG 8-11 series can be explained through this comparison.

7.5.2 Samanid Silver, Bismuth, and the Malmer KG 8-11

Samanid silver, as previously mentioned (see **5.3.4**), is known for its distinctively high bismuth contents. Thirty-seven Samanid dirhams were analyzed in this study as well as four Abbasid dirhams from the regions of Central Asia and Afghanistan. The results of the elemental analysis confirm the prior analyses of Samanid dirhams and indicate that bismuth is commonly found in high quantities in the dirhams from these regions. All Samanid dirhams from northern Afghanistan have bismuth contents above 0.4 percent and can be as high as 14 percent. The dirhams from Transoxania are also bismuth rich, containing an average bismuth content of around 0.6 percent. No silver from other parts of the early medieval world have such high bismuth levels recorded. Gold contents of the dirhams from Afghanistan are significantly lower than those from Transoxania, but on average the Samanid dirhams analyzed have well under 0.1 percent gold.

The lead isotope analysis has added a new layer to the discussion. The lead isotope composition of Samanid dirhams covers a broad range, but produces a general linear pattern when plotted (**Figures 7.10-7.11**). The slope of this line is offset from other types of silver and has higher ^{208}Pb ratios than, for instance, galena from the Rhenish Massif[7] or England (compare Rohl 1996). The isotopic composition of Samanid dirhams is controlled by the regional ore geology in Central Asia, which is characterized by lead that is slightly more thorogenic, probably caused by the incorporation of lead originating from lower crustal rock (Chiaradia et al. 2006, 418; and see **Appendix I**), and this is simply different than that of Central Europe and the British Isles.

It is therefore clear that Samanid silver has special distinguishing characteristics well suited for the provenancing of silver. The high bismuth level of Samanid silver and the generally higher ^{208}Pb ratios are not apparent in the composition of the KG 7 coins, but these two traits can be seen in the KG 8-11 group[8] and other silver dating from the 10th century. In several objects of Volga-Bulghar[9] and Scandinavian manufacture,[10] and of

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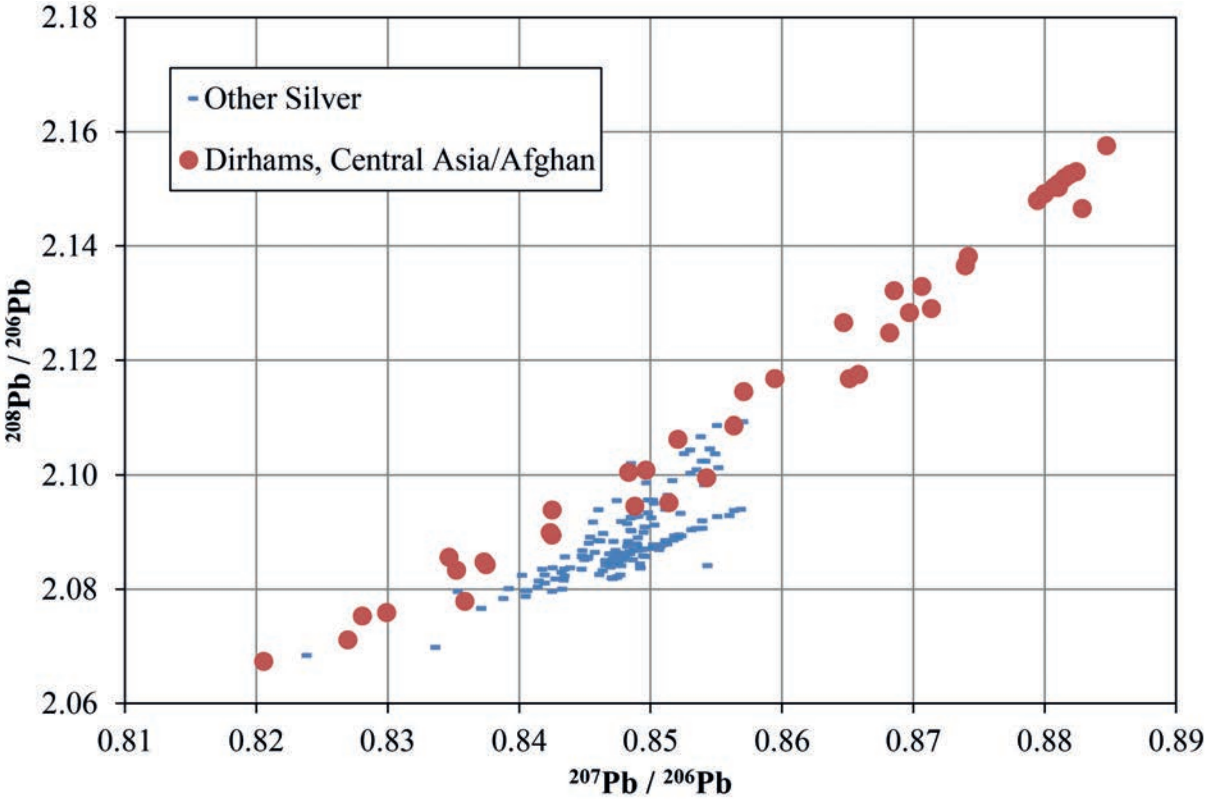
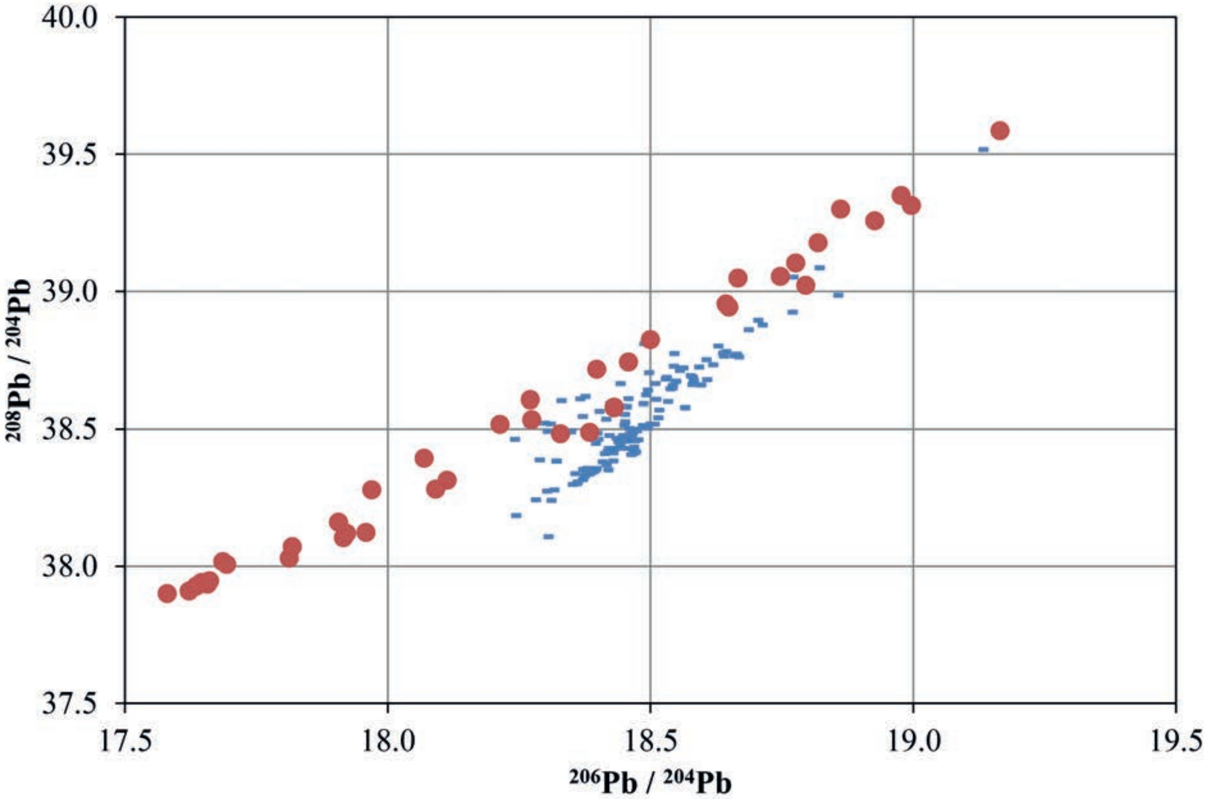
[7] Compare Bielicki/Tischendorf (1991); Bode (2008); Brauns (1995); Durali-Müller 2005; Hatz et al. (1991); Krahn/Baumann (1996); Lehmann (2011); Lévêque/Jakobus (1994); Schneider (1994); Schneider (1998); Wagner/Schneider (1999).

[8] Of the coins of Group 2 these are **Cat. 126, 127, 131, 134**, and **135**.

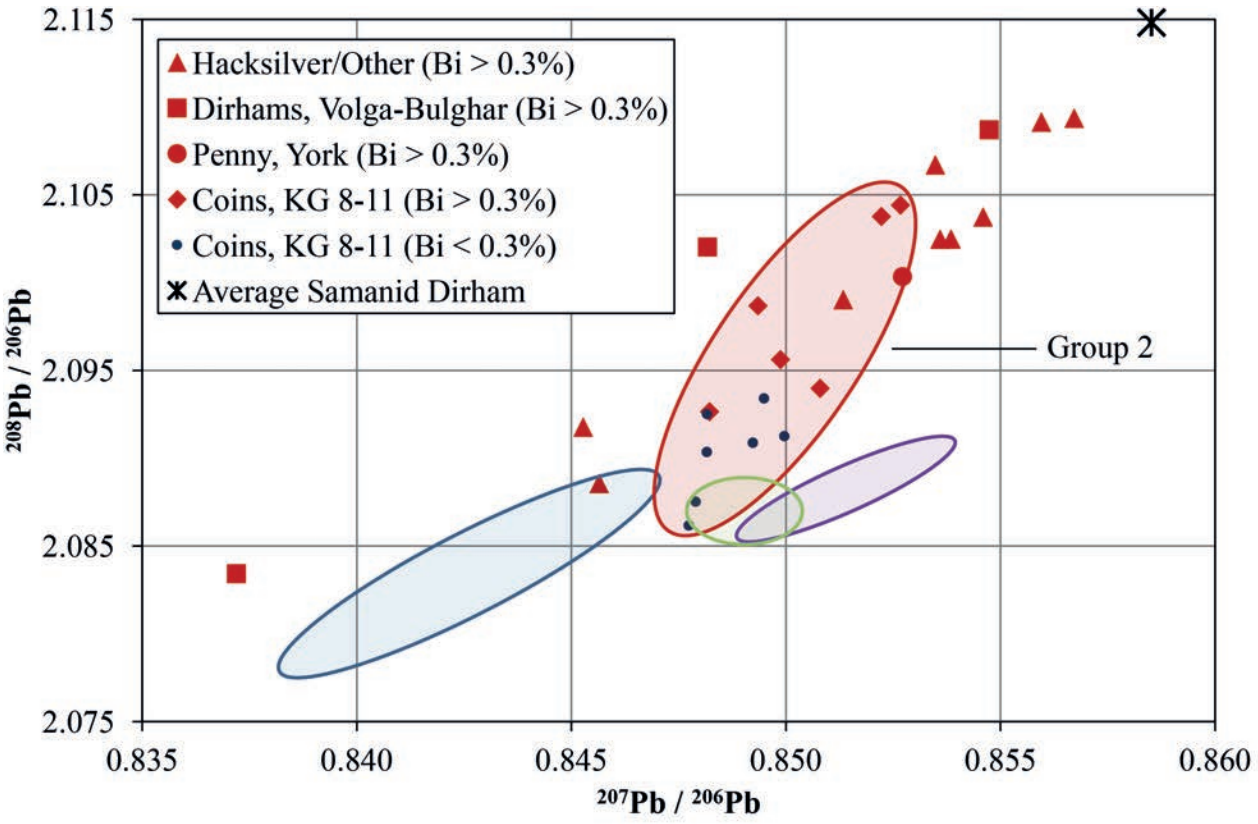
[9] **Cat. 54**, **56**, and **59** (potentially Kiev).

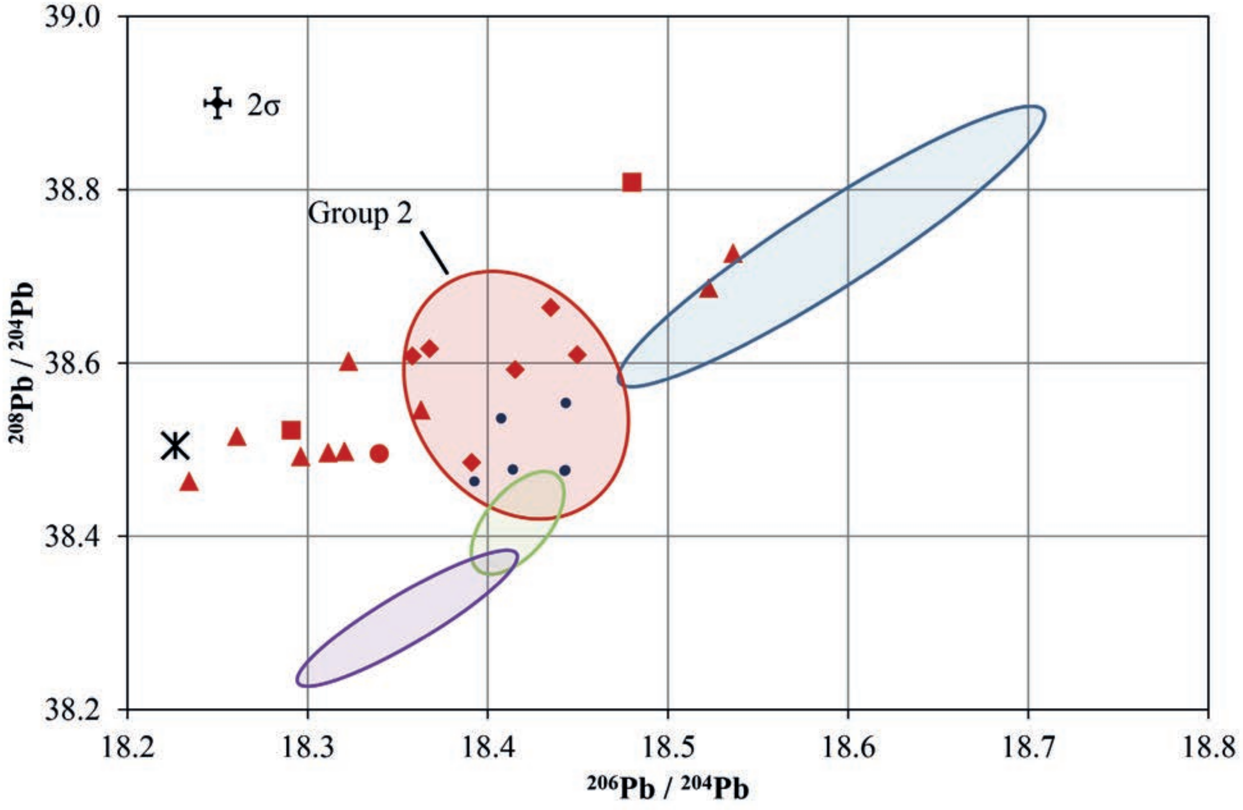
[10] **Cat. 178, 183, 185, 186**, and **189**.



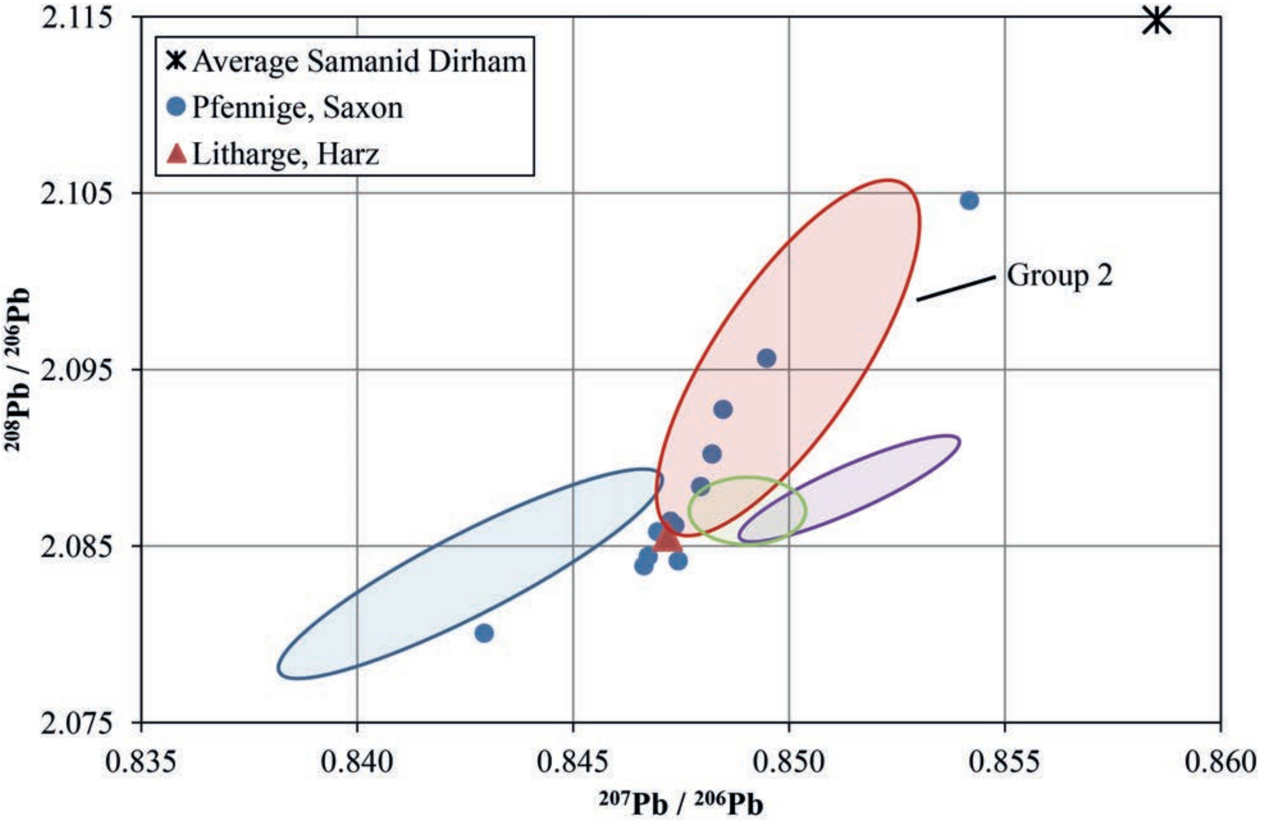


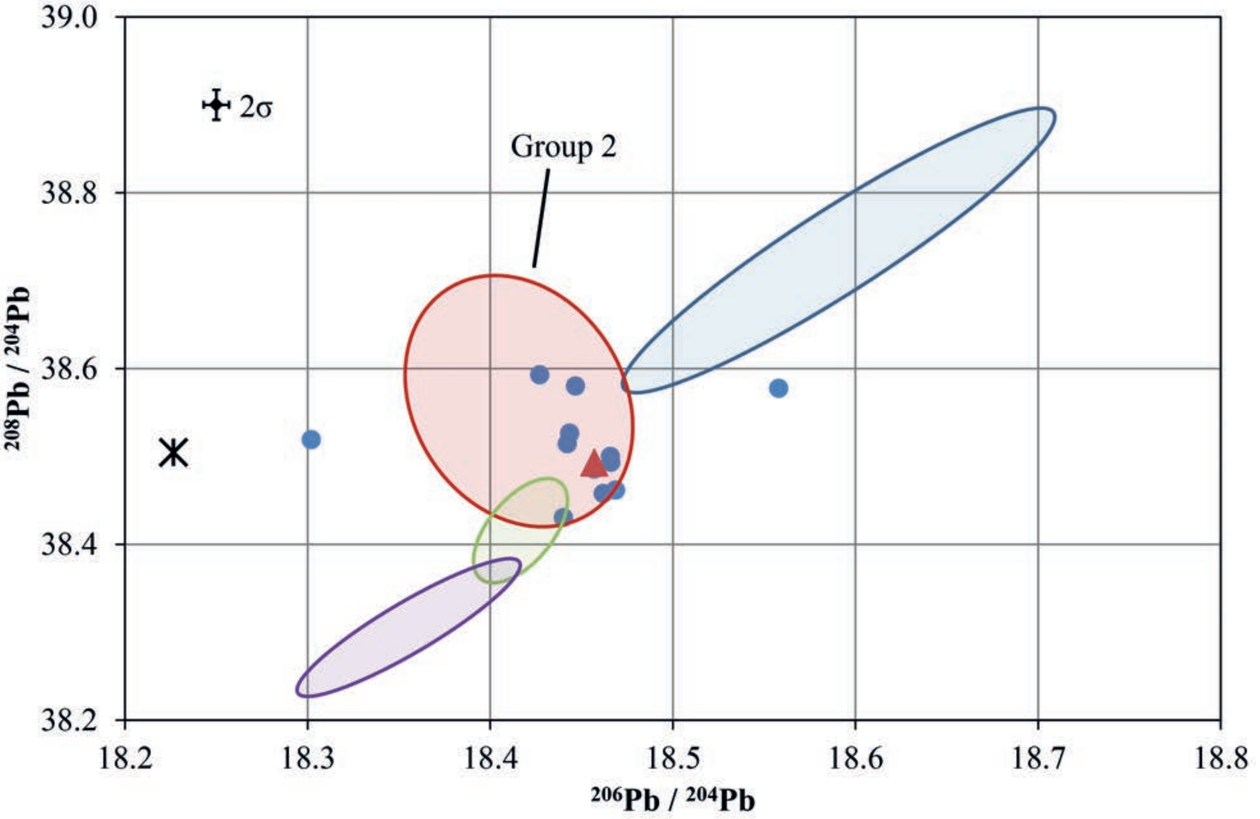
Figures 7.10 and 7.11 *These diagrams show the lead isotope ratios of dirhams from mints in Central Asia and Afghanistan (mostly Samanid) compared to all other silver coins and objects measured. The dirhams from the mints Central Asia and Afghanistan (Samarqand, al-Shāsh, Andarāba, Balkh, and Bukhārā) broadly form a line. The lead isotope ratios of silver from Central Asian and Afghanistan tend to have higher in 208Pb than other types of silver. 2σ is smaller than the symbol.*



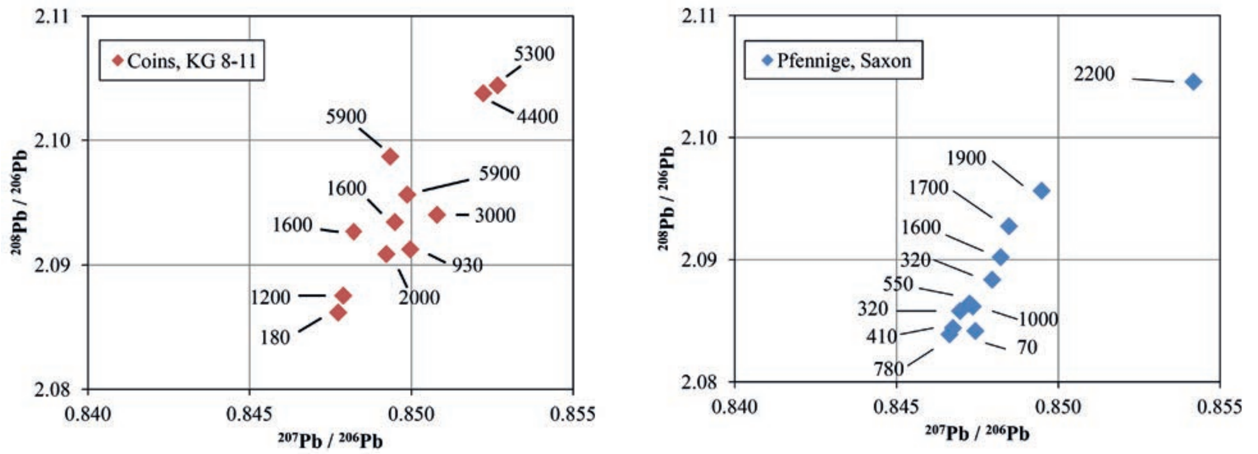


Figures 7.12 and 7.13 *Lead isotope diagrams of several types of silver high in bismuth (excluding Ottonian and Samanid coins). The dirhams from Central Asia and Afghanistan are excluded for clarity, but the average lead isotope composition of forty-one dirhams from these regions is included. The silver objects with the highest bismuth contents plot in specific regions of the diagrams, possibly showing the influence of mixing with Samanid silver, which is itself high in bismuth and has higher* ^{208}*Pb ratios. 2σ is smaller than the symbol unless otherwise specified.*





Figures 7.14 and 7.15 *Lead isotope diagrams comparing the ratios of Sachsenpfennige (950-1000 AD), cupellation litharge from a 9th/10th century silver production site of Badenhausen in the Harz (BROCKNER et al. 1989), and the Hedeby/Danish coin groups. Half of the Sachsenpfennige match with the field of Group 2 (KG 8-11). Several of the Sachsenpfennige are consistent with the lead isotope field of the Bad Grund/Upper Harz and the litharge from Badenhausen. 2σ is smaller than the symbol unless otherwise specified.*



***Figures 7.16 and 7.17** Lead isotope diagrams with bismuth contents (in ppm) are presented to illustrate the general relationship between bismuth content and the ^{208}Pb/^{206}Pb in the KG 8-11 and the Sachsenpfennige. In both cases, the coins with the highest bismuth also have the highest ^{208}Pb/^{206}Pb ratios. 2σ is smaller than the symbol.*

unknown origin,[11] there is a general correlation between the bismuth content and the ^{208}Pb ratios. In **Figures 7.12-7.13**, all silver objects containing bismuth above 0.3 percent are plotted with the exception of Samanid dirhams and Ottonian pfennige. The hacksilver objects and coins with higher contents of bismuth tend to plot in particular parts of the lead isotope diagrams.

Although this relationship between higher ^{208}Pb ratios and higher bismuth contents seems to be evidence for the recycling of Samanid dirhams, the relatively small range of the lead isotope compositions is in stark contrast to the broad range of compositions seen in the Samanid dirhams themselves. Additionally, the average bismuth content of Samanid silver remains higher than that found in silver objects of Volga-Bulghar or Viking making. The explanations for this are twofold:

1. Recycling by simply melting objects together acts as a homogenization process and creates an average of both the elemental and lead isotope compositions.
2. To take this one step further, the mixing of Samanid dirham fragments with silver of other sources will dilute both the bismuth content and the lead isotope ratios. This is perhaps why the objects of non-Samanid manufacture do not reach the theoretical average Samanid elemental or lead isotope compositions.

If Samanid dirhams or dirham fragments were melted in a crucible together, the silver produced would be an average of its constituents, and mixing with pre-Samanid silver, European silver or other types of silver would all have the effect of reducing the bismuth content and the ^{208}Pb ratios. One could speculate if the 'dilution' of Samanid silver was done intentionally to lower the bismuth content. This would in effect help to neutralize the negative impacts of this element on the working properties of the silver.

7.5.3 Ottonian Silver, Sachsenpfennige, and the Malmer KG 8-11

While about half of the KG 8-11 coins have bismuth contents higher than 0.3 percent correlated with higher ^{208}Pb ratios, the other half have less bismuth and lower ^{208}Pb ratios.[12] Unlike the former, the coins having less bismuth seem to reflect an alternate silver source from the Samanids. The silver of Melle is isotopically and elementally comparable, but it is thought that the mine was in decline in the 10th century (Téreygeol 2013) and the extreme rarity of 10th century silver objects of Frankish origin in Scandinavia supports a lack of silver export from this region, however lead may have been exported.

Perhaps the most significant development in mining in the mid-10th century is the expansion of the exploitation of an alternative source of silver that could be found in Saxony. It has been suggested that mining in the Harz Mountains began in the second half of the 10th century. Although the official date for the discovery of silver in the Harz is 968 AD, it is clear that the ecclesiastics of Magdeburg had interests at Gittelde on the western edge of the Harz a few decades earlier (see **4.2.4.2** and **4.3.2.2**).

The Sachsenpfennige have bismuth contents that range from 2200 ppm to 70 ppm and gold contents are under 1250 ppm. The lead isotope ratios of the Sachsenpfennige are plotted in **Figures 7.14-7.15** and half of them plot within the field of the Hedeby/Danish coins of Group 2. Like with the KG 8-11 coins, there is a relationship between the ^{208}Pb ratios with the bismuth content, though the Sachsenpfennige have generally less bismuth (**Figures 7.16-7.17**). The Sachsenpfennige with the least bismuth also have the lowest gold contents

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[11] **Cat. 50c, 114c**, and **167a** (Oriental/eastern origin).

[12] These are **Cat. 124, 125, 128, 129, 13**2, and **133**.

and have lower ^{208}Pb ratios.[13] Several of these coins are consistent with ore from the Upper Harz, such as the Bad Grund deposit (compare Hatz et al. 1991; Lehmann 2011; Lévêque/Haack 1993; Tischendorf et al. 1993). Cupellation litharge from an archaeological site at Badenhausen, a metallurgical site securely dated to the 9th/10th century by the ceramic assemblage (Brockner et al. 1989), plots at the center of a cluster of Sachsenpfennige (**Figures 7.14-7.15)**. Badenhausen is located near Gittelde, and documentary evidence from the year 968 AD indicates that the control of Badenhausen was given to the Archbishop of Magdeburg by Otto I (Reissner 1988, 48), and this litharge provides evidence that silver was being produced there from Upper Harz ore (Brockner et al. 1989, 205). None of the Sachsenpfennige have isotope ratios similar to the polymetallic ore deposit of the Rammelsberg in the northern Harz. The fact that the Sachsenpfennige that are consistent with the Upper Harz isotopically also have low bismuth and gold contents possibly indicates that these pfennige were made of freshly produced silver from the Harz. However, some of the Sachsenpfennige have higher bismuth and higher ^{208}Pb ratios and are not consistent with the lead isotope ratios of ore from the Harz Mountains. As previously mentioned, these characteristics seem to indicate that some of the pfennige are mixtures with Samanid silver. As Magdeburg was at the eastern border of the Ottonian Empire, eastern silver that crossed the Elbe may have been collected at this point to be minted into Sachsenpfennige.

7.5.4 Byzantine Miliaresia

The scarcity of silver coins from the Byzantine Empire found in Viking-age Scandinavia is thought to reflect a small, but politically significant, export of silver (Williams 2011, 357), but to get an impression of the comparability of Byzantine silver to the trends seen in the 2nd half of the 10th century, a small number of Byzantine Miliaresia were analyzed. Three coins were analyzed, and two of these coins were fitted with suspension loops. The silver of the Miliaresia and the riveted loops are isotopically dissimilar to the Danish coins of Group 2. The Byzantine coins can be characterized as having moderate gold contents, and very low bismuth, tin, and zinc. One Miliaresion is debased with nearly pure copper, but has lead isotope ratios that are nearly identical to another Miliaresion of high purity. This means that the copper probably contributed very little to the lead isotope composition or the copper and silver originate from the same deposit. These two coins (**Cat. 61** and **63a**) are consistent with Hedeby/Danish Group 1, but they are chronologically unrelated. Their lead isotope signature is comparable to ore from the Central Rhodope Mountains in Thrace (compare Stos-Gale 2004, Figure 24.3), and with regard to the geography seems to be a viable source for the silver or the lead used in refining. The third Miliaresion (**Cat. 62a**) is isotopically dissimilar and, for example, is comparable with ore from the deposit of Arak-Kashan in Iran (compare Stos-Gale 2004, Figure 24.2) in addition to several lead objects from the early 11th century Serçe Limani shipwreck of the coast of western Turkey. The suspension loops and ring could have been attached to the coins anywhere between the Aegean and the Baltic and are made from silver that is distinct from the Miliaresia themselves. They are made of silver with less gold and more bismuth and are isotopically different. The ring and loop of one coin (**Cat. 63**) are made of the same silver that is slightly debased with brass indicating that they were added at the same time.

7.5.5 Summary and Conclusions

To return to the discussion of the silver of Group 2, there are clear similarities between the Magdeburger Sachsenpfennige and the coins of the Malmer KG 8-11. They are contemporary and show an analogous range of lead isotope compositions that seem to indicate that in the years between 950 and 980 AD both older Islamic silver and newly produced silver from the Harz Mountains were circulating. One Malmer KG 10a coin (**Cat. 133**), which has a lead isotope signature consistent with the Upper Harz, is made of silver that is practically free of bismuth, gold, zinc, and tin. This silver is so fresh that it may originate directly from the Upper Harz without having been mixed with silver of another source. In another example of a Malmer KG 10a (**Cat. 131**), on the other extreme, the silver is entirely unrelated to the former alloy and is heavily alloyed with gold, bismuth, zinc, tin and lead. This silver is clearly mixed, and, due to its trace element and isotopic signature, it seems that the silver may be a mixture of Anglo-Saxon and Samanid silver or perhaps other silver types.[14] None of the coins of the Malmer KG 8-11 coins seem to be made solely of Samanid dirhams, but, rather, represent mixtures of Samanid silver, the older silver stock, and European silver, some of which probably came from the Harz.

This chronological period seems to be a period of transition with large fluctuations in the trace element and lead isotope compositions. During the height of the hacksilver economy, highly fragmented silver was in circulation. The Waterneversdorf Hoard (terminus post quem 976 AD) in Schleswig-Holstein, for example, contains two Malmer KG 9 coins and consists mostly of fragmented Samanid dirhams, Sachsenfennige, and jewelry objects/scrap metal (Wiechmann 1996, 488-505); it provides a glimpse into the types of silver circulating in this period. It seems that two types of silver may have been

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[13] These are **Cat. 74, 76, 77, 80, 81, 82**, and **84**.

[14] On a related side note, the one mid-10th century penny from York (**Cat. 68**) has also a high bismuth and ^{208}Pb ratios similar to many KG-8-11 coins and Sachsenpfennige, however the high zinc and gold content of this coin is typical of Anglo-Saxon silver and seems to indicate that it is an alloy of Samanid silver with the more commonly used silver of the British Isles.

	Alloy Type	Analy-ses	Ag	Cu	Au	Bi	Zn	Sn	Pb
			%	%	ppm	ppm	ppm	ppm	ppm
Otto-Adelheid-pfennig	A	x5	96.2	3.7	10	230	20	-	3100
			± 1.2	± 1.2	± 10	± 210	± 40		± 1200
Otto-Adelheid-pfennig	B	x4	97.9	1.5	2400	3000	290	-	330
			± 0.2	± 0.2	± 320	± 510	± 330		± 120
Otto-Adelheid-pfennig	(C?)	x1	97.8	2.1	900	160	240	10	840
Colonia Imitation, E. Frisia	(A?)	x8	97.4	2.6	10	120	80	3	2400
			± 0.9	± 0.9	± 20	± 80	± 170	± 6	± 900
Colonia/Lower Rhine/ Westph.	C	x10	97.8	2.1	720	900	1600	400	2800
			± 0.9	± 0.9	± 300	± 360	±1500	± 370	± 1400

Table 7.2 *This table gives the average compositions of several Ottonian coin types with their standard deviation. The Otto-Adelheid-Pfennig divided into two groups, but the silver of one seems more like what is found in Westphalia and on the Lower Rhine. The Colonia imitations from East Frisia are made of similar silver to the Otto-Adelheid-Pfennig Group A.*

most important for the Group 2 coins, the Samanid dirham and Ottonian Sachsenpfennig, but a focus on these two sources alone is a great oversimplification of the silver stock in the third quarter of the 10th century.

7.6 Årstad and Harthacnut Coinages (1015-1042 AD) and Related Silver

7.6.1 Introduction

Group 3 consists of the four coins of the Årstad 95-96 types and two coins of Harthacnut, all of which are attributed to a mint at Hedeby.[15] The Danish coins of Group 3 are much more homogenous than the prior two groups and can be characterized by low bismuth contents (350-900 ppm), a gold content ranging from 700 to 1800 ppm, and a variable zinc content under 4400 ppm. The higher bismuth contents and ^{208}Pb ratios suggestive of Samanid silver are no longer visible in the silver of Group 3. The coins are made of high quality silver and the silver content is directly comparable to the quality of the Ottonian, Anglo-Saxon, and Hiberno-Norse coins of the late 10th and early 11th century analyzed in this study. The lead isotope ratios plot in a relatively small field that is completely distinct from Group 1, but partially overlaps with the lower part of Group 2 (see **Figures 7.18-7.19**).

As we know from the archaeological record, the trade routes that connected Central Asia to the Baltic collapsed in the 10th century and by the end of the 10th century silver coins were primarily being imported from the Ottonian Empire and Anglo-Saxon England (see **4.3.2**). The Otto-Adelheid-pfennig, which began to be minted around the year 985 AD, is the most commonly found German coin type in 11th century Scandinavia. Pfennige of the Colonia type[16] are also found in significant numbers. Several examples of Otto-Adelheid-pfennige, Colonia-pfennige, Anglo-Saxon pennies, and Hiberno-Norse pennies were analyzed to compare to the Danish coins of Group 3.

7.6.2 Otto-Adelheid-pfennige and Harz Silver

The perception that the Otto-Adelheid-pfennige were probably produced from Harz silver and that there are no other contemporary European silver mines of such prominence place the Otto-Adelheid-pfennige at the forefront in the discussion of silver production in the late 10th and early 11th century. Ten specimens of Otto-Adelheid-pfennige were analyzed in this study. The elemental composition of the Otto-Adelheid-pfennige form two clear groupings; however, one of the ten specimens is different and will be discussed separately (**Table 7.2**). One group (A), consisting of five pfennige, is made of remarkably pure silver that seems to be freshly made; the low gold and bismuth contents of the silver may come from Upper Harz deposits like from Bad Grund.[17] The Otto-Adelheid-pfennige that have both high bismuth and high gold (B) more closely fit the description of Rammelsberg silver as defined by Kraume (1961, 5, 9) and Zwicker et al. (1991, 59-60).[18] The lead content of these coins is extremely low, less than 500 ppm, and this may be an indication that there was an attempt to control the bismuth content of the silver. Due to the behavior of bismuth during cupellation, nearly all the lead must be removed from the silver before bismuth can effectively be oxidized and separated from the silver (Pernicka/Bachmann 1983, 595). With such low lead contents, it is clear that this silver was carefully refined

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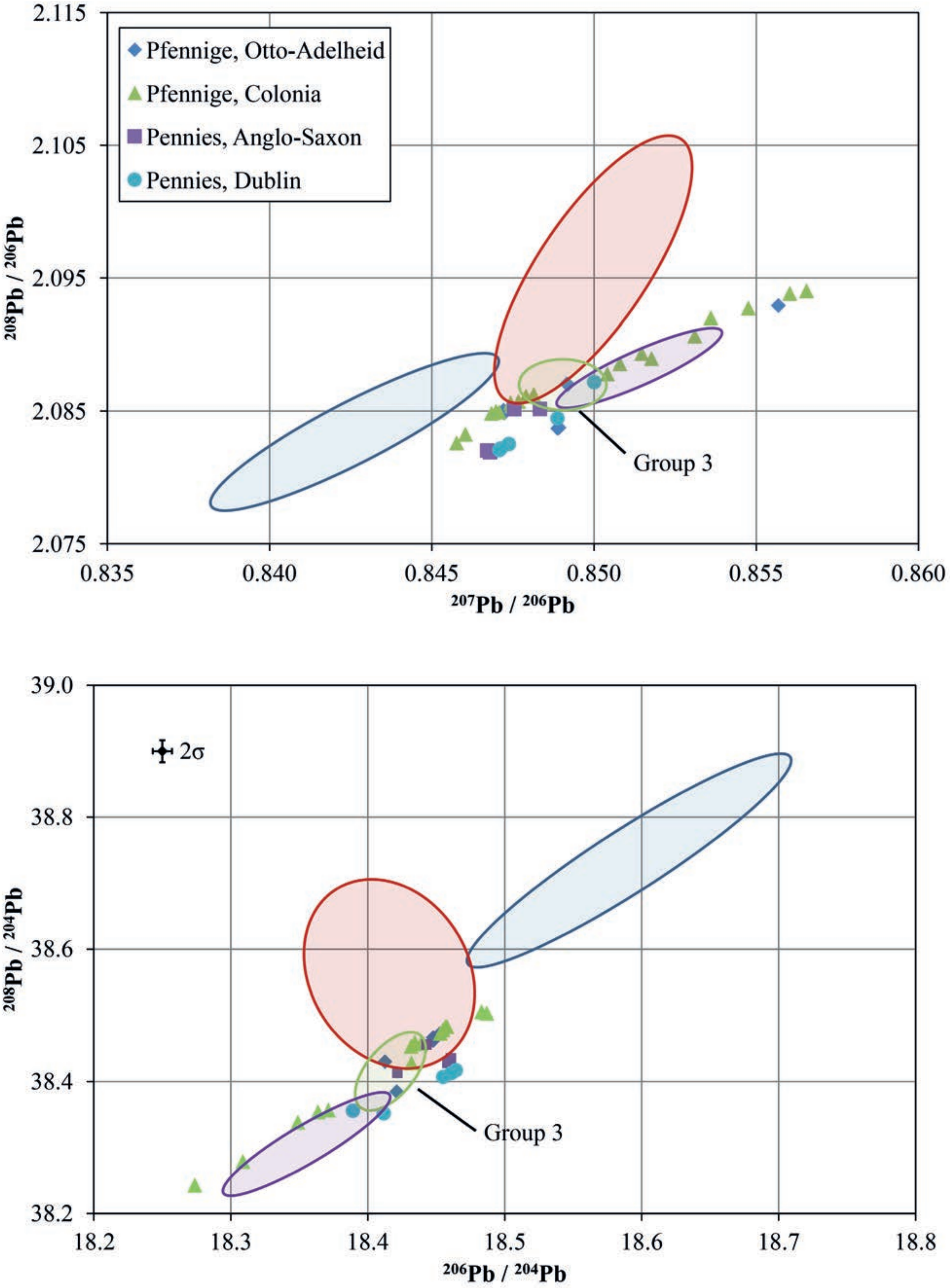
[15] See Wiechmann (2013) and the Harthacnut coins are type 50 after Hauberg (1900).

[16] From Cologne, but also including its imitations from Westphalia, the Lower Rhine, and Frisia.

[17] **Cat. 88**, **92**, **93**, **94**, and **95**.

[18] **Cat. 86**, **87**, **89**, and **91**.



Figures 7.18 and 7.19 *Lead isotope diagram comparing the lead isotope composition of Anglo-Saxon, Hiberno-Norse, and German silver coins with the early 11th century Danish coins represented by the Group 3 field. The Ottonian, Anglo-Saxon, and Hiberno-Norse coins date from the last decades of the 10th to the first half of the 11th century. Group 3 may be a homogenization of coins of European origin. 2σ is smaller than the symbol unless otherwise specified.*

to enhance the purity and working properties of the metal.

The two groups of silver used to make the Otto-Adelheid-pfennige can be faintly recognized in the analyses of Ilisch et al. (2003, 161) and Hatz et al. (1991, 79); however, the groups are not as clear-cut as in the analyses presented here. As Brockner et al. (1989, 205) write, the elemental and lead isotope analysis of litharge from Badenhausen proves that silver was being produced from both Rammelsberg ore and ore from the Upper Harz and that the ore were smelted and cupelled separately. It is evident that the two types of silver used to make the Otto-Adelheid-pfennige were not mixed together, but were processed separately. Though this seems straight-forward, there is a complication. The lead isotope ratios of the two types of Otto-Adelheid-pfennige are the same, and have the isotope signature of the Upper Harz (**Figures 7.20-7.21**). A possible explanation is that after the initial silver production, the silver stemming from Rammelsberg ore was refined using lead from the Upper Harz, which may have helped in lowering the bismuth content. Nevertheless, this is a major divergence from the data of Hatz et al. (1991), where both Rammelsberg and Upper Harz lead isotope signatures were identified in the Otto-Adelheid-pfennige.

7.6.3 Colonia-pfennige Alloys and Implications

Several coins from the mint of Cologne, imitations from the Lower Rhine / Westphalia, and a single coin from Deventer, have intermediate gold and bismuth contents compared to the two Otto-Adelheid groups and can have much higher zinc contents.[19] They are made of silver with lead isotope ratios that are consistent with ore from many deposits in the Rhenish Massif, but ratios tend to be distinctly geologically older than those of the Upper Harz deposit. The compositions of this group are much more heterogeneous than the Otto-Adelheid groups and the zinc content of the coins indicates mixing with brass to varying degrees. One OttoAdelheid-pfennig (**Cat. 90**) stands out from the others chemically as it is of different elemental and lead isotope composition, and it is physically different because it was struck on only one side. Its composition is not compatible with what is known about the elemental compositions of Harz silver, and it is much more similar to the silver used in the Lower Rhine area and in Westphalia. Due to its unusual character, it may be an imitation produced to the west of the Harz region.

At the moment there is no evidence that the silver used in the Cologne / Lower Rhine region originated in the Harz Mountains in the Ottonian period. There are noticeable differences in the silver composition between the Lower Rhine and the Harz. Although it is quite tempting to speculate about the use of local silver supplies from the Rhenish Massif, too few coins have been analyzed to get a clear picture. The heterogeneity of the compositions and the mixed nature of the silver alloys mask any particular mines that may be behind their production. Silver refining using locally produced lead and subsequent mixing could make the provenance untraceable with current analytical methods.

However, a group of Colonia-pfennig imitations thought to be made in East Frisia is unrelated to the alloys used on the Lower Rhine and has its closest similarities to silver from the Upper Harz. These coins are made of very clean silver with few gold, bismuth, zinc, and tin impurities. The purity of the alloy and the lead isotopic range matching the Upper Harz, together, seem to indicate that freshly-produced silver, possibly in ingot form, was transported down the Elbe or the Weser to East Frisia. Interestingly, these Colonia-pfennig imitations are made of high quality silver that is different from that used on the Lower Rhine, though, the region in which they were made was economically connected to the Rhine and under Cologne's sphere of cultural influence.

7.6.4 Anglo-Saxon / Hiberno-Norse Silver

A small number of Anglo-Saxon and Hiberno-Norse pennies dating from the end of the 10th to the first decades of the 11th century were analyzed. The two coins of Æthelred II are elementally similar, though originating from the mints of Winchester and Exeter, which lay geographically far apart. They are characterized by high gold contents (> 0.3 %), moderate zinc content, but very little bismuth and tin. The two Anglo-Saxon Quatrefoil coins minted under Cnut the Great have less, but still notable gold contents, and contain zinc, but have again little bismuth and tin. The coins from Dublin, contemporary with the Long-Cross coinage of Æthelred II, are remarkably similar with relatively high gold contents (0.18-0.27 %), moderate to sizable zinc contents (0.09-0.4 %), and low bismuth and tin. The few Anglo-Saxon / Hiberno-Norse coins analyzed in this study can hardly be called representative, but the trend that the silver contains consistently high gold and zinc contents is confirmed by the analyses of Metcalf and Northover (1986) and Ilisch et al. (2003). The low bismuth and tin and high gold and zinc contents measured in this study are most comparable with the analyses of contemporary Anglo-Saxon and Hiberno-Norse coins presented by Bornholdt (1999), Heslip and Northover (1990), and Metcalf and Northover (2002).

Two Anglo-Saxon style silver clasps, two brooch fragments and a belt end were also analyzed, all dating from the second half of the 10th century. The pattern is repeated with all silver objects having high gold (0.2-0.6 %), variable but high zinc contents, and low bismuth (< 0.1 %). Tin, though, is in all instances high; the belt end (**Cat. 164**) is unique and made of debased silver that was alloyed with bronze, not brass. A brooch fragment (**Cat. 162**) consisting of a back plate and a riveted

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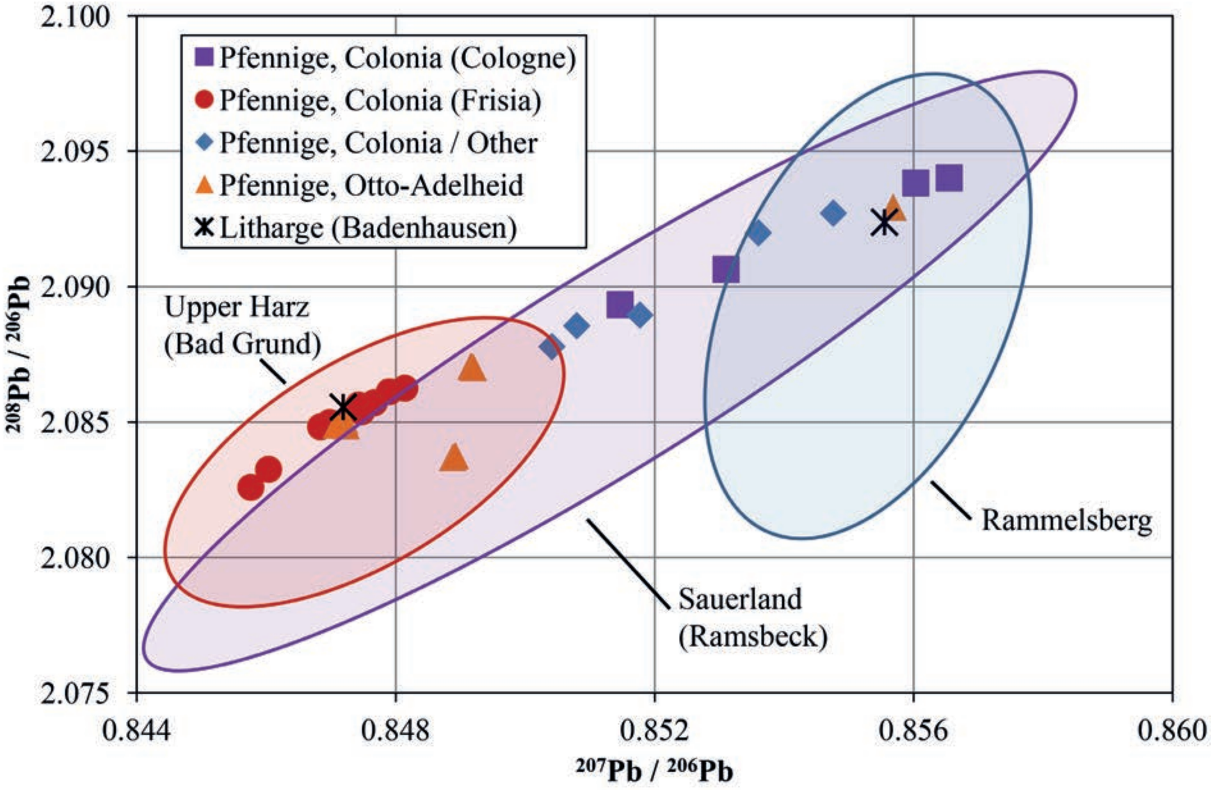
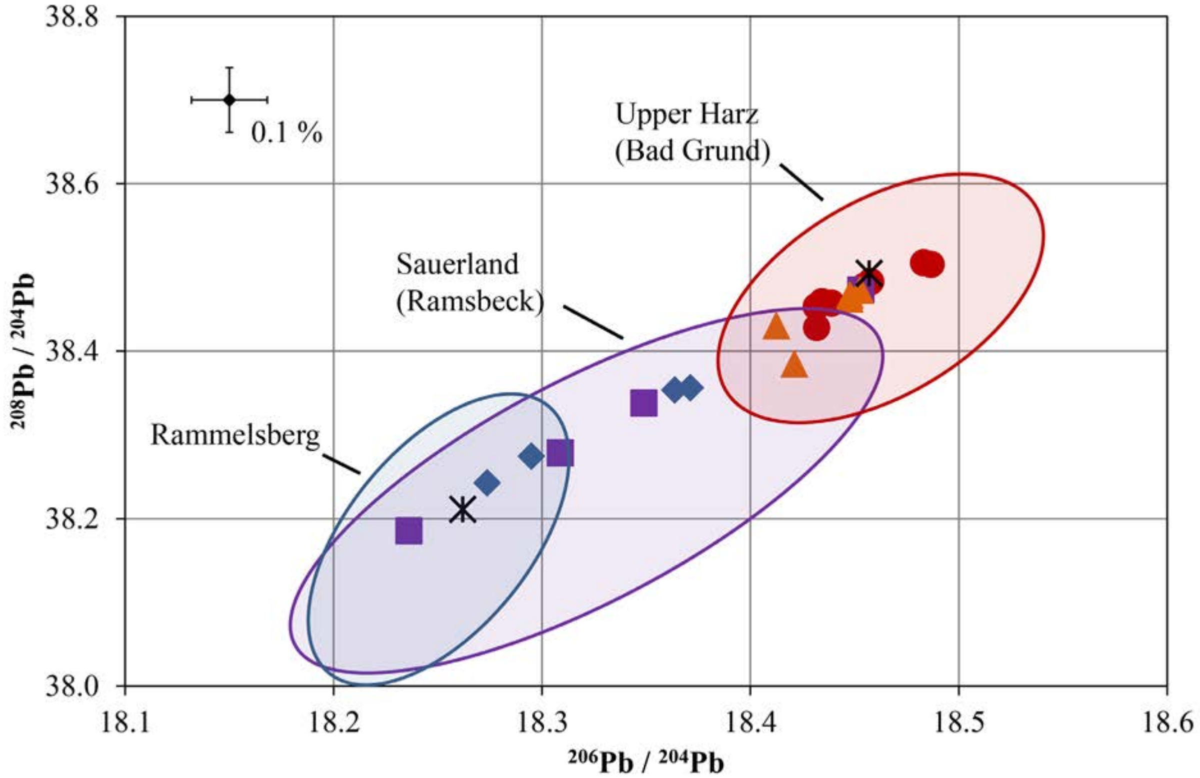
[19] **Cat. 96-104** and **Cat. 113**





Figures 7.20 and 7.21 *Lead isotope diagrams relating the composition of Ottonian coins to galena from three ore deposits and litharge from the Harz (BROCKNER et al. 1989). The Ottonian pfennige fall in the fields of Rammelsberg ore, Upper Harz ore from Bad Grund (HATZ et al. 1991; LEHMANN 2011; LÉVÊQUE/HAACK 1993; TISCHENDORF et al. 1993), and the ore from Ramsbeck in Sauerland (BODE 2008; WAGNER/SCHNEIDER 1999). There is a clear concentration of pfennige in the Upper Harz field, but several of the Colonia pfennige fall outside this field and possibly reflect the use of more local silver resources or refining with lead from the Rhenish Massif. 2σ is smaller than the symbol unless otherwise specified.*

boss is made of silver debased with brass, and both parts of the brooch are made of silver of similar composition.

The lead isotope analyses of these objects of Anglo-Saxon and Hiberno-Norse origin provide no distinguishing characteristics that can be used to separate them from the field of ore from the Upper Harz, with the exception of one debased silver-brass object (**Cat. 162**) which plots slightly outside this field. There is widespread overlap in the lead isotope field of many British ore deposits with the Harz and the Rhenish Massif as many of these ore deposits formed at the same time. The lead ore deposits in Cumbria near Durham,[20] in Derbyshire,[21] and the Mendips (Rohl 1996) all have isotope ratios that overlap with the Upper Harz. The elemental differences between the silver used on the British Isles and Harz silver, i.e. Otto-Adelheid-pfennige, show that they do not derive from the same source. The consistently and substantially higher gold content of Anglo-Saxon silver, often with very little bismuth, is incompatible with what is known about the silver produced in the Harz and the silver used on the Lower Rhine. Although Anglo-Saxon England probably imported silver from Central Europe, in England this silver must have been mixed with other silver containing higher gold concentrations, the source of which remains unknown.

7.6.5 European Silver and the Årstad/ Harthacnut Coinages

The alloy of the Danish coins of Group 3, the Årstad and Harthacnut coins, fit well in the range of compositions found in the coins from Central Europe and the British Isles. Archaeologically speaking, coins from the Ottonian and Salian Empire and Anglo-Saxon England dominate the coin finds of the first half of the 11th century at Hedeby as elsewhere in Scandinavia, and no contradictory evidence was identified that would point to sources outside these two regions. It is clear from the compositions of the coins of Group 3 that they are not made solely of Rammelsberg or Harz silver, but are mixed with silver that circulated in other regions in Central and western Europe. The variable zinc and gold contents but generally low bismuth contents indicate that the silver used on the Lower Rhine and the British Isles was mixed with any Otto-Adelheid-pfennige that were melted down in Hedeby for recycling. The slight offset of the lead isotope field away from the Upper Harz signature seems to confirm mixing with the silver used on the Lower Rhine, which have lead isotope ratios reflecting a slightly older geologic origin.

It makes sense to reiterate at this point that the lead isotope ratios found in the silver may not represent the geologic origin of the silver but could instead be introduced during refining. There seems to not be a dire need to refine the silver being imported to Scandinavia in the early 11th century because many of the silver coins analyzed are of high quality silver. However, there is evidence of cupellation at Viborg, in Central Denmark, during the reign of Cnut the Great, 1018-1035 AD (Hjermind et al. 2009, 139; Jouttijärvi/Andersen 2005, 359-60),[22] and a cupellation hearth was found on Gotland with a calibrated radiocarbon date of 970-1160 AD (Söderberg/Gustafsson 2006). The circulation of lead metal originating from European deposits and clear evidence for cupellation make that tracking the movement of silver by lead isotope analysis potentially problematic. This makes the consideration of the impurities in the silver and elements like gold and bismuth more even important.

7.7 Sven Estridsen and Cnut the Holy Coinage (1048-1086 AD)

7.7.1 Introduction

The coins of Sven Estridsen and Cnut the Holy are characterized by high zinc contents due to the intentional addition of brass to the silver. One coin of Sven Estridsen minted at Viborg is of excellent quality silver; however, all other coins analyzed attributed to the reigns of Sven Estridsen and Cnut the Holy are below 90 percent silver and are debased with brass. The coin of good quality silver has a zinc content of close to one percent indicating that brass with a high percentage of zinc (ca. 28 %) was alloyed with the silver. There is a long tradition of adding brass to silver on the British Isles, but the low gold content of this coin is atypical for silver used there. The gold to silver and the bismuth to silver ratios for the coins of Sven Estridsen are close to that of Group 3, and this possibly indicates a continuity of the core or base silver stock or silver sources. The seven stylized Danish imitations of pennies of Edward the Confessor, probably minted under Cnut the Holy, are very homogenous and have lower gold and bismuth ratios than nearly all earlier Danish coins. This probably reflects slight changes to the silver stock, at least for this group of coins.

7.7.2 Interpreting the Lead Isotope Ratios of Group 4

The lead isotope field of the coins of Group 4 is distinct from Group 1 and Group 2 (**Figures 7.22** and **7.23**), but there is a slight overlap with Group 3. Some of the same imported coin types that are similar to Group 3 also match with Group 4; however, the coins of Cologne, Westphalia, and the Lower Rhine best reflect the

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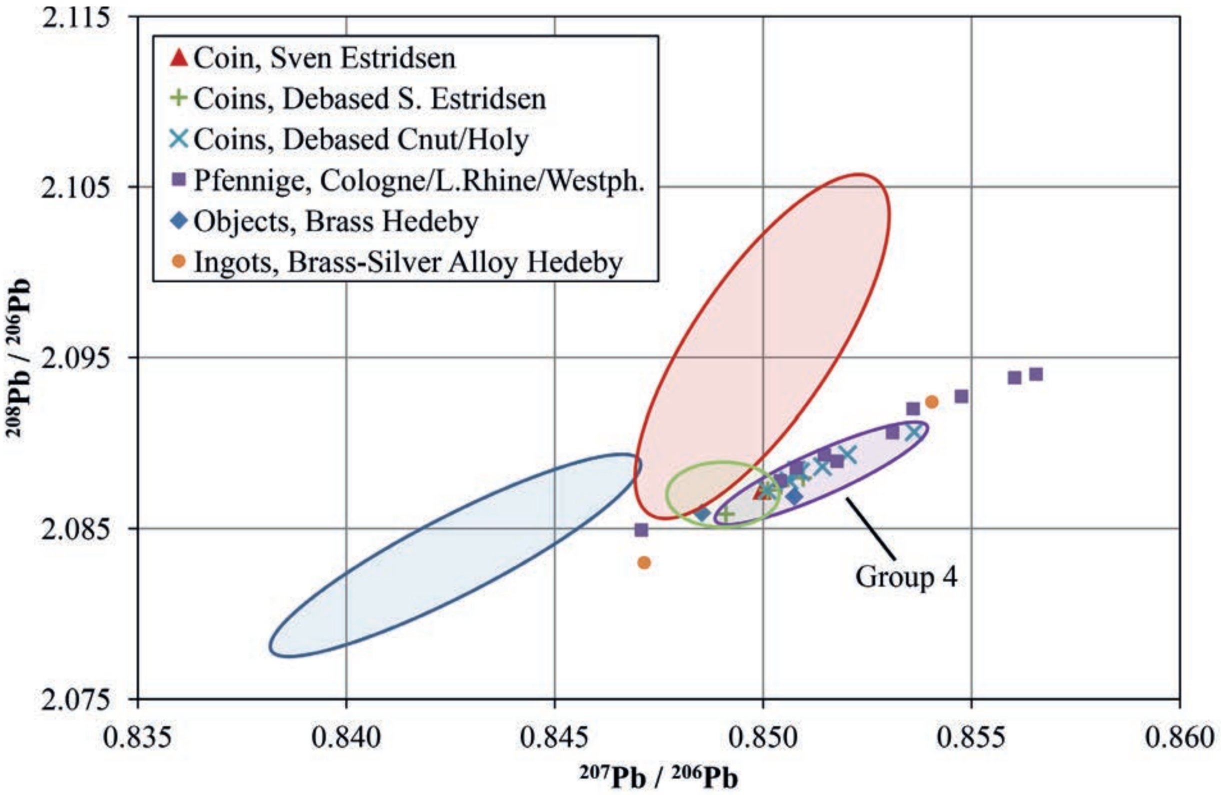
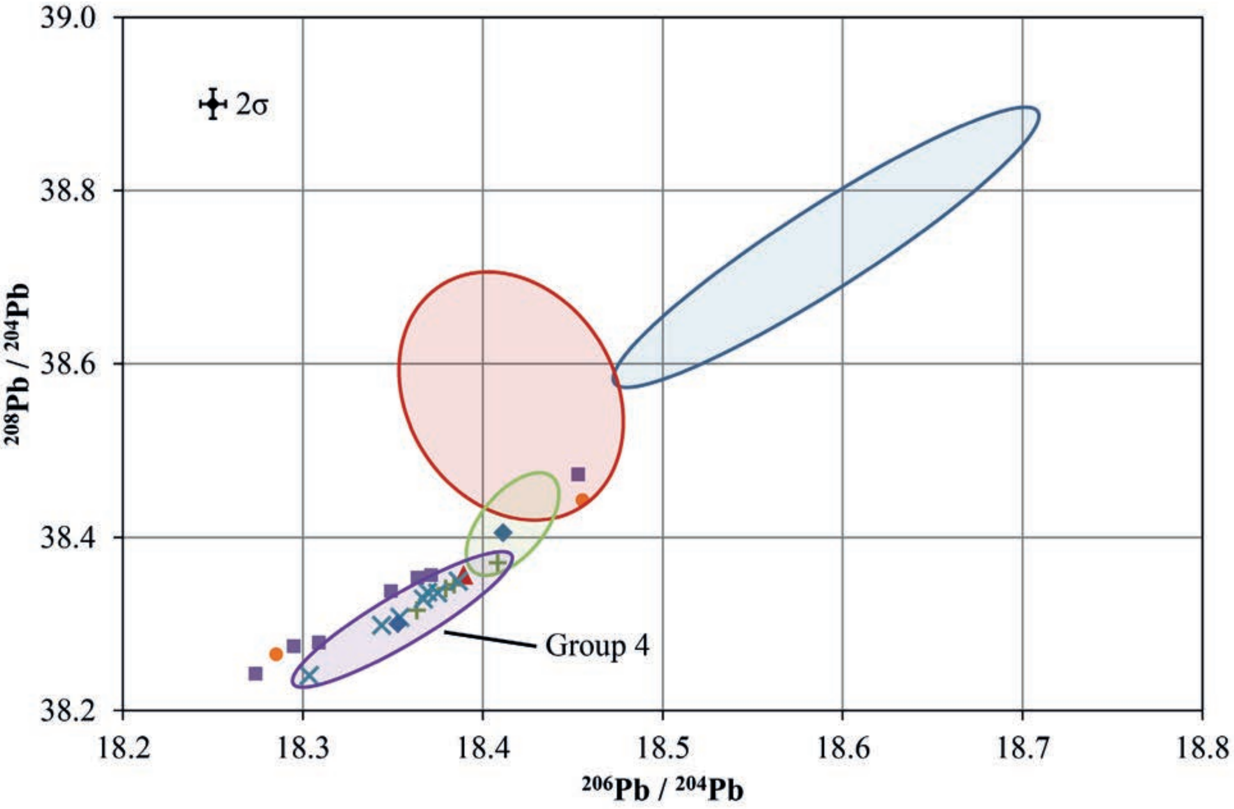
[20] Cumbria / Durham: Alston Nenthead, Teesdale, Weardale.

[21] Derbyshire: Castleton, Cromford, Matlock, Wirksworth.

[22] A silver smithing workshop has been excavated at Viborg that was seasonally used. Evidence of cupellation has been found there in the form of two fragments of litharge impregnated calcareous ash material and can be dated to the years between 1018 and 1023 by dendrochronology.





Figures 7.20 and 7.21 *Lead isotope diagrams comparing pfennige from Cologne, Westphalia, and the Lower Rhine to the Danish coins of Group 4. Two brass objects (Cat. 193 and 195) and two silver ingots debased with brass (Cat. 191 and 194) found at Hedeby are also plotted. 2σ is smaller than the symbol unless otherwise specified.*

range of lead isotope compositions found in Danish coins of Group 4. The range of gold to silver and bismuth to silver ratios are not dissimilar enough to distinguish Group 4 from the coins of Cologne, Westphalia, and the Lower Rhine. The parallels in elemental and lead isotope composition may be meaningful and require critical evaluation.

The lead isotope data of the coins of Group 4 must be interpreted carefully due the variable and often significant debasement of the silver. Three factors potentially contribute to the lead isotope signature of the debased coins of Group 4:

3. They may represent the lead associated with the silver, hence giving information about the lead used during silver refining, whether it reflects the origin of the silver, silver of mixed origins, or secondary cupellation.
4. They could stem from the brass, reflecting lead acquired during the brass making process. Depending on the technology used, a certain lead content may result from the zinc ore being heated with the copper during brass making.
5. They could represent lead that is unrelated to the silver origin or the brass making process. They could stem from lead-bearing copper used to make the brass, or lead metal could have been simply added to the brass or brass-silver alloy for economic reasons.

Some possibilities are less likely than others, and an effort will be made to narrow down the discussion, but it must be stated that there is considerable uncertainty in the interpretation due to the number of unknown factors.

7.7.3 Viking-Age Brass and Debasement

A key to the discussion is the re-creation of the brass alloy used in debasement. To give an impression of the nature of the brass alloyed with the silver, a hypothetical composition was calculated by separating and normalizing the four major and minor elements that likely represent the brass added. The zinc content ranges between 7.5 to about 20 percent with minor amounts of tin and lead (**Table 7.3**). The analyses presented in **Table 7.3** show that during the reign of Sven Estridsen there is a higher lead contribution (2-6 % Pb) to be expected from the brass than in the later coins attributed to Cnut the Holy (1-2 % Pb). Additionally, two silver-brass alloy ingots were discovered at Hedeby. These ingots were surface enriched and were thought to be true silver, but upon drilling the brass-rich interior was revealed. The alloy of these ingots is much richer in lead than the coins of Group 4. The lead contents of the coins of Group 4 are above average compared to the earlier Danish coin groups (see **Table 7.1**) and likely there is some contribution of lead from the brass added to the silver.

To date, very little brass from the Viking Age has been analyzed with both elemental and lead isotope analysis, and there has yet to be a theoretical discussion about how the results of the lead isotope analysis of medieval brass can and should be interpreted. If the lead isotope ratios of the silver of Group 4 indeed reflect the brass used in the debasement, what information do they actually tell us? Do the lead isotope ratios reflect the copper source, the zinc source, or simply lead added to stretch the metal supply? There are potentially two ways forward with the discussion. Firstly, it is necessary to determine if significant amounts of lead are normally found in brass of this period and in what quantities, and, secondly, to determine at which production step(s) this lead was likely introduced. To investigate these questions we must rely on the few analyses available.

From Hedeby itself, of the four analyzed copper-alloy objects published by DRESCHER (1994), three are brasses and have lead contents between 0.4 and 6 percent and 15 to 24 percent zinc. From the present study, two of the copper-alloy objects were of ternary lead-zinc-copper alloys (**Cat. 193** and **195**), however with more lead than zinc. Viking period copper-alloys from Gotland are also determined to be mostly leaded brasses containing on average 12 percent lead and 15 percent zinc (ARRHENIUS 1989, 13-4). At the Viking-age settlement of Kaupang, nearly all the copper-alloy objects analyzed are brasses containing between 5 and 20 percent zinc and varying quantities of lead (PEDERSEN 2010, 253-257, 269). Similar alloys can be found in Westphalia. At Kückshausen, a brass production site dated to the 9th and 10th centuries near Dortmund and at the foot of the lead-zinc deposit of Iserlohn, production waste was analyzed and found to be droplets of leaded brass (CAPELLE 1974, 300). Copper-alloy objects of the 8th to 11th century from Höxter / Corvey in East Westphalia were analyzed with lead isotope analysis (ZIENTEK et al. 1998) and closely parallel the range of lead isotope compositions found in the pfennige from Cologne, Westphalia and the Lower Rhine. The objects analyzed range from fairly pure copper to mixed gunmetal, but one of these objects is a brass bar ingot fragment containing 9 percent lead and 12 percent zinc and is dated to the 9th century AD (ZIENTEK 1998, 164, HC-44).

Brass making crucibles and associated slag from the sites of Dortmund Adlerturm, Soest Plettenberg, and Kückshausen were analyzed by lead isotope analysis and the isotope ratios are again of a similar range and are consistent with zinc ore from deposits in Sauerland, like Iserlohn but also ore from the North Eifel (KRABATH et al. 1999), but unfortunately, the data are only presented in one diagram and the accompanying numerical dataset was not published. The early medieval production of brass is thought to be concentrated in the North Eifel / Ardennes where deposits of high quality calamine could be found (DAY 1998, 133-4), but the oxidation zone of the lead-zinc deposit of Iserlohn and other deposits in Sauerland are also potential sources of calamine and

Cat. Nr.	Description	"Silver"	"Brass"	Cu	Zn	Sn	Pb
		%	%	%	%	%	%
144	Coin, Sven Estridsen	80	20	77.7	19.8	0.4	2.2
145	Coin, Sven Estridsen	87	13	76.6	19.9	0.1	3.5
146	Coin, Sven Estridsen	67	33	79.4	12.5	1.7	6.4
146 (Repeat)	Coin, Sven Estridsen	75	25	87.8	7.5	1.2	3.5
147	Coin, Sven Estridsen	74	26	81.4	11.7	1.8	5.0
148	Coin, Cnut the Holy?	62	38	79.4	18.2	0.9	1.5
149	Coin, Cnut the Holy?	80	20	83.8	15.0	0.6	0.7
150	Coin, Cnut the Holy?	70	30	81.9	15.9	0.9	1.3
151	Coin, Cnut the Holy?	76	24	81.5	16.2	1.1	1.1
152	Coin, Cnut the Holy?	77	23	85.7	12.6	1.0	0.7
153	Coin, Cnut the Holy?	67	33	77.5	20.2	0.5	1.7
154	Coin, Cnut the Holy?	64	36	78.9	19.4	0.7	1.0
191	Ingot, Silver-Brass Alloy	40	60	72.8	17.8	1.6	7.8
194	Ingot, Silver-Brass Alloy	62	38	65.1	15.5	4.9	15.3
192	Bead, Copper Alloy	-	-	71.5	0.3	16.7	11.5
193	Pennanular, Copper Alloy	-	-	81.4	7.3	0.1	11.2
195	Neck Ring, Copper Alloy	-	-	66.9	8.1	0.02	24.9

***Table 7.3** Hypothetical brass compositions alloyed with the debased silver coins of Sven Estridsen and Cnut the Holy compared to the composition of debased silver ingots and copper-alloy finds from Hedeby. To account for the core silver composition 2.5 parts copper and 0.45 parts lead per 100 parts silver were subtracted. The remaining copper, zinc, tin, and lead were added together and normalized to 100 percent.*

may have supplied the production of brass in Westphalia (Krabath et al. 1999, 436).

It is clear from the analyses that brasses, even when freshly produced such as at Kückshausen, can contain significant quantities of lead, but, from the work of Zientek (1998; Zientek et al. 1998), the medieval copper-alloys of Höxter and Braunschweig, whether the alloys contained zinc or not, seem to cluster in the same field, and this field is mirrored by the Danish coins of Group 4 and the pfennige of Cologne / Westphalia / Lower Rhine. It should be noted that the range of lead isotope ratios found in copper-alloy objects from Hedeby, Höxter, and Braunschweig, and the debased coins of Group 4 are only a fragment of the spread of isotope ratios found in Viking-age lead objects (see **Appendix H** and Pedersen 2010, 271-84), which speaks toward the interpretation that the copper-alloy lead isotope field is independent. Rather than representing an addition of metallic lead to the brass, the isotopes probably reflect the ore used to make the copper or lead acquired during the brass making process.

There may be a relationship between the isotope compositions of the brass artifacts and the ore deposits of the Rhenish Massif, like Iserlohn or Aachen Stolberg, but it must be concluded that at the present state of research, the question of the meaning of the lead isotope ratios of brasses from the early medieval period cannot be answered. More light will be shed on this issue with the further sampling and analysis of early medieval copper-alloy, lead, and tin objects, work that is currently in progress as part of a Volkswagen-Stiftung project with the aim to better understand the transition from Viking-Age Hedeby to the age of the Hanseatic League and Schleswig.

7.7.4 Summary and Conclusions

The analyses of the coins of Sven Estridsen and the imitative Anglo-Saxon style coins of Cnut the Holy confirm the debasement already recognized in Denmark (Gullbekk 2000) and mirror the debasement found in Norway during the same period (see Skaare 1976). The core silver used in the coinages of Group 4 seem to be related or otherwise similar to the silver of Group 3, but the major difference is that brass was added in quantities as high as 38 percent. The brasses used during the reign of Sven Estridsen seem to be higher in lead than in the later coins. The lead isotope composition of Group 4 may be masked by the brass used in debasement, but it is unclear at this point what the lead isotope ratios of brass mean due to insufficient comparison material and the gap of research on early medieval brass production and use. The coins of Group 4 have lead isotope compositions that are most similar in range to the pfennige of the Cologne / Lower Rhine / Westphalia region. This might not be coincidental, and it might reflect the use of copper-alloys processed from ore from this region, but little can be said concerning these potential relationships without further investigation of base-metal objects.

7.8 Closing

The goal of this chapter was to explore the relationships among silver objects through lead isotope and elemental analysis and to document the chronological changes to the silver stock within the framework of the Hedeby / Danish coins of the 10th and 11th centuries. It is clear from the analytical results that the silver stock used for the Hedeby / Danish coinage evolved over time. These changes reflect the emergence and disappearance of silver types, which are in turn related to changes in the trade routes and the output of mining regions. Although there is some overlap between the chronological groupings, there are often attributes that are characteristic for the alloys used in each of the four periods.

The discovery of a relationship between high bismuth contents and the ^{208}Pb ratios in the silver of the mid to late 10th century is distinctive and seems to indicate the incorporation of Samanid silver into the silver stock. The results of this study thus shed light on developments occurring inside and outside Scandinavia. There is some promise in the use of elemental and lead isotope composition as a tool for relative dating based on the framework developed in this thesis. It is probably possible to place Scandinavian Viking-age silver objects into groups such as pre-Samanid period, Samanid period, and Post-Samanid period. This study has revealed and in some cases rehashed many issues concerning the sources and circulation of silver outside Scandinavia, issues that are in need of further discussion. The following chapter will provide a synthesis of the information gained in this study, about its implications for the study of silver metallurgy and mining in the Viking Age, and it will provide new directions for future research.

8. Chapter
Conclusions and Recommendations for Future Research

8.1 Introduction

The material science analysis of Viking silver is able to reveal information about mining and trade that cannot be obtained in any other way and enriches our understanding of economic development in the Viking Age. The analysis of early medieval silver with elemental and isotope analysis is still in an early stage of development, and the limits of these methods to gain information about the past are far from known. A number of points about the sources of silver in various regions remain uncertain, but gradually the relationships between silver mining, coin production, and long-distance trade are becoming clearer. The aim of this final chapter is to look at the broader implications of the analytical results and to help delineate the boundary of what is known and what remains unknown. The chapter is divided into five themes each covering a different facet of the study.

8.2 Towards the Question of Refining in the Viking Age

Silver can be recycled in a number of ways. Silver alloys can be physically or chemically altered to suit the demand for production. How these alloys were treated by the Vikings directly impacts how the elemental and isotope compositions can be interpreted. With a combination of analytical techniques in addition to the analysis of lead artifacts, crucible fragments, and refining slag, an argument can be made about the recycling practices used at Hedeby. It is known that cupellation was carried out by the Vikings at various times and that heating trays were used to clean precious metal alloys with the addition of lead (see **Appendix G**), but it can be asked to what extent was silver refined at Hedeby?

One way forward is by contrasting the lead isotope ratios of the Viking silver objects with the lead available at Hedeby. It is rational to assume that when cupellation did occur, then lead metal that was in circulation would be used for the process; this is one reason why the analysis of lead finds is important. As far as it is now known, the Danish coins of Groups 1 and 2 neither match with the lead found at Hedeby (**Appendix H**) nor the lead found at Viking settlement of Kaupang (Pedersen 2010, 271-84), but there are matches with Groups 3 and 4 (see **Figure 8.1**). This is a strong indication that the silver of Groups 1 and 2 was not refined with the type of lead available at Hedeby, lead that most likely originates from ore deposits in western or Central Europe. If refining processes were commonplace then the lead isotope ratios of the silver probably would reflect a similar range of isotope ratios as the lead objects from Hedeby, but this is not the situation. The majority of lead objects plot outside fields of the Hedeby / Danish coin compositions. The evidence suggests that many of the Hedeby / Danish silver coins were produced simply by recycling silver by re-melting and the process of cupellation perhaps played only a minor role. Naturally, this conclusion cannot be applied to the debased coins of the second half of the 11th century, which may have been alloyed with imported brass in Scandinavia. Concerning the silver prior to this debasement, the chronological differences in the elemental and isotope compositions can be best explained as differences in the source or sources of the silver and / or silver refined outside Scandinavia. It is possible that the testing of purity of the silver traded by the Vikings (see **2.5.2**) and the social consequences of fraudulency prevented debasement and maintained the silver standard to the extent that refining by cupellation was often unnecessary.

Although recycling without refining seems to best reflect the situation at Hedeby, this may not have been so elsewhere in the early medieval world. For instance, it is unclear if the lead isotope compositions of the Colonia type coinages in Westphalia and on the Lower Rhine stem from silver production in the Rhenish Massif or if silver from mines in the Upper Rhine Valley or other sources was refined with lead from the Rhenish Massif. Both possibilities would produce silver with an identical range of lead isotope ratios, but the resulting interpretation has real archaeological implications. Regional studies would be required to specifically look at issues of recycling and minting practice on a case-by-case basis.

8.3 Silver of the Islamic World and the Dirham Imitations

As discussed in **Chapter 5** and **Chapter 7**, the silver of the Islamic world is not static, nor is production

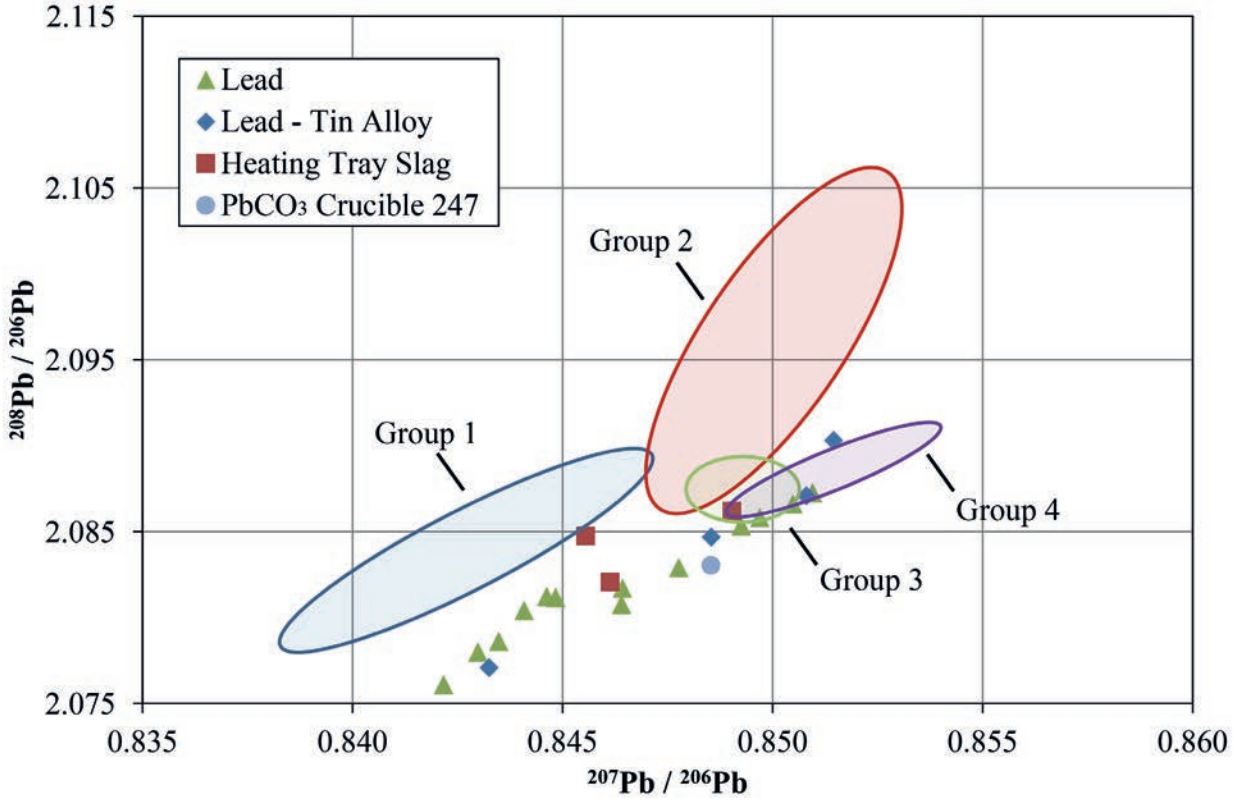


Figure 8.1 *TLead isotope diagram comparing Hedeby/Danish coin groups (1-4) and lead and tin finds, lead-rich slag from heating trays, and the lead carbonate residue in crucible Cat. 247.*

dominated by one, or even a hand-full of silver mines. It is clear from the compositions of the dirhams analyzed in the past, and in this study, that there are both chronological and regional differences, which reflect different silver sources. Dirhams from the Samanid mints of Transoxania and Afghanistan dating from the late 9th to the 10th century are much better characterized[1] than the dirhams of the earlier Umayyad, Abbasid, and Saffarid dynasties and misleadingly seem to be viewed as representative of the silver used in the Islamic world during the Viking Age.[2] The exportation of dirhams out of Samanid Central Asia followed earlier waves of silver exportation from other parts of the eastern and western Islamic lands. The development of trade routes that connected the central and eastern Islamic world to northern Europe perhaps has its roots prior to the Viking period (see Grierson 1993, 143; Noonan 1981, 53), but during the Viking period powerful trading centers and states emerged that facilitated the transfer of goods across Continental Asia. Centers like Atil and Bulghār, capitals of the Khazar kingdom and the Volga-Bulghar state, were fuelled by the growth of trade and thrived in the 9th and 10th centuries, respectively (Noonan 2001). As the Khazar kingdom declined at the end of the 9th century, Volga Bulgharia rose to power. The shift from trade routes from a Khazaria-Iran-Iraq orientation to the Volga Bulgharia-Central Asia orientation seems to mirror the shift in the location of silver mining. There is some indication that a decline of mining in Iran coincided with the growth of silver mining in Samanid Central Asia and Afghanistan.

The elemental and lead isotope analysis of the imitation dirhams produced in Khazaria and Volga Bulgharia are important to characterize the silver stock moving through Russia during the 9th and 10th centuries. Whereas the Khazar imitation dirhams should be made from 9th century silver stock, possibly originating in the Abbasid Caliphate, Volga-Bulghar dirham imitations are typically dated to the 10th century and are contemporary to the massive influx of Samanid dirhams westward. As the analyses of Steuer (2003) have shown, the coins of the Volga Bulghars were not made entirely from Samanid dirhams because their average bismuth contents are much lower. Through the application of lead isotope analysis it has been revealed that the Volga-Bulghar dirham imitations are heterogeneous. Some are made of silver that is similar to the KG7 coinage, thought to be produced at Hedeby around the first two decades of the 10th century, but some are made of silver that has a more Samanid character with higher bismuth contents

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[1] See **5.3.4** and the analytical results of this study.

[2] Though Samanid dirhams are the most commonly found dirham type in Viking-age Scandinavia, their survival in the archaeological record may be biased by a number of factors. Their use coincides with the Scandinavian hacksilver period, and whereas in the earlier period silver was perhaps more commonly melted down to produce weight-adjusted ingots and rings. In the hacksilver period coins were kept whole or cut into small but still identifiable pieces. Another question is if the increase in hoarding in the 10th century is a factor in the survival rate of Samanid dirhams.

and higher ^{208}Pb ratios. Does this represent the transition in Volga Bulgharia from the use of pre-Samanid to Samanid silver around the turn of the 10th century? This first look into the elemental and isotopic composition of the Volga-Bulghar coinage seems to indicate that this might be true. There may be a lag in time between when the introduction of Samanid silver occurred and when it completely dominated the silver stock in Volga Bulgharia. A more thorough analysis of particularly well-dated Volga-Bulghar dirham imitations would be necessary to discern whether the elemental and isotopic trends are truly chronological.

8.4 Early Medieval Silver Mining – The Analytical Evidence

Through the combination of lead isotope analysis and elemental analysis, numismatics, and archaeology, information about the mining of silver in the early medieval period can be gained. The analyses help to characterize types of silver available, and though at times these characteristics can be traced to particular regions or mining areas, in many cases the information is less specific, only indicating differences in silver source while the origin or origins remain unknown. An example of this is the origin of the silver used in Anglo-Saxon England in the 10th and 11th centuries. It is thought by some that the major increase in minting at the end of the 10th century reflects the importation of silver from the Harz (see **5.3.2**); however, the analyses of coins and silver objects indicates that this explanation may not be entirely correct. The higher gold contents of the Anglo-Saxon silver seen repeatedly in the analyses argue for an independent source of silver from that of the Ottonian continent. The large-scale recycling of gilded silver objects might be responsible for this discrepancy, but it is unclear if this explanation is truly feasible considering the quantities of silver coins in circulation. Like the question of the source of Anglo-Saxon silver, in the Carolingian Empire there are hints of alternative silver sources to Melle, but they remain obscure for the moment due to the state of research.

The analyses of the Magdeburger Sachsenpfennige provide some indication that silver production in the Harz began at least in the second half of the 10th century, and by the time of the Otto-Adelheid-pfennig the analyses show that silver production was in full bloom. Differences in the elemental composition and isotope ratios of the silver from the Rhine valley and Westphalia points to independent sources of silver from the Harz, and this cannot be explained only by differences in the lead used in the cupellation process due to the differences in gold and bismuth contents. The source or sources of silver in the Rhine valley is a question remaining to be studied in depth.

In the Islamic world, mining was carried out in many regions, but most are poorly studied. The few lead isotope ratios of coins from Iraq and Iran seem to indicate production in the Taurus Mountains of Anatolia and several parts of Iran (see **7.4.3.**). The analysis of ore and slag from al-Radrād in Yemen, though mentioned historically and providing archaeological evidence for medieval silver production, has yet to reveal connections to the wider Islamic world in the 9th and 10th centuries, but this is a research gap in need of further study (Merkel et al. 2016). Based on the elemental and lead isotope analysis of dirhams, ore, and slag, the boom of dirham production in Samanid Central Asia in the late 9th to the mid-10th century seem to be partially supplied by silver production in the Īlāq region of Uzbekistan, but it is clear that the silver produced in northern Afghanistan is of a different character (see **Appendix I**). How each of the silver producing regions in the eastern Islamic lands was related to the massive export of silver in the 9th and 10th centuries is a question for future research. It would require the joint collaboration of numismatics, history, mining archaeology, and archaeometallurgy to answer.

8.5 Composition of Hedeby / Danish Coins and its Implications

Much can be learned from the silver finds from Hedeby, and, above all, the study of numismatic finds has provided a basis for the reconstruction of the trade of silver coins at Hedeby as elsewhere in the early medieval world. A major facet of this study is to look at the interrelationships between the trends seen in the field of numismatics and the physical substance from which the coins were made. The interdisciplinary study of the Hedeby / Danish coins has revealed parallels between the historical / archaeological records and the material characteristics of the silver. This study helps to strengthen the evidence for many long standing assumptions concerning the flow of events and the movement of silver in the Viking Age, and it is also a way to explore the discord between the archaeological and historical records.

A major problem in the study of Viking silver is that the Danes levied tributes in silver, the so-called 'Danegeld,' in the Carolingian Empire, but very little of this money has been found in Scandinavia (see Hatz 1974, 29; Suchodolski 1990). It has often been assumed that the Vikings took this money back to Denmark bringing about the decline of silver currency in western Europe (see Spufford 1988, 61-4). Sawyer (1971, 100-101; 1990, 285) argues that the silver of western Europe was not taken back to Scandinavia in the 9th century; instead it was used in the lands where it was acquired in order to buy supplies or to exert financial influence.[3] Although 9th century Carolingian and Anglo-Saxon coins and silver objects are quite rare in the Baltic region, Islamic dirhams

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[3] Lieber (1981, 18, 27) argues similarly for the Danegelds levied by the Vikings in Anglo-Saxon England in the late 10th and early 11th centuries.

are found in more significant quantities (see Hatz 1974, 15-37; Kilger 2008a; 2008b). The clash in the archaeological and historical record is seen in an earlier article by Coupland in which he argues that the immense amounts of silver collected by the Vikings in western Europe were melted down to bullion, however, the Islamic dirhams somehow escaped the melting pot (Coupland 2007, XV 13-7). Were these dirhams seen as exotic and, therefore, preserved and curated, or could it really be that Islamic silver was used in the Baltic area in the 9th century and that western silver was not imported on any significant scale? Grasping with this question, a more recent study of Viking coin hoards in Frisia buttresses the argument that the silver won in western Europe probably stayed there (Coupland 2011).

Little is known about the composition of Scandinavian silver objects of the 9th century as there have been few elemental and lead isotope analyses performed on material from this period. What can be said is that it appears that the Malmer KG 7 coins were made from eastern silver with similarities to some Volga-Bulghar dirham imitations and pre-Samanid dirhams. This is not definitive, but likely, and requires further analyses particularly of late 9th century Carolingian and Anlgo-Saxon coinages and Abbasid and Saffarid dirhams to confirm. The silver used to make the Malmer KG 7 pre-dates the large-scale recycling of Samanid silver that is thought to have first entered the Baltic around 900 AD. This is a clear indication that the minting of the KG 7 was unrelated to the influx of Samanid silver and relied on an earlier silver stock, possibly a wave of silver from the Iran / Iraq area in the 9th century.

This naturally raises the question about the relationship of the dating of the KG 7 and the arrival of Samanid dirhams at Hedeby. If the dating of the KG 7 between 900 and 920 AD is indeed correct, than the full impact of Samanid silver on the silver stock at Hedeby must have occurred afterwards. The study of coin finds from Kaupang indicates that this may actually the case. As Kilger explains, Abbasid dirhams dominated the coin finds of Kaupang from the last quarter of the 9th century into the first two decades of the 10th century. The Gotlanders were some of the first in the Baltic to develop trading connections to Samanid Central Asia via Volga Bulgharia, and although on Gotland Samanid silver began to arrive shortly after the year 900 AD, the major wave of Samanid silver did not arrive at Kaupang before the decline of the settlement in the 920s (Kilger 2008b, 242-6). There is apparently a time lapse between when Samanid silver reached the eastern Baltic and when it dominated the silver stock in the western Baltic.

If a break in minting did occur at Hedeby between 920 and 950 AD then this period would likely coincide with the ascendancy of Samanid dirham silver in the western Baltic. As minting resumed in the second half of the 10th century Samanid silver as well as other types of silver were available for the making of coins. The analyses show that at this point the silver stock could have consisted of Samanid dirhams homogenized through recycling, newly mined silver probably from the Harz Mountains, silver possibly of Anglo-Saxon origin, and some silver left over from the older silver stock. More analyses of the Hedeby / Danish KG 8-11 coin types would be required to characterize any chronological trends in composition between the years 950 and 980 AD, the supposed transition period from the use of Asian to European silver. In the 11th century traces of non-European silver in the Hedeby / Danish coin compositions disappear and could reflect sources in Continental Europe, like the Harz and regions connected to the Rhine Valley, and possibly independent sources on the British Isles. The compositions of the Hedeby / Danish coins from the mid-10th century to the 11th century, thus, align with what would be expected based on the archaeological record of silver finds and hoards in the Baltic Sea region (see **4.3.2**).

8.6 Relationship of Non-Minted Silver and Minting at Hedeby

The last theme to discuss is the minting at Hedeby itself and its relationship to non-minted silver in the 10th century. As discussed in **Chapter 7**, there seem to be relationships between unminted silver objects of presumed Viking manufacture and the 10th century Hedeby / Danish coinages. Some objects seem to be made of similar silver stock to the Malmer KG7, particularly important are the silver bar ingots of the Wiechmann Type 1, which have a high concentration in southern Scandinavia, and it is argued that they may have been produced, in large part, at Hedeby itself (Wiechmann 1996, 65-7, 620). Other types of objects like ribbed and twisted bar fragments, ring fragments, and wires also match isotopically and many have similar elemental compositions to the Malmer KG7. The low bismuth and high gold concentrations of this silver indicate that it is unrelated to the Samanid silver of the 10th century. A group of hacksilver objects, mostly wire fragments, have higher bismuth concentrations and plot in another region of the lead isotope diagram and seem more similar to the high bismuth silver used for some of the coins of the Malmer KG8-11 type (**Figures 8.2** and **8.3**). These differences in composition seen in the non-minted silver are mirrored in the Hedeby / Danish coinage and possibly reflect a chronological relationship.

One must assume that the form of the silver collected at Hedeby to supply the mint was both non-minted silver and foreign coins. The analysis of their compositional relationships may reveal information about their chronology and movements in the silver trade, but there is also a political dimension to be explored. Why are there hacksilver fragments of ingots and jewelry found at Hedeby that are made of the same silver stock as the Malmer KG7? The locally produced coinage at Hedeby was traded alongside hacksilver of similar com-

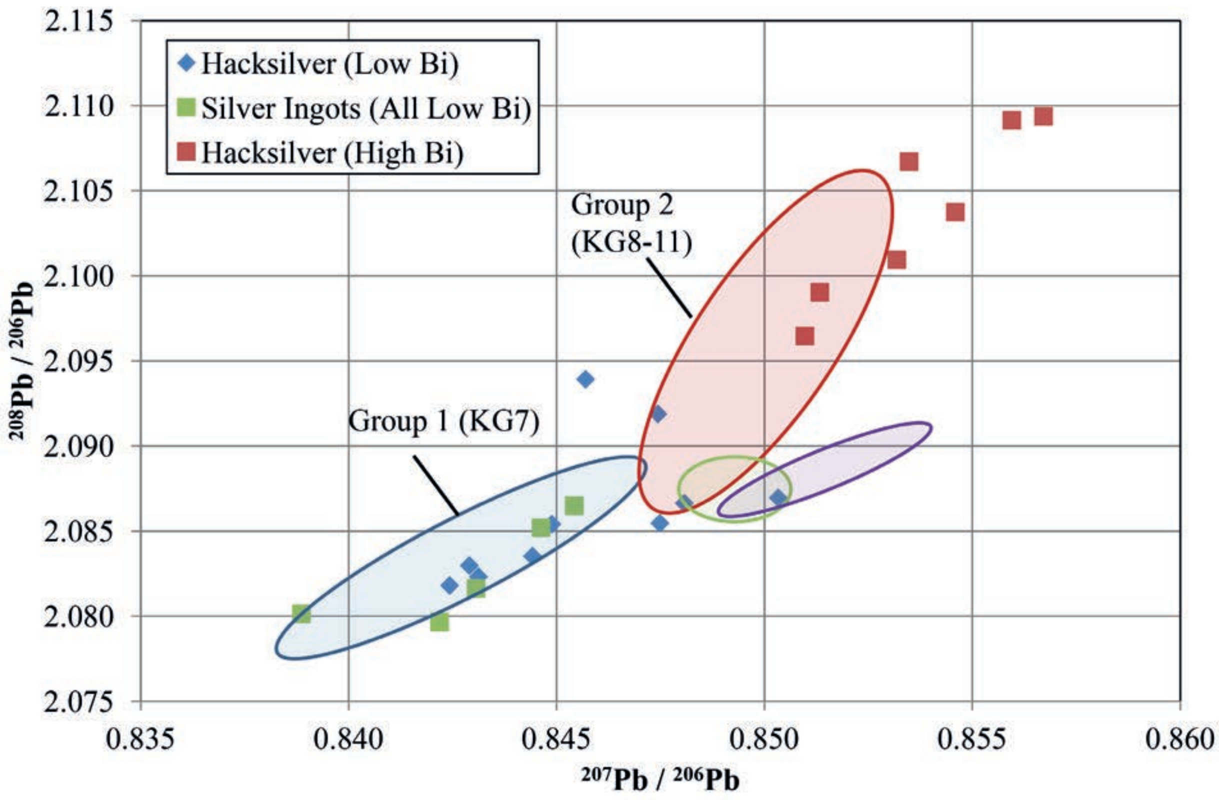


Figure 8.2 *Lead isotope diagram showing the relationship between hacksilver with bismuth contents above and below 3000 ppm. The bar ingots and low bismuth hacksilver clusters primarily in the area of the Malmer KG7 and the high bismuth hacksilver partially matches the Hedeby/Danish KG8-11 coins.*

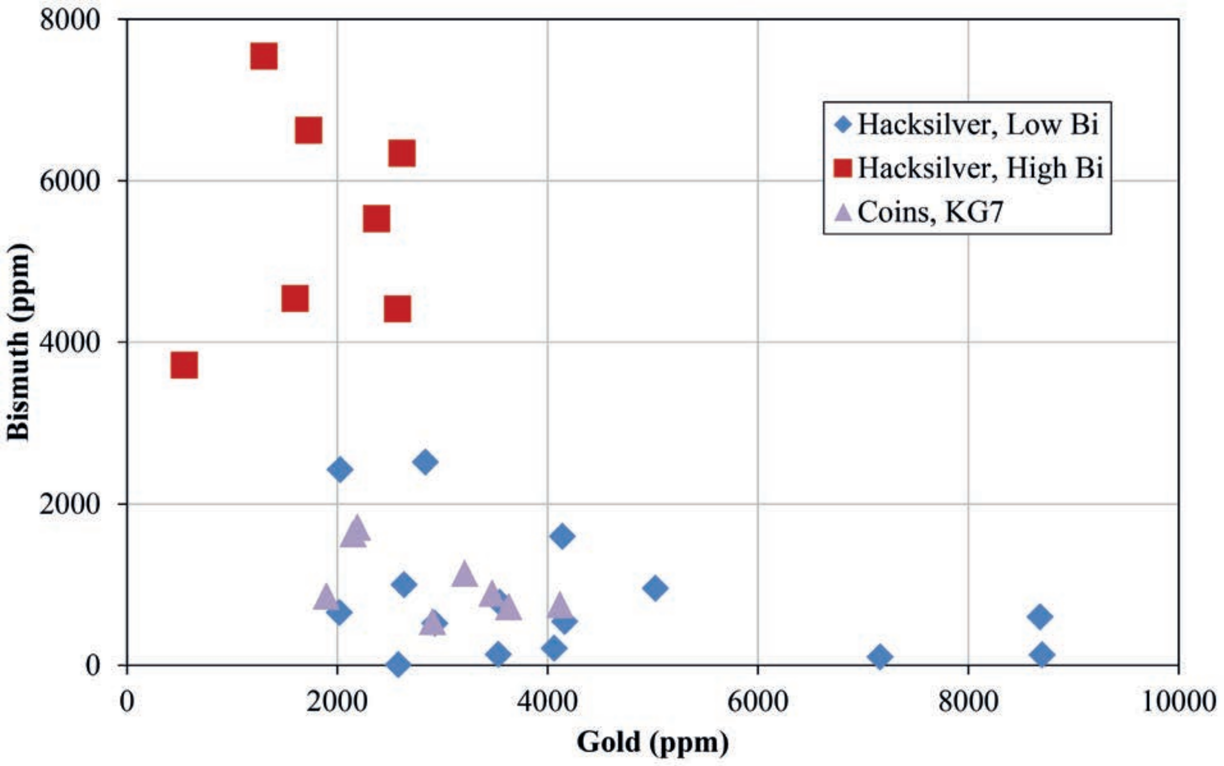


Figure 8.3 *The hacksilver groups plotted in Figure 8.2 are mirrored by their gold and bismuth contents. The Malmer KG7 coins probably minted at Hedeby between the years 900 and 920 AD align closely with the low bismuth hacksilver.*

positions and origins, or, in other words, it seems that a coin-based and a weight-based exchange system co-existed that relied on practically identical raw materials. This rehashes the need for discussion about the meaning of minting at Hedeby during the age of widespread silver commodity exchange in the Viking world (see **3.4**). The political and economic implications for the coexistence of conflicting systems of reckoning at Hedeby have yet to be sufficiently explored. Such an investigation would touch upon the role of kingship in the development and enforcement of currency systems (see KILGER 2011; WILLIAMS 2007).

8.7 Some Final Thoughts

Silver in the Viking Age is a theme of continual rebirth. As new silver hoards and metal-detected finds come to light, the theories of the past require reinterpretation. Innovative scientific methods are becoming available for the study of archaeological metals, which are opening many fresh avenues of research. A field of rapid development is the analysis of early medieval silver by laser ablation mass spectrometry, a method showing great promise in approaching issues of silver production, trade, and use. Although the analytical studies presented in this thesis were quite successful in exploring many details of the metallurgy and trade of silver at Hedeby and beyond, many of the data trends that have been elucidated by this study must be supported by further analyses due to the often unsatisfactory sample size.

In this study approximately 250 objects from Hedeby were sampled and analyzed by multiple methods in order to gain insight into the possibility of sourcing Viking-age silver and to better understand the mining history and metallurgy of the early medieval period. The study has identified a number of new possibilities for future research. The compositions of the Danish coins analyzed in this study form four groups or clusters. For the future, these coin groups should be broadened with further sampling to strengthen the interpretational basis. Particularly important are the analyses of dirhams of the 9th century and Carolingian and Anglo-Saxon coins in the later 9th century. An area of exciting possibilities is how the unminted silver and jewelry objects could fit into the chronology developed through the analysis of the Hedeby and Danish coin groups.

Laser ablation is a relatively new and cost-effective method of analysis and is semi-non-destructive; with a microscopic ablation enough sample material can be collected to measure lead isotope ratios and trace element compositions. The lowering of the financial cost of analysis with a minimization of damage to priceless archaeological objects and the proliferation of laser ablation technology will hopefully resolve the issue of sample size in the near future.

Appendix A
Catalogue

Introduction

The catalogue is meant to provide basic descriptions of the finds analyzed in this study and their find contexts. The material analyzed is heterogeneous ranging from coins. non-ferrous finds. and crucibles from Hedeby to slag and ore from Uzbekistan. The archaeological objects were collected in a number of surveys, archaeological excavations, and from hoard finds. There are a number of contributors that worked to collect, identify, and curate the archaeological finds. The coin finds from Hedeby form the core material of this study (**Table 1**), and their numismatic identification can be credited to Volker Hilberg, Lutz Ilisch, Peter Ilisch, Ralf Wiechmann, and Jens Christian Moesgaard. Care has been taken to give credit to the individuals who worked on the numismatic material and to provide references for the published objects. Additionally. the non-numismatic silver and base-metal finds from Hedeby (**Table 2**) have been identified by Volker Hilberg or are otherwise published with the reference given. A note should be made that the descriptions of the objects are not comprehensive., and features like pecking marks and nicking were not systematically recorded.

The technical ceramics from Hedeby (**Tables 3** and **4**) were selected from artifacts collected during excavations in 1963 and 1969 with the exception of one crucible fragment (**Cat. 247**), which came from a recent excavation by Volker Hilberg. The selection. identification. and description of the technical ceramics were performed by the author.

The ore and slag samples from Uzbekistan (**Table 5**) were kindly provided by Leonid Sverchkov of the Institute of Fine Arts, Academy of Science in Tashkent. Slag samples were collected at the site of Tunket by Sverchkov in 2012, but other slag and ore samples were obtained through A. D. Kanash of the Geological Museum, V. S. Minasyants from the Museum of History in Tashkent and through A. H. Atahojaev of the Institute of Archaeology in Samarqand.

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
Abbasid						
1	135	776-786	Kairouan [Tunesia]	al-'Abbāsiyya. ca. 160-170 AH. Governeurs of Ifriqiya. Yazid ibn Hātim al-Mukallebi. 0.40g. dirham fragment	Hedeby. detector find. Hb 2007/14062	L. Ilisch
2	136	787-792	Kairouan [Tunesia]	al-'Abbāsiyya. postum 171-175 AH. Gouverneurs of Ifriqiya. Yazid ibn Hātim al-Mukallebi. 0.69g. dirham fragment. one nick	Hedeby. detector find. Hb 2006/12993	L. Ilisch
3	137	Unknown	(North African mint)	Mint?. date?. 0.21g. dirham fragment	Hedeby. excavation. Hb LA 48/ Fd.Nr. 9550	L. Ilisch
4	187	786-790	Kairouan [Tunesia]	al-'Abbāsiyya. 17(0-3) AH. 0.47g. dirham fragment	Giekau Hoard. Kr. Plön. Coin 34 (WIECHMANN 1996. Cat. Nr. 9.34. hoard t.p.q. 921/2)	Published
5	139	808-811	Balkh [Afghanistan]	Madīnat Balkh. 193-195 AH. al-Ma'mūn as crowned prince under his brother al-Amīn with his vizier al-Fadl. 0.68g. dirham fragment. four nicks	Hedeby. detector find. Hb 2003/4198	L. Ilisch
6	140	808-811	Balkh [Afghanistan]	Madīnat Balkh. 193-195 AH. al-Ma'mūn as crowned prince under his brother al-Amīn with his vizier al-Fadl. 0.44g. dirham fragment	Hedeby. detector find. Hb 2003/3422	L. Ilisch
7	138	794-803	Tehrān [Iran]	al-Muhammadīyya. ca. 178-187 AH. al-Amin Muhammad as crowned prince under Hārūn ar-Rashid with Ğa 'far the Barmakide. 0.73g. dirham fragment. five nicks	Hedeby. detector find. Hb 2003/247	L. Ilisch
8	141	810/811	Samarqand [Uzbekistan]	M(adīnat Samarqand). 195 AH. al-Ma'mūn. (SNAT XV 594 ff.). 0.38g. dirham fragment	Hedeby. detector find. Hb 2011/14541	L. Ilisch
9	142	(84)7	Baghdād [Iraq]	(Madīnat al-Sa)lām. (23)3 AH. al-Mutawakkil 'ala Ilāh. (Nützel 1482). 0.20g. dirham fragment	Hedeby. detector find. Hb 2004/8487	L. Ilisch
10	232	871/872	Samarra [Iraq]	Surra man ra'a. 258 AH. al-Mu 'tamid 'alā Ilāh. (Lavoix 1029. Ilisch. Gift-Coin D II 1). 2.70g. dirham	Hedeby. detector find. Hb 2003/4191	L. Ilisch
11	143	875/876	Panjhīr [Afghanistan]	Panjhīr. 262 AH. al-Mu 'tamid 'alā Ilāh. (SNAT XIV d57). 2.17g. dirham	Hedeby. detector find. Hb 2004/9671	L. Ilisch
Saffarid						
12	144	878-884	Shiraz [Iran]	(Fāris). ca. 265-270 AH. Abu Hafs 'Amr ibn al-Layt. 0.67g. dirham fragment	Hedeby. detector find. Hb 2006/12246	L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
Samanid						
13	108	912/913	al-Shāsh [Uzbekistan]	al-Shāsh. 300 AH. Caliph (al-Muqtadir)/Emir (Ahmad ibn Isma'il). 1.03g. dirham corroded	Hedeby. solitary find. Haithabu 1968 N 6.00 O 221.15. Level V (Wiechmann 2007. Cat. Nr. 18)	Published
14	107	90(9)/9(10)	al-Shāsh [Uzbekistan]	al-Shāsh. 29(7) AH. Caliph (al-Muqtadir)/Emir (Ahmad ibn Isma'il). 2.1g. dirham complete	Hedeby. solitary find. Haithabu 1968 N 5.20 O221.55. Level III (Wiechmann 2007. Cat. Nr. 17)	Published
15	146	900/901	al-Shāsh [Uzbekistan]	al-Shāsh. 288 AH. Ismā 'il ibn Ahmad. (Leimus 1248-1249). 2.67g. dirham with broken edge	Hedeby. detector find. Hb 2004/8733	L. Ilisch
16	148	905/906	al-Shāsh [Uzbekistan]	al-Shāsh. (2)93 AH. Ismā 'il ibn Ahmad. (Leimus 1337). 0.38g. dirham fragment with one cut edge and one broken	Hedeby. detector find. Hb 2006/13433	L. Ilisch
17	149	907/908	al-Shāsh [Uzbekistan]	al-Shāsh. 295 AH. Ahmad ibn Ismā 'il. (Leimus 1507-1520).1.45g. dirham halved	Hedeby. detector find. Hb 2006/13814	L. Ilisch
18	150	896-907	al-Shāsh [Uzbekistan]	al-Shāsh. (283-295) AH. Ismā 'il ibn Ahmad. 0.71g. dirham fragment	Hedeby. detector find. Hb 2006/10959	L. Ilisch
19	151	900/901	al-Shāsh [Uzbekistan]	al-Shāsh. (28?)8 AH. Ismā 'il ibn Ahmad. 0.29 g. dirham fragment	Hedeby. detector find. Hb 2006/12402	L. Ilisch
20	154	910/911	al-Shāsh [Uzbekistan]	al-Shāsh. 298 AH. Ahmad ibn Ismā 'il. 2.27g. complete dirham bent	Hedeby. detector find. Hb 2006/12387	L. Ilisch
21	156	907-914	al-Shāsh [Uzbekistan]	al-Shāsh. (295-301 AH). Ahmad ibn Ismā 'il. 0.42g. dirham fragment	Hedeby. detector find. Hb 2004/8946	L. Ilisch
22	158	909/911	al-Shāsh [Uzbekistan]	al-Shāsh. (297/298 AH). Ahmad ibn Ismā 'il. 0.85g. dirham fragment	Hedeby. detector find. Hb 2007/14342	L. Ilisch
23	162	929/930	al-Shāsh [Uzbekistan]	al-(Shāsh). (317 AH). (Nasr ibn Ahmad). (Leimus 2485). 0.60g. dirham fragment	Hedeby. detector find. Hb 2003/3441	L. Ilisch
24	165	932-941	al-Shāsh [Uzbekistan]	al-(Shāsh). 320-330 AH. Nasr ibn Ahmad. 0.41g. dirham fragment	Hedeby. detector find. Hb 2004/10468	L. Ilisch
25	166	933-942	al-Shāsh [Uzbekistan]	al-(Shāsh). (322-330 AH). Nasr ibn Ahmad or Nūh ibn Nasr. (Leimus 2568-2636). 1.92 g. dirham fragment halved	Hedeby. detector find. Hb 2003/3305	L. Ilisch
26	168	930-947	al-Shāsh [Uzbekistan]	(al-Shāsh). 3xx - style of the period around 318-335 AH. Nasr ibn Ahmad or Nūh ibn Nasr. 0.38g. dirham fragment	Hedeby. excavation. Hb LA 48/Fd.Nr. 11800	L. Ilisch
27	172	953/954	al-Shāsh [Uzbekistan]	al-Shāsh. (ca. 342 AH). Nūh ibn Nasr with the caliph al-Mustakfi billāh. (SNAT XVb 349). 1.52g. dirham fragment	Hedeby. detector find. Hb 2003/1578	L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
28	105	904/905	Samarqand [Uzbekistan]	Samarqand. 292 AH. Isma’il ibn Ahmad with caliph al-Muktafi. 2.34g. dirham nearly complete slightly bent	Hedeby Grave 867 (Wiechmann 2007. Cat. Nr. 13)	Published
29	106	908	Samarqand [Uzbekistan]	Samarqand. 295 AH. Ahmad ibn Isma’il with caliph al-Muktafi. 2.42g. complete dirham	Hedeby. solitary find. Haithabu 1968 N 0-10 O220-225. Level V (Wiechmann 2007. Cat. Nr. 16)	Published
30	145	892/894	Samarqand or al-Shāsh [Uzbekistan]	Samarqand or al-Shāsh. ca. 279/280 AH. Emir’s name not preserved. 0.49g. dirham fragment	Hedeby. detector find. Hb 2006/12277	L. Ilisch
31	155	907-912	Samarqand [Uzbekistan]	S(amarqand). (ca. 295-299 AH). time of Ahmad ibn Ismā ‘il. (Leimus 1426-1474). 0.39g. dirham fragment	Hedeby. detector find. Hb 2006/12336	L. Ilisch
32	163	938/939	Samarqand [Uzbekistan]	Samarqand. 327 AH. Nasr ibn Ahmad. (Leimus 2179). 3.23g. nearly complete dirham	Hedeby. detector find. Hb 2004/8792	L. Ilisch
33	164	939/940	Samarqand [Uzbekistan]	(Samarqan)d. presumably (32)8 AH. (Nasr ibn Ahmad). (Leimus 2056-2066). 0.37g. dirham fragment	Hedeby. detector find. Hb 2003/1586	L. Ilisch
34	167	942/943	Samarqand [Uzbekistan]	(Samarqand). (33)1 AH. Nasr ibn Ahmad. (Leimus 2215-2217). 0.57g. dirham fragment	Hedeby. detector find. Hb 2004/8812	L. Ilisch
35	170	950/951	Samarqand [Uzbekistan]	(Samarqan)d. 339 AH. Nūh ibn Nasr. (Leimus 2902). 0.27g. dirham fragment	Hedeby. detector find. Hb 2003/9733	L. Ilisch
36	171	948-951	Samarqand? [Uzbekistan]	presumably Samarqand. 33(7-9) AH. Nūh ibn Nasr. 2.23g. dirham fragment	Hedeby. detector find. Hb 2004/8302	L. Ilisch
37	173	945-954	Samarqand [Uzbekistan]	(Samarqan)d. (334-343) AH. Nūh ibn Nasr. (Leimus 2878-2937). 0.35g. dirham fragment	Hedeby. detector find. Hb 2004/8666	L. Ilisch
38	174	945-954	Samarqand [Uzbekistan]	(Samarqan)d. (334-343) AH. Nūh ibn Nasr. (Leimus 2877 ff.). 0.52g. dirham fragment	Hedeby. detector find. Hb 2006/12369	L. Ilisch
39	175	958-961	Samarqand [Uzbekistan]	(Samarqan)d. 34(7-9) AH. ‘Abd-al-Malik ibn Nūh. (Leimus 2029). 0.27g. dirham fragment	Hedeby. detector find. Hb 2003/4020	L. Ilisch
40	112a	906/907	Andarāba [Afghanistan]	Three partially melted dirhams. the largest: Andarāba. 29(4) AH. Isma’il ibn Ahmad/Ahmad ibn Muhammad ibn Ahmad. others unidentified. 1.26g. dirhams fragmentary	Hedeby. detector find. Hb 2003/4535	L. Ilisch
41	147	905/906	Balkh [Afghanistan]	Madīnat Balkh. (ca. 293 AH). Ismā ‘il ibn Ahmad. (Leimus 1002/3). 0.89g. dirham fragment	Hedeby. detector find. Hb 2006/12216	L. Ilisch
42	152	904/905	Andarāba [Afghanistan]	(Andarāba). 29[2] AH. Ismā ‘il ibn Ahmad. (Leimus 984). 0.34g. dirham fragment	Hedeby. excavation. Hb LA 48/ Fd.Nr. 3800	L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
43	153	907-910	Andarāba [Afghanistan]	Andarāba. (295/7) AH. Ahmad ibn Ismā ʻil. (Leimus 1399). 0.59g. dirham fragment	Hedeby. detector find. Hb 2007/13985	L. Ilisch
44	157	914/915	Andarāba [Afghanistan]	Andarāba. 301 AH. Ahmad ibn Ismā ʻil. (Leimus 1410; SNAT XIVc 104). 0.79g. dirham fragment	Hedeby. detector find. Hb 2004/8757	L. Ilisch
45	159	918/919	Andarāba [Afghanistan]	Andarāba. 30(?)6 AH. Nasr ibn Ahmad with Ahmad ibn Sahl?. (The reading "30(?)6" is definite; cf. Leimus 3351 to "305" H). 0.53g. dirham fragment	Hedeby. detector find. Hb 2003/2738	L. Ilisch
46	160	924-927	Balkh [Afghanistan]	Madīnat Balkh. (312-314 AH). Nasr ibn Ahmad. (Leimus 1749-1771). 0.29g. dirham fragment	Hedeby. detector find. Hb 2006/12422	L. Ilisch
47	161	922-933	Andarāba or Ma ʻdin or Balkh [Afghanistan]	Andarāba or Ma ʻdin or Balkh. (310/320 AH). (Nasr ibn Ahmad). 0.28g. dirham fragment	Hedeby. detector find. Hb 2004/10125	L. Ilisch
48	169	934-945	Balkh [Afghanistan]	Madīnat Balkh. (323-333 AH). Nasr ibn Ahmad or Nūh ibn Nasr. (Leimus 782). 1.10g. dirham fragment	Hedeby. detector find. Hb 2006/13040	L. Ilisch
49	176	980-990	Bukhārā [Uzbekistan] or Nīshāpūr [Iran] ?	Bukhārā or Nīshāpūr. 370-379 AH. time of Nūh ibn Nasr. 0.27g. dirham fragment	Hedeby. detector find. Hb 2003/209	L. Ilisch
Unidentified Dirham						
50	113a	Unknown	Unknown	Melted Silver fragment. 0.75g. 2 dirham fragments not legible. coin fragments melted together with a silver wire 0.2 cm diameter	Hedeby. detector find. Hb 2003/4586	L. Ilisch
Dirham Imitations						
51	177	870-890 AD	Khazaria [Russia]	Mint?. ca. 870-890 AD. Khazar imitation of an Abbasid dirham of al Mu ʻtamid. 1.15g. dirham fragment cut. broken with 6 nicks on the edge	Hedeby. excavation. Hb LA 48/ Fd.Nr. 13570	L. Ilisch
52	178	Early 10th c.	Volga Bulgharia [Russia]	Mint?. early 10th c.. East European dirham imitation. Volga-Bulghar. 0.57g. dirham fragment with broken edges	Hedeby. excavation. Hb LA 48/ Fd.Nr. 9356	L. Ilisch
53	179	Early 10th c.	Volga Bulgharia [Russia]	Mint?. early 10th c.,Volga-Bulghar imitative dirham. modeled on a dirham from Samarqand or al-Shāsh from 280 AH/893/4 AD (Leimus 3396-3397 (rev.). 3398 (av.)). 0.55g. dirham fragment with worn and broken edges	Hedeby. detector find. Hb 2004/8803	L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
54	181	Early 10th c.	Volga Bulgharia [Russia]	Mint?. early 10th c., Volga-Bulghar imitative dirham. modeled on a dirham of the Samanid Isma ʻil ibn Ahmad. both sides from reverse dies. (Rispling 2005: Nr. 1436). 1.72g. dirham fragment halved	Hedeby. detector find. Hb 2003/4195	L. Ilisch
55	182	After 906/907	Volga Bulgharia [Russia]	Mint?. t.p.q. of the dies after 294 AH according to Rispling. Volga-Bulghar imitative dirham. modeled on a dirham of the Samanid Isma ʻil ibn Ahmad. (Rispling 2005:Nr. 1429 (die K89 2/R1)). 0.31g. dirham fragment with cut and broken edges	Hedeby. detector find. Hb 2006/12421	L. Ilisch
56	180	After 922	Volga Bulgharia [Russia]	Mint?. after 310 AH. Volga-Bulghar imitative dirham. Mikāʼil ibn Ǧa ʻfar. modeled on a Samanid dirham from Naysābūr (?). (Leimus 3539; Rispling 1990:276). 0.68g. dirham fragment with cut edges	Hedeby. excavation. Hb LA 48/ Fd.Nr. 12040	L. Ilisch
57	184	After 922	Volga Bulgharia [Russia]	(Madīnat Bulgār). without year. after 310 AH. Volga-Bulghar imitative dirham. Mikāʼil ibn Ǧa ʻfar. modeled on a Samanid dirham of Nasr ibn Ahmad (914-943 AD) with the caliph al-Muqtadir (908-932 AD). (Rispling 1990:Nr. 16; Leimus 3527-3528). 0.33g. dirham fragment	Hedeby. detector find. Hb 2006/12241	L. Ilisch
58	185	After 907-914	Volga Bulgharia [Russia]	Mint?. after 907-914 AD. Volga-Bulghar imitative dirham. modeled on a Samanid dirham of Ahmad ibn Isma ʻil (907-914 AD?). 0.48g. dirham fragment with cut and broken edges	Hedeby. detector find. Hb 2003/2719	L. Ilisch
59	186	922-932	Volga Bulgharia [Russia]	Mint?. without year. 922-932 AD (according to Rispling). Imitative dirham with the depiction of crosses. Volga-Bulghar or from the Kiev Rus. modeled on Samanid dirhams of Nasr ibn Ahmad. (Rispling 1987:76 fig. A). 0.22g. dirham fragment with cut edges	Hedeby. detector find. Hb 2004/9744	L. Ilisch
60	183	932-941	Volga Bulgharia [Russia]	Mint?. ca. 320-330 AH. Volga-Bulghar imitative dirham. modeled on a Samanid dirham of Nasr ibn Ahmad and the caliph al-Muqtadir billāh (908-932 AD). (Leimus 3486; Rispling chain 102 54/R34). 1.42g. dirham fragment corroded	Hedeby. detector find. Hb 2006/12316	L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
Byzantine						
61	198	963-969	Constantinople	Miliaresion. 963-969. Nicephorus II Phocas. 1.85g. broken with nicked edge	Waterneverstorf Hoard I. Kr. Plön. coin Nr. 321 (WIECHMANN 1996. Cat. Nr. 45. 321. t.p.q. 976)	Published
62	199a	977-989	Constantinople	Miliaresion. 977-989. Basil II Bulgaroctonos with Constantine VIII. 2.33g. Coin complete with one complete riveted loop and one broken loop	Hedeby. Detector Find. Hb 2003/2499	V. Hilberg
63	218a	977-989	Constantinople	Miliaresion. 977-989. Basil II Bulgaroctonos with Constantine VIII. 4.54g. complete coin with riveted loop and silver ring	List Hoard. Isle of Sylt. coin Nr. 9 (WIECHMANN 1996. 16.A.1/B.9. hoard t.p.q. ca. 1000/1003)	Published
Anglo-Saxon						
64	83	985-991	Exeter	Penny. 985-991. Second hand. Hildebrand type B2. Nr. 540. moneyer Godda. 0.67g. halved	Hedeby. detector find. Hb 2005/11816	V. Hilberg
65	84	997-1003	Winchester	Penny. 997-1003. Long Cross. Hildebrand type D. Nr. 4243 Var.. moneyer Godwine. 1.56g. complete	Hedeby. detector find. Hb 2005/11299	V. Hilberg
66	85	1017-1025	Lincoln?	Penny. 1017/18-1023/25. Quatrefoil. Hildebrand type E. Nr. xxx. moneyer Wœlrafn. 0.32g. fragmentary	Hedeby. detector find. Hb 2007/14334	V. Hilberg
67	119	1017-1025	Unknown	Penny. 1017/18-1023/25. Quatrefoil-Type. Cnut (1016-35) Hildebrand type E. Nr. xxx. 0.2g. fragmentary	Hedeby. excavation. Hb LA 48. Fd. 8013	V. Hilberg
68	188	942/3	York	Penny. 942/3. Anglo-Norse. Anlaf Quaran Sihtricsson. 0.27g. fragmentary and corroded	Hedeby. surface find. A23 (WIECHMANN 2007. Cat. Nr. 60)	Published
Hiberno-Norse						
69	200	997-1003	Dublin	Penny. ca. 997-1003. Sihtric III Silkbeard. moneyer Faeremin. 1.27g. complete	List Hoard. Isle of Sylt. coin Nr. 740 (WIECHMANN 1996. Cat. Nr. 16.B.740. t.p.q. ca. 1000/1003)	Published
70	201	997-1003	Dublin	Penny. ca. 997-1003. Sihtric III Silkbeard. moneyer Faeremin. 1.31g. complete	List Hoard. Isle of Sylt. coin Nr. 741 (WIECHMANN 1996. Cat. Nr. 16.B.741. t.p.q. ca. 1000/1003)	Published

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
71	202	997-1003	Dublin	Penny. ca. 997-1003. Sihtric III Silkbeard. moneyer Faeremin. 1.37g. complete	List Hoard. Isle of Sylt. coin Nr. 742 (Wiechmann 1996. Cat. Nr. 16.B.742. t.p.q. ca. 1000/1003)	Published
72	203	997-1003	Dublin	Penny. ca. 997-1003. Sihtric III Silkbeard. moneyer Faeremin. "Thymn Roex". 1.24g. complete	List Hoard. Isle of Sylt. coin Nr. 750 (Wiechmann 1996. Cat. Nr. 16.B.750. t.p.q. ca. 1000/1003)	Published
73	204	997-1003	Dublin	Penny. ca. 997-1003. Sihtric III Silkbeard. moneyer Faeremin. "Thymn Roex". 1.22g. complete	List Hoard. Isle of Sylt. coin Nr. 751 (Wiechmann 1996. Cat. Nr. 16.B.751. t.p.q. 1000/1003)	Published
Sachsenpfennige						
74	67	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. (Kluge 1991. Nr. 49; Kilger 2000. 48 f. KN 1. Older Saxon Pfennig group type – Schmalbalkentyp (Thin Beam-Frame type)). 1.02g. complete but corroded	Hedeby. detector find. Hb 2003/3205	V. Hilberg
75	68	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. (Kluge 1991. Nr. 49; Kilger 2000. 48 f. KN 1. Older Saxon Pfennig group type – Schmalbalkentyp (Thin Beam-Frame type)). 0.41g. coin fragment	Hedeby. detector find. Hb 2003/3262	V. Hilberg
76	69	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. (Kluge 1991. Nr. 49; Kilger 2000. 48 f. KN 1. Older Saxon Pfennig group type – Schmalbalkentyp (Thin Beam-Frame type)). 1.26g. complete	Hedeby. detector find. Hb 2005/11490	V. Hilberg
77	189	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000 (Gumowski 1939) or 965-985 (Kilger 2000). made into an amulet. loop soldered to the back (Kluge 1991:Nr. 49; Kilger 2000:48 f. KN 1. Older Saxon Pfennig group type – Schmalbalkentyp (Thin Beam-Frame type)). DBG.. Nr. 1325. Gumowski 1939. Nr. 320 var: Rs. +IIIIII+IIIIIoIIII. 1.35g. complete	Hedeby Grave 1249. Find Year 1970 (Arents/ Eisenschmidt 2010; Steuer 1974. Grave 52; Wiechmann 2007. Cat. Nr. 56)	Published/ V. Hilberg

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
78	190	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000 (Gumowski 1939) or 965-985 (Kilger 2000). (Kluge 1991. Nr. 49; Kilger 2000. 48 f. KN 1. Older Saxon Pfennig group type – Schmalbalkentyp (Thin Beam-Frame type)). 1.07g. complete	Hedeby Excavation 1937. N. 0.96. E. 85.5. D. x -0.77. KS. 19615 (Wiechmann 2007. Cat. Nr. 57)	Published/V. Hilberg
79	191	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000 (Gumowski 1939) or ca. 975-985 (Kilger 2000). (Kluge 1991. Nr. 49; Kilger 2000 group KN 2:1(Bardowick. Bremen). DBG.. Nr. 1328 var: inscription in temple backwards. Gumowski 1939. Nr. 304-308. 0.39g. fragment	Hedeby Excavation 1969. N. 42.40. E. 199.75. Level V (Wiechmann 2007. Cat. Nr. 58)	Published/ V. Hilberg
80	234	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. too small to identify further. 0.33g. fragment	Tüb 5.Tübingen. inv. Nr. Pb 155. Forschungsstelle für Islamische Numismatik. Universität Tübingen.find location unknown. anonymous West Slavonic hacksilver hoard deposited before 985 AD	L. Ilisch
81	235	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. too small to identify further. 0.31g. fragment	Tüb 6. Tübingen. inv. Nr. Pb 156. West Slavonic hacksilver hoard deposited before 985 AD	L. Ilisch
82	236	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. too small to identify further. 0.30g. fragment	Tüb 3. Tübingen. inv. Nr. Pb 153. West-Slavonic hacksilver hoard deposited before 985 AD	L. Ilisch
83	237	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. too small to identify further. 0.28g. fragment	Tüb 4. Tübingen. inv. Nr. Pb 154. West Slavonic hacksilver hoard deposited before 985 AD	L. Ilisch
84	238	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. too small to identify further. 0.22g. fragment	Tüb 1. Tübingen. inv. Nr. Pb 151. West Slavonic hacksilver hoard deposited before 985 AD	L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
85	239	950-1000	Magdeburg?	Denar. Sachsenpfennig. 950-1000. too small to identify further. 0.18g. fragment	Tüb 2. Tübingen. inv. Nr. Pb 152. West Slavonic hacksilver hoard deposited before 985 AD	L. Ilisch
Otto-Adelheid-pfennige						
86	73	985-1010	Goslar?	Denar. Otto-Adelheid-pfennig. after 985/90 (Kluge) 990/95-1005/10 (Rundberg 2000). OAP Hz III: 6e/f Var.. 1.13g. nearly complete	Hedeby. detector find. Hb 2003/2220	V. Hilberg
87	74	990-1010	Goslar?	Denar. Otto-Adelheid-pfennig. ca. 990/95-1005/10 (Rundberg 2000). OAP Hz III:6h. 1.0g. nearly complete. edges torn. three pecks	Hedeby. detector find. Hb 2004/9729	V. Hilberg
88	75	985-1010	Goslar?	Denar. Otto-Adelheid-pfennig. after 985/90 (Kluge). ca. 990-995/1000-1010 (Rundberg 2000). OAP Hz III: 6 Var.. 1.25g. complete	Hedeby. detector find. Hb 2003/3904	V. Hilberg
89	76	985-995	Goslar?	Denar. Otto-Adelheid-pfennig. after 985/90 (Kluge). ca. 990-995(Rundberg 2000). OAP Hz III: 7. 1.34g. complete	Hedeby. excavation. Hb LA 48. Fd. 1855	V. Hilberg
90	77	985-1010 or later	Goslar?	Denar. Otto-Adelheid-pfennig. ca. 990/95-1005/1010 (Rundberg 2000). After ca. 1010 because of the dotted rim (P. Ilisch). OAP Hz III: 6-9. Vs. Blank. Rs. Inscription T Є A … Church without embellishments. 0.97g. complete but bent	Hedeby. detector find. Hb 2003/181	V. Hilberg
91	78	985-1010	Goslar?	Denar. Otto-Adelheid-pfennig. after 985/90 (Kluge). ca. 990-995/1000-1010 (Rundberg 2000). OAP. Vs.: Hz III:7. Rs.: Hz IV: 17c/d (P. Ilisch). 1.42g. nearly complete	Hedeby. detector find. Hb 2003/4176	V. Hilberg/ P. Ilisch
92	79	1010-1030	Goslar?	Denar. Otto-Adelheid-pfennig. ca. 1010/15-1025/30 (Rundberg 2000). after ca. 1010 (P. Ilisch). OAP Hz IV. most probably Hz IV:6. 0.91g. complete and bent	Hedeby. detector find. Hb 2004/10563	V. Hilberg/ P. Ilisch
93	80	991-1040	Goslar?	Denar. Otto-Adelheid-pfennig. 991-1030/40 (Hatz). ca. 995-1025 (Rundberg 2000). OAP Hz IV:5/6; possibly Hz IV:6 (after P. Ilisch). 1.01g. complete and bent	Hedeby. detector find. Hb 2003/3688	V. Hilberg/ P. Ilisch/ R. Wiechmann

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
94	81	1020-1035	Goslar?	Denar. Otto-Adelheid-pfennig. 1020-1030/35 (Rundberg 2000). after ca. 1010 (P. Ilisch). OAP Hz IV:9d Var. (E in inscription ATEAHLHT turned sideways). 1.14g. complete and bent	Hedeby. detector find. Hb 2003/4982	V. Hilberg/ P. Ilisch
95	82	990-1020	Goslar?	Denar. Otto-Adelheid-pfennig. ca. 990/95-1000 for IV:19. ca. 990/95 to 1010/20 for IV:20 (Rundberg 2000). OAP Hz IV:19 or 20 (The embellishments to the right of the church are unrecognizable due to wear). 0.61g. fragmentary	Hedeby. detector find. Hb 2003/1917	V. Hilberg
Archbishop of Cologne						
96	63	983-996	Cologne	Denar. S COLONIA. 983-996. Otto III as king. COLONIA-type Häv. 34. (Ilisch 1983. 58). 1.13g. complete and bent	Hedeby. detector find. Hb 2003/2373	V. Hilberg/ P. Ilisch/ R. Wiechmann
97	64	983-996	Cologne	Denar. S COLONIA. 983-996. Otto III as king. COLONIA-type Häv. 34. (Ilisch 1983.58). 1.38g. complete	Hedeby. detector find. Hb 2003/2251	V. Hilberg/ P. Ilisch/ R. Wiechmann
98	65	983-996	Cologne	Denar. S COLONIA. 983-996. Otto III as king. COLONIA-type Häv. 67a/c Var.. (Ilisch 1983. 59). 1.25g. complete	Hedeby. detector find. Hb 2003/3795	V. Hilberg/ P. Ilisch
99	121	1014-24	Cologne	Denar. S COLONIA. 1014-1024. Heinrich II. COLONIA-type Häv. 189h. 0.83g. nearly complete	Hedeby. detector find. Hb 2003/2662	V. Hilberg/ P. Ilisch
100	122	1027-36	Cologne	Denar. S COLONIA. 1027-1036. Archbishop/ Pilgrim from Cologne/Konrad II. t.p. 1027. COLONIA-type Häv. 222b. 1.23g. complete	Hedeby. detector find. Hb 2003/4174	V. Hilberg/ P. Ilisch
101	70	1000-1040	Soest	Denar. S COLONIA. ca. 100-1040. imitation of Colonia coinage. Häv. 73/8496. 1.06g. complete	Hedeby. detector find. Hb 2003/4254	P. Ilisch
102	71	1030-1050	Soest	Denar. S COLONIA. ca 1030-1050. Häv. 850. 0.54g. halved	Hedeby. detector find. Hb 2003/243	P. Ilisch
103	72	11th c.	Westphalia	Denar. S COLONIA. 11th c. imitation of Colonia Pfennig. too small to identify further. 0.26g. fragment	Hedeby. detector find. Hb 2004/8173	P. Ilisch/ V. Hilberg

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
Lower Lotheringia						
104	66	1014-1024	Deventer	Denar. 1014-1024. Heinrich II. Dbg. 564. Ilisch 1997/1998. 1.9.1-2 Var.. 0.99g. complete and bent	Hedeby. detector find. Hb 2003/4473	R. Wiechmann/ V. Hilberg
Frisian Imitations						
105	55	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. end of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.14g. complete	Hedeby. detector find. Hb 2003/4203	V. Hilberg/ P. Ilisch
106	56	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. end of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.10g. complete	Hedeby. detector find. Hb 2003/4275	V. Hilberg/ P. Ilisch
107	57	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. End of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.00g. complete	Hedeby. detector find. Hb 2003/4305	V. Hilberg/ P. Ilisch
108	58	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. End of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.07g. complete	Hedeby. detector find. Hb 2004/9721	V. Hilberg/ P. Ilisch
109	59	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. End of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.15g. complete	Hedeby. detector find. Hb 2004/9788	V. Hilberg/ P. Ilisch
110	60	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. End of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.11g. complete	Hedeby. detector find. Hb 2004/9791	V. Hilberg/ P. Ilisch
111	61	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. End of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 0.98g. complete	Hedeby. detector find. Hb 2004/10439	V. Hilberg/ P. Ilisch
112	62	End of 10th c.	Unknown. East Frisia	Denar. S COLONIA. End of the 10th c.. East-Frisian imitation of Cologne coinage (Häv. 29. ILISCH 2007). 1.22g. complete	Hedeby. detector find. Hb 2011/14424	V. Hilberg/ P. Ilisch
113	120	1002-1024	Unknown. near Nijmegen/ Tiel	Denar. COLONIA-type. 1002-1024. Heinrich II. Nijmegen/Tiel region. 0.72g. halved	Hedeby. detector find. Hb 2004/8562	V. Hilberg
Early Scandinavian/Danish						
114	86a	900-920	Hedeby?	Malmer KG 7 fused to unidentifiable coin fragments. 900-920 (WIECHMANN 2007) or 900-950 (MALMER 2002). Dorestad imitation KG 7. D III A1/A2 (several variations possible). 1.75g. fragmentary	Hedeby. detector find. Hb 2003/4584	V. Hilberg
115	87	900-920	Hedeby?	Malmer KG 7. 900-920 (WIECHMANN 2007) or 900-950 (MALMER 2002). Dorestad imitation KG 7. CE III A2.16/D III A2.12. 0.53g. fragmentary	Hedeby. excavation. Hb LA 48. Fd. 2600	V. Hilberg

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
116	88	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A2.22/D III A1 Var.. 0.50g. nearly complete	Hedeby. excavation. Hb LA 48. Fd. 2673	V. Hilberg
117	89	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A1.1-3/D III A1.10. 0.49g. complete with heavy corrosion	Hedeby. excavation. Hb LA 48. Fd.2688	V. Hilberg
118	90	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A2.22/D III A2.8-14. 0.21g. fragmentary	Hedeby. excavation. Hb LA 48. Fd.2700	V. Hilberg
119	101	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A1/D III A1. 0.62g. complete	Steinfeld Hoard. Kr. Schleswig-Flensburg. Inv.Nr. KS 19624.1 (Wiechmann 1996. Cat. Nr. 39.1)	V. Hilberg
120	102	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A1/D III A1. 0.49g. complete	Steinfeld Hoard. Kr. Schleswig-Flensburg. Inv.Nr. KS 19624.2 (Wiechmann 1996. Cat. Nr. 39.2)	V. Hilberg
121	103	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A1/D III A1. 0.48g. complete	Steinfeld Hoard. Kr. Schleswig-Flensburg. Inv.Nr. KS 19624.3 (Wiechmann 1996. Cat. Nr. 39.3)	V. Hilberg
122	116	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CE III A1 Var./DIII A1.5. 0.69g. complete	Hedeby. surface find. LA 48. Fd. Nr. 14361	V. Hilberg
123	118	900-920	Hedeby?	Malmer KG 7. 900-920 (Wiechmann 2007) or 900-950 (Malmer 2002). Dorestad imitation KG 7. CEIII A2.22 (var.)/VIII AL 12. 0.35g. fragmentary	Hedeby. surface find. LA48. Fd. Nr. 13947	V. Hilberg
124	192	950-965	Hedeby?	Malmer KG 8. 950-965 (Wiechmann 2007) or 950-960 (Malmer 2002). Dorestad imitation KG 8. CE III B1b/D III B2. 0.33g. fragmentary and corroded	Hedeby. stray find. 1938. KS.19620a? (Wiechmann 2007. Cat. Nr. 117)	V. Hilberg

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
125	193	965-975	Hedeby?	Malmer KG 9a. after 975 (Wiechmann 2007) or 950-970 (Malmer 2002). Dorestad imitation KG 9a. CE III B1b/D III B2. 0.36g. nearly complete and corroded	Hedeby Excavation 1938. Nord B 3. Alter Bach. Level 6. Depth x-187/197. KS.19621 (Wiechmann 2007. Cat. Nr. 119)	V. Hilberg
126	194	965-975	Hedeby?	Malmer KG 9a. after 965 (Wiechmann 2007) or 950-970 (Malmer 2002). Dorestad imitation KG 9a. CEIII B1b.19D III B2.16. 0.37g. nearly complete and corroded	Waterneverstorf I Hoard. Kr. Plön. coin Nr. 403 (Wiechmann 1996. Cat. Nr. 45.403. t.p. 976)	V. Hilberg
127	195	975-980	Hedeby?	Malmer KG 9b. after 975 (Wiechmann 2007) or 960-980 (Malmer 2002). CE III C2b.1/D III C1a. 0.48g. complete	Waterneverstorf I Hoard. Kr. Plön. coin Nr. 404 (Wiechmann 1996 Cat. Nr. 45.404. t.p. 976)	V. Hilberg
128	91	975-980	Hedeby?	Malmer KG 9b. after (Wiechmann 2007) or 960-980 (Malmer 2002). CE III C2a.15/D III C1a. 0.18g. fragment	Hedeby. detector find. Hb 2006/12127	V. Hilberg
129	92	975-980	Hedeby?	Malmer KG 9c-d. after 975 (Wiechmann 2007) or 960-990 (Malmer 2002). 0.21g. fragment	Hedeby. excavation. Hb LA 48. Fd. 1963	V. Hilberg
130	93	975-980	Hedeby or Lund?	Malmer KG 10a. 975-980 (Wiechmann 2007). Cross-type KG 10a. Bå: A 1a.7 without circle/K: A 1a.2 without circle. 0.27g. fragments	Hedeby. excavation. Hb LA 48. Fd. 1621	V. Hilberg/ J.C. Moesgaard
131	94	975-980	Hedeby or Lund?	Malmer KG 10a. 975-980 (Wiechmann 2007). Cross-type KG 10a. Bå: A 1a.7 without circle/K: A 1a.2 without circle. 0.27g. nearly complete	Hedeby. excavation. Hb LA 48. Fd. 2390	V. Hilberg/ J.C. Moesgaard
132	95	975-980	Hedeby or Lund?	Malmer KG 10a. 975-980 (Wiechmann 2007). Cross-type KG 10a Bå: A 1a 10/K: A 2b 17. 0.34g. complete	Hedeby. detector find. Hb 2004/9001	V. Hilberg/ J.C. Moesgaard
133	114	975-980	Hedeby or Lund?	Malmer KG 10a. 975-980 (Wiechmann 2007). Cross-type KG 10a. Bå: A 3a/K: A 2b. 0.31g. complete	Hedeby. detector find. Hb 2006/13665	V. Hilberg
134	196	975-980	Hedeby or Lund?	Malmer KG 10a-b. 975-980 (Wiechmann 2007). Cross-type KG 10a-b. 0.07g. fragment	Tübingen. inv. Nr. 91-29. West Slavonic hacksilver hoard deposited before 985 AD	V. Hilberg/ L. Ilisch
135	197	975-980	Hedeby or Lund?	Malmer KG 10b. 975-980 (Wiechmann 2007). Cross-type KG 10b. 0.09g. fragment	Tübingen. inv. Nr. 91-29. West Slavonic hacksilver hoard deposited before 985 AD	V. Hilberg/ L. Ilisch

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
136	117	975-980	Unknown. Denmark. Lund?	Malmer KG 11. 975-980 (WIECHMANN 2007). Cross-type KG 11. A1a5 - K B2a. 0.23g. fragment	Hedeby. excavation. Hb LA 49 Fd. 1910	V. Hilberg
137	115	1015-1030	Hedeby?	Årstad 95 (P. Ilisch type). 1015-1030 (WIECHMANN 2013). 0.51g. fragment	Hedeby. excavation. Hb LA 48. Fd. 680	V. Hilberg
138	96	1015-1030	Hedeby or S. Scandinavia	Årstad 96 (P. Ilisch type). 1015-1030 (WIECHMANN 2013). 0.46g. fragment	Hedeby. detector find. Hb 2003/1977	R. Wiechmann
139	97	1015-1030	Hedeby or S. Scandinavia	Årstad 96 (P. Ilisch type). 1015-1030 (WIECHMANN 2013). 0.54g. fragment	Hedeby. detector find. Hb 2003/4168	R. Wiechmann
140	98	1015-1030	Hedeby or S. Scandinavia	Årstad 96 (P. Ilisch type). 1015-1030 (WIECHMANN 2013). 0.45g. fragment	Hedeby. detector find. Hb 2004/8914	R. Wiechmann
141	99	1035-1042	Hedeby	Denar. 1035-1042. Harthacnut. (HAUBERG 1900. Nr. 50; BECKER 1981. 154). 0.73g. broken but complete	Hedeby. detector find. Hb 2003/3832	V. Hilberg
142	100	1035-1042	Hedeby	Denar. ca. 1035-1042. Harthacnut. (HAUBERG 1900. Nr. 50; BECKER 1981. 154). 0.71g. complete	Hedeby. detector find. Hb 2003/3988	V. Hilberg
143	205	1047-1076	Viborg	Denar. 1047-1074/6. Sven Estridsen. 0.51g. complete	Hedeby. solitary find. 1967 (WIECHMANN 2007. Cat. Nr. 133)	V. Hilberg
144	206	1050-1060	Viborg	Denar. 1047-1074/6 or ca. 1050-1060. Sven Estridsen. 0.62g. complete	Schleswig Hafengang 11. Inv.Nr. KSD 598.0814	V. Hilberg
145	207	1047-1076	Hedeby	Denar. 1047-1074/6. Sven Estridsen. 0.49g. complete	Hedeby. stray find. 1974 (WIECHMANN 2007. Cat. Nr. 134)	V. Hilberg
146	208	1047-1076	Hedeby	Denar. 1047-1074/6. Sven Estridsen. 0.48g. complete	Hedeby. stray find. 1974 (WIECHMANN 2007. Cat.Nr135)	V. Hilberg
147	209	1047-1076	Hedeby	Denar. 1047-1074/6. Sven Estridsen. 0.47g. complete	Hedeby. stray find. 1974 (WIECHMANN 2007. Cat.Nr136)	V. Hilberg
148	210	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.72g. complete	Schleswig Hafengang11. Inv.Nr. KSD 598.2016	V. Hilberg
149	211	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.19g. corroded	Schleswig Hafengang 11. Inv.Nr. KSD 598.0829	V. Hilberg

Cat.	DBM	Year (AD)	Mint	Description	Find Context/ Number	Identifier
150	212	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.59g. complete	Schleswig Hafengang 11. Inv.Nr. KSD 598.0556.4	V. Hilberg
151	213	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.63g. complete	Schleswig Hafengang 11. Inv.Nr. KSD 598.0556.7	V. Hilberg
152	214	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.48g. complete	Schleswig Hafengang 11. Inv.Nr. KSD 598.0556.9	V. Hilberg
153	215	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.38g. complete	Schleswig Hafengang11. Inv.Nr. KSD 598.0556.11	V. Hilberg
154	216	1080-1086?	Unknown. Denmark	Denar. ca 1080-1086?. Cnut the Holy (1080-1086)? Imitation of an expanded-cross penny Edward Conf. (ca. 1050-53). 0.35g. near complete. corroded	Schleswig Hafengang11. Inv.Nr. KSD 598.0556.17	V. Hilberg
Tin-Lead Coins						
155	104	After 894/895	Hedeby?	Tin dirham. al-Shāsh. 281 AH. Caliph al-Mutadid/Emir Isma’il ibn Ahmad. 3.91g. complete	Hedeby Harbor Excavation 1980. G42+44. Level VI (Weichmann 2007: Cat. Nr. 12)	Published
156	109	9th c.?	Hedeby?	Tin dirham. Madīnat al-Salām. 192 AH. Caliph Hārūn ar-Rashid. 2.23g. complete	Hedeby Harbor Excavation 1980. Fl. G42+44. Level V (Wiechmann 2007. Cat. Nr. 34)	Published
157	110	9th c.?	Hedeby?	Tin dirham. Madīnat al-Salām. 192 AH. Caliph Hārūn ar-Rashid. 2.20g. complete	Hedeby Harbor Excavation 1980. washing complex. Level IV+V (Wiechmann 2007. Cat. Nr. 35)	Published
158	111	9th c.?	Hedeby?	Tin dirham. Madīnat al-Salām. 192 AH. Caliph Hārūn ar-Rashid. 2.04g. complete	Hedeby Harbor Excavation 1980. washing complex. Level IV+V (Wiechmann 2007. Cat. Nr. 36)	Published

Table 1 *Catalogue of coins analyzed in this study.*

Cat.	DBM	Date	Style	Type	Description	Find Context and Nr.
159	217	850-925	Anglo-Saxon	Belt end	Silver. copper. niello. Anglo-Saxon strap end. Trewhiddle style. 12.15g. complete	Füsing. Kr. SchleswigFlensburg. detector find Nr. 1310. (Dobat 2010. Cat. Nr. 1310. Plate 6)
160	219	950-1000	Anglo-Saxon	Clasp	Silver. Anglo-Saxon hooked clasp. 1.38g. hook broken	List Hoard. Isle of Sylt. hacksilver Nr. 4 (Wiechmann 1996. Cat. Nr. 16.A.4)
161	220	950-1000	Anglo-Saxon	Clasp	Silver. Anglo-Saxon hooked clasp. partly gilded. tested. 1.92g. hook broken	List Hoard. Isle of Sylt. hacksilver Nr. 3 (Wiechmann 1996. Cat. Nr. 16.A.3)
162	221	950-1000	Anglo-Saxon	Circular brooch	Silver. circular brooch with engraved ornament and boss. Anglo-Saxon. 2.50g. fragment	List Hoard. Isle of Sylt. hacksilver Nr. 5 (Wiechmann 1996. Cat. Nr. 16.A.5)
163	222	950-1000	Anglo-Saxon	Circular brooch	Silver. circular brooch with engraved ornament and boss. 0.99g. fragment	List Hoard. Isle of Sylt. hacksilver Nr. 6 (Wiechmann 1996. Cat. Nr. 16.A.6)
164	223	950-1000	Anglo-Saxon	Belt end	Silver. Niello. Anglo-Saxon strap end. Trewhiddle stlye. 1.14g. fragmented (upper part with rivets is lacking)	Hedeby. detector find. Hb 2003/1105. (Hilberg 2009. 97. Figure 15.3)
165	224	800-850	Carolingian	Fitting	Fire-gilded silver. niello. and brass ring. 7.30g. nearly complete - original fitting tangs missing	Hedeby. detector find Hb 2004/11146. (Hilberg 2009. 93. Figure 10.1)
166	225	800-850	Carolingian	Fitting	Fire-gilded silver. glass/enamel inlay?. (rev. brass pin. copper pin holder. brass needle holder. iron pin. tin solder. brass loop). Carolingian fitting reused as a brooch. 9.14g. complete	Hedeby. excavation. LA 48. Fd.Nr. 13641. (unpublished. identified by V. Hilberg)
167	226	900-1000?	Oriental	Brooch	Silver boss. Cu-Pb frame (rev. Cu-Pb loop. ring. and pin-needle holder). Base metal brooch. in the center oriental silver buckle with plant ornament. 14.45g. nearly complete - the pin and needle are missing	Hedeby. detector find Hb 2003/476. (unpublished. identified by V. Hilberg)
168	227	900-1100	Volga Bulgharia?	Fitting	Silver. Volga-Bulghar strap fitting with palmette decoration. 0.68g. fragment	Hedeby. excavation. LA 48. Fd.Nr. 7755 (unpublished. identified by V. Hilberg)
169	228	1000-1100	Russian?	Cross	Silver. cross pendant of eastern/Russian style. 7.80g. complete	Hedeby. detector find Hb 2004/8698 (unpublished. identified by V. Hilberg)
170	229	850-950	Scandinavian	Cross	Silver. cross pendant with the stylized image of Christ. supposedly locally manufactured in Hedeby. 4.26g. complete	Hedeby. detector find Hb 2003/3174 (unpublished. identified by V. Hilberg)

Cat.	DBM	Date	Style	Type	Description	Find Context and Nr.
171	230	850-950	Scandinavian	Thor Hammer	Silver. Thor's hammer amulet. supposedly locally manufactured in Hedeby. 1.84g. complete	Hedeby. detector find Hb 2003/4032. (unpublished. identified by V. Hilberg)
172	231	900-1025	Scandinavian	Miscast	Silver. decoratice part of a Scandinavian armring. workshop debris. 2.29g. fragment - production waste?	Hedeby. detector find Hb 2006/13700 (unpublished. identified by V. Hilberg)
173	233	?	Scandinavian	Disk brooch	Copper-alloy disk brooch with tin decoration. 14.14g. nearly complete	Hedeby. Grave 110 Ks 12370 (CAPELLE 1968. Cat. Nr. 73. Plate 25.3; HILBERG 2009. 98; WAMERS 1985. Cat. Nr. 165. Plate 3.2)
174	27	-	-	Bar ingot	Silver. 73.66g. complete	Hedeby. detector find. Hb 2003-217 (unpublished)
175	28	-	Scandinavian/ Baltic	Ribed bar	Silver. 3.06g. fragment	Hedeby. detector find. Hb 2003-609 (unpublished)
176	29	-	Russian/ Eastern Baltic	Permian spiral ring terminal	Silver. 50.67g. fragment	Hedeby. detector find. Hb 2003-788 (unpublished)
177	30	-	Scandinavian/ Baltic	Arm ring	Silver. 1.15g. fragment	Hedeby. detector find. Hb 2003-1064 (unpublished)
178	31	-	-	Wire	Silver. 4.08g. fragment	Hedeby. detector find. Hb 2003-2788 (unpublished)
179	32	-	-	Bar	Silver. 4.22g. fragment	Hedeby. detector find. Hb 2003-3456 (unpublished)
180	33	-	-	Two twisted wires	Silver. 1.95g. fragment	Hedeby. detector find. Hb 2003-3834 (unpublished)
181	34	-	-	Bar	Silver. 4.57g. fragment	Hedeby. detector find. Hb 2004-6119 (unpublished)
182	35	-	-	Bar ingot	Silver. 6.23g. fragment	Hedeby. detector find. Hb 2004-8163 (unpublished)
183	36	-	-	Wire	Silver. 3.63g. fragment	Hedeby. detector find. Hb 2004-8540 (unpublished)
184	37	-	-	Bar ingot	Silver. 2.42g. fragment	Hedeby. detector find. Hb 2004-10611 (unpublished)
185	38	-	Scandinavian/ Baltic	Arm ring	Silver. 2.21g. fragment	Hedeby. detector find. Hb 2004-11071 (unpublished)
186	39	-	-	Bar	Silver. 5.75g. fragment	Hedeby. detector find. Hb 2004-12396 (unpublished)
187	40	-	-	Twisted wire	Silver. 9.45g. fragment	Hedeby. detector find. Hb 2006-12467 (unpublished)
188	41	-	-	Bar ingot	Silver. 11.82g. fragment	Hedeby. detector find. Hb 2006-12587 (unpublished)
189	42	-	-	Wire	Silver. 4.07g. fragment	Hedeby. detector find. Hb 2007-13926 (unpublished)
190	43	-	-	Bar wire	Silver. 4.82g. fragment	Hedeby. excavation. 2007 LA 48. Fd.Nr. 8476. Fdst: NW-Sektor. Kulturschicht ab 1. Planum. N 10.566. E 3.146. D NN+11.668 (unpublished)
191	44	-	-	Bar ingot	Silver-brass alloy. 15.49g. fragment	Hedeby. detector find. Hb 2003-114 (unpublished)
192	45	-	-	Cast bead	Leaded bronze. 24.77g. fragment	Hedeby. detector find. Hb 2003-867 (unpublished)

Cat.	DBM	Date	Style	Type	Description	Find Context and Nr.
193	46	-	-	Pennanular brooch	Leaded brass. 15.79g. fragment	Hedeby. detector find. Hb 2003-1023 (unpublished)
194	47	-	-	Bar ingot	Silver-brass alloy. 5.99g. complete?	Hedeby. detector find. Hb 2003-1330 (unpublished)
195	48	-	-	Neck ring	Leaded brass. 9.10g. fragment	Hedeby. detector find. Hb 2003-1447 (unpublished)
196	49	-	-	Folded sheet	Lead. 35.59g. fragment	Hedeby. excavation. 2005 LA 48. Fd.Nr. 1890. Grubenhaus 1 (ab 4. Planum). N 7.792. E 12.458. D NN+10828 (unpublished)
197	50	-	-	Scrap	Lead. 1.73g. fragment	Hedeby. excavation. 2005 LA 48. Fd.Nr. 2161. Grubenhaus 1 (ab 4. Planum). N 6.005. E 11.015. D NN+10.864 (unpublished)
198	51	-	-	Weight	Lead. 3.5g. fragment	Hedeby. excavation. 2006 LA 48. Fd.Nr. 2573. Grubenhaus 1 (ab 7. Planum). N 5.540 . E 11.985. D NN+10.310 (unpublished)
199	52	-	-	Scrap	Lead-tin. 0.09g. fragment	Hedeby. excavation. 2006 LA 48. Fd.Nr. 2605. Grubenhaus 1 (ab 7th Planum) N 5.728. E 12.718. D NN+10.241 (unpublished)
200	53	-	-	Ingot	Lead. 498g. fragment?	Hedeby. excavation. 2007 LA 48. Fd.Nr. 6645. Grubenhaus 10 (ab 5. Planum) N 7.370. E 4.610. D NN+10.269 (unpublished)
201	54	-	-	Scrap	Lead. 12.45g. fragment	Hedeby. excavation. 2006 LA 48. Fd.Nr. 2592. Grubenhaus 1 (ab 7. Planum). N 5.247. E 11.719. D NN+10.257 (unpublished)
202	123	-	-	Scrap	Tin-lead alloy. 15.95g. fragment	Hedeby. detector find. Hb 2003/240. (unpublished)
203	124	-	-	Bar ingot	Lead. 12.0g. fragment	Hedeby. detector find. Hb 2003/602 (unpublished)
204	125	-	-	Bar ingot	Lead. 7.7g. fragment	Hedeby. detector find. Hb 2003/747 (unpublished)
205	126	-	-	Bar ingot	Lead. 49.41g. complete	Hedeby. detector find. Hb 2003/783 (unpublished)
206	127	-	-	Bar ingot	Lead. 8.93g. fragment	Hedeby. detector find. Hb 2003/1538 (unpublished)
207	128	-	-	Bar ingot	Lead-tin alloy. 26.90g. fragment	Hedeby. detector find. Hb 2003/1752 (unpublished)
208	129	-	-	Pyramidal (weight?)	Lead. 25.20g. complete	Hedeby. detector find. Hb 2003/4808 (unpublished)
209	130	-	-	Ingot	Lead. 223.70 g (after drilling). fragment	Hedeby. detector find. Hb 2004/9673 (unpublished)
210	131	-	-	Production waste	Lead. 28.31g. fragment	Hedeby. detector find. Hb 2004/9704 (unpublished)
211	132	-	-	Ingot	Lead. 230.36 g (after drilling). fragment	Hedeby. detector find. Hb 2005/11891 (unpublished)

Cat.	DBM	Date	Style	Type	Description	Find Context and Nr.
212	133	-	-	Ingot	Lead. 248.83 g (after drilling). fragment	Hedeby. detector find. Hb 2007/13863 (unpublished)
213	-	-	-	Ingot	Lead. Approx. 4 kg	Hedeby. KSD 602.204 (MAIXNER 2010. Figure 186)

***Table 2** Catalogue of silver. copper-alloy, lead, and lead-tin alloy objects sampled in this study.*

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
214	DBM 1	Heating tray	Heating tray rim fragment with thin glaze on interior. The tray is made of a silty crumbly ceramic with a dark and carbon-rich core. There are fine quartz grains and some white rock inclusions. The exterior surface is gray and has finger imprints from the formation of the dish. The rim is slightly glazed and is mostly colorless. There are some red-green and dark colorations. Below the rim is a band of black residue with some red and green patches. Below this band is an indentation where the metal may have sunk into the ceramic. There are flecks of glaze in this lower area with some remains of a tan-colored coating. Diameter approx. 60 mm. (48 mm x 34 mm x 7 mm thick. 25% of the object)	11.9g (A.S. 10.4g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 27.50/ East 105.35 Level V. Box 4 (unpublished)
215	DBM 2	Heating tray	This is a heating tray fragment with gold prills on the interior. The ceramic is dense and gray with no visible temper. The exterior is friable towards the base and becomes harder and lightly glazed at the rim. The interior has a very light glazing on the upper half of the rim, but towards the middle of the heating tray there is a thicker glass that is black-purple, green and tan. Gold prills dot the interior surface, but are larger in the thicker glaze (up to 200 µm). Diameter approx. 50 mm (26 mm x 13 mm x 8 mm thick)	3.5g	SEM	Hedeby Excavation 1969. North 23.60/ East 103.30 Level V. Box 1 (unpublished)
216	DBM 3	Crucible	It is made from a fine whitish-grey ceramic. The walls are thin. The shape is uncommon and irregular. The crucible is somewhat conical in shape. narrowing to a point at the base, but the rim is not circular, but triangular. There is cracking on both the interior and exterior and there is a slight matte glaze on the exterior, mostly colorless, showing the underlying gray ceramic. Where the glaze is thicker it is green and there are spots of red (cuprite) and black (tenorite). The interior is a peculiar pinkish-purple with conglomerations of corroded copper and concretions. Droplets of leaded-brass were found on the interior. Diameter between 40-60 mm assuming it is circular. (fragment approx. 50 mm x 45 mm x 3 mm thick. 35% of original object)	19.1g (A.S. 16.7g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 25.45/ East 102.20 Level V. Box 1 (unpublished)
217	DBM 4-1	Heating tray	This is a complete heating tray. The ceramic on the underside is gray with quartz temper and there are a number of cracks, which probably formed while forming, but worsened during use. Interestingly, there are traces of burnt out hair on the ceramic surface pointing to the use of hair to reinforce the clay. The interior is black, brown and vitreous. The rim is more reddish due to cuprite. There is a distortion of the rim that appears to have been caused by tongs or by manipulation at high temperatures. Diameter 40-43 mm. (43 mm x 17 mm x 5-9 mm thick)	17.7g	-	Hedeby Excavation 1969. North 27.15/ East 97.15. Level V. Box 1 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
218	DBM 5	Heating tray	Made from sandy course ceramic that looks similar to the ceramic used for large crucibles like DBM 9. Gray. not very fused ceramic on the bottom and the rim and upper surface are vitrified. The slag on the upper surface is brightly colored with purple, red, gray, brown, blue, and green. The outer rim is mostly green with some blue. Just inside the rim the glass is mostly red and purple. Towards the center of the upper surface it is darker and more liver brown. Iridescence can be seen in the glassy parts. The upper surface. despite being glassy is not smooth, but irregular and jagged, showing many broken bubbles. One of the larger heating trays discovered, and one of the thickest. No traces of uncorroded metal can be seen on any surface. Diameter approx. 70 mm. (55 mm x 32 mm x 15 mm thick. 25% of original object)	22.6g (A.S. 21.3g)	XPLM/ SEM-EDS	Hedeby Excavation 1969. North 7.05/ East 131.85. Level V. Box 1 (unpublished)
219	DBM 6	Heating tray	Made from a very fine. refractory, apparently a kaolin-containing ceramic. Fine particles of sand and mica can be seen in the ceramic matrix. The form is circular dish that is approx. 12 mm deep. The interior of the vessel has a coating of dark. brownish-tan glassy slag. There are some black corrosion products, which might be silver sulfide. The rim of the vessel is denser than the ceramic on the underside. There are some small cracks on the underside from the formation of the dish. Diameter 60 mm. (fragment approx. 48 mm x 46 mm x 6 mm thick. 30% of rim)	10.6g (A.S. 8.8g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 43.45/ East 206.40. Level V. Box 1 (unpublished)
220	DBM 7	Heating tray	Made from sandy course ceramic. that looks similar to the ceramic used for large crucibles. Gray, not very fused ceramic on the bottom and the rim and upper surface are vitrified. The slag on the upper surface is brightly colored with purple, red, gray, brown, blue, and green. The outer rim is mostly red with purple and some blue. Just inside the rim the glass is mostly red and green. Towards the center of the upper surface it is darker and more olive green-brown. On the underside of the heating tray there are streaks of opalescent blue and purple glaze (reminiscent of Chinese Jun-ware glaze). The upper surface is for the most part smooth and glassy. No traces of uncorroded metal can be seen on any surface, but there does appear to be black corrosion products and possibly iron corrosion (ochre). Diameter approx. 50 mm. (34 mm x 25 mm x 6 mm thick. 25% of rim)	7.3g (A.S. 0.5g)	SEM-EDS. XPLM. LIA	Hedeby Excavation 1969. North 28.10/ East 101.70. Level V. Box 1 (unpublished)
221	DBM 8-1/2	Melting ball	These two fragments either form the round base of a cylindrical crucible or half of a melting ball. The ceramic is dark gray, porous, frothy, and filled with quartz sand temper. The exterior is heavily vitrified by the fluxing of fuel ash and varies from clear, green, and red. The interior is smooth and buff in color. SEM-EDS revealed enrichment of zinc on the interior. Diameter 41 mm. (41 mm x 32 mm x 10 mm thick)	29.2g	SEM-EDS	Hedeby Excavation 1969. North 24.25/ East 106.85 from Level V. Box 1 (unpublished)
222	DBM 8-3	Crucible	Dark, heavily bloated and vitrified ceramic crucible - porous with coarse quartz sand inclusions. Common ceramic for the larger variety of crucibles. The exterior of the crucible is glazed by fuel ash and is green to red in color. Glass can be up to 1 mm thick. The interior is tan to pink with some corrosion products from copper (copper carbonate). Lower wall fragment. diameter between 40-50 mm. (42 mm x 35 mm x 8 to 10 mm thick)	8.9g (A.S. 7.3g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 24.25/ East 106.85 from Level V. Box 1 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
223	DBM 9	Crucible	This is nearly a complete cylindrical crucible consisiting of two fragments that fit together. The ceramic is gray, porous, and frothy with some quartz sand temper. The interior is gray and smooth with few incrustations. The exterior is vitreous but has a gradient from being glassy and molten at the bottom to having a slight glaze near the rim. The glaze is colorless where thin, but ranges from black, green and red where it is thicker. A large quartz fragment adheres to the glass at the bottom (8 mm x 6 mm). Diameter is 35-40 mm at the rim and 44 mm towards the bottom (60 mm x 44 mm x 8 mm thick)	52.6g	-	Hedeby Excavation 1969. North 22.90/ East 100.20 Level V. Box 1 (unpublished)
224	DBM 10	Crucible	This is a partially complete cylindrical crucible. The ceramic is light gray, dense with abundant quartz inclusions. The interior is gray with tan and brown discolorations. There are some structural cracks on the interior, but they do not go through to the exterior. The exterior is glassy and frothy. The glaze is red, green and black with some drips. Diameter 36 mm at rim. 42mm near base (53 mm x 42 mm x 6-7 mm thick. 30% of rim. base complete)	35.8g	-	Hedeby Excavation 1969. North 22.65/ East 108.95. Level V. Box 1 (unpublished)
225	DBM 11	Hearth with tuyère Impression	This is a portion of a melting hearth with a circular-shaped hole presumably for the tuyère. The ceramic ranges from porous, orange, friable, silty, low fired to completely vitreous towards the hearth interior. The hearth material contains quartz grains. The glassy surface is black and green and with drips forming. The tuyère was perhaps made of iron, but it did not adhere to the glass. The impression of the tuyère is approx. 24 mm diameter and is 14 mm deep. The dimensions of the whole fragment are 66 mm x 38 mm x 21 mm thick.	46.0g	-	Hedeby Excavation 1969. North 23.50/ East 109.60 Level VIII. Box 2 (unpublished)
226	DBM 12	Crucible	Small cylindrical crucible fragment made from a gray ceramic. fairly dense with lots of angular quartz. Thin and hard. Some evidence of vitrification and circular pores, but, for the most part, it seems in good condition. Many of the pores are thin and align in an orientation parallel to the walls. Patches of red glaze on the exterior. On the interior there is evidence for copper melting. There is a drip of nearly pure copper (97 wt % Cu) remaining on the interior lip. It is now coated with what appears to be tenorite. cuprite and malachite. Some vitreous black slag can be found on the interior as well. Diameter 30 mm (finger sized) (28 mm x 23 mm x 3.5 mm thick)	4.2g (A.S. 3.0g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 22.30/ East 105.90 Level III. Box 2 (unpublished)
227	DBM 13-1	Heating tray	This is a rim fragment of a heating tray with gold prills on the interior surface. The ceramic is hard and gray with no visible tempering. The exterior is slightly glazed near the rim with colorless glass. Burnt out impressions of hair can be seen the exterior surface. The interior is glazed with lead-silicate glass ranging from clear, green, red, and black. A structural crack that goes through to the exterior is glazed and may have resulted in the loss of metal. Gold prills dot the interior surface. Diameter approx. 50-60 mm. (25 mm x 19 mm x 5 mm thick)	2.0g	SEM	Hedeby Excavation 1969. North 35-30/ East 100-105 Level III. Box 2 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
228	DBM 13-2	Heating tray	This is a heating tray fragment with gold prills on the interior surface. The ceramic is porous and frothy and varies from dark gray to pale gray. The underside is lightly glazed and is dark gray-green. The interior surface is vitreous with green and clear glass. Prills of gold are visible to the eye, but under 300 µm. Diameter unknown. (20 mm x 13 mm x 13 mm thick)	2.6g	SEM-EDS	Hedeby Excavation 1969. North 35-30/ East 100-105 Level III. Box 2 (unpublished)
229	DBM 14-1	Heating tray	Heating tray rim fragment with thin glaze on interior. The tray is made of a silty crumbly gray ceramic with a dark core. There are fine quartz grains and some white rock inclusions. One large quartz grain protrudes out of the ceramic. very round 4mm long. The exterior surface is gray to tan. The rim is slightly glazed and is mostly clear. Below the rim is a band of brownish-black matte but vitreous residue. Below this band is an indentation where the metal regulus was. The ceramic is broken, revealing ceramic that was very bloated and bubbly. Diameter approx. 60 mm. (32 mm x 24 mm x 10+ mm thick. 10% of object)	6.8g (A.S. 5.7g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 20-30/ East 95-105 Level III. Box 2 (unpublished)
230	DBM 14-2	Crucible	This is a cylindrical crucible fragment with gold on the interior surface. The ceramic is refractory, hard, and light gray in color and has a texture similar to DBM 12, 17, 20 and 24. The interior of the crucible is glassy with a thin layer of slag containing lead, copper, silver, and zinc. This crucible was used for multiple metals, but the last cast was for gold, and there are a number of prills visible. the largest being 3 mm. The exterior is slightly glazed and frothy. The glaze is colorless except one splotch of green. Diameter unknown. (22 mm x 13mm x 5 mm thick)	1.8g	SEM-EDS	Hedeby Excavation 1969. North 20-30/ East 95-105 Level III. Box 2 (unpublished)
231	DBM 14-3	Crucible	Extremely fine crucible of dense grayish-tan ceramic. It looks like the crucible was formed over a finger. Ceramic is fine grained, but one quartz inclusion can be seen in the profile that is the thickness of the wall (1 mm). There is a hint of glazing on the exterior, but the crucible does not seem heavily used. Diameter approx. 25 mm. (33 mm x 22 mm x 1 mm. 20% of rim)	1.4g (A.S. 0.9g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 20-30/ East 95-105 Level III. Box 2 (unpublished)
232	DBM 15	Heating tray	This is a heating tray with prills of electrum on the interior and exterior surfaces. The ceramic is gray with no visible temper. Very small grains of quartz and muscovite can be seen. It seems to be identical to the ceramic from DBM 23-3. The underside of the heating tray is friable, but becomes better sintered towards the rim. The rim exterior is glazed red, while the interior is glazed with clear, green, brown or black glass. Large numbers of prills up to 1 mm in size dot the interior of the heating tray and small prills are also on the exterior. In the center of the heating tray there is a resession 3 mm deep where the metal regulus appears to have sunken into the ceramic. Diameter approx. 60 mm. (29 mm x 28 mm x 13 mm thick)	8.8g	SEM-EDS	Hedeby Excavation 1969. North25-30/ East 95-100 Level IV. Box 3 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
233	DBM 16	Crucible	This is a small and very thin cylindrical crucible that is incomplete. It has been partially reconstructed from three fragments. The ceramic is light gray and dense. The interior is dark, but has no incrustations. Traces of silver and zinc were found on the interior by SEM-EDS. The exterior is slightly glazed with dark splotches and some red streaks. The wall profile is not complete, but the base is. The crucible appears to have been formed over a finger. or could be called thimble shaped. Diameter approx. 20 mm. (31 mm x 20 mm x 1-3 mm thick)	3.0g	SEM-EDS	Hedeby Excavation 1969. North 27-27.50/East 101.70-120.20 Level IV. Box 3 (unpublished)
234	DBM 17	Crucible	This is a cylindrical crucible fragment with gold on the interior surface. The ceramic is refractory, hard, and light gray in color and has a texture similar to DBM 12, 14-2, 20 and 24. The interior of the crucible is glassy with a thin layer of slag containing iron, silver and zinc. This crucible was used for multiple metals, but the last cast was for gold, and there are a number of prills visible, the largest being 2 mm. The exterior is thickly glazed with red, green and blue glass. Diameter approx. 40 mm. (29 mm x 26 mm x 9 mm thick)	6.2g	SEM-EDS	Hedeby Excavation 1969. North 25.90/ East 109.60 Level IV. Box 3 (unpublished)
235	DBM 18	Heating tray	Made from sandy course ceramic that looks similar to the ceramic used for large crucibles. Gray. not very fused ceramic on the bottom and the rim and upper surface are more vitrified. The slag on the upper surface is dull olive-green, red and burgundy. This heating tray has traces of oxidation with buff-orange coloration of the ceramic, but this is not uniform. On the underside of the heating tray is gray to buff in color. The upper surface is for the most part smooth and glassy, and in some parts the glass penetrates into the ceramic about 0.5 mm. No traces of uncorroded metal can be seen on any surface. There is some whitish residue on the upper surface, which might be corroded glass. Diameter approx. 40 mm. (31 mm x 31 mm x 10 mm thick. 25% of rim)	5.9g (A.S. 3.7g)	SEM-EDS. XPLM two thin-sections made. A and B	Hedeby Excavation 1969. North 24.45/ East 99.70 from Level IV. Box 3 (unpublished)
236	DBM 19	Heating tray	This is a fragment of a heating tray. The ceramic is dark gray, porous, with few sand inclusions. The interior is vitrified with color variations ranging from dark green, tan to black. There may be a thin protective layer on the interior towards the center of tray. The underside is relatively uneffected by the heat and is grayish-buff. The impressions of fingers can be seen from the formation of the dish, and in some cases finger prints can be seen. Diameter approx. 60 mm. (46 mm x 31 mm x12 mm thick. 25% of rim)	10.9g (A.S. 10.6g)	LIA	Hedeby Excavation 1969. North 26.45/ East 96.65. Level IV. Box 3 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
237	DBM 20	Crucible	This is the bottom of a cylindrical crucible. It is made of a gray ceramic with white stones and quartz grains. Made of refractory clay. Porosity similar to DBM 12 and 24 with pores aligning parallel to the walls. Dark discoloration on the interior with brown to black incrustations. There are no visible traces of metal. No visible oxides of copper on the interior. The exterior is covered with an ash glaze, which is mostly green or clear with some splotches of red cuprite. The ceramic is gray to white under the glaze. A piece of slagged clay is stuck to the bottom of the crucible. Vitrification is superficial and did not penetrate into the ceramic. Diameter approx. 40 mm. (larger than finger sized) (40 mm x 33 mm x 8-9 mm thick)	15.2g (A.S. 13.7)	SEM-EDS. XPLM	Hedeby Excavation 1969.North 25.45/ East 101.85 Level III. Box 1 (unpublished)
238	DBM 21	Heating tray	Heating tray rim fragment with thick glaze. Made from a silty ceramic similar to DBM 23-2 with fine quartz inclusions and at least one large white rock fragment. The ceramic is a bit crumbly in the core. but is heavily vitrified on the upper surface particularly at the rim. The ceramic is dark gray and carbon-rich. The rim is banded with a rich red glaze, which overflows to the exterior. Immediately below the rim, the glaze darkens and is dark olive green in color. Towards the middle of the dish there is a depression where the metal may have sunken into the ceramic. After crushing for the lead isotope analysis, two flattened silver prills were found (5 mm and 3 mm). Diameter 50-60 mm (24 mm x 24 mm x >8 mm thick)	4.1g (A.S. 0.04g Silver)	SEM-EDS. XPLM. LIA	Hedeby Excavation 1969. North 20-25/ East 100-105 Level V. Box 4 (unpublished)
239	DBM 22	Heating tray	Heating tray fragment. The ceramic is porous, silty, and dark with abundant quartz inclusions. The underside is friable, but the upper walls and interior are vitreous. The glass on the exterior is green or clear, but the interior rim is reddish from cuprite. The interior is glassy and black with corrosion products. presumably silver sulfide. Diameter approx. 50-60 mm (39 mm x 25 mm x 14 mm thick. 30% of rim)	11.5g	-	Hedeby Excavation 1963. South 10.40/ East 108.70 + 0.90NN. Box 6 (unpublished)
240	DBM 23-1	Heating tray	This is a heating tray fragment with gold prills on the interior surface. The ceramic is dense, gray, and has no visible temper. The ceramic is friable towards the base, but becomes hard and glazed towards the rim. The interior is thickly coated with red-green lead-silicate glass. Gold prills are visible and are entrapped in the glass. A large structural crack goes all the way through the ceramic wall and is completely glazed. It may have resulted in the loss of metal. Diameter approx. 70 mm. (26 mm x 16 mm x 8 mm thick)	3.9g	SEM-EDS	Hedeby Excavation 1969. North 20-30/ East 95-105 Level V. Box 7 (unpublished)
241	DBM 23-2	Heating tray	Fragment of a ceramic heating tray. Rim to interior. The ceramic is silty and crumbly and is black to gray in color. Lots of fine quartz grains can be seen in the profile. There is a band of reddish-green glaze below the rim. There is a stepped depression towards the interior with a film of glaze where the metal sank into the ceramic. There is a coating of some black tannish material towards the middle of the dish, below the band of red glaze. Diameter approx. 60 mm. (33 mm x 31 mm x 12 mm thick. 15% of rim)	9.4g (A.S. 8.8g)	SEM-EDS. XPLM	Hedeby Excavation 1969. North 20-30/ East 95-105 Level V. Box 7 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
242	DBM 23-3	Heating tray	This is a fragment of a heating tray with visible gold prills on the interior surface. The ceramic is gray with no visible temper. Small grains of muscovite are visible. The underside is friable, but the upper wall is better fired. The interior is vitreous with a reddish-brown lead-rich glass. Visible gold prills are concentrated on the interior wall at the boundary between the glassy slag and the ceramic, but continue to the rim. The prills are 100 µm and smaller. Diameter approx. 60 mm. (18 mm x 18 mm x 6 mm)	2.6g	SEM-EDS	Hedeby Excavation 1969. North 20-30/ East 95-105 Level V. Box 7 (unpublished)
243	DBM 23-4	Crucible	Wall fragment of a cylindrical crucible. The ceramic is thin with a gray core. The ceramic does not appear to be highly fired and may not have actually been used for melting metal. There are some black and reddish discolorations on the interior. The ceramic is soft and filled with inclusions of quartz and muscovite. Diameter approx. 30 mm (finger sized). (25 mm x 15 mm x 3.5 mm thick)	1.7g (A.S. 1.2g)	SEM-EDS. XPLM	Hedeby Excavation 1969.North 20-30/ East 95-105 Level V. Box 7 (unpublished)
244	DBM 24	Crucible	Small cylindrical crucible wall fragment. Most of the profile can be seen. Ceramic is gray, dense, and hard with quartz inclusions. Its porosity is similar to that of DBM 12. The pores are thin and form in parallel to the wall. There is a large crack in the ceramic, which formed while in the hearth, but the crucible was used regardless. The glassy vitrification on the exterior has sealed the crack, but it is clearly visible on the interior and through the wall. The exterior is heavily slagged and vitrified. This vitrification penetrates about a millimeter into the ceramic. The crucible was well-used and made out of a refractory clay. The exterior is coated with a thick mottled red-orange-green glass with some incrustations on it. The interior is greenish-purplish in color with incrustations of brown material. No macroscopic trace of metal. but microscopically prills of silver-brass alloy were found. Diameter approx. 30 mm (finger sized). (44 mm x 29 mm x 6-8 mm thick. 25% of the object)	14.3g (A.S. 11.0g)	SEM-EDS. XPLM	Hedeby Excavation 1969.North 24.00/ East 95.20 Level VI. Box 13 (unpublished)
245	DBM 25	Melting ball	This round crucible fragment is either the base of a cylindrical crucible or a melting ball. The ceramic is dark gray, porous and filled with inclusions of quartz temper (4 mm largest, average 0.5 mm). The exterior is glazed by ash and is green-tan in color. The interior has a tan-gray color with incrustation with charcoal and sand. Diameter 40 mm. (40 mm x 28 mm x 13 mm thick)	11.3g	-	Hedeby Excavation 1969. North 25-30/ East 105-110 Level VI. Box 13 (unpublished)

Cat.	Sample	Object Type	Description	Weight	Analyses	Find Context and Nr.
246	DBM 26	Crucible	Complex crucible. The original crucible is made of fine buff-gray ceramic with little visible porosity. The bottom of the crucible is lightly fired compared to the upper walls of the crucible. Cracks developed coming down from the rim and red-green glass can be seen in the fracture. After cracks formed resulting in the loss of silver, an attempt to prolong the life-span of the crucible can be seen with a coating of a quartz-rich clay that was brushed on to the exterior (not on the bottom) and interior. The quartz-rich coating was applied as a liquid and shrinking cracks can be seen as well as the brush strokes. This coating is up to 1 mm thick. The crucible was used at least once more after the coating was applied. The interior of the crucible has a glaze that is mostly olive-green with some hints of red. Near the bottom of the vessel there are copper corrosion products (copper carbonate). Diameter approx. 35 mm. (47 mm x 28 mm x 5 mm. 15% of rim)	9.3g (A.S. 8.2g)	XPLM/SEM	Hedeby Excavation 1969. North 64.60/ West 0.70 from Level VIII. Box 15 (unpublished)
247	DBM 134	Crucible	It is the base of a (wheel-thrown) flat-based vessel with a white powdery residue on the inside with drips of lead silicate on the outside. The ceramic is thought to be formed by wheel because of the circular striations on the base. The ceramic is red-orange in color and is tempered with abundant quartz and feldspar of various sizes (largest 4 mm, average 1 mm). The residue on the interior is approx. 1-3 mm thick and consists of lead carbonate, phosphate, and corroded glass. It is probably that the crucible was a pot for melting lead-silicate glass, which is now corroded. Diameter of the base is 80 mm, but the rim should be wider. (78 mm x 40 mm x 16 mm thick. 50% of the base)	89.9g	ICP-MS. LIA. SEM-EDS	Hedeby. excavation. LA 48. Fd. Nr. 1358. Grubenhaus 1 (ab 2. Planum). N 6.401. E 12.764. D NN+11.286 (unpublished)

Table 3 *Catalogue of technical ceramics investigated in this study. Analyses: ICP-MS inductively-coupled plasma mass spectrometry, LIA lead isotope analysis, SEM-EDS scanning electron microscopy energy dispersive spectroscopy, and XPLM cross-polarized light microscopy. Concerning the object weights, A.S. means after sampling.*

Cat.	Coordinates				Level	Object Type
214	N	27.5	E	105.35	5	Heating Tray Frag.
215	N	23.6	E	103.30	5	Heating Tray Frag.
216	N	25.45	E	102.20	5	Crucible Frag.
217	N	27.15	E	97.15	5	Heating Tray. Complete
218	N	7.05	E	131.85	5	Heating Tray Frag.
219	N	43.45	E	206.40	5	Heating Tray Frag.
220	N	28.10	E	101.70	5	Heating Tray Frag.
220	N	24.25	E	106.85	5	Crucible Frag.
221	N	24.25	E	106.85	5	Crucible Frag.
222	N	24.25	E	106.85	5	Crucible Frag.
223	N	22.90	E	100.20	5	Crucible
224	N	22.65	E	108.95	5	Crucible Frag.
225	N	23.50	E	109.60	8	Hearth w/ Slag and tuyère
226	N	22.30	E	105.90	3	Crucible Frag.
234	N	25.90	E	109.60	4	Crucible Frag.
235	N	24.45	E	99.70	4	Heating Tray Frag.
236	N	26.45	E	96.65	4	Heating Tray Frag.
237	N	25.45	E	101.85	3	Crucible Frag.
244	N	24.00	E	95.20	6	Crucible Frag.
227	N	35-30	E	100-105	3	Heating Tray Frag.
228	N	35-30	E	100-105	3	Heating Tray Frag.
229	N	20-30	E	95-105	3	Heating Tray Frag.
230	N	20-30	E	95-105	3	Crucible Frag.
231	N	20-30	E	95-105	3	Crucible Frag.
232	N	25-30	E	95-105	4	Heating Tray Frag.
233	N	27-27.5	E	101.70-120.20	4	Crucible Frag.
238	N	20-25	E	100-105	5	Heating Tray Frag.
240	N	20-30	E	95-105	5	Heating Tray Frag.
241	N	20-30	E	95-105	5	Heating Tray Frag.
242	N	20-30	E	95-105	5	Heating Tray Frag.
243	N	20-30	E	95-105	5	Crucible Frag.
245	N	25-30	E	105-110	6	Crucible Frag.
246	N	64.60	W	0.70	8	Crucible Frag.
239	S	10.40	E	108.70	(+0.50 m)	Crucible Frag.

Table 4 *The find locations of technical ceramics from the 1963 and 1969 excavations of Hedeby used in this study.*

Cat.	Sample	Label	Source	Material	Object Type	Analysis Type
248	DBM 265	Ge 1	Tunket [Uzbekistan]	Slag	Dense iron-calcium-manganese silicate slag with clinopyroxene and fayalite phases, and contains metallic lead, copper antimonide speiss, and small sulfide inclusions mostly of bornite often with galena eutectic phases. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
249	DBM 266	Ge 2	Apantepe [Uzbekistan]	Slag	Furnace fragment with no traces of non-ferrous metallurgy. Sample from the Geological Museum in Tashkent.	pXRF
250	DBM 267	Ge 3	Lashkerek [Uzbekistan]	Slag	Glassy slag containing quartz fragments, galena, and silver-rich phases. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
251	DBM 268	LK 1	Lashkerek [Uzbekistan]	Slag	Museum of History, slag field in Karamazar (near Lashkerek) collected by O. I. Islamov 1960-70s. Dense iron-calcium-manganese silicate slag with clinopyroxene phases. and contains metallic lead. copper antimonide speiss. and small sulfide inclusions mostly of bornite often with galena eutectic phases.	pXRF, XRD, SEM-EDS, ICP-MS, LIA
252	DBM 269	LK 2a	Lashkerek [Uzbekistan]	Slag	Museum of History, slag field in Karamazar (near Lashkerek) collected by O. I. Islamov 1960-70s. Dense iron-calcium-manganese silicate slag with clinopyroxene phases. and contains metallic lead and small sulfide inclusions mostly of bornite often with galena eutectic phases.	pXRF, XRD, SEM-EDS, ICP-MS, LIA
253	DBM 270	LK 2b	Lashkerek [Uzbekistan]	Slag	Museum of History, slag field in Karamazar (near Lashkerek) collected by O. I. Islamov 1960-70s. Dense iron-calcium-manganese silicate slag with fayalite and hedenbergite phases. and contains small sulfide inclusions mostly of bornite often with galena eutectic phases.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
254	DBM 271	Tun-a	Tunket [Uzbekistan]	Slag	Dense iron-calcium-manganese silicate slag with fayalite and clinopyroxene phases. and contains argentiferous lead and small sulfide inclusions mostly of bornite often with galena eutectic phases.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
255	DBM 272	Tun-b	Tunket [Uzbekistan]	Slag	Finely crystalline slag containing crystals of clinopyroxene and small amounts of magnetite. This slag contains metallic antimonial copper, lead, and chalcocite.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
256	DBM 273	Tun-c	Tunket [Uzbekistan]	Slag	Fayalite-hedenbergite slag containing sulfide inclusions consisting of anglesite-barite, iron sulfide, chalcopyrite, and galena.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
257	DBM 274	Tun-d	Tunket [Uzbekistan]	Slag	Fayalite-hedenbergite slag containing bornite, chalcopyrite, galena, metallic lead, allargentum, and copper antimonide speiss.	XRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
258	DBM 275	Tun-e	Tunket [Uzbekistan]	Slag	Finely crystalline slag containing crystals of hedenbergite and small amounts of magnetite. This slag contains metallic antimonial copper, argentiferous lead and chalcocite.	XRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA

Cat.	Sample	Label	Source	Material	Object Type	Analysis Type
259	DBM 276	Tun-f	Tunket [Uzbekistan]	Slag	Coarse, porous fayalite-hedenbergite slag containing quartz fragments, bornite, and argentiferous lead.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
260	DBM 277	Ge-4	Lashkerek [Uzbekistan]	Ore	Chalcopyrite. bornite. galena. acanthite. native silver. pyrite. and argentiferous tetrahedrite in mixture of quartz and carbonates of the dolomite-ankerite-kutnohorite system with the formula Ca(Fe, Mg, Mn)$(CO_3)_2$. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
261	DBM 278	Ge-5	Lashkerek [Uzbekistan]	Ore	Chalcopyrite. galena. acanthite. pyrite. and argentiferous tetrahedrite in mixture of quartz and carbonates of the dolomite-ankerite-kutnohorite system with the formula Ca(Fe, Mg,Mn) $(CO_3)_2$. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
262	DBM 279	Ge-6	Lashkerek [Uzbekistan]	Ore	Chalcopyrite. galena. acanthite. pyrite. and argentiferous tetrahedrite in mixture of quartz and carbonates of the dolomite-ankerite-kutnohorite system with the formula Ca(Fe, Mg, Mn) $(CO_3)_2$. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
263	DBM 280	Ge-7	Lashkerek [Uzbekistan]	Ore	Chalcopyrite. galena. pyrite. tennantite. and argentiferous tetrahedrite in a quartz and calcite-dolomite-ankerite matrix. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, XPLM, ICP-MS, LIA
264	DBM 281	Ge-8	Lashkerek [Uzbekistan]	Ore	Malachite, azurite, hematite, and clay minerals. Sample from the Geological Museum in Tashkent.	pXRF, XRD, SEM-EDS, ICP-MS, LIA
265	DBM 283	TC 1	Tunket [Uzbekistan]	Slag	Coarse, porous fayalite-hedenbergite slag containing quartz fragments, bornite, and argentiferous lead.	SEM-EDS, XPLM
266	DBM 284	TC 2	Tunket [Uzbekistan]	Slag	Coarse, porous fayalite-hedenbergite slag containing quartz fragments. bornite. and argentiferous lead.	SEM-EDS, XPLM
267	DBM 285	TC 3	Tunket [Uzbekistan]	Slag	Coarse, porous fayalite-hedenbergite slag containing quartz fragments, bornite, and argentiferous lead.	SEM-EDS, XPLM
268	DBM 286	TC 4	Tunket [Uzbekistan]	Slag	Coarse, porous fayalite-hedenbergite slag containing quartz fragments, bornite, and argentiferous lead.	SEM-EDS, XPLM
269	DBM 287	TD 3	Tunket [Uzbekistan]	Slag	Coarse, porous fayalite-hedenbergite slag containing quartz fragments, bornite, and argentiferous lead.	SEM-EDS, XPLM
270	DBM 288	TD 5	Tunket [Uzbekistan]	Slag	This is a dense iron-calcium-manganese silicate slag with fayalite and hedenbergite phases. Sulfide inclusions are mostly bornite often with galena eutectic phases. Sulfide inclusions are quite small.	SEM-EDS, XPLM
271	DBM 289	TD 7	Tunket [Uzbekistan]	Slag	This is a dense iron-calcium-manganese silicate slag with fayalite and hedenbergite phases. Sulfide inclusions are mostly bornite often with galena eutectic phases. Sulfide inclusions are quite small.	SEM-EDS, XPLM

Cat.	Sample	Label	Source	Material	Object Type	Analysis Type
272	DBM 290	TD 9	Tunket [Uzbekistan]	Slag	This is a dense iron-calcium-manganese silicate slag with fayalite and hedenbergite phases. Sulfide inclusions are mostly bornite often with galena eutectic phases. Sulfide inclusions are quite small.	SEM-EDS. XPLM
273	DBM 291	TD 16	Tunket [Uzbekistan]	Slag	This is a dense iron-calcium-manganese silicate slag with fayalite and hedenbergite phases. Sulfide inclusions are mostly bornite often with galena eutectic phases. Sulfide inclusions are quite small.	SEM-EDS. XPLM
274	DBM 282	Ge-10	Aktepe [Uzbekistan]	Ore	Arsenic-nickel-cobalt-iron minerals with amounts of lead and silver. Sample from the Geological Museum in Tashkent.	XRF. SEM-EDS. PLM
275	DBM 292	Sam-1	Sarmich deposit [Uzbekistan]	Ore	Pyrite with quartz and dolomite.	XRF. XRD. ICP-MS. LIA
276	DBM 293	Sam-2	Zarmitan deposit [Uzbekistan]	Ore	Quartz and pyrite.	XRF
277	DBM 294	Sam-3a	Sarmich deposit [Uzbekistan]	Ore	Arsenopyrite with quartz and muscovite.	XRF. XRD. ICP-MS. LIA
278	DBM 295	Sam-3b	Sarmich deposit [Uzbekistan]	Ore	Polymetallic sulfide ore consisting of pyrite, galena. sphalerite, fahlore, and silver-rich minerals.	XRF. XRD. SEM-EDS. PLM. ICP-MS. LIA
279	DBM 296	Sam-4	Mardjanbulak deposit [Uzbekistan]	Ore	Galena, sphalerite, and silver minerals in a quartz and calcite matrix.	XRF. XRD. ICP-MS. LIA
280	DBM 297	Sam-5	Zarmitan deposit [Uzbekistan]	Ore	Pyrite with quartz and alumosilicates. There is no silver or lead in this rock fragment.	XRF
281	DBM 298	Sam-6	Kosmonachi deposit [Uzbekistan]	Ore	Polymetallic sulfide ore consisting of pyrite. galena, sphalerite, fahlore, and silver-rich minerals.	XRF. XRD. SEM-EDS. PLM. ICP-MS. LIA

Table 5 *Catalogue of slag and ore specimens from Uzbekistan.*

Cat. 1

Cat. 2

Cat. 3

Cat. 4

Cat. 5

Cat. 6

Cat. 7

Cat. 8

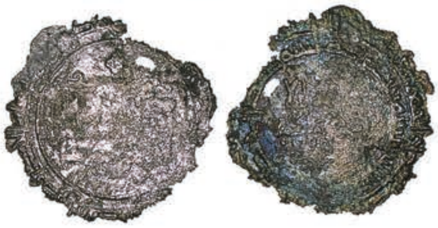
Cat. 9

Cat. 10

Cat. 11

Cat. 12

Cat. 13



Cat. 14

Cat. 15

Cat. 16

Cat. 17

***Plate 1** Coins. Scale 1:1.*

Cat. 18

Cat. 19

Cat. 20

Cat. 21

Cat. 22

Cat. 23

Cat. 24

Cat. 25

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Cat. 28

Cat. 29

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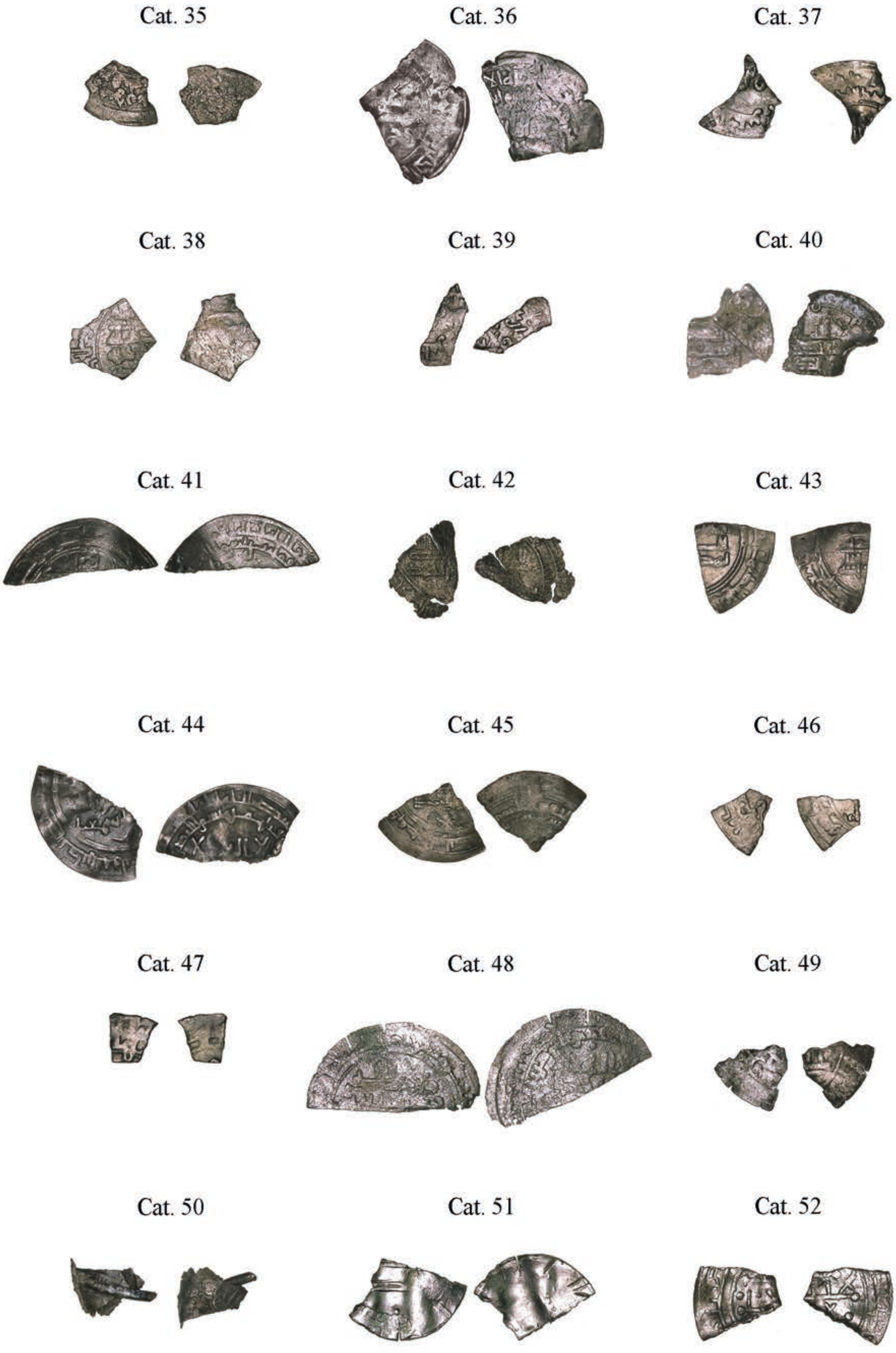
Cat. 31

Cat. 32

Cat. 33

Cat. 34

Plate 2 *Coins. Scale 1:1.*



Cat. 35

Cat. 36

Cat. 37

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Cat. 41

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Cat. 52

Plate 3 *Coins. Scale 1:1.*

Cat. 53

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Cat. 69

***Plate 4** Coins. Scale 1:1.*

Cat. 70

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Cat. 86

Cat. 87

Plate 5 *Coins. Scale 1:1.*

Cat. 88

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Cat. 102

Cat. 103

Cat. 104

Cat. 105

***Plate 6** Coins. Scale 1:1.*

Cat. 106

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Cat. 123

***Plate 7** Coins. Scale 1:1.*

Cat. 124

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Cat. 140

Cat. 141

Plate 8 *Coins. Scale 1:1.*

Cat. 142

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Cat. 158

***Plate 9** Coins. Scale 1:1.*

Cat. 159

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Cat. 170

Cat. 171

Cat. 172

Plate 10 *Silver Finds. Scale 1:1.*

Cat. 174

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Cat. 187

Cat. 188

Cat. 189

Plate 11 *Silver Finds. Scale 1:1.*

Plate 12 *Silver. Copper-Alloy. and Lead-Tin Finds. Scale 1:1.*

Cat. 202

Cat. 203

Cat. 204

Cat. 205

Cat. 206

Cat. 207

Cat. 208

Cat. 209

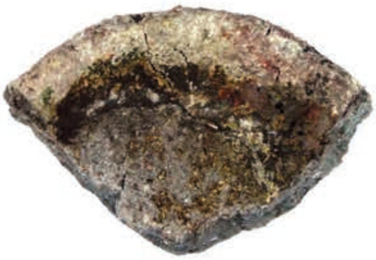
Cat. 210

Cat. 211

Cat. 212

Plate 13 *Lead-Tin Finds. Scale 1:1.*

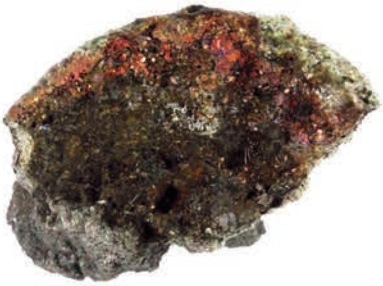
Cat. 214



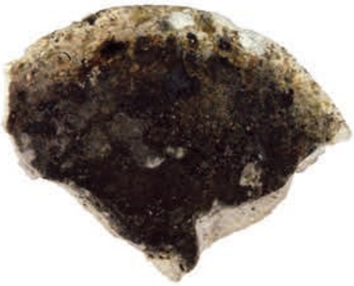
Cat. 215

Cat. 217

Cat. 218

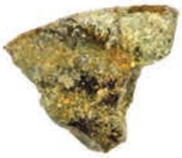


Cat. 219



Cat. 220

Cat. 227



Cat. 228

Cat. 229

Cat. 232

Cat. 235

Cat. 238

Cat. 240

Cat. 241

Cat. 242

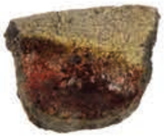
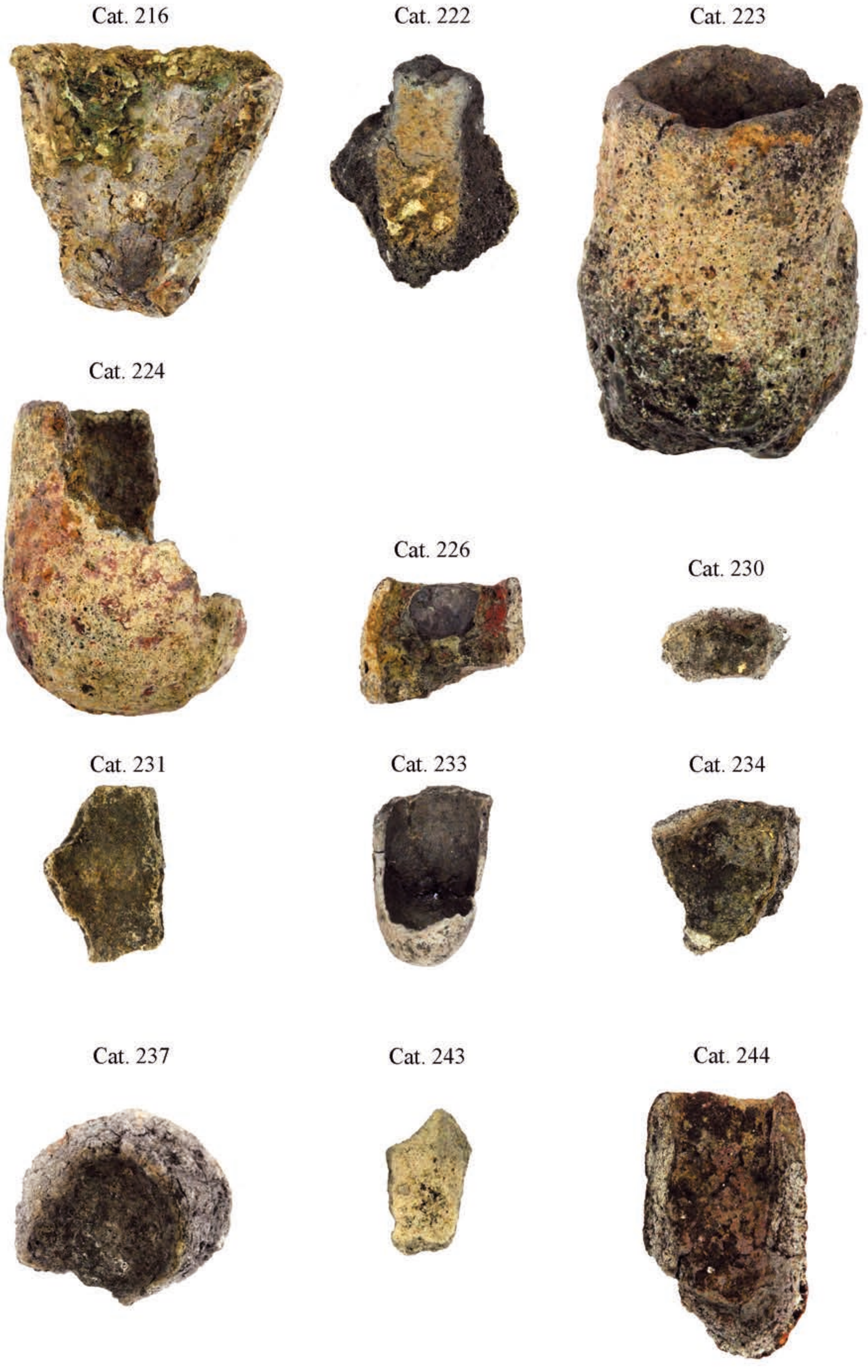


Plate 14 *Heating Trays. Scale 1:1.*



Cat. 216

Cat. 222

Cat. 223

Cat. 224

Cat. 226

Cat. 230

Cat. 231

Cat. 233

Cat. 234

Cat. 237

Cat. 243

Cat. 244

Plate 15 *Cylindrical Crucibles. Scale 1:1.*

Cat. 246

Cat. 221

Cat. 245

Cat. 247

Plate 16 *Cylindrical Crucible. Melting Balls. and Glass Pot. Scale 1:1.*

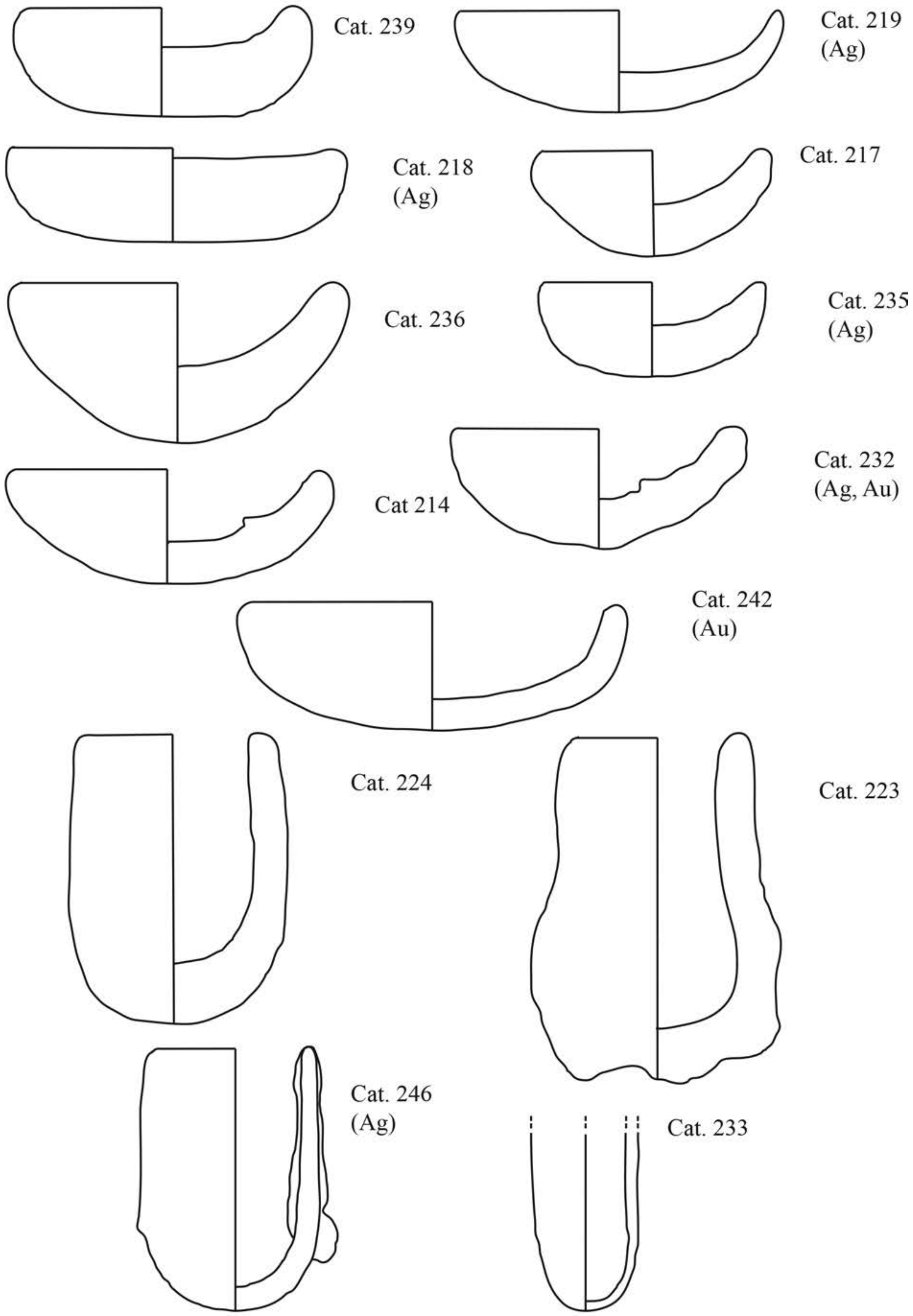


Plate 17 *Heating Trays and Cylindrical Crucibles. Scale 1:1.*

Appendix B
List of Analyses

Cat. Nr.	Year (AD)	Mint / Origin	Object	Type	Material	Weight	DBM Nr.	LIA Nr.	LIA Place	LIA Date
1	776-786	Kairouan/ al-’Abbāsiyya	Coin	Abbasid Dirham	Ag	0.40g	135	188	Hannover	29.09.2012
2	787-792	Kairouan/ al-’Abbāsiyya	Coin	Abbasid Dirham	Ag	0.69g	136	189	Hannover	29.09.2012
3	Unknown	(N. Afr. mint)	Coin	Abbasid Dirham	Ag	0.21g	137	190	Hannover	29.09.2012
4	786-790	Kairouan/ al-’Abbāsiyya	Coin	Abbasid Dirham	Ag	0.47g	187	157	Hannover	29.09.2012
5	808-811	Balkh	Coin	Abbasid Dirham	Ag	0.68g	139	192	Hannover	29.09.2012
6	808-811	Balkh	Coin	Abbasid Dirham	Ag	0.44g	140	193	Hannover	29.09.2012
7	794-803	Tehrān	Coin	Abbasid Dirham	Ag	0.73g	138	191	Hannover	29.09.2012
8	810/811	Samarqand	Coin	Abbasid Dirham	Ag	0.38g	141	194	Hannover	29.09.2012
9	(84)7	Baghdād	Coin	Abbasid Dirham	Ag	0.20g	142	195	Hannover	29.09.2012
10	871/872	Samarra	Coin	Abbasid Dirham	Ag	2.17g	232	242	Hannover	29.09.2012
11	875/876	Panjhīr	Coin	Abbasid Dirham	Ag	2.17g	143	196	Hannover	29.09.2012
12	878-884	Shiraz	Coin	Saffarid Dirham	Ag	0.67g	144	197	Hannover	29.09.2012
13	912/913	al-Shāsh	Coin	Samanid Dirham	Ag	1.03g	108	55	Hannover	02.02.2012
14	90(9)/9(10)	al-Shāsh	Coin	Samanid Dirham	Ag	2.10g	107	59	Hannover	02.02.2012
15	900/901	al-Shāsh	Coin	Samanid Dirham	Ag	2.67g	146	199	Hannover	29.09.2012
16	905/906	al-Shāsh	Coin	Samanid Dirham	Ag	0.38g	148	203	Hannover	29.09.2012
17	907/908	al-Shāsh	Coin	Samanid Dirham	Ag	1.45g	149	204	Hannover	29.09.2012
18	896-907	al-Shāsh	Coin	Samanid Dirham	Ag	0.71g	150	205	Hannover	29.09.2012
19	900/901	al-Shāsh	Coin	Samanid Dirham	Ag	0.29g	151	206	Hannover	29.09.2012
20	910/911	al-Shāsh	Coin	Samanid Dirham	Ag	2.27g	154	209	Hannover	29.09.2012
21	907-914	al-Shāsh	Coin	Samanid Dirham	Ag	0.42g	156	211	Hannover	29.09.2012
22	909/911	al-Shāsh	Coin	Samanid Dirham	Ag	0.85g	158	213	Hannover	29.09.2012
23	929/930	al-Shāsh	Coin	Samanid Dirham	Ag	0.60g	162	217	Hannover	29.09.2012
24	932-941	al-Shāsh	Coin	Samanid Dirham	Ag	0.41g	165	220	Hannover	29.09.2012
25	933-942	al-Shāsh	Coin	Samanid Dirham	Ag	1.92g	166	221	Hannover	29.09.2012
26	930-947	al-Shāsh	Coin	Samanid Dirham	Ag	0.38g	168	223	Hannover	29.09.2012
27	953/954	al-Shāsh	Coin	Samanid Dirham	Ag	1.52g	172	227	Hannover	29.09.2012
28	904/905	Samarqand	Coin	Samanid Dirham	Ag	2.34g	105	56	Hannover	02.02.2012
29	908	Samarqand	Coin	Samanid Dirham	Ag	2.42g	106	57	Hannover	02.02.2012
30	892/894	Samarqand/al-Shāsh	Coin	Samanid Dirham	Ag	0.49g	145	198	Hannover	29.09.2012
31	907-912	Samarqand	Coin	Samanid Dirham	Ag	0.39g	155	210	Hannover	29.09.2012
32	938/939	Samarqand	Coin	Samanid Dirham	Ag	3.23g	163	218	Hannover	29.09.2012
33	939/940	Samarqand	Coin	Samanid Dirham	Ag	0.37g	164	219	Hannover	29.09.2012
34	942/943	Samarqand	Coin	Samanid Dirham	Ag	0.57g	167	222	Hannover	29.09.2012
35	950/951	Samarqand	Coin	Samanid Dirham	Ag	0.27g	170	225	Hannover	29.09.2012
36	948-951	Samarqand	Coin	Samanid Dirham	Ag	2.23g	171	226	Hannover	29.09.2012

Cat. Nr.	Year (AD)	Mint / Origin	Object	Type	Material	Weight	DBM Nr.	LIA Nr.	LIA Place	LIA Date
37	945-954	Samarqand	Coin	Samanid Dirham	Ag	0.35g	173	228	Hannover	29.09.2012
38	945-954	Samarqand	Coin	Samanid Dirham	Ag	0.52g	174	229	Hannover	29.09.2012
39	958-961	Samarqand	Coin	Samanid Dirham	Ag	0.27g	175	230	Hannover	29.09.2012
40a	906/907	Andarāba	Coin	Samanid Dirham	Ag	1.26g	112a	70	Hannover	02.02.2012
40b	Unknown	Unknown	Coin	Unk. Coin	Ag	1.26g	112b	-	-	N.M.
40c	Unknown	Unknown	Coin	Unk. Coin	Ag	1.26g	112c	71	Hannover	02.02.2012
41	905/906	Balkh	Coin	Samanid Dirham	Ag	0.89g	147	202	Hannover	29.09.2012
42	904/905	Andarāba	Coin	Samanid Dirham	Ag	0.34g	152	207	Hannover	29.09.2012
43	907-910	Andarāba	Coin	Samanid Dirham	Ag	0.59g	153	208	Hannover	29.09.2012
44	914/915	Andarāba	Coin	Samanid Dirham	Ag	0.79g	157	212	Hannover	29.09.2012
45	918/919	Andarāba	Coin	Samanid Dirham	Ag	0.53g	159	214	Hannover	29.09.2012
46	924-927	Balkh	Coin	Samanid Dirham	Ag	0.29g	160	215	Hannover	29.09.2012
47	922-933	N. Afgh.	Coin	Samanid Dirham	Ag-Pb-Bi	0.28g	161	216	Hannover	29.09.2012
48	934-945	Balkh	Coin	Samanid Dirham	Ag	1.10g	169	224	Hannover	29.09.2012
49	980-990	Bukhārā or Nīshāpūr	Coin	Samanid Dirham	Ag	0.27g	176	231	Hannover	29.09.2012
50a	Unknown	Unknown	Coin	Unidentified Dirham	Ag	0.75g	113a	72	Hannover	02.02.2012
50b	Unknown	Unknown	Ornament	Wire	Ag	0.75g	113b	-	-	N.M.
50c	Unknown	Unknown	Coin	Unk. Coin	Ag	0.75g	113c	74	Hannover	02.02.2012
50d	Unknown	Unknown	Coin	Unk. Coin	Ag	0.75g	113d	73	Hannover	02.02.2012
51	870-890 AD	Khazaria	Coin	Khazar Dirham	Ag	1.15g	177	232	Hannover	29.09.2012
52	Early 10th C.	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	0.57g	178	233	Hannover	29.09.2012
53	Early 10th C.	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	0.55g	179	234	Hannover	29.09.2012
54	Early 10th C.	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	1.72g	181	236	Hannover	29.09.2012
55	After 906/907	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	0.31g	182	237	Hannover	29.09.2012
56	After 922	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	0.68g	180	235	Hannover	29.09.2012
57	After 922	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	0.33g	184	239	Hannover	29.09.2012
58	After 907-914	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	0.48g	185	240	Hannover	29.09.2012
59	922-932	Volga Bulgharia or Kiev	Coin	Volga-Bulghar Dirham	Ag	0.22g	186	241	Hannover	29.09.2012
60	932-941	Volga Bulgharia	Coin	Volga-Bulghar Dirham	Ag	1.42g	183	238	Hannover	29.09.2012
61	963-969	Constantinople	Coin	Miliaresion	Ag	1.85g	198	168	Hannover	29.09.2012
62a	977-989	Constantinople	Coin	Miliaresion	Ag	2.33g	199a	169	Hannover	29.09.2012
62b	After 977-989	Unknown	Ornament	Loop	Ag	2.33g	199b	170	Hannover	29.09.2012
63a	977-989	Constantinople	Coin	Miliaresion	Ag	4.54g	218a	256	Hannover	29.09.2012
63b	After 977-989	Unknown	Ornament	Loop	Ag	4.54g	218b	257	Hannover	29.09.2012
63c	After 977-989	Unknown	Ornament	Ring	Ag	4.54g	218c	255	Hannover	29.09.2012
64	985-991	Exeter	Coin	Penny, Second Hand	Ag	0.67g	83	31	Hannover	02.02.2012

Cat. Nr.	**Year (AD)**	**Mint / Origin**	**Object**	**Type**	**Material**	**Weight**	**DBM Nr.**	**LIA Nr.**	**LIA Place**	**LIA Date**
65	997-1003	Winchester	Coin	Penny, Long Cross	Ag	1.56g	84	30	Hannover	02.02.2012
66	1017-1025	Lincoln?	Coin	Penny, Quatrefoil	Ag	0.32g	85	29	Hannover	02.02.2012
67	1017-1025	Unknown	Coin	Penny, Quatrefoil	Ag	0.20g	119	63	Hannover	02.02.2012
68	942/3	York	Coin	Penny, Hiberno-Norse	Ag	0.27g	188	158	Hannover	29.09.2012
69	997-1003	Dublin	Coin	Penny	Ag	1.27g	200	171	Hannover	29.09.2012
70	997-1003	Dublin	Coin	Penny	Ag	1.31g	201	172	Hannover	29.09.2012
71	997-1003	Dublin	Coin	Penny	Ag	1.37g	202	173	Hannover	29.09.2012
72	997-1003	Dublin	Coin	Penny	Ag	1.24g	203	174	Hannover	29.09.2012
73	997-1003	Dublin	Coin	Penny	Ag	1.22g	204	175	Hannover	29.09.2012
74	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	1.02g	67	20	Hannover	02.02.2012
75	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.41g	68	14	Hannover	02.02.2012
76	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	1.26g	69	15	Hannover	02.02.2012
77	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	1.35g	189	159	Hannover	29.09.2012
78	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	1.07g	190	160	Hannover	29.09.2012
79	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.39g	191	161	Hannover	29.09.2012
80	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.33g	234	151	Hannover	29.09.2012
81	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.31g	235	152	Hannover	29.09.2012
82	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.30g	236	153	Hannover	29.09.2012
83	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.28g	237	154	Hannover	29.09.2012
84	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.22g	238	155	Hannover	29.09.2012
85	950-1000	Magdeburg?	Coin	Sachsenpfennig	Ag	0.18g	239	156	Hannover	29.09.2012
86	985-1010	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.13g	73	-	-	N.M.
87	990-1010	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.00g	74	34	Hannover	02.02.2012
88	985-1010	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.25g	75	242	Hannover	03.02.2010
89	985-995	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.34g	76	35	Hannover	02.02.2012
90	985-1010/later	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	0.97g	77	244	Hannover	03.02.2012
91	985-1010	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.42g	78	245	Hannover	03.02.2012
92	1010-1030	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	0.91g	79	37	Hannover	02.02.2012
93	991-1040	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.01g	80	33	Hannover	02.02.2012
94	1020-1035	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	1.14g	81	32	Hannover	02.02.2012
95	990-1020	Goslar?	Coin	Otto-Adelheid-Pfennig	Ag	0.61g	82	-	-	N.M.
96	983-996	Cologne	Coin	Colonia	Ag	1.13g	63	23	Hannover	02.02.2012
97	983-996	Cologne	Coin	Colonia	Ag	1.38g	64	16	Hannover	02.02.2012
98	983-996	Cologne	Coin	Colonia	Ag	1.25g	65	17	Hannover	02.02.2012
99	1014-24	Cologne	Coin	Colonia	Ag	0.83g	121	250	Hannover	03.02.2012

Cat. Nr.	Year (AD)	Mint / Origin	Object	Type	Material	Weight	DBM Nr.	LIA Nr.	LIA Place	LIA Date
100	1027-36	Cologne	Coin	Colonia	Ag	1.23g	122	65	Hannover	02.02.2012
101	1000-1040	Soest	Coin	Colonia Imitation	Ag	1.06g	70	19	Hannover	02.02.2012
102	1030-1050	Soest	Coin	Colonia Imitation	Ag	0.54g	71	243	Hannover	03.02.2012
103	11th c.	Westphalia	Coin	Colonia Imitation	Ag	0.26g	72	18	Hannover	02.02.2012
104	1014-1024	Deventer	Coin	Denar	Ag	0.99g	66	24	Hannover	02.02.2012
105	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.14g	55	10	Hannover	02.02.2012
106	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.10g	56	40032	Hannover	02.02.2012
107	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.00g	57	11	Hannover	02.02.2012
108	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.07g	58	12	Hannover	02.02.2012
109	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.15g	59	13	Hannover	02.02.2012
110	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.11g	60	21	Hannover	02.02.2012
111	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	0.98g	61	241	Hannover	03.02.2012
112	End of 10th c.	Unknown, East Frisia	Coin	Colonia Imitation	Ag	1.22g	62	22	Hannover	02.02.2012
113	1002-1024	Unknown, Nijmegen	Coin	Colonia Imitation	Ag	0.72g	120	64	Hannover	02.02.2012
114a	900-920	Hedeby?	Coin	Malmer KG7	Ag	1.75g	86a	66	Hannover	02.02.2012
114b	Unknown	Unknown	Coin	Unk. Coin	Ag	1.75g	86b	67	Hannover	02.02.2012
114c	Unknown	Unknown	Coin	Unk. Coin	Ag	1.75g	86c	68	Hannover	03.02.2012
114d	Unknown	Unknown	Coin	Unk. Coin	Ag	1.75g	86d	69	Hannover	02.02.2012
115	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.53g	87	45	Hannover	02.02.2012
116	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.50g	88	47	Hannover	02.02.2012
117	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.49g	89	48	Hannover	02.02.2012
118	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.21g	90	54	Hannover	02.02.2012
119	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.62g	101	42	Hannover	02.02.2012
120	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.49g	102	43	Hannover	02.02.2012
121	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.48g	103	44/46	Hannover	02.02.2012
122	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.69g	116	246	Hannover	03.02.2012
123	900-920	Hedeby?	Coin	Malmer KG7	Ag	0.35g	118	62	Hannover	02.02.2012
124	950-965	Hedeby?	Coin	Malmer KG8	Ag	0.33g	192	162	Hannover	29.09.2012
125	965-975	Hedeby?	Coin	Malmer KG9a	Ag	0.36g	193	163	Hannover	29.09.2012
126	965-975	Hedeby?	Coin	Malmer KG9a	Ag	0.37g	194	164	Hannover	29.09.2012
127	975-980	Hedeby?	Coin	Malmer KG9b	Ag	0.48g	195	165	Hannover	29.09.2012
128	975-980	Hedeby?	Coin	Malmer KG9b	Ag	0.18g	91	247	Hannover	03.02.2012
129	975-980	Hedeby?	Coin	Malmer KG9c-d	Ag	0.21g	92	40	Hannover	02.02.2012
130	975-980	Hedeby or Lund?	Coin	Malmer KG10a	Ag	0.27g	93	41	Hannover	02.02.2012
131	975-980	Hedeby or Lund?	Coin	Malmer KG10a	Ag	0.27g	94	39	Hannover	02.02.2012
132	975-980	Hedeby or Lund?	Coin	Malmer KG10a	Ag	0.34g	95	38	Hannover	02.02.2012

Cat. Nr.	Year (AD)	Mint / Origin	Object	Type	Material	Weight	DBM Nr.	LIA Nr.	LIA Place	LIA Date
133	975-980	Hedeby or Lund?	Coin	Malmer KG10a	Ag	0.31g	114	58	Hannover	02.02.2012
134	975-980	Hedeby or Lund?	Coin	Malmer KG10a-b	Ag	0.07g	196	166	Hannover	29.09.2012
135	975-980	Hedeby or Lund?	Coin	Malmer KG10b	Ag	0.09g	197	167	Hannover	29.09.2012
136	975-980	Unk., Denmark, Lund?	Coin	Malmer KG11	Ag	0.23g	117	61	Hannover	02.02.2012
137	1015-1030	Hedeby?	Coin	Årstad 95	Ag	0.51g	115	60	Hannover	02.02.2012
138	1015-1030	Hedeby or S. Scandinavia	Coin	Årstad 96	Ag	0.46g	96	251	Hannover	03.02.2012
139	1015-1030	Hedeby or S. Scandinavia	Coin	Årstad 96	Ag	0.54g	97	25	Hannover	02.02.2012
140	1015-1030	Hedeby or S. Scandinavia	Coin	Årstad 96	Ag	0.45g	98	26	Hannover	02.02.2012
141	1035-1042	Hedeby	Coin	Denar	Ag	0.73g	99	27	Hannover	02.02.2012
142	1035-1042	Hedeby	Coin	Denar	Ag	0.71g	100	28	Hannover	02.02.2012
143	1047-1076	Viborg	Coin	Denar	Ag	0.51g	205	176	Hannover	29.09.2012
144	1050-1060	Viborg	Coin	Denar	Ag	0.62g	206	177	Hannover	29.09.2012
145	1047-1076	Hedeby	Coin	Denar	Ag	0.49g	207	178	Hannover	29.09.2012
146	1047-1076	Hedeby	Coin	Denar	Ag	0.48g	208	179	Hannover	29.09.2012
147	1047-1076	Hedeby	Coin	Denar	Ag	0.47g	209	180	Hannover	29.09.2012
148	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.72g	210	181	Hannover	29.09.2012
149	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.19g	211	182	Hannover	29.09.2012
150	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.59g	212	183	Hannover	29.09.2012
151	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.63g	213	184	Hannover	29.09.2012
152	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.48g	214	185	Hannover	29.09.2012
153	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.38g	215	186	Hannover	29.09.2012
154	1080-1086?	Unk., Denmark	Coin	Denar	Ag	0.35g	216	187	Hannover	29.09.2012
155	After 894/895	Hedeby?	Coin	Tin Dirham	Sn-Pb	3.91g	104	49/50	Hannover	02.02.2012
156	9th c.?	Hedeby?	Coin	Tin Dirham	Sn-Pb	2.23g	109	53	Hannover	02.02.2012
157	9th c.?	Hedeby?	Coin	Tin Dirham	Sn-Pb	2.20g	110	52	Hannover	02.02.2012
158	9th c.?	Hedeby?	Coin	Tin Dirham	Sn-Pb	2.04g	111	51	Hannover	02.02.2012
159a	850-925	Anglo-Saxon	Ornament	Belt End-Body	Ag	12.15g	217a	267	Hannover	29.09.2012
159b	“	“	Ornament	Belt End-Niello	Niello	12.15g	217b	268	Hannover	29.09.2012
159c	“	“	Ornament	Belt End-Pin	Cu?	12.15g	217c	269	Hannover	29.09.2012
159d	“	“	Ornament	Belt End-Niello	Niello	12.15g	217d	270	Hannover	29.09.2012
160	950-1000	Anglo-Saxon	Ornament	Clasp	Ag	1.38g	219	249	Hannover	29.09.2012
161	950-1000	Anglo-Saxon	Ornament	Clasp	Ag	1.92g	220b	248	Hannover	29.09.2012
162a	950-1000	Anglo-Saxon	Ornament	Brooch-backplate	Ag	2.50g	221a	259	Hannover	29.09.2012
162b	“	-	Ornament	Brooch-boss	Ag	2.50g	221b	260	Hannover	29.09.2012
163a	950-1000	Anglo-Saxon	Ornament	Brooch-backplate	Ag	0.99g	222a	261	Hannover	29.09.2012

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163b	“	-	Ornament	Brooch-boss	Ag	0.99g	222b	262	Hannover	29.09.2012
164a	950-1000	Anglo-Saxon	Ornament	Belt end-body	Ag-Cu	1.14g	223a	243	Hannover	29.09.2012
164b	“	“	Ornament	Corrosion	Ag	1.14g	223b	244	Hannover	29.09.2012
164c	“	“	Ornament	Niello	Ag	1.14g	223c	245	Hannover	29.09.2012
164d	“	“	Ornament	Niello	Ag	1.14g	223d	246	Hannover	29.09.2012
165	800-850	Carolingian	Ornament	Fitting	Ag	7.30g	224	254	Hannover	29.09.2012
166b	800-850	Carolingian	Ornament	Fitting	Ag-Cu-Zn	9.14g	225b	263	Hannover	29.09.2012
166a	“	“	Ornament	Needle	Cu-Zn-Pb	9.14g	225a	264	Hannover	29.09.2012
167a	900-1000	Oriental	Ornament	Brooch-boss	Ag	14.45g	226a	265	Hannover	29.09.2012
167b	“	“	Ornament	Brooch-backplate	Cu-Pb?	14.45g	226b	266	Hannover	29.09.2012
167c	“	“	Ornament	Brooch-boss-pin	Ag	14.45g	226c	-	-	N.M.
168	900-1100	Volgabulghar	Ornament	Hacksilver	Ag	0.68g	227	250	Hannover	29.09.2012
169	1000-1100	Russian	Ornament	Cross	Ag	7.80g	228	258	Hannover	29.09.2012
170	850-950	Scandinavian	Ornament	Cross	Ag	4.26g	229	251	Hannover	29.09.2012
171	850-950	Scandinavian	Ornament	Thor hammer	Ag	1.84g	230	252	Hannover	29.09.2012
172	900-1025	Scandinavian	Ornament	Miscast	Ag	2.29g	231	253	Hannover	29.09.2012
173a	9th-10th c.?	Scandinavian	Ornament	Brooch-body	Cu alloy	14.14g	233a	271	Hannover	29.09.2012
173b	“	“	Ornament	Brooch-body	Cu alloy	14.14g	233b	272	Hannover	29.09.2012
173c	“	“	Ornament	Brooch-center	Cu alloy	14.14g	233c	273	Hannover	29.09.2012
173d	“	“	Ornament	Brooch-tinning	Sn	14.14g	233d	274	Hannover	29.09.2012
174	9th-10th c.?	Unknown	Ingot	Bar ingot	Ag	73.66g	27	4105/12	Frankfurt/Main	06.03.2012
175	9th-10th c.?	Scandinavian/Baltic	Ornament	Ribed bar	Ag	3.06g	28	4106/12	Frankfurt/Main	15.10.2012
176	9th-10th c.?	Russian/Eastern Baltic	Ornament	Permian spiral ring	Ag	50.67g	29	4107/12	Frankfurt/Main	06.03.2012
177	9th-10th c.?	Scandinavian/Baltic	Ornament	Arm ring frag.	Ag	1.15g	30	4108/12	Frankfurt/Main	06.03.2012
178	9th-10th c.?	Unknown	Ornament	Wire	Ag	4.08g	31	4109/12	Frankfurt/Main	15.10.2012
179	9th-10th c.?	Unknown	Ingot	Bar frag.	Ag	4.22g	32	4110/12	Frankfurt/Main	15.10.2012
180a	9th-10th c.?	Unknown	Ornament	Two twisted wires	Ag	1.95g	33a	4111/12	Frankfurt/Main	15.10.2012
180b	9th-10th c.?	Unknown	Ornament	Two twisted wires	Ag	1.95g	33b	76	Hannover	02.02.2012
181	9th-10th c.?	Unknown	Ornament	Bar frag.	Ag	4.57g	34	4112/12	Frankfurt/Main	06.03.2012
182	9th-10th c.?	Unknown	Ingot	Bar ingot frag.	Ag	6.23g	35	4113/12	Frankfurt/Main	06.03.2012
183	9th-10th c.?	Unknown	Ornament	Wire	Ag	3.63g	36	4114/12	Frankfurt/Main	06.03.2012
184	9th-10th c.?	Unknown	Ingot	Bar ingot frag.	Ag	2.42g	37	4115/12	Frankfurt/Main	06.03.2012
185	9th-10th c.?	Scandinavian/Baltic	Ornament	Arm ring frag.	Ag	2.21g	38	4116/12	Frankfurt/Main	06.03.2012
186	9th-10th c.?	Unknown	Hacksilver	Bar frag.	Ag	5.75g	39	4117/12	Frankfurt/Main	06.03.2012
187a	9th-10th c.?	Unknown	Ornament	Twisted wire	Ag	9.45g	40a	4118/12	Frankfurt/Main	06.03.2012
187b	9th-10th c.?	Unknown	Ornament	Twisted wire	Ag	9.45g	40b	75	Hannover	02.02.2012

Cat. Nr.	Year (AD)	Mint / Origin	Object	Type	Material	Weight	DBM Nr.	LIA Nr.	LIA Place	LIA Date
188	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Ag	11.82g	41	4119/12	Frankfurt/Main	06.03.2012
189	9^{th}-10^{th} c.?	Unknown	Ornament	Wire	Ag	4.07g	42	4120/12	Frankfurt/Main	06.03.2012
190	9^{th}-10^{th} c.?	Unknown	Ornament	Bar wire	Ag	4.82g	43	4121/12	Frankfurt/Main	06.03.2012
191	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Ag-Cu-Zn	15.49g	44	4122/12	Frankfurt/Main	21.06.2012
191 (Repeat)	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Ag-Cu-Zn	15.49g	44	4122/12	Frankfurt/Main	25.09.2012
192	9^{th}-10^{th} c.?	Unknown	Ornament	Cast bead frag.	Cu-Sn-Pb	24.77g	45	4123/12	Frankfurt/Main	21.03.2012
192 (Repeat)	9^{th}-10^{th} c.?	Unknown	Ornament	Cast bead frag.	Cu-Sn-Pb	24.77g	45	4123/12	Frankfurt/Main	25.02.2014
193	9^{th}-10^{th} c.?	Unknown	Ornament	Pennanular frag.	Cu-Pb-Zn	15.79g	46	4124/12	Frankfurt/Main	25.02.2014
194	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Ag-Cu-Zn	5.99g	47	4125/12	Frankfurt/Main	21.03.2012
194 (Repeat)	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Ag-Cu-Zn	5.99g	47	4125/12	Frankfurt/Main	25.02.2014
195	9^{th}-10^{th} c.?	Unknown	Ornament	Neck ring frag.	Cu-Pb-Zn	9.1g	48	4126/12	Frankfurt/Main	21.03.2012
196	9^{th}-10^{th} c.?	Unknown	Production waste	Folded sheet	Pb	35.59g	49	4127/12	Frankfurt/Main	06.03.2012
197	9^{th}-10^{th} c.?	Unknown	Production waste	Scrap	Pb	1.73g	50	4128/12	Frankfurt/Main	06.03.2012
198	9^{th}-10^{th} c.?	Unknown	Object	Weight	Pb	3.5g	51	4129/12	Frankfurt/Main	06.03.2012
199	9^{th}-10^{th} c.?	Unknown	Production waste	Scrap	Pb-Sn	0.09g	52	4130/12	Frankfurt/Main	06.03.2012
200	9^{th}-10^{th} c.?	Unknown	Ingot	Ingot frag.	Pb	498g	53	4131/12	Frankfurt/Main	06.03.2012
201	9^{th}-10^{th} c.?	Unknown	Production waste	Scrap	Pb	12.45g	54	4132/12	Frankfurt/Main	06.03.2012
202	9^{th}-10^{th} c.?	Unknown	Production waste	Object frag.	Sn-Pb	15.95g	123	4310/12	Frankfurt/Main	16.10.2013b
203	9^{th}-10^{th} c.?	Unknown	Ingot	Bar frag.	Pb	12.0g (a.s)	124	4311/12	Frankfurt/Main	16.10.2013b
204	9^{th}-10^{th} c.?	Unknown	Ingot	Bar frag.	Pb-Sn	7.7g (a.s.)	125	4312/12	Frankfurt/Main	25.02.2014
205	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot	Pb	49.41g	126	4313/12	Frankfurt/Main	25.02.2014
206	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Pb	8.93g	127	4314/12	Frankfurt/Main	25.02.2014
207	9^{th}-10^{th} c.?	Unknown	Ingot	Bar ingot frag.	Pb-Sn	26.90g	128	4315/12	Frankfurt/Main	15.10.2013
208	9^{th}-10^{th} c.?	Unknown	Ingot	Pyramidal object	Pb	25.20g	129	4316/12	Frankfurt/Main	16.10.2013a
209	9^{th}-10^{th} c.?	Unknown	Ingot	Ingot frag.	Pb	223.7g	130	4317/12	Frankfurt/Main	16.10.2013a
210	9^{th}-10^{th} c.?	Unknown	Production waste	Melted frag.	Pb	28.31g	131	4318/12	Frankfurt/Main	16.10.2013a
211	9^{th}-10^{th} c.?	Unknown	Ingot	Ingot frag.	Pb	230.36g	132	4319/12	Frankfurt/Main	25.02.2014

Cat. Nr.	Year (AD)	Mint / Origin	Object	Type	Material	Weight	DBM Nr.	LIA Nr.	LIA Place	LIA Date
212	9th-10th c.?	Unknown	Ingot	Ingot frag.	Pb	248.83g	133	4320/12	Frankfurt/Main	16.10.2013b
213	9th-10th c.?	Unknown	Ingot	Ingot	Pb	c. 4kg	-	4381/13	Frankfurt/Main	15.10.2013

Table 1 *List of metal objects analyzed by mass spectrometry. The DBM numbers and laboratory / LIA (lead isotope analysis) numbers are given because they were used internally for both elemental and lead isotope analysis. The LIA date is the date the lead isotope ratios were analyzed. This information can be used to connect the measurement with the standard measurements (see Appendix D, Table 8). The 'a.s.' means weight after sampling.*

Cat. Nr.	Year (AD)	Find Location	Object	Type	Material	Weight	DBM Nr.	Lab/LIA Nr.	LIA Place	LIA Date
219	9th-11th c.	Hedeby	Technical Ceramic	Heating tray slag	Pb-Si-O	10.6g	7	4706/11	Frankfurt/Main	15.10.2012
236	9th-11th c.	Hedeby	Technical Ceramic	Heating tray slag	Pb-Si-O	10.9g	19	4503/12	Frankfurt/Main	15.10.2012
238	9th-11th c.	Hedeby	Technical Ceramic	Heating tray slag	Pb-Si-O	4.1g	21	4133/12	Frankfurt/Main	15.10.2012
247	9th-11th c.	Hedeby	Technical Ceramic	Cerussite/Phosph.	PbCO3-P-O	89.9g	134	4321/12	Frankfurt/Main	25.09.2012
248	9th-10th c.?	Tunket	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	265	5153/12	Frankfurt/Main	04.12.2012
250	9th-10th c.?	Lashkerek	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	267	5154/12	Frankfurt/Main	04.12.2012
251	9th-10th c.?	Lashkerek	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	268	5155/12	Frankfurt/Main	04.12.2012
252	9th-10th c.?	Lashkerek	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	269	5156/12	Frankfurt/Main	04.12.2012
253	9th-10th c.?	Lashkerek	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	270	5157/12	Frankfurt/Main	04.12.2012
254	9th-10th c.?	Tunket	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	271	5158/12	Frankfurt/Main	04.12.2012
255	9th-10th c.?	Tunket	Smelting slag	Hedenbergite slag	Cu	-	272	5159/12	Frankfurt/Main	04.12.2012
256	9th-10th c.?	Tunket	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	273	5160/12	Frankfurt/Main	04.12.2012
257	9th-10th c.?	Tunket	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	274	5161/12	Frankfurt/Main	04.12.2012
258	9th-10th c.?	Tunket	Smelting slag	Hedenbergite slag	Cu	-	275	5162/12	Frankfurt/Main	04.12.2012
259	9th-10th c.?	Tunket	Smelting slag	Fayalite slag	Pb-Cu-Ag	-	276	5163/12	Frankfurt/Main	04.12.2012
260	-	Lashkerek Mine	Metalliferous Mineral	Ttr-Ccp	Cu-As-Sb-Ag	-	277	4015/13	Frankfurt/Main	31.01.2013
261	-	Lashkerek Mine	Metalliferous Mineral	Ttr-Ccp	Cu-As-Sb-Ag	-	278	4016/13	Frankfurt/Main	31.01.2013
262	-	Lashkerek Mine	Metalliferous Mineral	Ttr-Ccp	Cu-As-Sb-Ag	-	279	4017/13	Frankfurt/Main	31.01.2013
263	-	Lashkerek Mine	Metalliferous Mineral	Ttr-Ccp	Cu-As-Sb-Ag	-	280	4018/13	Frankfurt/Main	31.01.2013
264	-	Lashkerek Mine	Metalliferous Mineral	Malachite	Cu	-	281	4019/13	Frankfurt/Main	31.01.2013
275	-	Sarmich Mine	Metalliferous Mineral	Pyrite	Fe	-	292	4020/13	Frankfurt/Main	31.01.2013
277	-	Sarmich Mine	Metalliferous Mineral	Arsenopy.	As-Fe	-	294	4021/13	Frankfurt/Main	31.01.2013
278	-	Sarmich Mine	Metalliferous Mineral	Galena	Pb-Cu-Ag	-	295	4022/13	Frankfurt/Main	31.01.2013
279	-	Mardjanbulak Mine	Metalliferous Mineral	Galena	Pb-Cu-Ag	-	296	4023/13	Frankfurt/Main	31.01.2013
281	-	Kosmonachi Mine	Metalliferous Mineral	Galena	Pb-Cu-Ag	-	298	4024/13	Frankfurt/Main	31.01.2013

Table 2 *List of slag, technical ceramic and mineralogical samples analyzed by mass spectrometry. The DBM numbers and Deutsches Bergbau-Museum Bochum laboratory numbers / LIA (lead isotope analysis) numbers are given because they were used internally for both elemental analysis at the Deutsches Bergbau-Museum Bochum and lead isotope analysis at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften. The LIA date is the date the lead isotope ratios were analyzed. This information can be used to connect the measurement with the standard measurements (see* ***Appendix D, Table 8****). Mineral abbreviations: Ttr – tetrahedrite, Ccp – chalcopyrite, Arsenopy - arsenopyrite.*

Appendix C
Elemental Analysis

Contents

Cat. Nr.	Material > 10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe %	Pt ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Pd ppm	In ppm	Hg ppm	Tl ppm
1	Ag	100.6	-	95.4	4.6	4	20	6	1	6200	1.0	-	0.6	9	-	3	25	-	3	0.2	190	-
2	Ag	101.3	-	97.9	2.0	15	8	20	3	12800	0.8	-	0.6	15	1	2	20	-	1	-	210	0.3
3*	Ag	100.8	-	97.8	2.2	25	20	40	3	7400	0.7	-	0.1	5	1	130	20	-	1	-	200	0.4
4	Ag	101.0	-	94.0	6.0	1	9	-	2	10300	0.5	-	-	2	6	6	-	-	4	-	300	-
5	Ag	101.0	-	95.6	4.2	390	1500	45	4	10000	0.5	-	3	9	50	20	15	-	3	0.3	160	0.3
6	Ag	100.4	-	99.3	0.6	740	40	85	-	4500	0.5	0.2	0.1	0.8	-	0.3	15	-	1	-	160	0.1
7	Ag	101.2	-	98.8	1.0	490	450	40	2	12400	0.6	0.2	0.1	1	-	0.3	15	-	1	-	180	1
8	Ag	100.6	13.2	99.3	0.4	1100	550	650	-	6300	0.4	0.2	0.1	0.5	-	0.2	10	-	1	-	130	0.1
9	Ag	100.3	-	94.7	5.3	10	200	9	15	2500	0.3	-	3	10	2	2	10	-	3	0.3	120	-
10	Ag	100.3	15.0	99.0	0.6	2500	10	1100	15	3300	0.2	0.9	0.2	0.4	1	0.8	3	-	1	-	60	0.2
11**	Ag	100.4	-	98.7	0.1	3	11800	20	4	3600	0.4	0.2	0.1	0.8	5	7	8	-	-	0.1	130	2
12	Ag	100.9	-	97.0	2.7	2300	740	310	200	9200	0.2	0.7	0.3	3	35	15	5	-	2	0.7	190	0.2
13	Ag	100.2	-	98.1	1.3	270	5200	10	-	1600	-	0.2	0.2	-	-	3	2	-	1	-	-	0.1
14	Ag	100.2	-	98.1	1.3	100	5800	20	1	2400	-	0.3	0.1	-	-	3	2	-	2	-	-	0.7
15	Ag	100.4	-	98.5	1.1	1200	2700	75	2	4200	0.2	0.2	0.2	1	1	3	3	-	1	-	85	0.8
16	Ag	100.2	-	98.7	1.0	1100	1700	20	1	2500	0.1	0.2	0.1	0.3	-	2	4	-	1	-	80	0.5
17	Ag	100.4	-	97.9	1.3	590	8000	30	1	4100	0.1	0.2	-	0.3	-	4	4	-	1	-	10	1
18*	Ag	100.3	-	98.6	1.0	1000	2800	240	3	2700	0.1	0.2	0.1	0.3	-	4	3	-	1	-	70	0.9
19	Ag	100.1	-	98.7	0.9	420	3500	30	2	980	0.1	0.3	0.1	-	-	3	4	-	1	-	85	0.1
20	Ag	100.1	-	98.7	1.0	370	2900	150	1	1200	-	0.3	0.1	-	-	0.7	-	-	1	-	25	0.3
21	Ag	100.3	-	97.2	2.0	140	7500	110	2	2900	-	0.3	-	1	2	10	-	-	2	-	20	0.7
22	Ag	100.3	-	96.3	2.6	680	10000	50	4	3300	-	0.3	-	2	4	20	-	-	2	-	20	0.8
23	Ag	100.9	-	97.1	2.3	1300	4200	80	3	8500	-	0.6	-	2	2	10	-	-	3	-	20	0.6
24	Ag	101.9	-	95.8	2.7	1000	14100	70	2	19000	-	0.9	-	3	9	50	-	-	2	-	15	1
25	Ag	101.2	-	96.9	2.1	1800	8100	30	4	12400	-	0.3	-	3	9	35	-	-	2	-	8	0.3
26	Ag	101.2	2.6	96.9	2.3	1200	6900	590	-	12000	0.1	0.2	0.1	-	-	8	-	-	2	-	6	1
27	Ag	101.1	-	96.2	3.7	30	900	15	6	10800	-	-	0.1	6	30	290	-	-	3	-	-	0.9
28	Ag	100.6	-	98.9	0.8	1100	2100	15	2	5800	-	0.2	0.1	-	-	1	5	-	0.9	-	-	0.6
29	Ag	100.3	-	98.6	0.9	980	3900	120	3	3100	-	0.2	0.1	0.1	-	2	4	-	1	-	-	3
30**	Ag	100.7	-	98.7	0.6	350	6600	30	8	7400	0.2	0.2	0.2	0.9	1	2	6	-	0.7	0.1	95	0.5
30 (Repeat)	Ag	100.2	-	99.5	0.2	300	2000	200	5	1900	-	0.2	-	0.5	0.6	1	0.2	-	0.4	-	15	0.3
31	Ag	100.8	-	97.6	1.6	890	7300	140	3	8000	-	0.3	-	0.3	-	2	-	-	2	-	15	0.9
32	Ag	101.1	-	96.2	2.9	890	7500	130	1	11300	0.1	0.3	0.1	0.2	-	2	-	1	3	-	30	2
33	Ag	100.4	-	98.4	1.1	1200	3900	140	15	4400	0.4	0.3	0.1	0.5	-	1	7	-	1	-	6	0.1
33 (Repeat)	Ag	100.3	-	98.5	1.2	930	2400	25	6	2500	0.1	0.2	-	-	-	1	0.8	-	1	-	15	0.1
34	Ag	100.9	-	95.6	4.0	690	3100	150	1	8800	0.2	0.2	0.1	2	1	8	-	2	3	-	9	0.9

Cat. Nr.	Material > 10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe %	Pt ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Pd ppm	In ppm	Hg ppm	Tl ppm
35	Ag	100.7	-	95.7	3.8	240	5400	190	40	7400	-	-	0.3	4	5	30	-	-	3	0.2	-	0.7
36	Ag	100.9	-	96.3	3.1	520	5400	180	200	8800	-	0.2	0.5	6	10	85	-	-	2	0.9	6	0.1
37	Ag	100.4	-	96.4	2.9	630	5700	340	15	4000	-	0.2	0.1	6	6	30	-	2	2	-	-	2
38	Ag	100.6	-	96.4	2.5	620	9600	180	5	6100	-	0.3	-	3	4	30	-	-	2	-	9	-
39	Ag	100.4	-	96.1	2.9	970	9200	140	2	4400	-	0.2	0.1	-	-	1	-	-	2	-	9	0.2
40a	Ag	101.0	-	98.4	0.5	35	10600	180	20	10300	-	-	-	0.3	7	10	-	-	0.5	0.3	-	0.1
40b	Ag	100.4	1.5	96.1	3.4	3000	1400	500	80	3800	-	0.2	-	0.3	5	20	-	-	3	0.4	-	0.1
40c	Ag	100.2	-	96.2	3.3	2700	1700	210	50	2000	-	0.4	0.4	2	6	20	-	-	3	0.5	-	0.1
41	Ag	103.7	-	98.1	0.4	9	14500	30	2	37200	0.2	0.2	0.1	0.8	3	15	5	-	0.5	0.1	80	3
42	Ag	100.3	-	98.8	0.1	110	9900	270	8	3200	0.1	-	0.3	0.5	2	3	75	-	-	-	55	0.5
43	Ag	103.6	-	95.6	0.1	15	42100	230	2	36000	-	-	0.1	0.3	20	4	3	-	-	0.1	85	2
44	Ag	100.0	-	99.4	0.1	25	4300	110	4	400	-	-	0.2	0.6	1	2	-	-	-	-	20	0.9
45	Ag	102.8	-	97.6	0.1	7	22300	170	8	28200	-	-	0.6	0.5	2	2	-	-	0.2	0.1	30	2
46	Ag	102.4	-	97.0	0.3	160	27800	80	-	26300	-	0.3	0.1	-	3	230	-	-	0.7	-	40	2
46 (Repeat)**	Ag	103.1	-	96.6	0.3	140	30700	50	-	30900	-	0.2	-	-	5	290	0.2	-	0.7	-	10	1
47	Ag-Pb-Bi	100	-	66	0.4	670	0.15	130	3	0.19	-	0.5	0.1	0.5	2	140	-	1	1	-	6	3
48	Ag	100.3	-	96.8	1.7	110	15000	6	3	3500	0.1	-	0.1	-	-	1	-	-	1	-	-	1
49**	Ag	100.9	-	98.8	0.9	630	2000	170	3	9400	-	-	0.3	6	-	5	4	-	0.8	-	5	0.2
50a	Ag	100.9	1.8	95.4	3.7	2200	5600	670	20	9200	-	0.1	0.1	1	5	95	-	1	3	0.1	-	0.1
50b	Ag	100.6	-	95.3	3.7	8700	600	460	540	5100	-	1.9	0.2	2	5	20	-	-	3	2	-	0.1
50c	Ag	100.2	-	98.0	1.5	550	3700	110	2	2000	-	0.2	0.2	0.9	2	7	-	-	1	-	-	0.9
51*	Ag	100.9	-	97.6	2.2	1900	490	80	390	8100	0.5	0.6	0.8	2	17	10	-	-	2	1	50	0.3
52	Ag	100.9	10.1	95.6	3.4	3700	2600	3800	2000	6800	0.5	0.3	0.7	4	26	55	-	-	3	7	4	0.7
53	Ag	100.1	-	97.6	2.0	2200	1700	40	1	670	0.4	0.6	-	0.5	-	0.4	-	-	2	-	-	-
54	Ag	100.1	-	98.0	1.6	970	3400	250	1	820	0.4	0.3	-	-	-	0.3	-	-	1	-	4	-
55*	Ag	100.1	-	98.0	1.7	1400	1400	9	35	1100	0.3	0.3	-	-	-	0.5	-	-	1	0.1	-	-
56	Ag	100.3	-	96.4	3.0	1100	4800	140	4	3400	0.4	0.2	-	0.9	2	35	-	-	2	-	20	0.1
57	Ag	100.4	-	96.5	3.1	1300	3000	9	9	3500	0.7	0.2	-	7	16	25	-	-	2	-	45	0.1
58	Ag	100.0	-	98.7	1.0	510	2800	40	-	430	-	0.2	-	-	-	0.2	-	-	0.7	-	10	-
59	Ag	100.0	-	96.1	3.4	1700	3600	70	-	430	0.6	0.5	-	0.2	-	0.3	-	-	3	-	75	-
60	Ag	100.4	-	96.5	3.1	2500	1200	20	6	4100	0.7	0.7	-	3	6	50	-	-	3	-	90	0.1
61	Ag	100.2	-	96.6	2.8	5500	390	-	1	2100	0.6	1.3	-	0.2	-	0.4	-	-	3	-	160	-
61 (Repeat)	Ag	100.1	-	97.7	1.8	4000	400	1	2	1500	-	1.3	-	-	-	0.5	-	-	2	-	60	-
62a	Ag	100.5	-	96.9	2.9	1800	260	10	15	5000	-	0.5	0.2	2	0.5	2	-	-	1	-	25	0.2
62b	Ag	100.3	-	95.9	3.9	1500	1200	130	180	2400	-	0.2	0.3	3	2	9	0.6	-	1	0.6	25	0.1

Cat. Nr.	Material > 10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe %	Pt ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Pd ppm	In ppm	Hg ppm	Tl ppm
63a*	Ag-Cu	100.4	-	81.8	18.0	2100	470	55	480	3300	0.2	0.4	1	30	160	160	3	-	6	7	100	-
63b	Ag	100.6	9.9	89.6	9.1	1500	1700	10000	470	5900	0.1	0.5	2	45	60	30	8	-	3	2	95	2
63c	Ag-Cu	100.8	10.3	87.5	10.8	1900	2000	12500	560	6900	0.1	0.5	2	50	70	40	10	-	4	2	120	2
64	Ag	100.4	6.9	97.3	2.2	3100	370	1600	590	3700	-	0.4	0.1	2	5	8	-	-	2	2	-	2
65	Ag	100.4	4.1	96.9	2.6	3600	330	1100	230	4000	-	1	0.1	2	4	4	-	-	2	0.8	-	5
66	Ag	100.5	7.0	96.8	2.8	1300	840	2100	460	4100	-	0.3	0.1	4	10	20	-	-	2	2	-	25
67	Ag	100.4	9.7	97.1	2.4	2400	230	2600	300	4000	-	0.5	0.1	2	6	8	-	-	2	1	-	2
68	Ag	101.5	18.3	96.4	2.3	4700	3400	5100	3100	11400	0.6	0.5	0.1	0.5	10	180	-	-	2	10	70	0.8
69	Ag	100.4	4.5	95.3	4.2	2700	260	2000	220	4200	-	0.8	0.5	35	15	8	-	-	1	0.8	25	2
70	Ag	100.3	3.0	96.5	3.2	1800	600	970	690	2500	-	0.9	0.3	7	8	7	-	-	1	2	65	8
71	Ag	100.7	4.8	96.0	3.6	2500	330	1800	160	7100	-	0.8	0.8	20	15	6	-	-	1	0.6	30	5
72	Ag	100.5	9.9	95.5	3.8	2000	220	4200	290	4400	-	0.5	0.8	20	20	10	-	-	1	1	100	2
73	Ag	100.2	15.8	97.2	2.1	2300	110	4000	90	2000	-	0.5	0.3	7	5	3	-	-	0.9	0.3	30	0.6
74	Ag	100.1	-	98.7	1.3	250	70	40	2	1200	0.1	0.1	0.4	2	2	0.5	8	-	1	-	25	0.5
75	Ag	100.5	-	95.5	4.1	1100	2200	140	340	4300	-	0.3	0.3	3	5	25	5	-	3	1	30	0.6
76*	Ag	100.2	-	98.8	1.2	240	320	35	150	2000	-	-	0.3	4	7	5	5	-	0.8	0.5	15	3
77*	Ag	100.7	-	96.1	3.8	70	780	4	15	7100	0.5	-	-	0.9	-	4	-	-	3	-	200	1
78	Ag	100.6	-	92.8	6.9	1200	1600	60	95	6000	0.5	0.3	-	0.9	4	15	-	-	5	0.3	120	6
79	Ag	100.7	-	97.2	2.7	250	1200	60	490	5900	0.9	-	-	1	2	250	-	-	2	2	50	7
80	Ag	100.6	-	95.7	4.1	840	1000	60	90	6100	-	0.2	0.1	2	3	10	2	-	3	0.3	60	3
81*	Ag	100.2	-	93.5	6.5	25	410	30	1	2400	-	-	-	32	3	50	-	-	4	-	100	0.6
82*	Ag	100.4	-	96.5	3.3	630	550	110	110	4000	-	0.2	0.1	2	7	7	2	-	2	0.4	110	2
83	Ag	100.2	-	95.8	3.9	960	1700	370	180	1900	-	0.3	3	6	6	10	2	-	3	0.7	80	1
84*	Ag	100.2	-	95.3	4.6	450	320	130	150	2300	-	0.1	0.3	4	4	15	4	-	3	0.5	170	2
85*	Ag	100.5	2.2	93.4	6.1	1100	1900	1400	1100	4100	-	0.4	2	15	30	45	3	-	4	4	150	2
86	Ag	100.0	-	97.7	1.7	2100	3900	10	1	420	-	0.9	-	15	0.9	6	1	-	2	-	9	85
87	Ag	100.0	-	98.1	1.3	2800	2600	240	-	150	-	1.4	-	2	2	2	2	-	1	-	15	85
88	Ag	100.3	-	94.5	5.4	25	420	2	-	2800	-	0.1	-	30	75	15	2	-	3	-	10	6
89	Ag	100.0	-	97.9	1.5	2700	3100	60	-	290	-	1.7	-	0.3	-	1	3	-	2	-	9	55
90	Ag	100.1	-	97.8	2.1	890	160	240	-	840	-	0.3	-	4	-	20	0.2	-	1	0.4	8	3
91	Ag	100.0	4.7	97.7	1.7	2100	2700	840	-	470	-	0.8	-	-	-	0.8	4	-	1	-	7	140
92	Ag	100.2	-	95.9	4.1	-	25	6	-	2200	-	-	-	20	30	4	2	-	2	-	5	35
93	Ag	100.5	-	97.1	2.8	7	140	100	-	5400	-	-	-	50	30	20	4	-	1	-	9	15
94	Ag	100.2	-	97.9	2.1	1	30	2	-	2200	-	-	-	15	80	5	0.8	-	1	-	6	8
95	Ag	100.3	-	95.8	4.1	7	540	1	-	2800	0.1	-	-	15	10	25	3	-	2	-	10	1
96	Ag	100.2	15.1	97.8	1.7	290	1200	3100	2	1500	0.1	0	-	1	2	1	3	-	0.9	-	10	1
97	Ag	100.2	-	97.8	2.0	930	1100	370	370	2000	-	0.4	0.1	2	3	9	3	-	1	1	10	5

Cat. Nr.	Material > 10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe %	Pt ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Pd ppm	In ppm	Hg ppm	Tl ppm
98	Ag	100.4	-	97.9	1.9	970	400	620	400	3200	-	0.2	-	1	3	10	3	-	1	1	15	6
99	Ag	100.1	-	96.1	3.6	1200	1600	150	15	980	-	0.1	-	9	0.8	185	2	-	2	-	15	0.2
100	Ag	100.5	-	97.7	2.1	1000	700	440	1300	3300	-	0.3	0.1	1	2	8	0.8	-	1	5	9	5
101	Ag	100.6	4.7	96.1	3.6	460	1100	1800	190	5900	-	0.1	0.3	6	5	120	2	-	2	1	10	7
102	Ag	100.5	18	97.2	2.2	450	1100	4800	210	4300	-	0.1	0.2	3	6	45	2	-	1	2	10	4
103	Ag	100.2	33	99.0	0.6	350	680	3100	150	1500	0.1	0.2	0.1	3	3	65	2	0.8	0.5	1	6	2
104	Ag	100.3	3.5	97.7	2.1	770	520	760	680	2700	-	0.2	0.1	5	4	20	2	-	1	2	10	6
105	Ag	100.3	-	97.3	2.7	55	150	70	2	2900	0.1	-	-	3	-	10	4	-	1	-	25	6
106	Ag	100.3	1.8	96.9	3.0	10	270	540	1	3200	0.3	-	-	3	0.9	45	4	-	1	-	20	6
107	Ag	100.4	-	95.4	4.6	2	70	2	1	3700	-	-	-	3	-	10	3	-	2	-	20	5
108	Ag	100.2	-	96.9	3.1	16	200	5	3	1700	-	-	-	10	130	4	5	-	1	-	15	3
109	Ag	100.1	-	98.2	1.8	4	20	1	1	1100	-	-	-	0.8	0.6	0.9	3	-	0.9	-	10	3
110	Ag	100.3	-	97.8	2.1	2	130	3	1	3100	-	-	-	5	-	1	1	-	1	-	10	2
111	Ag	100.1	-	98.4	1.6	2	50	5	20	1300	-	0.1	-	2	2	1	2	-	0.8	0.1	10	4
112	Ag	100.2	-	98.2	1.8	3	100	9	-	2000	-	-	-	3	120	7	1	-	0.9	-	15	4
113	Ag	100.3	9.5	98.3	1.4	760	600	1400	710	2600	0.1	0.3	0.1	2	3	6	2	-	1	2	9	7
114a	Ag	100.5	2.9	96.7	2.9	2900	540	850	1300	3700	-	0.8	2	7	10	20	0.2	-	2	5	25	0.1
114a (Repeat)	Ag	101.0	-	95.4	4.2	2600	650	280	3000	6600	-	0.7	1	6	20	35	-	-	3	10	-	0.1
114b	Ag	101.8	-	97.0	2.8	1500	690	50	20	18200	-	0.4	0.8	5	6	15	-	-	2	0.1	-	0.3
114c	Ag	101.5	-	95.7	3.4	1300	7500	90	15	14500	-	0.2	0.1	1	15	15	-	0.8	-	0.2	-	1
114d	Ag	100.1	-	99.8	0.1	170	1000	25	2	1200	-	-	-	-	1	0.5	-	-	0.2	-	-	0.1
115	Ag	100.8	-	96.6	2.9	3500	900	390	710	7500	-	0.6	0.3	2	10	10	-	-	2	3	-	0.3
116	Ag	100.4	21.5	98.6	0.9	1900	860	2400	130	4200	-	0.5	0.2	1	8	9	3	3	1	0.5	40	0.3
118	Ag	100.4	1.8	98.0	1.5	3200	1100	270	560	3400	-	0.7	0.5	3	15	10	1	-	2	2	-	0.1
119	Ag	100.8	4.1	96.6	2.9	2200	1600	1300	2700	5600	-	0.4	2	8	15	20	5	-	3	9	-	0.1
120	Ag	100.7	2.8	93.9	5.5	3600	700	1600	1200	5500	-	0.7	2	10	30	40	5	-	4	4	-	0.1
121	Ag	100.5	1.3	96.3	3.2	2200	1700	440	550	4800	-	0.4	0.7	4	25	10	4	-	3	2	-	0.2
123	Ag	100.5	8.1	97.9	1.5	4100	750	1300	1200	3800	-	0.4	0.4	0.5	9	30	-	-	2	4	-	0.3
124	Ag	100.6	-	89.8	9.9	660	2000	4	35	5600	0.8	0.2	-	4	4	40	-	-	6	0.1	55	1
125	Ag-Cu	100.4	-	89.5	10.3	1200	1200	2	1	3600	0.8	0.3	-	0.5	-	3	-	-	7	-	120	0.2
126	Ag-Cu	100.2	-	88.6	10.6	2500	5300	1	2	2100	0.7	0.6	-	0.6	-	7	-	-	7	-	130	-
127	Ag	100.2	-	93.0	6.3	2600	4400	25	55	2200	0.7	0.6	-	0.3	1	5	-	-	5	0.2	180	0.1
128	Ag	100.1	-	97.3	2.4	980	1600	15	2	600	-	0.2	-	-	-	0.9	-	-	2	-	-	1
129	Ag	100.2	3.0	98.0	1.8	900	930	550	190	2100	-	0.2	-	0.3	-	6	2	6	1	0.6	-	0.2
131	Ag	103.1	35.2	93.4	3.4	8200	5900	18200	7000	23900	-	1.6	0.2	2	35	110	20	1	3	25	-	3
132	Ag	100.3	-	95.3	4.5	1200	1600	130	45	2900	-	0.3	-	0.5	2	8	-	-	3	0.1	-	0.6

Cat. Nr.	Material > 10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe %	Pt ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Pd ppm	In ppm	Hg ppm	Tl ppm
133	Ag	100.3	-	96.3	3.7	6	180	1	2	2500	-	-	-	5	6	3	-	-	2	0	-	5
134	Ag-Cu	100.7	-	89.0	10.1	3000	5900	3	2	6900	0.7	0.6	-	0.3	0.8	9	-	-	7	-	300	1
135	Ag-Cu	101.1	-	88.5	10.8	3700	3000	160	750	9800	0.7	0.7	-	10	55	70	-	-	8	3	200	0.7
137	Ag	100.3	-	97.4	2.4	1100	680	330	60	2700	-	0.4	-	0.7	2	4	-	-	2	0.2	-	2
138	Ag	100.3	6.2	97.8	1.9	1000	350	1300	380	2500	-	0.3	-	2	6	10	-	-	2	1	-	45
139	Ag	100.3	-	97.1	2.7	1200	430	230	530	2900	-	0.4	-	2	10	7	-	-	2	2	-	0.9
140	Ag	100.3	12.2	97.2	2.3	700	570	3200	470	2700	-	0.3	0.1	3	10	10	-	-	2	2	-	5
141	Ag	101.2	10.2	96.3	3.2	1400	880	3600	2500	9200	-	0.4	0.2	4	10	50	-	-	3	10	-	10
142	Ag	100.9	7.0	93.5	5.8	1800	870	4400	1400	7400	-	0.7	0.8	15	25	50	-	-	4	6	-	15
143	Ag	100.9	28.4	96.4	2.5	740	330	10000	2200	6100	-	0.3	0.5	2	20	380	-	-	1	15	40	45
144	Ag-Cu	101.0	18.4	78.8	17.2	940	150	38800	740	7800	-	0.2	4	120	65	1200	-	-	4	4	20	6
145	Ag-Cu	100.9	17.7	85.0	12.3	500	800	26300	120	8500	0.1	0.5	0.3	1	6	200	9	-	4	6	10	6
146***	Ag-Cu	103.1	12.9	67.8	27.8	1600	1100	41100	5600	23900	-	0.5	2	3	100	1600	10	5	8	60	10	110
146 (Repeat)	Ag-Cu	101.6	7.3	74.3	23.7	660	480	18800	3000	12100	-	0.3	0.8	2	130	860	9	4	10	35	5	75
147	Ag-Cu	102.2	11.7	73.5	23.2	830	680	30700	4800	16500	-	0.4	1	4	70	960	6	3	6	30	10	95
148	Ag-Cu	101.4	17.9	61.0	32.0	600	320	69600	3400	8500	-	0.2	15	170	220	2400	3	-	9	15	7	20
149*	Ag-Cu	100.7	13.9	77.8	19.0	640	270	30600	1200	4900	-	0.2	8	80	135	540	2	-	5	8	5	15
150*	Ag-Cu	101.0	15.4	68.6	26.5	630	200	48200	2600	7100	-	0.2	15	110	180	580	3	-	7	15	5	9
151*	Ag-Cu	100.9	15.4	74.4	21.6	450	240	39400	2800	6100	-	0.2	15	80	160	450	3	-	6	15	-	9
152*	Ag-Cu	100.8	11.8	75.9	21.2	490	210	28500	2300	5000	-	0.2	10	90	140	450	2	-	6	10	-	8
153*	Ag-Cu	101.2	19.7	66.0	27.2	370	250	66700	1700	8600	0.2	0.1	10	140	240	1300	6	8	9	15	15	9
154*	Ag-Cu	101.0	18.9	62.9	30.0	400	440	69900	2600	6500	0.2	0.1	10	130	200	950	4	5	10	15	15	10
155	Sn	100	3.0	-	6.7	-	4	2000	0.88	0.03	-	-	10	30	20	45	-	1	4	2300	-	0.7
156	Sn-Pb	100	-	-	0.4	10	20	-	0.68	0.32	-	-	20	50	20	130	-	-	-	4200	-	1
157	Sn-Pb	100	-	-	0.1	10	20	-	0.84	0.16	-	-	20	45	20	220	-	-	-	3400	-	2
158	Sn-Pb	100	-	-	0.1	20	20	-	0.87	0.13	-	-	25	50	20	100	-	-	-	4200	-	1

Table 1 *The coins analyzed by ns-LA-ICP-QMS. The "-" means below the detection limit: < 0.1 % (Ag, Fe), < 5 ppm (Hg), < 1 ppm (Au, Bi, Zn, Sn, Pb), < 0.8 ppm (Cd), < 0.3 ppm (Pd), and < 0.1 ppm (Co, Ni, As, Sb, Se, In, Pt, Tl). Catalogue number 117, 122, 113d, 130, and 136 could not be quantified due to high levels of corrosion. lack of metal. or a poor signal.*

** Poor signal; ** Heterogeneous; *** Identifiable layer or coating.*

Italic / underlined values indicate that pXRF results were used for the major elements instead of the results from mass spectrometry due to unusual or unexpected alloys and the poor calibration of certain elements in higher quantities. These pXRF analyses are normalized to 100 percent.

The zinc to copper-zinc percentage, which emulates the zinc content of 'theoretical' brass, was only calculated when zinc contents were above 500 ppm.

Cat.Nr.	Material >10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe %	Pt ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Pd ppm	In ppm	Hg ppm	Tl ppm
160	Ag	100.8	3.8	91.9	7.1	6300	500	2900	1400	6300	-	1	0.6	5	15	30	3	-	3	5	90	0.1
161*	Ag	100.7	6.2	92.8	6.3	4100	660	4100	1500	5300	-	0.8	0.9	9	25	30	0.6	-	2	5	140	0.4
162a	Ag	100.8	19.9	87.5	9.8	2500	800	24300	2000	5700	-	0.4	0.5	7	65	70	-	-	3	7	45	1
162a* (Repeat)	Ag-Cu	100.6	16.9	83.6	13.4	2100	580	27200	1700	4500	-	0.4	3	35	90	55	0.8	-	7	7	30	1
162b	Ag-Cu	100.6	12.8	86.1	11.8	3000	460	17400	2400	3600	0.2	0.5	3	35	90	45	7	-	8	9	20	0.3
163a	Ag	100.5	27.2	96.9	2.1	2700	350	7700	1900	3400	-	0.4	0.3	2	15	25	6	-	1	7	12	0.1
163b	Ag	100.4	18.2	96.7	2.5	2400	320	5500	1200	2700	-	0.4	0.1	2	10	20	4	-	2	4	20	0.2
164	Ag-Cu	106.0	1.1	62.0	37.1	2600	360	4200	45400	11800	0.1	1	3	30	1600	940	10	-	10	151	20	0.6
165b	Ag	100.9	11.1	95.2	4.1	2300	220	3800	2600	4800	-	0.6	0.5	3	60	120	3	-	3	9	470	0.4
165b (Repeat)	Ag	100.8	8.4	93.0	5.9	2400	270	7400	3100	5400	0.1	0.6	2	7	100	140	2	-	3	10	120	0.7
166	Ag-Cu	102.7	28.6	70.5	21.0	1400	230	83800	14300	12000	0.1	0.4	55	45	760	240	9	-	15	50	20	1
167a	Ag	100.4	1.7	92.8	6.3	3000	5000	1100	480	3700	-	0.6	6	10	5	8	-	-	2	2	130	0.2
167a (Repeat)	Ag	100.4	2.0	93.4	5.7	3200	4800	1100	480	3600	-	0.6	5	8	4	8	-	-	2	2	110	0.3
167c	Ag	100.1	0.4	91.8	7.2	3500	5600	1300	520	4100	-	0.7	6	10	7	9	-	-	3	2	120	0.3
168	Ag	100.4	3.0	97.1	2.4	4100	210	750	950	3300	-	0.5	0.3	5	25	60	1	-	2	3	40	0.2
169	Ag-Cu	101.6	10.6	82.8	15.3	590	670	18100	1200	13400	0.2	0.3	3	40	370	840	6	-	9	25	-	5
169 (Repeat)	Ag-Cu	100.9	3.8	83.0	16.2	480	560	6400	1200	6800	0.1	0.2	0.9	15	60	670	2	-	8	25	50	5
170	Ag	100.1	-	99.6	0.2	320	1300	340	3	550	0.1	0.1	0.1	0.3	-	0.6	4	-	0.3	-	-	-
170 (Repeat)	Ag	100.1	-	99.5	0.3	730	1200	110	7	610	-	0.3	-	-	-	0.8	-	-	0.8	-	90	-
171	Ag	100.1	-	99.0	0.9	1200	490	65	40	600	-	0.4	-	0.1	-	0.4	4	-	0.9	0.1	-	0.1
171 (Repeat)	Ag	100.1	-	98.5	1.3	1300	960	270	70	1100	-	0.4	-	-	-	0.5	-	-	1	0.2	55	0.1
172	Ag	100.2	-	95.7	3.7	2800	2500	120	75	1900	-	0.4	2	3	-	5	0.6	-	1	0.3	85	0.1
180	Ag	100.5	0.2	96.7	2.8	4200	160	520	190	4900	-	1	0.3	2	5	7	9	-	3	0.7	6	0.3
187	Ag	101.0	9.3	96.1	3.4	1700	630	3500	250	9400	-	0.3	1	3	35	45	-	-	3	1	10	0.7

***Table 2** The silver objects analyzed by ns-LA-ICP-QMS. The “-” means below the detection limit: < 0.1 % (Ag, Fe), < 0.01 % (Cu), < 5 ppm (Hg), < 1 ppm (Au, Bi, Zn, Sn, Pb), < 0.8 ppm (Cd), < 0.3 ppm (Pd), and < 0.1 ppm (Co, Ni, As, Sb, Se, In, Pt, Tl).*

*The zinc to copper-zinc percentage was only calculated when zinc was above 500 ppm. Analyses 159, 166a, 167a, and 173 could not be quantified due to high levels of corrosion, lack of metal, or a poor signal. * Poor signal.*

Cat.Nr.	Material >10%	Total %	Zn/(Cu+Zn) %	Ag %	Cu %	Au ppm	Bi ppm	Zn ppm	Sn ppm	Pb ppm	Fe ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Cd ppm	Te ppm	Hg ppm
174	Ag	93.1	3.3	84.7	6.8	4140	1600	2370	2840	8500	180	2	25	220	60	75	15	65	-
175	Ag	91.9	-	85.6	6.0	7160	110	310	1280	1300	70	0.3	4	80	20	8	10	60	-
176	Ag	94.4	4.3	86.6	6.5	3550	780	2910	1310	8400	30	1	10	150	150	-	10	65	10
177	Ag	95.1	-	91.4	2.8	2580	10	830	3	6900	15	0.9	30	1	-	-	10	50	-
178	Ag	98.1	-	92.1	5.1	1600	4540	660	85	3800	130	1	3	15	10	230	10	70	-
179	Ag	96.9	-	90.9	5.8	8700	130	120	60	2200	40	0.3	0.2	3	1	-	20	65	-
180	Ag	95.8	-	91.0	4.2	3530	140	330	110	5200	50	0.1	2	15	5	7	10	70	-
181	Ag	97.7	0.9	90.0	6.7	4160	550	640	690	8300	70	0.3	5	60	55	7	10	75	-
182	Ag	96.7	1.1	87.3	7.2	5030	960	810	8610	11900	110	1	6	100	20	-	15	60	30
183	Ag	98.3	-	89.3	7.5	2620	6340	110	40	8900	110	5	3	150	480	25	10	70	-
184	Ag	99.0	1.5	88.2	8.0	2640	1000	1260	7230	18500	35	2	15	130	20	45	10	60	15
185	Ag	98.6	-	91.7	5.2	1730	6630	1240	360	8000	40	0.5	7	30	20	5	10	90	-
186	Ag	93.4	3.7	85.8	6.0	2570	4410	2330	1460	7600	50	1	15	100	35	-	15	170	-
187	Ag	98.7	-	90.2	6.8	2020	660	4440	230	11800	140	1	15	290	80	1	10	60	-
188	Ag	98.7	0.3	91.6	5.8	2030	2430	200	2330	9100	25	0.7	9	85	15	-	15	65	9
189	Ag	98.1	1.7	89.7	6.7	2370	5530	1140	630	9600	160	1	9	110	135	5	10	75	-
190	Ag	97.6	-	91.3	5.3	2930	520	1210	330	7300	45	0.1	5	30	10	20	10	60	-

Table 3 *Elemental analysis of ingots and hacksilver objects determined by single-collector ICP-MS at the Deutsches Bergbau-Museum Bochum. The "-" means below the detection limit: < 1 ppm (Sb, Se, Hg). The zinc to copper-zinc percentage was only calculated when zinc was above 500 ppm.*

Cat.Nr.	Material	Total %	Zn/(Cu+Zn) %	Ag %	Ag ppm	Cu %	Au ppm	Bi ppm	Zn %	Sn %	Pb %	Fe ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Te ppm	Hg ppm
191	Ag-Cu-Zn	94.1	19.3	33.2		44.4	1500	230	10.6	1	4.8	1200	5	130	60	170	6	20	-
192	Cu-Sn-Pb	95.8	0.4		400	68.4	30	10	0.3	16	11	340	6	90	600	360	35	10	-
193	Cu-Pb-Zn	89.2	8.2		11	72.6	25	10	6.5	0.1	10	500	100	3100	150	250	1	-	-
194	Ag-Cu-Zn	93.9	18.3	54.5		25.9	1400	110	5.8	1.8	5.8	560	8	60	1300	120	3	30	-
195	Cu-Pb-Zn	98.8	10.8		62	65.8	4	6	8.0	0.02	24.5	5400	4	20	600	70	40	-	-

Table 4 *Elemental analysis of copper and copper / silver alloys determined by single-collector ICP-MS at the Deutsches Bergbau-Museum Bochum. The "-" means below the detection limit: < 1 ppm (Te, Hg). Cd not measured.*

Cat.Nr.	Material	Total %	Pb %	Sn ppm	Ag ppm	Cu ppm	Bi ppm	Zn ppm	P ppm	Fe ppm	Co ppm	Ni ppm	As ppm	Sb ppm	Se ppm	Te ppm
196	Pb	97.5	97.2	1	90	55	15	6	2400	55	-	5	2	35	-	-
197	Pb	100.0	99.9	-	70	140	15	1	790	35	-	-	1	75	-	-
198	Pb	99.9	99.9	3	25	90	20	10	140	25	0.7	2	3	130	-	-
199	Pb-Sn	100	65	35%	45	440	10	110	4600	400	0.5	-	2	8	-	-
200	Pb	100.0	99.9	8	2	190	15	55	10	5	0.2	-	2	400	-	-
201	Pb	98.4	97.7	15	4700	430	25	40	1500	170	0.8	-	2	110	4	1
202	Sn-Pb	100	28	68%	30	440	150	34000	130	230	2	10	35	600	-	15
203	Pb	93.8	93.8	130	890	1700	20	450	610	65	3	9	3	660	9	55
204	Pb-Sn	100	74.7	25%	200	600	20	230	90	230	0.7	6	2	230	-	25
205	Pb	92.0	92.0	130	450	210	15	50	920	140	1	9	1	150	6	20
206	Pb	98.7	98.7	20	85	220	15	50	1100	60	0.8	5	-	120	-	55
207	Pb-Sn	100	85	12%	670	860	15	30	810	420	0.3	-	8	140	15	15
208	Pb	100.5	101.0	6	120	380	15	15	100	25	0.3	6	3	210	-	30
209	Pb	96.8	96.8	30	65	110	15	20	480	60	0.5	6	-	650	-	40
210	Pb	98.2	98.0	480	220	1100	20	50	3100	270	0.3	5	2	240	10	20
211	Pb	96.2	96.0	15	60	780	15	55	360	30	0.2	9	-	300	5	15
212	Pb	96.1	96.1	10	35	640	15	15	250	25	0.1	4	-	200	6	10
213	Pb	98.2	98.2	2	95	8600	15	4	1	5	0.2	6	-	160	8	9

Table 5 *Elemental analysis of lead and lead- tin alloys determined by single-collector ICP-MS at the Deutsches Bergbau Museum Bochum. The "-" means below the detection limit: < 4 ppm (Se), < 1 ppm (Sn, Ni, As, Te), < 0.1 ppm (Co).*

Italic / underlined values indicate pXRF results instead of the results from the mass spectrometer due to low analytical totals caused by corrosion and the precipitation of tin hydroxides from the sample solution. The pXRF analyses are normalized to 100 percent.

Na_2O %	K_2O %	CaO %	MgO %	Al_2O_3 %	SiO_2 %	P_2O_5 %	S %	TiO_2 %	Fe_2O_3 %	CuO %	BaO %	PbO %	ZnO %	As	Sb	Sr	Y	Zr	Ag	Cd	Sn	Te	Bi	V	Cr	Co	Ni	Se	Sum %
0.04	0.14	1.36	0.03	0.96	11.2	10.1	-	0.05	0.47	0.01	0.01	62.6	0.02	30	50	45	5	40	25	0.4	9	1	15	190	4	0.4	40	-	87.0

Table 6 *Elemental analysis of the contents from crucible Cat. 247 determined by single-collector ICP-MS at the Deutsches Bergbau-Museum Bochum. In ppm unless otherwise stated. The "-" means below the detection limit: < 0.01 % (S), < 4 ppm (Se).*

	Cat. 248	**Cat. 250**	**Cat. 251**	**Cat. 252**	**Cat. 253**	**Cat. 254**	**Cat. 255**	**Cat. 256**	**Cat. 257**	**Cat. 258**	**Cat. 259**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Na_2O	0.9	0.1	0.5	0.4	0.2	0.4	0.9	0.5	0.4	0.7	0.3
MgO	1.3	0.3	1.5	1.1	0.5	0.9	1.0	1.2	0.5	0.7	0.7
Al_2O_3	3.2	3.1	3.2	2.6	1.5	3.4	3.5	1.5	2.6	2.8	1.7
SiO_2	39.7	42.5	36.7	42.1	65.1	38.6	36.2	45.9	39.1	34.1	52.3
P_2O_5	0.4	0.3	0.3	0.4	0.3	0.3	0.5	0.4	0.3	0.5	0.3
K_2O	2.2	1.2	1.6	1.1	0.7	1.1	2.7	1.5	1.5	2.1	1.0
CaO	7.6	4.7	3.2	9.9	4.0	5.7	5.5	5.0	2.3	4.1	4.8
TiO_2	0.3	0.1	0.3	0. 2	0.1	0.2	0.3	0.2	0.2	0.3	0.2
MnO	3.0	0.2	0.2	8.8	4.6	10.6	1.1	5.0	7.1	0.8	6.3
Fe_2O_3	14.7	6.2	11.9	10.7	32.8	18.3	19.1	10.0	24.0	14.4	9.5
ZnO	0.3	3.2	4.8	3.1	0.1	2.2	0.2	0.7	0.5	0.2	3.6
BaO	0.3	0.9*	0.2	-	-	0.4	0.1	0.4	0.9	0.1	0.2
S	-	-	-	-	0.2	-	-	0.4	0.6	2.7	-
Cu	0.52	0.34	0.14	0.28	0.21	0.33	1.47	1.56	1.87	12.8	1.57
Pb	1.87	13.6	12.8	1.50	1.08	1.09	7.90	0.72	1.11	7.78	5.59

	ppm	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**
Ag	140	370	35	20	55	25	20	50	230	140	160
Sb	970	4300	9600	200	7700	390	900	580	2300	1400	1300
Te	-	-	3	-	-	-	3	-	-	2	9
Bi	50	110	6	7	20	30	10	30	230	15	120
Sn	4	3	40	10	7	-	5	10	3	3	45
Co	15	15	8	30	10	4	80	15	20	90	30
Ni	-	-	-	-	-	-	55	-	-	75	45
As	70	3300	300	100	990	25	45	60	165	70	360
Se	9	-	-	-	-	-	9	15	-	15	15
Sum %	75.9	75.9	77.1	82.1	111.4	83.0	80.1	74.6	82.2	84.0	87.9

Table 7 *Elemental composition of medieval polymetallic (Cu-Pb-Ag) slag samples from the Īlāq region of Uzbekistan determined by single-collector ICP-MS at the Deutsches Bergbau-Museum Bochum.* ***Cat. 250-253*** *come from slag heaps near the mine of Lashkerek and the other samples come from slag heaps in the medieval city of Tunket. The “-” means below the detection limit: < 0.1% (Ba, S), < 15 ppm (Ni), < 4 ppm (Se), < 2 ppm (Sn), < 1 ppm (Te).*

**There is a large discrepancy between the barium oxide contents determined by ICP-MS and by SEM-EDS. The SEM-EDS detected high levels of barium (14%) in slag, but less than one percent was detected by the mass spectrometer. There is no suitable explanation available for this problem.*

	Cat. 260	Cat. 261	Cat. 262	Cat. 263	Cat. 264	Cat. 275	Cat. 277	Cat. 278	Cat. 279	Cat. 281
	%	%	%	%	%	%	%	%	%	%
Na_2O	0.2	-	0.4	-	-	0.1	0.1	-	0.1	-
MgO	2.1	3.2	2.1	3.0	0.2	2.0	0.2	-	-	-
Al_2O_3	1.5	-	2	0.1	2.8	1.4	2.9	0.6	1.4	0.9
SiO_2	53.4	5.8	32.5	16.5	40.9	15.6	35.0	80.9	80.9	97.2
P_2O_5	-	-	-	-	-	-	-	0.3	0.2	0.2
K_2O	0.6	0.1	1.7	0.1	0.9	0.4	0.9	0.1	0.7	0.5
CaO	14.7	13.9	13.0	25.9	0.3	2.8	0.1	-	0.1	-
TiO_2	0.1	-	0.2	-	0.1	0.1	0.1	-	0.1	-
MnO	1.5	2.4	1.5	2.2	0.7	0.1	-	-	0.1	-
Fe_2O_3	6.4	7.1	9.0	7.3	7.4	49.8	29.4	6.51	1.3	0.6
ZnO	0.3	1.1	0.5	1.9	0.3	-	-	0.2	0.9	-
BaO	0.4	0.3	-	0.1	0.2	-	-	-	-	-
S	1.4	2.8	4.7	4.7	4.7	46.1	14.5	3.2	0.8	0.2
Cu	3.4	3.8	7.5	6.8	28.3	0.02	0.01	0.02	0.3	0.3
Pb	0.01	0.2	0.01	0.4	0.2	0.01	0.2	0.8	1.6	0.8

	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Ag	730	525	2100	68	580	-	20	150	1400	620
Sb	5000	7700	7800	11800	690	20	410	330	2400	1900
Te	-	-	-	-	-	-	-	15	2	20
Bi	0.8	-	0.7	-	65	0.4	0.4	7	1	3
Sn	-	10	-	-	-	-	3	8	10	7
Co	15	25	15	40	5	10	8	4	4	1
Ni	-	-	-	-	-	75	-	17	40	-
As	3400	18700	7600	34900	8100	60	243200	62300	310	4400
Se	-	-	-	-	-	6	5	30	55	130
Sum %	86.6	43.0	76.7	73.2	87.6	118.3	107.5	92.8	88.4	100.7

Table 8 *Elemental analysis of mineral specimens from the mine of Lashkerek and from deposits in the Nuratau mountains and the Navoi region of Uzbekistan. The compositions were determined by single-collector ICP-MS at the Deutsches Bergbau-Museum Bochum. Low sums in the ore from Lashkerek are due to carbonates. Carbon was not measured. The very low sum for* ***Cat. 261*** *may be due to incomplete digestion of silica. The "-" means below the detection limit: < 0.1 % (Na, Mg, Al, P, Ca, Ti, Mn, Zn, Ba),<15 ppm (Ni), < 4 ppm (Se), < 2 ppm (Ag. Sn), < 1 ppm (Te), < 0.2 ppm (Bi).*

Appendix D
Lead Isotope Anaylsis

Contents

Cat. Nr.	Material	^{206}Pb /^{204}Pb	2σ	^{207}Pb /^{204}Pb	2σ	^{208}Pb /^{204}Pb	2σ	^{207}Pb /^{206}Pb	2σ	^{208}Pb /^{206}Pb	2σ
1	Ag	**18.298**	0.004	**15.628**	0.005	**38.11**	0.01	**0.8540**	0.0001	**2.0841**	0.0003
2	Ag	**18.388**	0.004	**15.626**	0.004	**38.45**	0.01	**0.8497**	0.0001	**2.0925**	0.0002
3* **	Ag	**18.224**	0.101	**15.542**	0.074	**38.07**	0.15	**0.8528**	0.0007	**2.0904**	0.0033
4* **	Ag	**18.261**	0.061	**15.559**	0.058	**38.20**	0.13	**0.8520**	0.0005	**2.0933**	0.0008
5	Ag	**18.431**	0.005	**15.646**	0.006	**38.58**	0.01	**0.8488**	0.0001	**2.0945**	0.0004
6	Ag	**18.114**	0.004	**15.672**	0.004	**38.31**	0.01	**0.8651**	0.0001	**2.1167**	0.0003
7	Ag	**18.656**	0.005	**15.675**	0.005	**38.77**	0.01	**0.8401**	0.0001	**2.0798**	0.0004
8	Ag	**18.091**	0.004	**15.665**	0.005	**38.28**	0.01	**0.8658**	0.0001	**2.1175**	0.0004
9	Ag	**18.849**	0.007	**15.708**	0.004	**38.99**	0.01	**0.8333**	0.0001	**2.0698**	0.0002
10	Ag	**19.126**	0.009	**15.751**	0.008	**39.52**	0.03	**0.8235**	0.0002	**2.0684**	0.0007
11	Ag	**18.819**	0.017	**15.720**	0.007	**39.18**	0.04	**0.8352**	0.0005	**2.0833**	0.0003
12	Ag	**18.636**	0.005	**15.685**	0.005	**38.78**	0.02	**0.8416**	0.0001	**2.0825**	0.0005
13	Ag	**17.686**	0.012	**15.566**	0.009	**38.02**	0.03	**0.8800**	0.0003	**2.1491**	0.0012
14	Ag	**17.694**	0.008	**15.561**	0.006	**38.01**	0.02	**0.8795**	0.0002	**2.1479**	0.0006
15	Ag	**18.271**	0.005	**15.661**	0.006	**38.60**	0.02	**0.8571**	0.0002	**2.1144**	0.0005
16	Ag	**17.813**	0.004	**15.569**	0.005	**38.03**	0.01	**0.8740**	0.0001	**2.1365**	0.0004
17	Ag	**18.384**	0.004	**15.653**	0.005	**38.49**	0.01	**0.8514**	0.0001	**2.0951**	0.0004
18	Ag	**17.916**	0.007	**15.583**	0.006	**38.10**	0.01	**0.8697**	0.0002	**2.1283**	0.0006
19	Ag	**17.819**	0.006	**15.578**	0.006	**38.07**	0.02	**0.8742**	0.0002	**2.1381**	0.0005
20	Ag	**17.646**	0.004	**15.556**	0.005	**37.94**	0.01	**0.8815**	0.0002	**2.1519**	0.0006
21	Ag	**17.581**	0.005	**15.555**	0.005	**37.90**	0.01	**0.8847**	0.0001	**2.1575**	0.0004
22	Ag	**17.655**	0.007	**15.556**	0.006	**37.94**	0.02	**0.8811**	0.0002	**2.1509**	0.0005
23	Ag	**17.622**	0.008	**15.551**	0.006	**37.91**	0.03	**0.8824**	0.0003	**2.1530**	0.0013
24	Ag	**17.658**	0.006	**15.558**	0.008	**37.93**	0.02	**0.8810**	0.0002	**2.1502**	0.0008
25	Ag	**17.585**	0.093	**15.527**	0.073	**37.71**	0.40	**0.8829**	0.0006	**2.1465**	0.0120
26	Ag	**17.636**	0.006	**15.555**	0.006	**37.93**	0.03	**0.8819**	0.0002	**2.1525**	0.0010
27	Ag	**17.922**	0.007	**15.618**	0.010	**38.12**	0.03	**0.8714**	0.0003	**2.1290**	0.0011
28	Ag	**18.274**	0.007	**15.651**	0.006	**38.53**	0.02	**0.8564**	0.0001	**2.1086**	0.0004
29	Ag	**18.329**	0.015	**15.659**	0.014	**38.48**	0.03	**0.8543**	0.0002	**2.0995**	0.0005
30	Ag	**18.997**	0.009	**15.711**	0.008	**39.31**	0.03	**0.8270**	0.0002	**2.0711**	0.0006
31	Ag	**17.662**	0.011	**15.556**	0.004	**37.95**	0.01	**0.8807**	0.0004	**2.1502**	0.0009
32	Ag	**18.070**	0.004	**15.626**	0.005	**38.39**	0.01	**0.8647**	0.0002	**2.1265**	0.0005
33	Ag	**17.907**	0.006	**15.591**	0.007	**38.16**	0.02	**0.8707**	0.0002	**2.1329**	0.0006
34	Ag	**18.398**	0.005	**15.677**	0.005	**38.72**	0.01	**0.8521**	0.0001	**2.1062**	0.0003
35	Ag	**18.667**	0.006	**15.728**	0.005	**39.05**	0.02	**0.8425**	0.0001	**2.0938**	0.0003
36	Ag	**18.458**	0.005	**15.684**	0.006	**38.74**	0.02	**0.8497**	0.0002	**2.1008**	0.0006
37	Ag	**17.970**	0.005	**15.609**	0.005	**38.28**	0.01	**0.8685**	0.0001	**2.1321**	0.0003
38	Ag	**18.500**	0.005	**15.696**	0.007	**38.82**	0.02	**0.8483**	0.0002	**2.1004**	0.0006
39	Ag	**18.214**	0.005	**15.655**	0.005	**38.52**	0.02	**0.8595**	0.0001	**2.1167**	0.0004
40a	Ag	**18.644**	0.016	**15.707**	0.012	**38.95**	0.03	**0.8425**	0.0003	**2.0894**	0.0007
40c	Ag	**18.521**	0.014	**15.667**	0.012	**38.68**	0.03	**0.8459**	0.0003	**2.0885**	0.0007
41	Ag	**19.165**	0.008	**15.728**	0.012	**39.58**	0.05	**0.8206**	0.0003	**2.0673**	0.0011
42	Ag	**18.776**	0.005	**15.726**	0.005	**39.10**	0.02	**0.8375**	0.0001	**2.0843**	0.0003
43	Ag	**18.796**	0.007	**15.710**	0.009	**39.02**	0.04	**0.8359**	0.0003	**2.0779**	0.0014
44	Ag	**18.747**	0.024	**15.699**	0.015	**39.05**	0.04	**0.8373**	0.0005	**2.0848**	0.0008
45	Ag	**18.649**	0.006	**15.711**	0.008	**38.94**	0.02	**0.8424**	0.0002	**2.0899**	0.0007
46	Ag	**18.927**	0.015	**15.705**	0.026	**39.26**	0.04	**0.8299**	0.0006	**2.0759**	0.0013
47	Ag-Pb-Bi	**18.977**	0.011	**15.716**	0.013	**39.35**	0.04	**0.8281**	0.0004	**2.0753**	0.0013
48	Ag	**18.862**	0.010	**15.744**	0.014	**39.30**	0.05	**0.8347**	0.0004	**2.0856**	0.0014
49	Ag	**17.959**	0.007	**15.593**	0.009	**38.12**	0.03	**0.8682**	0.0003	**2.1248**	0.0008
50a	Ag	**18.523**	0.014	**15.665**	0.012	**38.69**	0.03	**0.8457**	0.0003	**2.0886**	0.0008
50c**	Ag	**18.321**	0.068	**15.639**	0.014	**38.50**	0.07	**0.8536**	0.0025	**2.1025**	0.0054
50d	Ag	**18.395**	0.015	**15.654**	0.015	**38.57**	0.04	**0.8510**	0.0004	**2.0964**	0.0011

Cat. Nr.	**Material**	**^{206}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{204}Pb**	**2σ**	**^{208}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{206}Pb**	**2σ**	**^{208}Pb /^{206}Pb**	**2σ**
51	Ag	**18.762**	0.006	**15.701**	0.006	**38.92**	0.02	**0.8368**	0.0001	**2.0767**	0.0005
52	Ag	**18.548**	0.004	**15.675**	0.005	**38.71**	0.01	**0.8451**	0.0001	**2.0891**	0.0003
53	Ag	**18.679**	0.017	**15.689**	0.014	**38.86**	0.03	**0.8399**	0.0002	**2.0824**	0.0005
54	Ag	**18.764**	0.010	**15.709**	0.010	**39.05**	0.03	**0.8372**	0.0002	**2.0834**	0.0006
55	Ag	**18.814**	0.009	**15.710**	0.008	**39.09**	0.02	**0.8350**	0.0002	**2.0796**	0.0004
56	Ag	**18.480**	0.005	**15.675**	0.005	**38.81**	0.01	**0.8482**	0.0001	**2.1020**	0.0002
57	Ag	**18.489**	0.003	**15.662**	0.003	**38.70**	0.01	**0.8471**	0.0001	**2.0955**	0.0002
58	Ag	**18.630**	0.008	**15.676**	0.007	**38.77**	0.02	**0.8414**	0.0002	**2.0835**	0.0005
59	Ag	**18.291**	0.015	**15.634**	0.012	**38.52**	0.04	**0.8547**	0.0004	**2.1087**	0.0019
60	Ag	**18.598**	0.004	**15.682**	0.004	**38.75**	0.01	**0.8432**	0.0001	**2.0857**	0.0003
61	Ag	**18.652**	0.008	**15.674**	0.008	**38.77**	0.02	**0.8403**	0.0002	**2.0798**	0.0004
62a	Ag	**18.487**	0.014	**15.678**	0.009	**38.64**	0.05	**0.8479**	0.0002	**2.0915**	0.0007
62b	Ag	**18.281**	0.004	**15.628**	0.005	**38.39**	0.01	**0.8548**	0.0001	**2.1013**	0.0003
63a	Ag	**18.660**	0.009	**15.678**	0.006	**38.76**	0.02	**0.8402**	0.0003	**2.0787**	0.0004
63b	Ag	**18.313**	0.004	**15.637**	0.004	**38.38**	0.01	**0.8538**	0.0001	**2.0984**	0.0002
63c	Ag	**18.314**	0.006	**15.635**	0.004	**38.38**	0.01	**0.8537**	0.0002	**2.0983**	0.0004
64	Ag	**18.443**	0.006	**15.632**	0.005	**38.46**	0.01	**0.8475**	0.0002	**2.0851**	0.0004
65	Ag	**18.461**	0.007	**15.632**	0.006	**38.44**	0.02	**0.8467**	0.0002	**2.0820**	0.0006
66	Ag	**18.422**	0.005	**15.629**	0.005	**38.41**	0.01	**0.8483**	0.0001	**2.0851**	0.0003
67	Ag	**18.458**	0.005	**15.631**	0.005	**38.43**	0.01	**0.8468**	0.0002	**2.0819**	0.0005
68	Ag	**18.340**	0.003	**15.640**	0.003	**38.50**	0.01	**0.8527**	0.0001	**2.1003**	0.0002
69	Ag	**18.461**	0.003	**15.640**	0.003	**38.41**	0.01	**0.8471**	0.0001	**2.0822**	0.0002
70	Ag	**18.389**	0.004	**15.632**	0.004	**38.36**	0.01	**0.8500**	0.0001	**2.0872**	0.0002
71	Ag	**18.464**	0.003	**15.642**	0.003	**38.42**	0.01	**0.8471**	0.0001	**2.0821**	0.0003
72	Ag	**18.455**	0.006	**15.639**	0.007	**38.41**	0.02	**0.8474**	0.0002	**2.0825**	0.0005
73	Ag	**18.412**	0.005	**15.630**	0.005	**38.35**	0.01	**0.8489**	0.0001	**2.0845**	0.0004
74	Ag	**18.440**	0.013	**15.627**	0.011	**38.43**	0.03	**0.8474**	0.0002	**2.0842**	0.0004
75	Ag	**18.302**	0.005	**15.634**	0.005	**38.52**	0.01	**0.8542**	0.0001	**2.1046**	0.0003
76	Ag	**18.442**	0.016	**15.640**	0.009	**38.51**	0.03	**0.8480**	0.0003	**2.0884**	0.0007
77	Ag	**18.469**	0.008	**15.638**	0.006	**38.46**	0.02	**0.8466**	0.0002	**2.0839**	0.0004
78	Ag	**18.444**	0.004	**15.645**	0.004	**38.53**	0.01	**0.8482**	0.0001	**2.0902**	0.0002
79	Ag	**18.558**	0.004	**15.644**	0.006	**38.58**	0.02	**0.8429**	0.0002	**2.0801**	0.0005
80	Ag	**18.466**	0.004	**15.648**	0.004	**38.50**	0.01	**0.8474**	0.0001	**2.0862**	0.0003
81	Ag	**18.462**	0.008	**15.633**	0.008	**38.46**	0.02	**0.8467**	0.0001	**2.0844**	0.0004
82	Ag	**18.457**	0.006	**15.639**	0.006	**38.49**	0.02	**0.8473**	0.0001	**2.0864**	0.0004
83	Ag	**18.447**	0.006	**15.652**	0.005	**38.58**	0.01	**0.8485**	0.0001	**2.0927**	0.0003
84	Ag	**18.466**	0.006	**15.641**	0.005	**38.49**	0.01	**0.8470**	0.0001	**2.0858**	0.0004
85	Ag	**18.427**	0.003	**15.654**	0.003	**38.59**	0.01	**0.8495**	0.0001	**2.0956**	0.0002
87	Ag	**18.421**	0.011	**15.638**	0.01	**38.38**	0.03	**0.8489**	0.0003	**2.0837**	0.0007
88*	Ag	**18.543**	0.262	**15.742**	0.219	**38.64**	0.54	**0.8489**	0.0003	**2.0838**	0.0008
89	Ag	**18.413**	0.013	**15.636**	0.012	**38.43**	0.03	**0.8492**	0.0002	**2.0871**	0.0004
90*	Ag	**18.367**	0.181	**15.720**	0.149	**38.44**	0.37	**0.8557**	0.0004	**2.0929**	0.0008
91*	Ag	**18.457**	0.124	**15.677**	0.106	**38.52**	0.25	**0.8492**	0.0002	**2.0870**	0.0005
92	Ag	**18.448**	0.010	**15.630**	0.009	**38.47**	0.02	**0.8472**	0.0002	**2.0851**	0.0005
93	Ag	**18.448**	0.004	**15.630**	0.005	**38.46**	0.01	**0.8472**	0.0002	**2.0849**	0.0006
94	Ag	**18.453**	0.006	**15.632**	0.006	**38.47**	0.02	**0.8471**	0.0002	**2.0849**	0.0005
96	Ag	**18.236**	0.010	**15.612**	0.010	**38.19**	0.03	**0.8560**	0.0003	**2.0938**	0.0008
97	Ag	**18.309**	0.009	**15.621**	0.006	**38.28**	0.02	**0.8531**	0.0002	**2.0906**	0.0004
98	Ag	**18.453**	0.007	**15.632**	0.006	**38.47**	0.02	**0.8471**	0.0001	**2.0849**	0.0003
99*	Ag	**18.353**	0.119	**15.721**	0.100	**38.43**	0.24	**0.8566**	0.0004	**2.0940**	0.0007
100	Ag	**18.349**	0.006	**15.624**	0.006	**38.34**	0.01	**0.8515**	0.0001	**2.0893**	0.0004
101	Ag	**18.274**	0.006	**15.620**	0.005	**38.24**	0.01	**0.8548**	0.0002	**2.0927**	0.0004
102*	Ag	**18.461**	0.452	**15.725**	0.377	**38.56**	0.92	**0.8518**	0.0005	**2.0889**	0.0012

Cat. Nr.	**Material**	**^{206}Pb/^{204}Pb**	**2σ**	**^{207}Pb/^{204}Pb**	**2σ**	**^{208}Pb/^{204}Pb**	**2σ**	**^{207}Pb/^{206}Pb**	**2σ**	**^{208}Pb/^{206}Pb**	**2σ**
103	Ag	**18.371**	0.007	**15.624**	0.007	**38.36**	0.02	**0.8504**	0.0002	**2.0878**	0.0006
104	Ag	**18.364**	0.005	**15.624**	0.005	**38.35**	0.01	**0.8508**	0.0001	**2.0886**	0.0003
105	Ag	**18.487**	0.010	**15.637**	0.008	**38.50**	0.02	**0.8458**	0.0002	**2.0826**	0.0004
106	Ag	**18.434**	0.019	**15.632**	0.007	**38.46**	0.03	**0.8479**	0.0006	**2.0861**	0.001
106 (Repeat)	Ag	**18.439**	0.013	**15.631**	0.008	**38.46**	0.03	**0.8477**	0.0005	**2.0857**	0.0008
106 (Repeat)	Ag	**18.455**	0.007	**15.632**	0.007	**38.48**	0.02	**0.8470**	0.0002	**2.0849**	0.0003
107	Ag	**18.432**	0.076	**15.624**	0.040	**38.43**	0.21	**0.8474**	0.0016	**2.0856**	0.0026
108	Ag	**18.483**	0.008	**15.638**	0.008	**38.51**	0.02	**0.8460**	0.0003	**2.0832**	0.0008
109	Ag	**18.458**	0.029	**15.631**	0.011	**38.48**	0.04	**0.8468**	0.0012	**2.0848**	0.0016
110	Ag	**18.432**	0.007	**15.633**	0.007	**38.45**	0.02	**0.8481**	0.0002	**2.0862**	0.0004
111*	Ag	**18.481**	0.219	**15.665**	0.180	**38.54**	0.44	**0.8475**	0.0004	**2.0854**	0.0008
112	Ag	**18.457**	0.008	**15.634**	0.006	**38.48**	0.02	**0.8470**	0.0002	**2.0850**	0.0004
113	Ag	**18.295**	0.005	**15.618**	0.004	**38.27**	0.01	**0.8536**	0.0001	**2.0920**	0.0003
114a	Ag	**18.611**	0.016	**15.664**	0.011	**38.73**	0.04	**0.8416**	0.0004	**2.0811**	0.0008
114b	Ag	**18.501**	0.004	**15.654**	0.005	**38.66**	0.01	**0.8461**	0.0003	**2.0898**	0.0007
114c**	Ag	**18.311**	0.046	**15.636**	0.017	**38.50**	0.06	**0.8538**	0.0018	**2.1025**	0.0028
114d**	Ag	**18.437**	0.019	**15.649**	0.012	**38.58**	0.05	**0.8487**	0.0007	**2.0928**	0.0012
115	Ag	**18.632**	0.006	**15.672**	0.005	**38.76**	0.01	**0.8411**	0.0001	**2.0804**	0.0004
116	Ag	**18.705**	0.007	**15.685**	0.006	**38.88**	0.02	**0.8385**	0.0002	**2.0784**	0.0006
117	Ag	**18.478**	0.004	**15.650**	0.005	**38.59**	0.01	**0.8469**	0.0002	**2.0884**	0.0005
118	Ag	**18.621**	0.008	**15.683**	0.008	**38.80**	0.03	**0.8422**	0.0004	**2.0838**	0.0010
119	Ag	**18.569**	0.004	**15.664**	0.004	**38.69**	0.01	**0.8435**	0.0001	**2.0837**	0.0004
120	Ag	**18.555**	0.005	**15.670**	0.005	**38.72**	0.01	**0.8445**	0.0002	**2.0868**	0.0005
121	Ag	**18.541**	0.005	**15.658**	0.004	**38.67**	0.01	**0.8445**	0.0002	**2.0858**	0.0004
121 (Repeat)	Ag	**18.540**	0.005	**15.658**	0.004	**38.67**	0.01	**0.8444**	0.0002	**2.0857**	0.0005
122*	Ag	**18.601**	0.304	**15.648**	0.250	**38.72**	0.62	**0.8412**	0.0003	**2.0814**	0.0010
123	Ag	**18.584**	0.007	**15.670**	0.006	**38.72**	0.02	**0.8431**	0.0002	**2.0836**	0.0005
124	Ag	**18.414**	0.003	**15.639**	0.003	**38.48**	0.01	**0.8492**	0.0001	**2.0909**	0.0002
125	Ag	**18.443**	0.006	**15.639**	0.005	**38.48**	0.01	**0.8479**	0.0001	**2.0875**	0.0002
126	Ag	**18.358**	0.007	**15.655**	0.006	**38.61**	0.02	**0.8527**	0.0001	**2.1044**	0.0003
127	Ag	**18.368**	0.005	**15.654**	0.004	**38.62**	0.01	**0.8522**	0.0001	**2.1038**	0.0002
128*	Ag	**18.611**	0.177	**15.786**	0.147	**38.95**	0.36	**0.8482**	0.0004	**2.0925**	0.0007
129	Ag	**18.393**	0.007	**15.633**	0.007	**38.46**	0.02	**0.8500**	0.0002	**2.0913**	0.0006
130	Ag	**18.450**	0.020	**15.651**	0.017	**38.61**	0.04	**0.8482**	0.0002	**2.0926**	0.0004
131	Ag	**18.415**	0.008	**15.652**	0.007	**38.59**	0.02	**0.8499**	0.0004	**2.0956**	0.0011
132	Ag	**18.407**	0.007	**15.638**	0.006	**38.54**	0.02	**0.8495**	0.0001	**2.0934**	0.0004
133	Ag	**18.443**	0.010	**15.635**	0.008	**38.48**	0.02	**0.8477**	0.0002	**2.0862**	0.0004
134	Ag	**18.435**	0.004	**15.659**	0.004	**38.66**	0.01	**0.8493**	0.0001	**2.0987**	0.0002
135	Ag	**18.391**	0.003	**15.648**	0.003	**38.49**	0.01	**0.8508**	0.0001	**2.0940**	0.0002
136	Ag	**18.443**	0.014	**15.644**	0.013	**38.55**	0.03	**0.8482**	0.0003	**2.0904**	0.0008
137	Ag	**18.410**	0.007	**15.624**	0.006	**38.42**	0.02	**0.8486**	0.0001	**2.0868**	0.0003
138*	Ag	**18.386**	0.123	**15.624**	0.099	**38.38**	0.24	**0.8499**	0.0002	**2.0878**	0.0005
139	Ag	**18.401**	0.007	**15.628**	0.006	**38.38**	0.01	**0.8493**	0.0001	**2.0858**	0.0004
140	Ag	**18.431**	0.012	**15.632**	0.006	**38.46**	0.03	**0.8481**	0.0003	**2.0865**	0.0005
141	Ag	**18.413**	0.005	**15.623**	0.006	**38.43**	0.02	**0.8484**	0.0003	**2.0869**	0.0007
142	Ag	**18.405**	0.004	**15.627**	0.004	**38.41**	0.01	**0.8490**	0.0002	**2.0869**	0.0004
143	Ag	**18.389**	0.003	**15.631**	0.003	**38.36**	0.01	**0.8500**	0.0001	**2.0872**	0.0002
144	Ag	**18.363**	0.005	**15.628**	0.005	**38.32**	0.01	**0.8510**	0.0001	**2.0880**	0.0003
145	Ag	**18.408**	0.003	**15.632**	0.003	**38.37**	0.01	**0.8491**	0.0001	**2.0858**	0.0002
146	Ag	**18.379**	0.005	**15.631**	0.005	**38.34**	0.01	**0.8504**	0.0001	**2.0875**	0.0003

Cat. Nr.	Materi-al	^{206}Pb /^{204}Pb	2σ	^{207}Pb /^{204}Pb	2σ	^{208}Pb /^{204}Pb	2σ	^{207}Pb /^{206}Pb	2σ	^{208}Pb /^{206}Pb	2σ
147	Ag	**18.384**	0.004	**15.630**	0.004	**38.35**	0.01	**0.8501**	0.0001	**2.0873**	0.0002
148	Ag	**18.367**	0.005	**15.629**	0.005	**38.33**	0.01	**0.8509**	0.0001	**2.0883**	0.0003
149	Ag	**18.354**	0.005	**15.628**	0.006	**38.31**	0.01	**0.8514**	0.0001	**2.0886**	0.0003
150	Ag	**18.369**	0.007	**15.630**	0.008	**38.34**	0.02	**0.8508**	0.0002	**2.0884**	0.0006
151	Ag	**18.386**	0.006	**15.631**	0.007	**38.35**	0.02	**0.8501**	0.0002	**2.0872**	0.0005
152	Ag	**18.375**	0.006	**15.631**	0.007	**38.34**	0.02	**0.8506**	0.0002	**2.0878**	0.0007
153	Ag	**18.304**	0.007	**15.625**	0.008	**38.24**	0.02	**0.8536**	0.0002	**2.0907**	0.0005
154	Ag	**18.344**	0.006	**15.630**	0.005	**38.30**	0.01	**0.8520**	0.0001	**2.0893**	0.0003
155	Sn-Pb	**18.377**	0.004	**15.618**	0.005	**38.33**	0.02	**0.8499**	0.0002	**2.0859**	0.0006
155 (Repeat)	Sn-Pb	**18.376**	0.007	**15.617**	0.007	**38.33**	0.03	**0.8499**	0.0004	**2.0857**	0.0014
156	Sn-Pb	**18.471**	0.004	**15.660**	0.005	**38.54**	0.01	**0.8478**	0.0003	**2.0866**	0.0007
157	Sn-Pb	**18.472**	0.004	**15.661**	0.006	**38.54**	0.03	**0.8478**	0.0003	**2.0861**	0.0014

Table 1 *Corrected lead isotope ratios of coins determined by fs-LA-MC-ICP-MS at the Leibniz Universität Hannover Institut für Mineralogie.*

** analyses with low lead contents / poor ^{204}Pb ratios, ** mixed or heterogeneous results with large standard deviations, *** with mercury contamination and poor ^{204}Pb ratios.*

Cat. Nr.	Material	^{206}Pb /^{204}Pb	2σ	^{207}Pb /^{204}Pb	2σ	^{208}Pb /^{204}Pb	2σ	^{207}Pb /^{206}Pb	2σ	^{208}Pb /^{206}Pb	2σ
159a	Ag	**18.507**	0.004	**15.662**	0.003	**38.54**	0.01	**0.8462**	0.0001	**2.0850**	0.0002
159b	Niello	**18.509**	0.003	**15.658**	0.003	**38.52**	0.01	**0.8459**	0.0001	**2.0834**	0.0002
159c	Cu?	**18.518**	0.008	**15.674**	0.005	**38.57**	0.02	**0.8463**	0.0002	**2.0853**	0.0005
159d	Niello	**18.549**	0.005	**15.664**	0.005	**38.59**	0.01	**0.8444**	0.0002	**2.0828**	0.0004
160	Ag	**18.492**	0.003	**15.660**	0.004	**38.52**	0.01	**0.8468**	0.0001	**2.0853**	0.0002
161	Ag	**18.477**	0.003	**15.651**	0.003	**38.51**	0.01	**0.8470**	0.0001	**2.0868**	0.0002
162a	Ag	**18.427**	0.005	**15.648**	0.005	**38.47**	0.01	**0.8491**	0.0001	**2.0899**	0.0003
162b	Ag	**18.440**	0.005	**15.650**	0.005	**38.48**	0.01	**0.8487**	0.0001	**2.0891**	0.0003
163a	Ag	**18.428**	0.006	**15.640**	0.008	**38.43**	0.02	**0.8487**	0.0002	**2.0878**	0.0011
163b	Ag	**18.435**	0.006	**15.644**	0.006	**38.45**	0.02	**0.8486**	0.0001	**2.0880**	0.0008
164a	Ag	**18.500**	0.006	**15.655**	0.009	**38.52**	0.02	**0.8462**	0.0002	**2.0842**	0.0008
164c	Ag	**18.352**	0.099	**15.614**	0.059	**37.85**	0.58	**0.8509**	0.0020	**2.0652**	0.0225
164d	Ag	**18.458**	0.024	**15.641**	0.021	**38.44**	0.07	**0.8473**	0.0008	**2.0849**	0.0025
165	Ag	**18.509**	0.007	**15.669**	0.009	**38.57**	0.03	**0.8465**	0.0002	**2.0862**	0.0008
166b	Ag	**18.530**	0.004	**15.658**	0.004	**38.64**	0.01	**0.8450**	0.0001	**2.0881**	0.0003
166a	Cu-Zn-Pb	**18.533**	0.004	**15.658**	0.004	**38.63**	0.02	**0.8448**	0.0001	**2.0871**	0.0003
167a	Ag	**18.536**	0.003	**15.669**	0.003	**38.73**	0.01	**0.8453**	0.0001	**2.0918**	0.0002
167b	Cu-Pb	**18.331**	0.005	**15.627**	0.006	**38.25**	0.02	**0.8525**	0.0001	**2.0891**	0.0007
168	Ag	**18.600**	0.006	**15.670**	0.006	**38.68**	0.02	**0.8424**	0.0002	**2.0818**	0.0004
169	Ag	**18.352**	0.004	**15.634**	0.005	**38.30**	0.02	**0.8518**	0.0001	**2.0895**	0.0006
170	Ag	**18.538**	0.009	**15.678**	0.009	**38.77**	0.02	**0.8457**	0.0002	**2.0939**	0.0004
171	Ag	**18.484**	0.005	**15.664**	0.005	**38.62**	0.02	**0.8474**	0.0001	**2.0919**	0.0003
172	Ag	**18.341**	0.004	**15.649**	0.004	**38.49**	0.01	**0.8532**	0.0001	**2.1009**	0.0003
173a	Cu-Alloy	**18.418**	0.004	**15.627**	0.004	**38.36**	0.01	**0.8485**	0.0001	**2.0855**	0.0003
173b	Cu-Alloy	**18.407**	0.007	**15.627**	0.008	**38.36**	0.02	**0.8490**	0.0002	**2.0866**	0.0008
173c	Cu-Alloy	**18.410**	0.004	**15.630**	0.004	**38.37**	0.01	**0.8489**	0.0001	**2.0869**	0.0003
173d	Sn	**18.464**	0.023	**15.621**	0.022	**38.38**	0.05	**0.8459**	0.0004	**2.0814**	0.0008
180b	Ag	**18.457**	0.017	**15.643**	0.016	**38.49**	0.04	**0.8475**	0.0004	**2.0855**	0.0011
187b	Ag	**18.535**	0.004	**15.662**	0.004	**38.66**	0.01	**0.8449**	0.0001	**2.0856**	0.0003

Table 2 *Corrected lead isotope ratios of jewelry and hacksilver determined by fs-LA-MC-ICP-MS at the Leibniz Universität Hannover Institut für Mineralogie.*

Cat. Nr.	**Material**	**^{206}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{204}Pb**	**2σ**	**^{208}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{206}Pb**	**2σ**	**^{208}Pb /^{206}Pb**	**2σ**
174	Ag	**18.503**	0.014	**15.643**	0.011	**38.61**	0.03	**0.8454**	0.0002	**2.0865**	0.0002
175	Ag	**18.451**	0.014	**15.649**	0.011	**38.50**	0.03	**0.8481**	0.0002	**2.0866**	0.0003
176	Ag	**18.574**	0.008	**15.660**	0.008	**38.68**	0.02	**0.8431**	0.0001	**2.0823**	0.0002
177	Ag	**18.572**	0.012	**15.656**	0.009	**38.69**	0.02	**0.8429**	0.0001	**2.0830**	0.0002
178	Ag	**18.296**	0.005	**15.637**	0.003	**38.49**	0.01	**0.8546**	0.0001	**2.1037**	0.0002
179	Ag	**18.371**	0.006	**15.622**	0.006	**38.34**	0.02	**0.8503**	0.0001	**2.0869**	0.0002
180a	Ag	**18.452**	0.004	**15.639**	0.004	**38.48**	0.02	**0.8475**	0.0001	**2.0855**	0.0004
181	Ag	**18.534**	0.009	**15.655**	0.008	**38.65**	0.02	**0.8446**	0.0001	**2.0852**	0.0002
182	Ag	**18.572**	0.004	**15.658**	0.004	**38.66**	0.01	**0.8431**	0.0001	**2.0816**	0.0002
183	Ag	**18.234**	0.004	**15.623**	0.004	**38.46**	0.01	**0.8567**	0.0001	**2.1094**	0.0002
184	Ag	**18.588**	0.003	**15.656**	0.004	**38.66**	0.01	**0.8422**	0.0001	**2.0796**	0.0002
185	Ag	**18.261**	0.008	**15.631**	0.007	**38.52**	0.02	**0.8560**	0.0001	**2.1091**	0.0003
186	Ag	**18.363**	0.030	**15.634**	0.026	**38.55**	0.06	**0.8513**	0.0003	**2.0990**	0.0004
187a	Ag	**18.533**	0.006	**15.660**	0.006	**38.65**	0.01	**0.8449**	0.0001	**2.0854**	0.0003
188	Ag	**18.697**	0.004	**15.685**	0.004	**38.89**	0.01	**0.8389**	0.0001	**2.0801**	0.0002
189	Ag	**18.323**	0.003	**15.639**	0.003	**38.60**	0.01	**0.8535**	0.0001	**2.1067**	0.0002
190	Ag	**18.525**	0.011	**15.644**	0.009	**38.60**	0.02	**0.8444**	0.0001	**2.0835**	0.0002

Table 3 *Corrected lead isotope ratios of hacksilver determined by ICP-MCMS at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften.*

Cat. Nr.	**Material**	**^{206}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{204}Pb**	**2σ**	**^{208}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{206}Pb**	**2σ**	**^{208}Pb /^{206}Pb**	**2σ**
191	Ag-Cu-Zn	**18.285**	0.004	**15.614**	0.004	**38.27**	0.01	**0.8539**	0.0001	**2.0927**	0.0003
191(Repeat)	Ag-Cu-Zn	**18.285**	0.005	**15.616**	0.004	**38.26**	0.01	**0.8541**	0.0001	**2.0924**	0.0003
192	Cu-Sn-Pb	**18.361**	0.007	**15.620**	0.007	**38.33**	0.02	**0.8506**	0.0001	**2.0874**	0.0002
192(Repeat)	Cu-Sn-Pb	**18.359**	0.054	**15.618**	0.045	**38.32**	0.11	**0.8507**	0.0005	**2.0873**	0.0012
193	Cu-Pb-Zn	**18.411**	0.060	**15.623**	0.045	**38.41**	0.13	**0.8485**	0.0006	**2.0859**	0.0012
194	Ag-Cu-Zn	**18.455**	0.007	**15.635**	0.006	**38.44**	0.02	**0.8472**	0.0001	**2.0830**	0.0002
194(Repeat)	Ag-Cu-Zn	**18.454**	0.024	**15.635**	0.021	**38.43**	0.06	**0.8474**	0.0003	**2.0825**	0.0008
195	Cu-Pb-Zn	**18.353**	0.003	**15.614**	0.002	**38.30**	0.01	**0.8507**	0.0001	**2.0869**	0.0001

Table 4 *Corrected lead isotope ratios of copper and copper-silver alloys determined by ICP-MCMS at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften.*

Cat. Nr.	**Material**	**^{206}Pb /^{20}4Pb**	**2σ**	**^{207}Pb /^{204}Pb**	**2σ**	**^{208}Pb /^{204}Pb**	**2σ**	**^{207}Pb /^{206}Pb**	**2σ**	**^{208}Pb /^{206}Pb**	**2σ**
196	Pb	**18.440**	0.004	**15.634**	0.004	**38.41**	0.01	**0.8478**	0.0001	**2.0829**	0.0002
197	Pb	**18.501**	0.005	**15.617**	0.004	**38.49**	0.01	**0.8441**	0.0001	**2.0804**	0.0002
198	Pb	**18.529**	0.004	**15.620**	0.004	**38.50**	0.01	**0.8430**	0.0001	**2.0780**	0.0002
199	Pb-Sn	**18.357**	0.005	**15.619**	0.004	**38.31**	0.01	**0.8508**	0.0001	**2.0871**	0.0002
200	Pb	**18.487**	0.003	**15.615**	0.004	**38.48**	0.01	**0.8446**	0.0001	**2.0812**	0.0002
201	Pb	**18.485**	0.003	**15.617**	0.005	**38.47**	0.01	**0.8448**	0.0001	**2.0812**	0.0003
202	Sn-Pb	**18.344**	0.020	**15.620**	0.019	**38.35**	0.05	**0.8515**	0.0003	**2.0903**	0.0010
203	Pb	**18.592**	0.021	**15.626**	0.019	**38.54**	0.05	**0.8404**	0.0003	**2.0729**	0.0010
204	Pb-Sn	**18.526**	0.032	**15.618**	0.025	**38.48**	0.07	**0.8432**	0.0003	**2.0771**	0.0010
205	Pb	**18.465**	0.056	**15.630**	0.042	**38.42**	0.12	**0.8464**	0.0006	**2.0807**	0.0012
206	Pb	**18.544**	0.032	**15.618**	0.027	**38.50**	0.07	**0.8422**	0.0003	**2.0761**	0.0012
207	Pb-Sn	**18.406**	0.076	**15.619**	0.055	**38.37**	0.15	**0.8485**	0.0007	**2.0847**	0.0014
208	Pb	**18.458**	0.016	**15.624**	0.014	**38.43**	0.04	**0.8464**	0.0002	**2.0817**	0.0008
209	Pb	**18.516**	0.020	**15.618**	0.017	**38.49**	0.05	**0.8435**	0.0002	**2.0786**	0.0009
210	Pb	**18.352**	0.016	**15.617**	0.015	**38.31**	0.04	**0.8509**	0.0002	**2.0872**	0.0009
211	Pb	**18.388**	0.056	**15.617**	0.042	**38.35**	0.12	**0.8493**	0.0005	**2.0853**	0.0011
212	Pb	**18.364**	0.023	**15.619**	0.020	**38.32**	0.06	**0.8505**	0.0002	**2.0866**	0.0008

Cat. Nr.	Material	^{206}Pb /^{20}4Pb	2σ	^{207}Pb /^{204}Pb	2σ	^{208}Pb /^{204}Pb	2σ	^{207}Pb /^{206}Pb	2σ	^{208}Pb /^{206}Pb	2σ
213	Pb	**18.379**	0.284	**15.617**	0.204	**38.34**	0.56	**0.8497**	0.0021	**2.0858**	0.0024

***Table 5** Corrected lead isotope ratios of lead and lead-tin alloys determined by MC-ICP-MS at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften.*

Cat. Nr.	Object	Type	^{206}Pb /^{204}Pb	2σ	^{207}Pb /^{204}Pb	2σ	^{208}Pb /^{204}Pb	2σ	^{207}Pb /^{206}Pb	2σ	^{208}Pb /^{206}Pb	2σ
219	Slag	Pb-Si-O	**18.482**	0.007	**15.628**	0.006	**38.53**	0.02	**0.8456**	0.0001	**2.0847**	0.0003
236	Slag	Pb-Si-O	**18.404**	0.005	**15.627**	0.005	**38.39**	0.01	**0.8490**	0.0001	**2.0862**	0.0002
238	Slag	Pb-Si-O	**18.489**	0.003	**15.645**	0.002	**38.50**	0.01	**0.8461**	0.0001	**2.0821**	0.0002
247	Lead Corrosion	Pb-Ca-P-O	**18.421**	0.005	**15.631**	0.004	**38.37**	0.01	**0.8485**	0.0001	**2.0830**	0.0001

***Table 6** Corrected lead isotope ratios of the lead-silicate slag in heating trays and the white powdery residue of crucible **Cat. 247** determined by MC-ICP-MS at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften.*

Cat. Nr.	Object	Type	^{206}Pb /^{204}Pb	2σ	^{207}Pb /^{204}Pb	2σ	^{208}Pb /^{204}Pb	2σ	^{207}Pb /^{206}Pb	2σ	^{208}Pb /^{206}Pb	2σ
248	Slag	Pb-Cu-Ag	**17.707**	0.044	**15.563**	0.036	**37.98**	0.10	**0.8789**	0.0004	**2.1449**	0.0009
250	Slag	Pb-Cu-Ag	**18.036**	0.031	**15.594**	0.023	**38.10**	0.07	**0.8646**	0.0004	**2.1126**	0.0009
251	Slag	Pb-Cu-Ag	**17.526**	0.032	**15.533**	0.026	**37.86**	0.07	**0.8862**	0.0003	**2.1604**	0.0008
252	Slag	Pb-Cu-Ag	**17.720**	0.044	**15.561**	0.036	**37.97**	0.09	**0.8781**	0.0005	**2.1427**	0.0011
253	Slag	Pb-Cu-Ag	**17.564**	0.055	**15.527**	0.047	**37.82**	0.12	**0.8840**	0.0005	**2.1533**	0.0011
254	Slag	Pb-Cu-Ag	**18.000**	0.053	**15.589**	0.044	**38.09**	0.11	**0.8660**	0.0004	**2.1160**	0.0011
255	Slag	Cu	**17.668**	0.027	**15.556**	0.022	**37.97**	0.06	**0.8804**	0.0003	**2.1490**	0.0009
256	Slag	Pb-Cu-Ag	**17.849**	0.056	**15.571**	0.046	**38.02**	0.12	**0.8723**	0.0006	**2.1300**	0.0012
257	Slag	Pb-Cu-Ag	**17.667**	0.031	**15.557**	0.024	**37.97**	0.06	**0.8805**	0.0004	**2.1494**	0.0009
258	Slag	Cu	**17.850**	0.045	**15.574**	0.038	**38.03**	0.10	**0.8724**	0.0004	**2.1305**	0.0011
259	Slag	Pb-Cu-Ag	**17.900**	0.039	**15.579**	0.030	**38.05**	0.08	**0.8703**	0.0004	**2.1255**	0.0010
260	Ore	Ttr-Ccp	**18.150**	0.027	**15.585**	0.023	**38.13**	0.07	**0.8586**	0.0003	**2.1007**	0.0013
261	Ore	Ttr-Ccp	**18.003**	0.029	**15.589**	0.026	**38.08**	0.07	**0.8659**	0.0004	**2.1150**	0.0011
262	Ore	Ttr-Ccp	**18.160**	0.070	**15.592**	0.058	**38.16**	0.15	**0.8585**	0.0006	**2.1011**	0.0014
263	Ore	Ttr-Ccp	**18.004**	0.028	**15.589**	0.025	**38.07**	0.07	**0.8658**	0.0004	**2.1148**	0.0013
264	Ore	Malachite	**18.009**	0.029	**15.582**	0.025	**38.06**	0.07	**0.8652**	0.0003	**2.1134**	0.0012
275	Ore	Pyrite	**18.454**	0.042	**15.702**	0.035	**38.38**	0.10	**0.8508**	0.0004	**2.0796**	0.0016
277	Ore	Arsenopy	**18.435**	0.028	**15.719**	0.025	**38.45**	0.06	**0.8527**	0.0004	**2.0856**	0.0011
278	Ore	Galena	**18.624**	0.031	**15.733**	0.025	**38.49**	0.07	**0.8448**	0.0004	**2.0669**	0.0013
279	Ore	Galena	**18.515**	0.028	**15.678**	0.024	**38.32**	0.07	**0.8467**	0.0003	**2.0693**	0.0012
281	Ore	Galena	**19.207**	0.026	**15.736**	0.021	**38.36**	0.06	**0.8193**	0.0003	**1.9973**	0.0012

***Table 7** Corrected lead isotope ratios of polymetallic (Cu-Pb-Ag) slag from Lashkerek and Tunket, Uzbekistan, and ore samples from ancient mines and ore deposits in Uzbekistan determined by MC-ICP-MS at the Goethe-Universität Frankfurt am Main. Mineral abbreviations: Ttr – tetrahedrite, Ccp – chalcopyrite, Arsenopy - arsenopyrite.*

Hannover	**Analysis #**	**^{205}Tl/203Tl**	**2σ**	**^{206}Pb/^{204}Pb**	**2σ**	**^{207}Pb/^{204}Pb**	**2σ**	**^{208}Pb/^{204}Pb**	**2σ**	**^{207}Pb/^{206}Pb**	**2σ**	**^{208}Pb/^{206}Pb**	**2σ**
02.02.2012	#6	**2.43234**	0.0003	**16.933**	0.009	**15.487**	0.010	**36.680**	0.029	**0.9146**	0.0005	**2.1662**	0.0014
03.02.2012	#218	**2.43498**	0.0004	**16.930**	0.008	**15.484**	0.010	**36.673**	0.026	**0.9146**	0.0004	**2.1662**	0.0011
29.09.2012	#149	**2.41294**	0.0003	**16.921**	0.007	**15.475**	0.011	**36.586**	0.151	**0.9145**	0.0004	**2.1626**	0.0071
29.09.2012	#200	**2.41289**	0.0004	**16.919**	0.015	**15.473**	0.022	**36.588**	0.175	**0.9145**	0.0007	**2.1628**	0.0087
29.09.2012	#275	**2.41572**	0.0007	**16.910**	0.013	**15.467**	0.018	**36.623**	0.091	**0.9147**	0.0005	**2.1660**	0.0033

Frankfurt/ Main	**Analysis #**	**^{205}Tl/^{203}Tl**	**2σ**	**^{206}Pb/^{204}Pb**	**2σ**	**^{207}Pb/^{204}Pb**	**2σ**	**^{208}Pb/^{20}4Pb**	**2σ**	**^{207}Pb/^{206}Pb**	**2σ**	**^{208}Pb/^{206}Pb**	**2σ**
06.03.2012	Std981-3	**2.4210**	0.0003	**16.934**	0.004	**15.486**	0.004	**36.688**	0.010	**0.9145**	0.0001	**2.1665**	0.0002
21.03.2012	Std981-1	**2.4241**	0.0003	**16.936**	0.007	**15.485**	0.006	**36.688**	0.014	**0.9143**	0.0001	**2.1663**	0.0003
25.09.2012	Std981-1	**2.4194**	0.0003	**16.935**	0.002	**15.490**	0.002	**36.692**	0.007	**0.9147**	0.0001	**2.1667**	0.0002
25.09.2012	Std981-3	**2.4196**	0.0003	**16.935**	0.004	**15.489**	0.003	**36.690**	0.007	**0.9146**	0.0001	**2.1666**	0.0002
25.09.2012	Std981-4	**2.4207**	0.0002	**16.935**	0.002	**15.490**	0.002	**36.692**	0.005	**0.9146**	0.0001	**2.1666**	0.0002
15.10.2012	Std981-6	**2.4240**	0.0002	**16.935**	0.003	**15.489**	0.002	**36.691**	0.008	**0.9146**	0.0001	**2.1666**	0.0002
15.10.2012	Std981-5	**2.4230**	0.0001	**16.935**	0.004	**15.489**	0.003	**36.692**	0.007	**0.9146**	0.0001	**2.1666**	0.0001
04.12.2012	Std981-5	**2.4247**	0.0011	**16.934**	0.028	**15.489**	0.024	**36.692**	0.064	**0.9147**	0.0003	**2.1667**	0.0010
04.12.2012	Std981-4	**2.4247**	0.0010	**16.935**	0.032	**15.490**	0.026	**36.692**	0.069	**0.9147**	0.0003	**2.1667**	0.0010
04.12.2012	Std981-3	**2.4239**	0.0009	**16.936**	0.025	**15.491**	0.021	**36.696**	0.055	**0.9147**	0.0003	**2.1668**	0.0008
31.01.2013	Std981-5	**2.4381**	0.0015	**16.940**	0.032	**15.494**	0.029	**36.709**	0.077	**0.9147**	0.0005	**2.1671**	0.0015
31.01.2013	Std981-4	**2.4377**	0.0017	**16.942**	0.034	**15.495**	0.032	**36.712**	0.091	**0.9146**	0.0004	**2.1669**	0.0016
31.01.2013	Std981-3	**2.4363**	0.0015	**16.940**	0.028	**15.489**	0.026	**36.701**	0.067	**0.9144**	0.0005	**2.1665**	0.0015
31.01.2013	Std981-2	**2.4360**	0.0011	**16.943**	0.028	**15.493**	0.025	**36.711**	0.069	**0.9144**	0.0004	**2.1668**	0.0011
31.01.2013	Std981-1	**2.4366**	0.0016	**16.941**	0.030	**15.491**	0.029	**36.705**	0.078	**0.9144**	0.0005	**2.1666**	0.0016
15.10.2013	Std981-3	**2.4274**	0.0012	**16.938**	0.086	**15.491**	0.068	**36.697**	0.178	**0.9145**	0.0007	**2.1665**	0.0013
15.10.2013	Std981-4	**2.4286**	0.0015	**16.934**	0.073	**15.487**	0.061	**36.686**	0.162	**0.9145**	0.0007	**2.1664**	0.0014
15.10.2013	Std981-5	**2.4285**	0.0014	**16.933**	0.062	**15.486**	0.049	**36.686**	0.130	**0.9146**	0.0006	**2.1665**	0.0015
16.10.2013a	Std981-1	**2.4234**	0.0010	**16.935**	0.019	**15.489**	0.018	**36.690**	0.049	**0.9146**	0.0003	**2.1665**	0.0010
16.10.2013a	Std981-2	**2.4252**	0.0011	**16.933**	0.022	**15.487**	0.021	**36.686**	0.057	**0.9146**	0.0003	**2.1665**	0.0010
16.10.2013a	Std981-3	**2.4254**	0.0011	**16.935**	0.020	**15.487**	0.019	**36.687**	0.049	**0.9146**	0.0004	**2.1664**	0.0010
16.10.2013b	Std981-5	**2.4247**	0.0011	**16.935**	0.018	**15.488**	0.018	**36.689**	0.049	**0.9146**	0.0003	**2.1665**	0.0011
16.10.2013b	Std981-4	**2.4246**	0.0011	**16.934**	0.017	**15.487**	0.016	**36.688**	0.043	**0.9146**	0.0003	**2.1666**	0.0011
25.02.2014	Std981-4	**2.4183**	0.0011	**16.933**	0.020	**15.488**	0.018	**36.688**	0.051	**0.9147**	0.0003	**2.1667**	0.0010
25.02.2014	Std981-3	**2.4151**	0.0010	**16.935**	0.018	**15.490**	0.018	**36.693**	0.045	**0.9147**	0.0002	**2.1667**	0.0008
25.02.2014	Std981-2	**2.4077**	0.0012	**16.935**	0.045	**15.489**	0.037	**36.690**	0.096	**0.9146**	0.0005	**2.1665**	0.0012

***Table 8** Values obtained for the SRM 997 Tl and SRM 981 Pb isotope standards on the days of measurement at the Leibniz Universität Hannover Institut für Mineralogie and at the Goethe-Universität Frankfurt am Main Institut für Geowissenschaften. The SRM 981 Pb measurement values were used for normalization.ancient mines and ore deposits in Uzbekistan determined by MC-ICP-MS at the Goethe-Universität Frankfurt am Main. Mineral abbreviations: Ttr – tetrahedrite, Ccp – chalcopyrite, Arsenopy - arsenopyrite.*

Appendix E
Glossary of Minerals and Phases

Type	Mineral/Phase	Formula
Metal / Speiss	Allargentum / Silver Antimonide	Ag_{1-x} Sbx
	Copper	Cu
	Copper Antimonide	Cu_2Sb, Cu_3Sb
	Dycrasite	Ag_3Sb
	Iron Arsenide	(Fe,As,Ni)
	Lead	Pb
	Native Arsenic	As
	Native Silver	Ag
Sulfides	Acanthite	Ag_2S
	Argentopyrite	$AgFe_2S_3$
	Arsenopyrite	FeAsS
	Bismuthinite	Bi_2S_3
	Bornite	Cu_5FeS_4
	Chalcocite	Cu_2S
	Chalcopyrite	$CuFeS_2$
	Covellite	CuS
	Cubanite	$CuFe_2S_3$
	Digenite	Cu_9S_5
	Freibergite	$(Ag,Cu,Fe)_{12}(Sb,As)_4S_{13}$
	Galena	PbS
	Guitermanite	$Pb_{10}As_6S_{19}$
	Lenaite	$FeAg_2S$
	Pyrargyrite	Ag_3SbS_3
	Pyrite	FeS_2
	Pyrrhotite	$Fe_{1-x}S$ ($x = 0$ to 0.2)
	Skinnerite	Cu_3SbS_3
	Sphalerite	ZnS
	Stephanite	Ag_5SbS_4
	Stibnite	Sb_2S_3
	Tennantite	$(Cu,Fe,Ag)_{12}As_4S_{13}$
	Tetrahedrite	$(Cu,Fe,Ag)_{12}Sb_4S_{13}$
	Zinc Sulfide	(Zn,Fe)S
Oxide / Hydroxide	Cuprite	Cu_2O
	Franklinite	$ZnFe_2O_4$
	Gahnite	$(Zn,Fe,Al)_3O_4$
	Hematite	Fe_2O_3
	Litharge	PbO
	Magnetite	Fe_3O_4
	Tenorite	CuO
	Wüstite	FeO
	Zinc Oxide / Zincite	ZnO
Halide	Cerargyrite	AgCl
	Fluorite	CaF_2
Carbonate	Ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$
	Azurite	$Cu_3(CO_3)_2(OH)_2$
	Calcite	$CaCO_3$
	Cerussite	$PbCO_3$
	Dolomite	$CaMg(CO_3)_2$
	kutnohorite	$CaMn(CO_3)_2$
	Malachite	$Cu_2CO_3(OH)_2$
	Siderite	$FeCO_3$
Sulfate	Anglesite	$PbSO_4$
	Barite	$BaSO_4$
	Jarosite	$KFe_3(OH)_6(SO_4)_2$

Type	Mineral/Phase	Formula
Silicate	Augite	$Ca(Fe,Mg,Zn)Si_2O_6$
	Fayalite	Fe_2SiO_4
	Hedenbergite	$CaFeSi_2O_6$
	Kaolin / Kaolinite	$Al_2Si_2O_5(OH)_4$
	Kirschsteinite	$CaFeSiO_4$
	Leucite	$KAlSi_2O_6$
	Melilite	$(Ca,Na)_2(Al,Mg,Fe)(Si,Al)_2O_7$
	Microcline	$KAlSi_3O_8$
	Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$
	Orthoclase	$KAlSi_3O_8$
	Pigeonite	$(Mg,Fe)Si_2O_6$
	Quartz	SiO_2
	Willemite	Zn_2SiO_4

Appendix F
XRF Artifact Scans

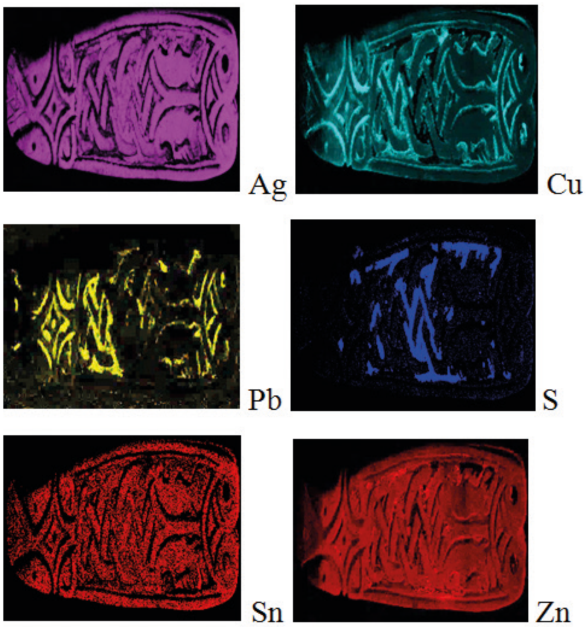

Figure 1 *Anglo-Saxon style belt end* ***Cat. 159****. The silver belt end is debased with a copper alloy containing lead, zinc, and tin as seen by the corrosion products found the relief. Some traces of niello consisting of only silver and sulfur are intact.*

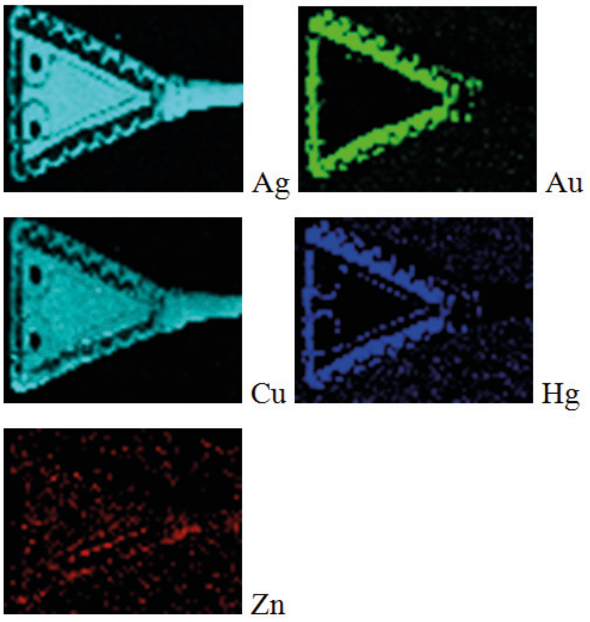

Figure 2 *Anglo-Saxon style clasp* ***Cat. 161****. Fire-gilding is indicated by the association of gold and mercury.*

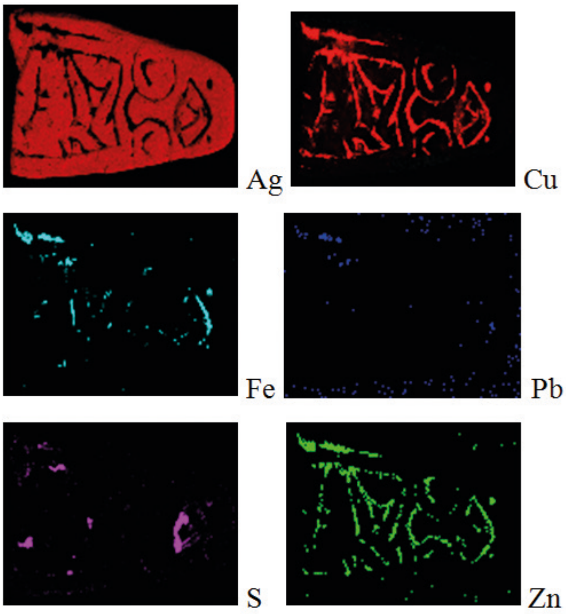

Figure 3 *Anglo-Saxon style belt end* ***Cat. 164****. The silver is debased as can be seen by the copper and zinc corrosion products in the relief. Small amounts of niello can be seen containing mostly of silver, sulfur, and zinc, but may contain a small amount of copper.*

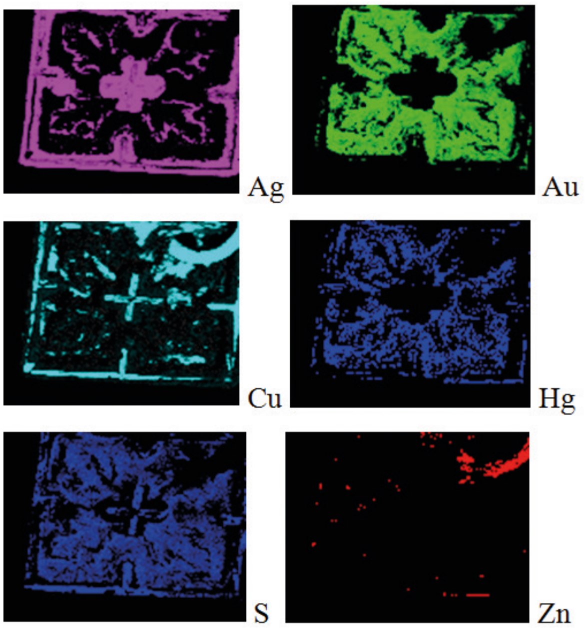

Figure 4 *Carolingian fitting* ***Cat. 165****. The silver fitting is fire-gilded and inlayed with niello that seems to be mostly copper and sulfur, but with some silver. It is pierced, and the loop appears to be made of brass.*

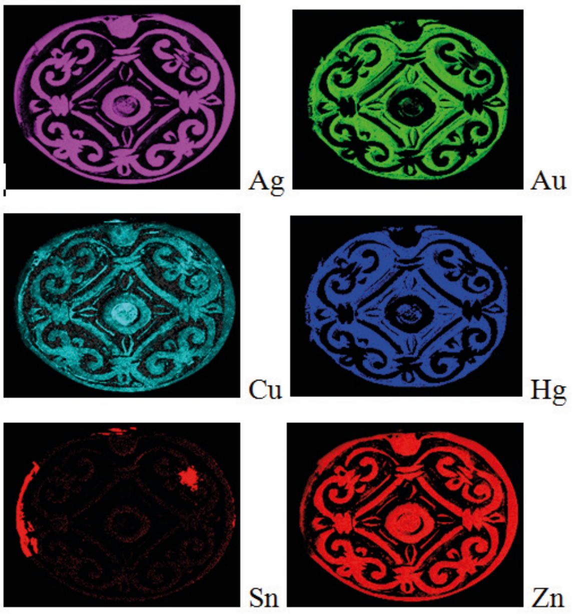

Figure 5 *Carolingian fitting / brooch* ***Cat. 166****. Fire-gilding can be seen in the recesses. The high zinc content can be seen in the silver. Drips of tin solder are obvious on the front surface, contamination from the attachment of the brooch pin on the back side.*

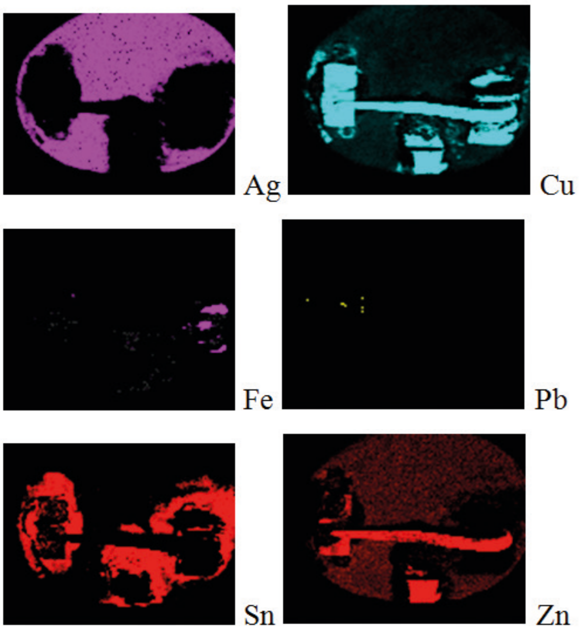

Figure 6 *Carolingian fitting / brooch* ***Cat. 166****, reverse side. The needle, suspension loop, and needle socket are made of brass, the hinge plate of copper and are soldered to the silver fitting with tin. The pivot pin for the needle is made of iron.*

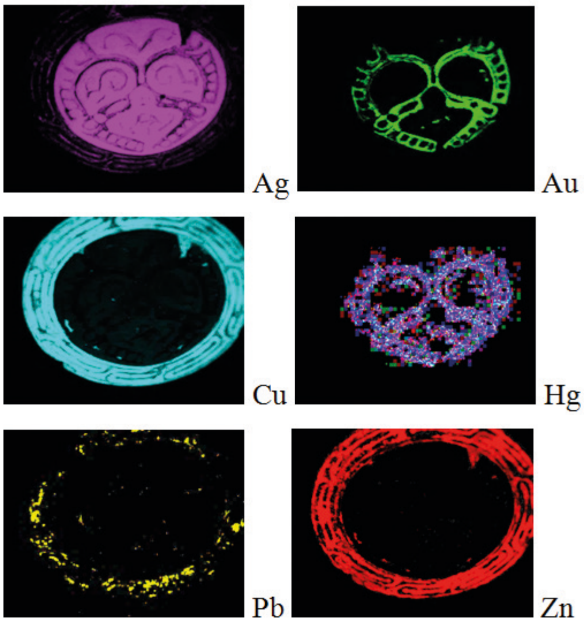

Figure 7 *Oriental brooch* ***Cat. 167****. The boss is made of silver. The traces of mercury and gold in the relief indicate that the silver was fire-gilded. The frame contains both zinc and lead.*

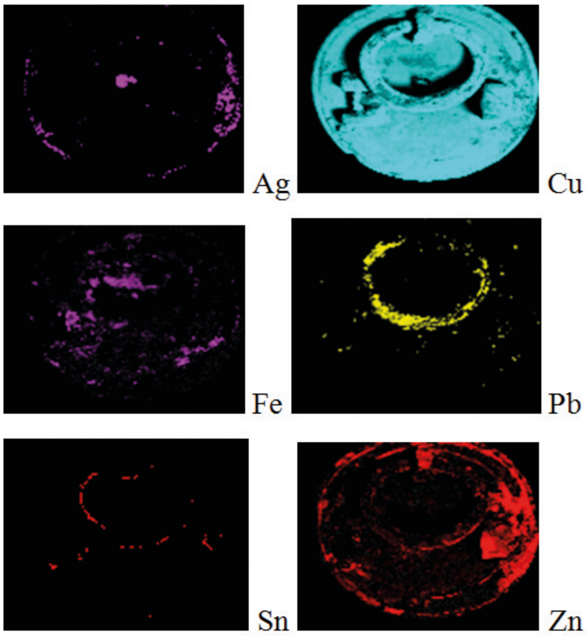

Figure 8 *Oriental style brooch* ***Cat. 167****, reverse. The silver rivet from the boss can be seen on the back side of the brooch. The back plate, ring, needle holder, and socket are made from a copper alloy or alloys containing zinc, lead and a small amount of tin.*

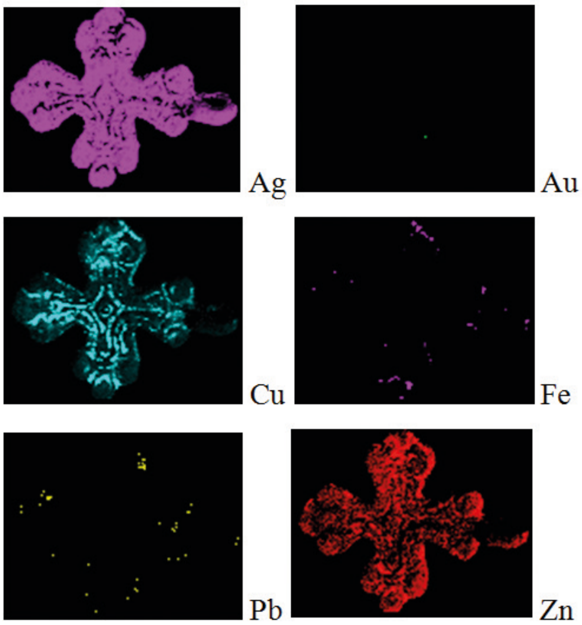

Figure 9 *Russian style cross pendant* ***Cat. 169****. The silver is slightly debased as evident by the higher zinc and copper corrosion in the relief.*

Appendix G
Analysis of Technical Ceramics Related to Gold and Silver Smithing at Hedeby

Summary

The crucibles from Hedeby give us a substantial amount of information about intentional processes carried out in the Viking Age but also about taphonomic processes that occurred that might mislead the interpretation of such finds. Crucible fragments and refining dishes from the 9th and 10th century were analyzed by scanning electron microscopy and by polarized light microscopy to characterize the technologies used in the recycling of precious metals at Hedeby. On a workshop scale, simple re-melting of scrap-metal occurs alongside more complex techniques of separating precious metals from impurities. Resulting from both recycling processes, the gold and silver prills are of the typical purity used in the Baltic region for objects of jewelry or exchange. The evidence from the crucible fragments suggests importation of refractory ceramic as well as local production of low-quality technical ceramics and that they were perceived and used in different ways. It was quickly realized that surface analyses of silver proved to be unreliable due to the corrosion, leading to quite unexpected results. Silver that was not sealed in vitreous slag had been transformed into silver sulfide (Ag_2S) and in some cases to lenaite ($AgFeS_2$). This enrichment of both iron and sulfur has been noted in Switzerland where copper metal was transformed into chalcopyrite ($CuFeS_2$) in the anaerobic waterlogged burial conditions (Rehren 2009); this phenomenon has now been documented with silver. This appendix is an extended and up-dated version of an abstract published in the conference proceedings for Archäometrie und Denkmalpflege 2012 (Merkel et al. 2012).

1. Introduction

Hedeby was not only a major trading center, but a production center in its own right, producing goods for all levels of society. Precious metals were among those that were worked and traded. The excavation and analysis of workshop debris are crucial to understanding the practice of craft production and its organization. Crucibles, casting waste, ingot moulds, and tools for the working of gold and silver alloys have been found during the excavations of Hedeby, which has a research history of over a century (see Hilberg 2009, 84-7). While some aspects of the production *chaîne opératiore* have been enlightened by technical studies of artifacts (see Armbruster 2002), the evidence from the crucible finds from Hedeby have received little attention.

Technological questions concerning the recycling and refining of precious metals in the early medieval period have arisen in recent academic discussion (see Jouttijärvi/Andersen 2005; Pedersen 2010; Söderberg 2011). The reconstruction of the technical processes used to recycle and refine precious metals requires an in-depth study of crucible material. The present study is not comprehensive; encompassing the entire range of material from the excavations of Hedeby is a monumental undertaking that is out of the scope of this study. A small collection of crucibles has been selected for elemental analysis and microscopy to provide a first glimpse into the technical ceramics and to clarify some details concerning the refractories, alloys, and recycling processes used at Hedeby. Crucible fragments of the two major crucible types, the cylindrical crucible and the dish-shaped crucible, known as the heating tray, form the core of this technical study (for illustration see **Catalogue Plate 17**). Crucibles with traces of gold and/or silver were preferentially selected for analysis, although not exclusively.

An important problem is the function of the shallow dish-shaped heating tray. They typically have a lead-rich slag on the interior with prills of gold or silver. The testing of alloys by analytical cupellation is one idea put forth (see Bayley 1992, 6; Bayley/Eckstein 1997, 110-1; Söderberg 2011); however this theory lacks an analytical basis. A goal of this study is to explore the technological differences between the two crucible types and to identify their functions. This investigation not only touches upon the technological skill of the metalworkers, but upon more abstract concepts concerning the economic framework in which precious metal alloys and raw materials were used at Hedeby.

2. Metalworking and Technical Ceramics at Hedeby

Despite the widespread evidence for metalworking at Hedeby,[1] with the possible exception of iron, no metals were produced there. All non-ferrous metals were imported via the long-distance trading networks stretch-

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[1] See Ansprach 2010; Armbruster 2002; Capelle 1968; 1970; Drescher 1983; Piaskowski 1983; Thomsen et al. 1971; Westphalen 1989.

ing over much of the known world. Metals in the form of ingots, coins, jewelry, and scrap metal were brought to the settlement for recycling. The excavations of Hedeby in the 1960s revealed the presence of metallurgical workshops in the center of the settlement. Within the 10 x 15 meter units, there appears to have been a significant overlap between ferrous and non-ferrous metalworking, and it is certainly possible that a number of metals were worked in the same workshops.

Waste from various types of metallurgical processes was found together in layers of the 9th and 10th centuries, and although the artifacts were collected in stratigraphic layers, no chronologic trends could be readily distinguished without a thorough and detailed analysis of all crucible material together with the dendrochronological dating of the arbitrary excavation levels. The debris from the working of non-ferrous metals was previously reported by Drescher (1983), but in light of recent work (Jouttijärvi/Andersen 2005; Lamm 2008; Pedersen 2010; Söderberg 1996; Söderberg 2008) some artifact classes are due for reinvestigation and possible reinterpretation. Among the metallurgical debris of smithing slag, hammer scale, casting sprues, metalworking tools; technical ceramics such as hearth material, casting moulds, cylindrical crucibles, dish-shaped crucibles, 'heating packages' for carborizing iron (see Söderberg 2008), and 'Schmelzkugeln' or 'melting balls' used to make brass-coated iron weights (see Söderberg 1996) have been found.[2] Crucibles were recovered in the excavations, but as of yet they have not been quantified nor closely studied. Most appear to be related to copper metallurgy due to green and red corrosion products and glazing. Crucibles with visible traces of gold or silver are much rarer.

3. The Crucibles and Heating Trays

The vast majority of crucibles found at Hedeby are handmade, cylindrical in shape, and have a rounded bottom. This form is common in northern and eastern Europe of the 8th to the 11th century (Eniosova/Mitoyan 2005, 327; Söderberg 1996, 5). The crucibles found at Hedeby vary in size and quality. As Bayley remarks, the crucibles used for gold tend to be smaller than crucibles for base metal casting (Bayley 1991, 117), and at Hedeby it appears that there may be a differentiation between crucible types used for precious metals and those used for brass and other copper alloys, but this has yet to be statistically proven. The Hedeby crucibles were made out of various types of ceramics and could have been produced at Hedeby from local or imported clays or imported as finished crucibles. Temperatures in the range of 1100°C are required for casting of most gold and silver alloys, therefore the crucibles must be able to withstand the temperature while being handled with tongs (see Bayley 1992, 3).

Heating trays have attracted attention in recent years because the exact function of this crucible type has been under debate. They go by many names: scorifiers, soldering trays, ceramic cupels, cupels, etc., showing their evasiveness of a clear interpretation. The history of literature on the subject goes back to Roesdahl (1977, 51–3) and this crucible form has since been identified at many important trading and production centers from the 6th to the 12th century. The geographic distribution of heating trays in published literature ranges from Ireland, western England, western and northern Germany, Denmark, Norway, Sweden, to Russia and possibly Iran (Bayley 1992, 6; Eniosova/Mitoyan 2005, 330; Söderberg 2011, 12; Stöllner et al. 2004b, 761, Cat. 451; Young 2006, 3). Their open form, small size, slagged interior surface, and droplets of silver and gold distinguish them from the more common crucible forms of the period. The limited chemical analyses performed on these finds have detected large amounts of lead, copper, and silver in the slagged areas of the crucible (Bayley 1992, 6; Bayley/Eckstein 1997, 110-1; Pedersen 2010, 197; Roesdahl 1977, 53). There are important parallels to the cupellation process and have even been interpreted by some to be used for testing the purity of metals, i.e. assaying or analytical cupellation (Bayley 1992, 6; Bayley/Eckstein 1997, 110-1; Lamm 2008, 191-198; Söderberg 2004; Söderberg 2011). Analytical cupellation is a method used to precisely calculate the precious metal content of an alloy by weighing the alloy before and after purification to determine the difference, i.e. the amount of impurities in the original alloy; however, the connection of heating trays to this method of testing seems to be anachronistic (Rehren/Eckstein 2002). Another interpretation is that they were part of a goldsmith's toolkit, used for the purification of metals for smithing purposes (Coatsworth/Pinder 2002, 34-6; Eilbracht 2004; Söderberg 2011). One aim of the present study is to try to better understand the technology and utility of this crucible type.

4. Sampling and Analytical Methods

The methodology begins with sample selection. The majority of crucibles come from the 1969 excavation in a highly developed part of the site, and many objects were recovered by water screening. The stratigraphy used in the excavation was arbitrary with 15 cm levels, and the objects in this study come from levels 3 to 8, generally dating to the mid-9th to the mid-10th centuries (Volker Hilberg pers. comm. 2011). Crucible fragments with traces of gold or silver metallurgy were preferentially chosen for this study, but it also includes some crucible material with traces of copper metallurgy on the interior. Eight fragments contained visual traces of gold,

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[2] The 'melting balls' are of particular importance in understanding the relationship between workshops and the governing power structure. The manufacture of this form of weight is technically challenging and direct evidence for production has only been found at Hedeby (Drescher 1983), Birka, Sigtuna (Eilbracht 2004, 40-1; Söderberg 1996) and at Kaupang (Pedersen 2010, 209). The distribution of such weights is much broader, showing not only the trading connections but perhaps the influential power these trading centers (or kings) had on the trading practices in the Baltic and North sea area (see Söderberg 2011, 16; Steuer et al. 2002). Production waste was found connected to the mint of King Olaf at Sigtuna, and weight manufacture remains were found within the settlement excavations of Hedeby and Birka, which were also centers of royal power (Gustin 1997).

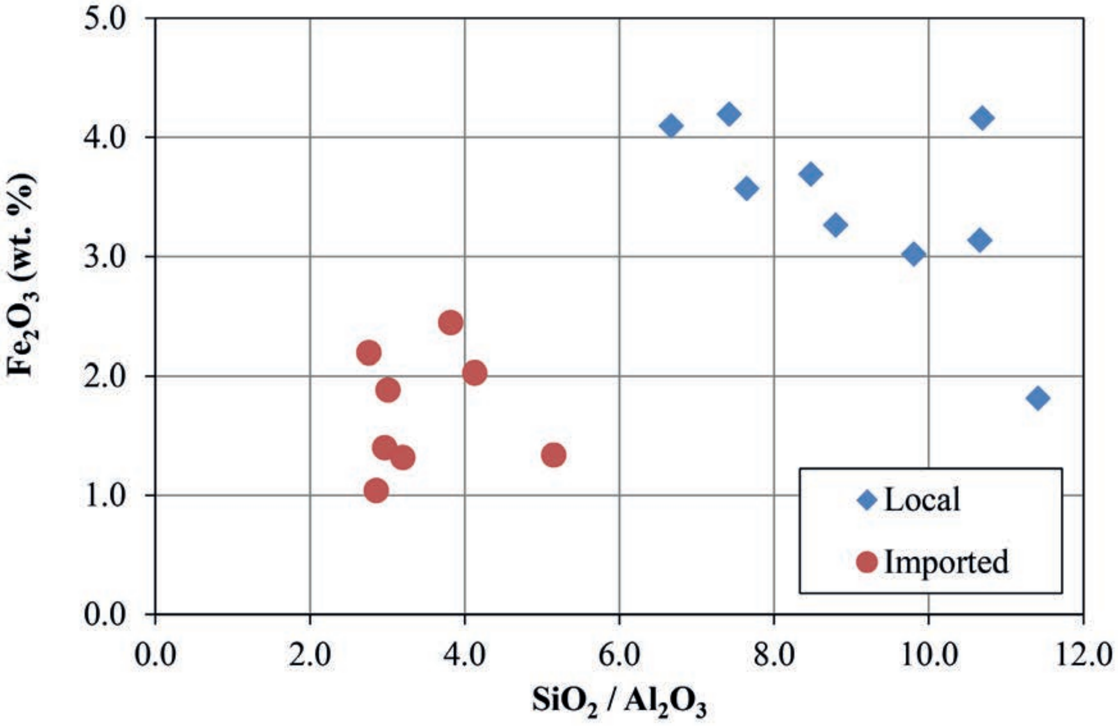

Figure 1 *Contrasting major elements of local (Type 1) and imported refractories (Types 2-3). With the local ceramics the value of silica (stemming from temper and clay) is inversely related to the iron oxide and alumina values (stemming mostly from clay), and this is directly proportional to the varying amounts of quartz sand temper added to the clay observed by the optical analysis of the thin-sections.*

but to find silver, crucibles with black corrosion and no visible traces of copper corrosion were sought. A range of crucible ceramic materials was chosen as well as crucible forms, but the samples were not taken representatively, but rather to capture the variability. In all, 10 cylindrical crucible fragments, 14 heating trays and two fragments of 'melting balls' were analyzed. The crucibles and technical ceramics selected for this investigation are listed in the **Catalogue**: **Tables 3** and **4**; **Catalogue Plates 15**-**17**).

Due to their rarity, eight fragments with visible traces of gold were analyzed non-destructively by scanning electron microscopy with energy dispersive spectrometry (SEM-EDS).[3] The gold prills and droplets appeared free of corrosion products, although some leaching of base metals may have occurred. Vitreous surfaces, with special regard to heating trays, were also analyzed with EDS to estimate the elemental composition. Crucibles with corrosion products of silver and copper were sectioned and polished in thin-section. Prills, droplets, and cracks with non-corroded metal could be analyzed by polarized light microscopy (PLM) and SEM-EDS. The mounting of crucible fragments made it possible to explore technological aspects of crucible manufacture and use (protective linings – inside and out, tempering material, fuel ash glazing, slag, and phase formation).

Three main categories of data were collected: ceramic, prill, and slag compositions. Ceramic compositions were measured by SEM-EDS area analysis. The areas were large enough to not be affected by heterogeneity caused by temper, but areas impacted by fluxing or corrosion were avoided. Typically, three or more areas were measured and averaged together to get a general composition. The vitreous slagged areas were measured on a smaller scale, to avoid the influence of corrosion products and metallic or mineral inclusions. Metallic prills were analyzed by area as well; the EDS analysis of prills larger than 50 µm had little background contamination from the surrounding matrix, but with smaller prills in the range of 20 µm, the matrix could be analyzed, scaled, and the background subtracted from the measurement to mitigate the influence of background in the results.

5. The Refractory

Macroscopically, the ceramics form groups depending on the texture and porosity. Drescher (1983, 182) noted the difference between the assumed 'local' ceramic and an imported variety of crucible ceramic that is dense, fine-grained, and thin walled. The compositions of the ceramics determined by SEM-EDS fall into two categories based on the ratios of alumina, silica, and iron oxide. The more refractory crucibles were probably imported and are typologically different from the less refractory crucibles, which are thicker, often larger, and far more common. In **Figure 1**, the divide in composition from the imported and local technical ceramics is illustrated.

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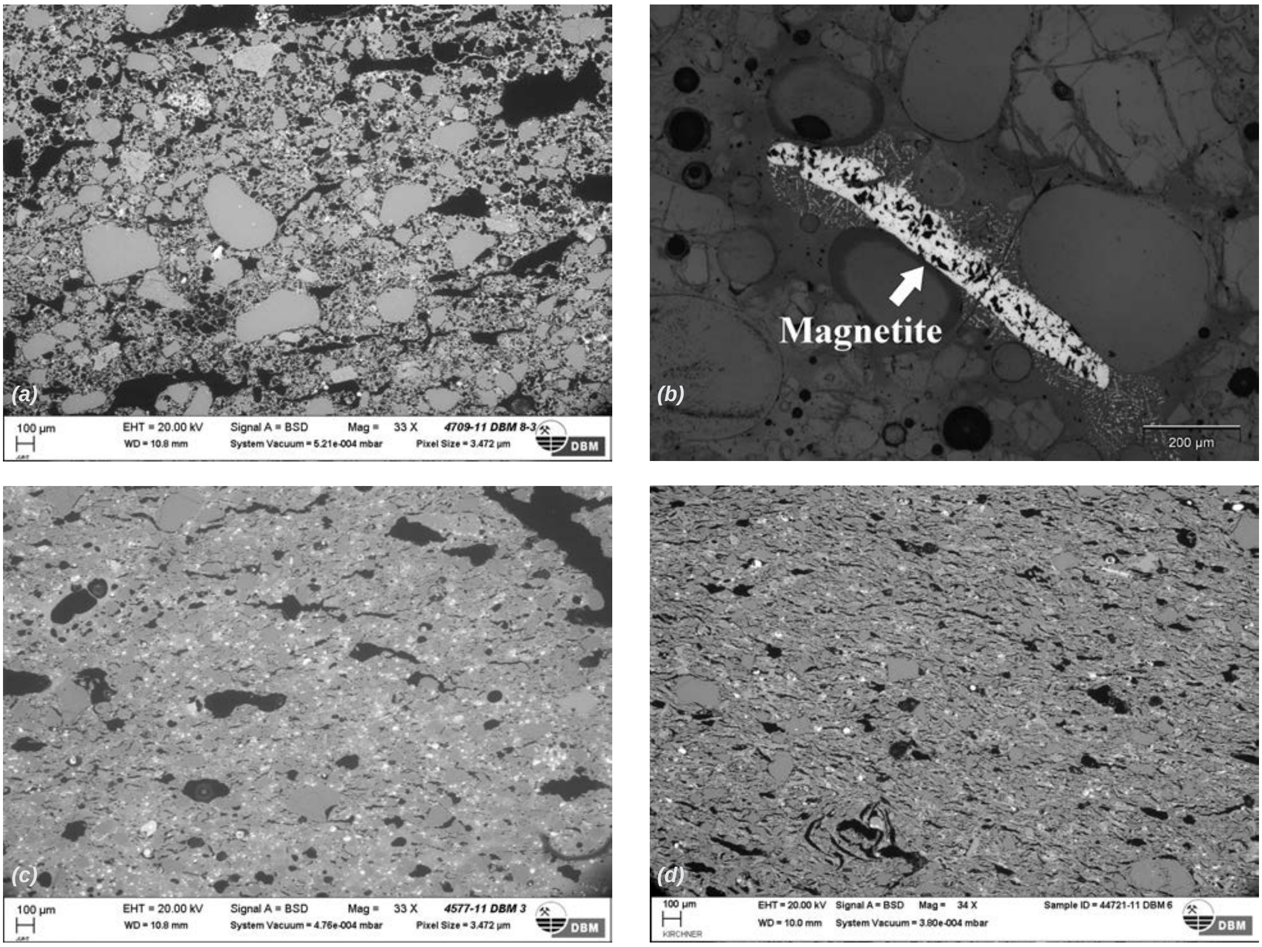
[3] SEM-EDS - Zeiss Gemini SEM with Noran System Seven Thermo UltraDry Silicon Drift X-ray Detector (SDD), 20.0kV.



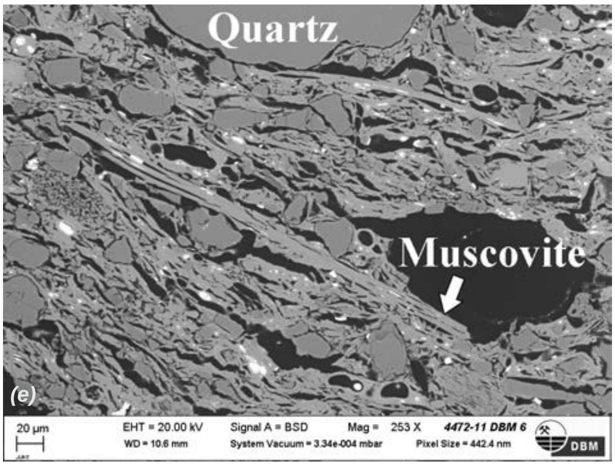


Figure 2 (a) *Ceramic Type 1 (**Cat. 220**, SEM-BSE) characterized by high porosity and large rounded quartz inclusions,* ***(b)*** *Oxidized iron hammer scale found in 'local ceramic', contamination from nearby iron working (**Cat. 218**, 5x magnification, frame 1.4 mm x 1mm, PLM),* ***(c)*** *Ceramic Type 2 (**Cat. 216**, SEM-BSE), and* ***(d)*** *Ceramic Type 3 (**Cat. 219**, SEM-BSE) are more dense with smaller quartz inclusions,* ***(e)*** *Ceramic Type 3 (**Cat. 219**) detailing the non-plastic inclusions. Angular to sub-rounded grains of quartz can be seen next to elongated crystals of heat-altered muscovite (**Cat. 219**, SEM-BSE).*

5.1 Local Ceramic: Low Alumina Type

Type 1: The ceramic is made from silty clay and is often tempered with sand (**Figure 2a**). Estimations of temper quantity based on thin-section analysis indicate a range of temper contents from no detectable additions to approximately 50 percent by volume sand. The sand temper is made up of rounded to angular quartz grains with small amounts of orthoclase and microcline. The sizes of the inclusions range from 500 µm to 10 µm with a concentration around 100 µm, and occasionally larger rock fragments of granite or quartzite are present. The ceramic is very porous and many examples, often cylindrical crucibles, were brought to their thermal limit. The high amount of quartz in the ceramic enables the cylindrical crucibles to be used for metallurgy; due to the low alumina and moderate iron content of the clay, it vitrifies at casting temperatures leaving behind quartz grains held together by a porous and frothy glass matrix. Many of the heating trays appear to be made from the same clay type, but often have less temper than the cylindrical crucibles and sometimes contain no visible temper. Because they were heated from above, they were not required to withstand the same thermal conditions as the cylindrical crucibles. A fragment of hammer scale from iron smithing was found in the matrix of one heating tray (**Cat. 218**) providing evidence for nearby ferrous metal working (**Figure 2b**). Ceramic Type 1 is

Type	Cat. Nr.	Form	Metal Traces	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K2O	CaO	TiO_2	Fe_2O_3	Notes
1	214	H.T.	Ag	1.2	1.2	10.5	78.3	0.7	2.6	0.7	0.6	4.2	Sand Tempered, Porous
1	229	H.T.	Ag	0.9	0.6	7.4	84.6	1.2	2.2	0.9	-	1.8	Sand Tempered, Porous
1	241	H.T.	Ag	0.9	0.9	9.4	79.9	1.7	2.1	0.7	0.7	3.7	Sand Tempered, Porous
1	218	H.T.	Ag	1.0	0.7	7.7	82.6	1.4	2.2	0.6	0.6	3.1	Sand Tempered, Porous
1	220	H.T.	Ag	1.0	0.8	8.4	81.9	1.4	2.2	0.8	0.5	3.0	Sand Tempered, Porous
1	238	H. T.	Ag	1.2	0.8	9.1	79.8	2.4	2.1	0.8	0.5	3.3	Sand Tempered, Porous
1	235	H.T.	Ag	1.0	0.6	9.9	76.0	5.0	1.9	1.4	0.6	3.6	Sand Tempered, Porous
1	222	Cr.	Cu	2.5	0.9	11.3	75.5	1.2	2.6	1.2	0.7	4.1	Sand Tempered, Porous
1	221 *	M.B.	Cu,Zn,Fe	1.5	1.1	10.8	72.1	1.6	2.0	1.6	0.7	4.2	Sand Tempered, Porous
2	244	Cr.	Ag,Cu,Zn	2.7	0.6	17.3	71.5	0.4	3.6	1.0	0.8	2.0	Quartz - Orthoclase
2	226	Cr.	Ag,Cu	2.0	0.9	22.2	66.9	0.7	3.8	0.9	0.7	1.9	Quartz - Orthoclase
2	216	Cr.	Cu,Zn,Pb	1.6	0.7	18.7	71.4	1.2	2.6	-	1.0	2.4	Quartz - Orthoclase
2	237	Cr.	Ag	2.6	0.8	22.1	65.5	1.4	4.7	0.6	0.9	1.4	Quartz - Orthoclase
3	243	Cr.	Never Used	0.6	0.6	20.4	65.3	6.3	2.5	2.2	0.8	1.3	Fine Quartz - Muscovite
3	231	Cr.	Ag	2.8	0.9	22.9	65.5	3.1	2.1	0.6	1.1	1.0	Fine Quartz - Muscovite
3	219	H.T.	Ag	1.0	0.8	23.8	65.8	2.2	2.4	0.6	1.2	2.2	Fine Quartz - Muscovite
3	246	Cr.	Ag	1.0	0.5	15.0	77.4	0.9	2.7	-	0.9	1.3	Fine Quartz - Muscovite
1	246	Cr.	Ag	1.2	0.6	7.8	83.2	1.3	2.4	0.9	0.7	1.9	Crucible Repair Coating

Table 1 *SEM-EDS semi-quantitative compositions of crucible fragments in polished section. H.T. = Heating tray, Cr. = Cylindrical crucible, and M. B. = Melting Bowl. * Analysis performed on rough breaks on the sherds and not in polished section. The three ceramic types were divided using the elemental compositions, temper, and ceramic texture. The "-" mean below detection limit (< 0.5 %). Values are normalized to 100 % and given in weight percent.*

the assumed local variety, and the largest crucibles, the 'melting balls', and most of the heating trays for both gold and silver were made from this ceramic type. [4]

5.2 Imported Ceramics: High Alumina Types

Type 2: This ceramic is tempered with quartz ranging from 500 µm to 25 µm, but the majority are 50µm or smaller, and the ceramic has a finer texture than the local variety (**Figure 2c**). Occasionally grains of orthoclase or microcline are present. Macroscopically the ceramic appears denser and ranges in color from gray to pinkish purple. Cracks within the crucible ceramic tend to run parallel to the crucible wall face. Structural cracking seems to be the reason for failure, in stark contrast to the melting and softening of the ceramic matrix in Ceramic Type 1. This Type 2 ceramic was used to make a particular type of round-bottomed cylindrical crucible (see **Cat. 224** for example).[5]

Type 3: This is made from fine and dense ceramic with mainly very fine quartz grains of 25-50 µm in size, though larger grains are occasionally present (**Figure 2d**). One easily distinguishable feature is the presence of muscovite in the range of 500 µm to 25 µm (**Figure**

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[4] Examples **Cat. 212, 215, 217, 218, 220, 221, 222, 223, 227, 228, 229, 232, 235, 236, 238, 239, 240, 241, 242,** and **245**.

[5] Examples **Cat**. **216**, **224**, **226**, **230**, **234**, **237**, **244**.

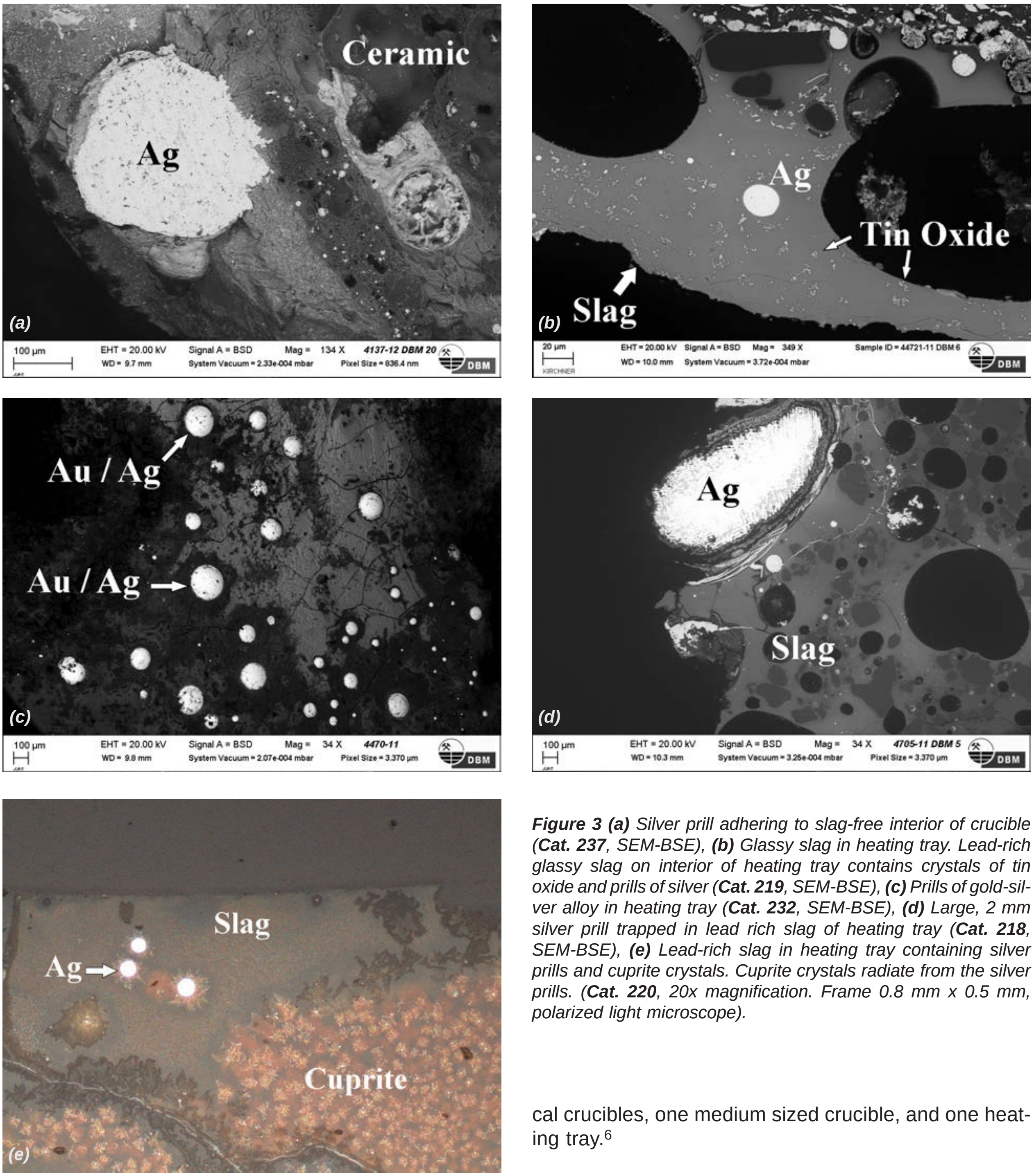

Figure 3 ***(a)*** *Silver prill adhering to slag-free interior of crucible (**Cat. 237**, SEM-BSE),* ***(b)*** *Glassy slag in heating tray. Lead-rich glassy slag on interior of heating tray contains crystals of tin oxide and prills of silver (**Cat. 219**, SEM-BSE),* ***(c)*** *Prills of gold-silver alloy in heating tray (**Cat. 232**, SEM-BSE),* ***(d)*** *Large, 2 mm silver prill trapped in lead rich slag of heating tray (**Cat. 218**, SEM-BSE),* ***(e)*** *Lead-rich slag in heating tray containing silver prills and cuprite crystals. Cuprite crystals radiate from the silver prills. (**Cat. 220**, 20x magnification. Frame 0.8 mm x 0.5 mm, polarized light microscope).*

2e). Of this group, one fragment of an unused crucible was found to contain muscovite, but in all used fragments the muscovite had been heat-altered indicating temperatures at or above 1100 °C (Cultrone et al. 2001, 626; Guggenheim et al. 1987). The ceramic is hard and compact with a tan to gray color. One medium sized crucible (**Cat. 246**) of this type of ceramic was repaired with a coating of very finely crushed quartz and clay after a crack formed which resulted in the loss of silver. A variety of crucible forms were made from Ceramic Type 3; the thinnest and smallest, finger (thimble)-sized cylindrical crucibles, one medium sized crucible, and one heating tray.[6]

5.3 Inter-site Comparison

Crucibles from two sites have been studied with published elemental compositions: from Kaupang (Pedersen 2010) and from Viborg (Jouttijärvi/Andersen 2005). The material from Kaupang in southern Norway is contemporaneous with the crucibles under investigation, and would have been a site with trading connections to Hedeby while 11th century Viborg, in Denmark, is contemporary to the later phases of Hedeby. In both cases kaolin-containing crucibles were imported (Jouttijärvi/Andersen 2005, 356; Pedersen 2010, 191). At Kaupang, Viborg, and Hedeby local ‘inferior’ varieties were also

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[6] Examples **Cat. 219**, **231**, **243**, **246**.

			Cu	σ	Ag	σ	Au	σ	Pb	σ
Cat. 232	Heating Tray	Gold-Silver (x8)	**1.7**	1.2	**40.5**	9.8	**57.8**	8.8	**-**	-
Cat. 227	Heating Tray	Gold-Silver (x10)	**2.4**	1.0	**12.5**	3.2	**85.1**	3.6	**-**	-
Cat. 242	Heating Tray	Gold-Silver (x16)	**4.5**	2.2	**31.4**	15.1	**64.1**	15.9	**-**	-
Cat. 228	Heating Tray	Gold (x7)	**4.8**	1.9	**3.5**	1.6	**91.6**	1.4	**-**	-
Cat. 215	Heating Tray	Gold-Silver (x12)	**1.0**	0.6	**9.9**	1.7	**89.2**	2.0	**-**	-
Cat. 240	Heating Tray	Gold-Silver-Lead (x13)	**3.0**	0.6	**8.5**	4.4	**74.2**	6.9	**14.2**	6.3
Cat. 234	Crucible	Gold-Silver (x9)	**2.0**	0.6	**12.7**	3.9	**84.7**	3.6	**-**	-
Cat. 230	Crucible	Gold-Silver (x5)	**1.7**	0.2	**10.6**	0.9	**87.8**	0.8	**-**	-

			Cu	σ	Sn	σ	Zn	σ	Ag	σ	Pb	σ	Bi	σ
Cat. 241	Heating Tray	Silver (x6)	**3.4**	1.4	**-**	-	**-**	-	**96.4**	1.3	**-**	-	-	**-**
Cat. 218	Heating Tray	Silver (x10)	**2.8**	1.0	**-**	-	**-**	-	**96.9**	1.2	**-**	-	-	**-**
Cat. 220	Heating Tray	Silver (x6)	**8.3**	2.4	**-**	-	**-**	-	**90.8**	2.9	**0.9**	1.3	-	**-**
Cat. 219	Heating Tray	Silver (x4)	**1.6**	0.9	**-**	-	**-**	-	**98.1**	1.4	**-**	-	-	**-**
Cat. 229	Heating Tray	Silver (x5)	**5.6**	2.2	**-**	-	**-**	-	**94.3**	2.2	**-**	-	-	**-**
Cat. 229	Heating Tray	Silver-Brass (x8)	**62.9**	14.9	**-**	-	**4.0**	0.9	**29.4**	15.4	**3.7**	1.4	-	**-**
Cat. 214	Heating Tray	Silver-Copper (x5)	**30.1**	19.8	**-**	-	**-**	-	**67.8**	19.8	**1.4**	1.4	0.7	**1.7**
Cat. 231	Crucible	Silver (x5)	**2.0**	1.2	**-**	-	**-**	-	**98.3**	1.2	**0.7**	0.7	-	**-**
Cat. 226	Crucible	Silver (x3)	**5.0**	2.0	**-**	-	**-**	-	**95.0**	2.0	**-**	-	-	**-**
Cat. 226	Crucible	Copper Alloy (x4)	**96.0**	2.9	**2.6**	0.5	**-**	-	**-**	-	**1.4**	2.7	-	**-**
Cat. 237	Crucible	Silver (x8)	**2.7**	0.6	**-**	-	**0.5**	0.5	**95.7**	1.1	**1.1**	1.4	-	**-**
Cat. 244	Crucible	Silver-Brass (x4)	**55.9**	16.9	**-**	-	**2.5**	1.7	**41.6**	18.1	**-**	-	-	**-**
Cat. 222	Crucible	Copper (x1)	**98.7**	-	**0.8**	-	**-**	-	**-**	-	**-**	-	-	**-**
Cat. 216	Crucible	Leaded Brass (x2)	**80.3**	1.0	**-**	-	**10.7**	1.1	**-**	-	**9.1**	0.2	-	**-**

***Table 2 and 3** These tables display the approximate elemental compositions of metallic inclusions and metallic prills found on and in heating trays and cylindrical crucibles. The standard deviations show the heterogeneity of prill compositions. High deviations indicate mixing of different metals either through intentionally alloying or by contamination from subsequent casts. Heating tray **Cat. 229** contained prills of relatively pure silver and prills of a silver-brass alloy. Crucible **Cat. 226** contained prills of silver and copper that are not mixed and indicate that the crucible was used to cast two different metals. Number in parentheses is the number of analyses averaged together. The "-" mean below detection limit (< 0.5 %). Values are normalized to 100 % and given in weight percent.*

used. Often in Viborg and Kaupang heating trays were made from local clay, as are the majority of heating trays inspected from Hedeby. It is also noted in the late 10th to early 11th century site of Borgeby in Scania that heating trays were made of local clay, the same used for loom weights and casting moulds (Brorsson 1998). The crucibles used at Ribe are similarly described to Hedeby Ceramic Type 1, being made of sand bound together by clay (Brinch-Madsen 1984, 25), and seems to indicate access to similar types of local raw materials. According to the analyses, the crucibles from Kaupang tend to have higher alumina values than those at both Viborg and Hedeby, but there are also issues comparing the crucibles from Viborg and Hedeby directly. The Viborg analyses show greater ranges of iron, alkali, and alkaline elemental concentrations, although the ranges of silica and alumina are compatible.

6. The Alloys

SEM-EDS was used to characterize the alloys melted in the crucibles and heating trays. As previously mentioned, fragments containing traces of gold were analyzed non-destructively, while those showing silver or copper corrosion products were sectioned so that metallic inclusions free of corrosion products could be studied. The alloys presented in **Tables 2** and **3** are the compositions of individual metallic prills averaged together and the standard deviations are shown to better assess the homogeneity of the prill compositions.

6.1 Crucibles

Two crucibles, both of Type 2 high alumina ceramic, showed visible traces of gold. The gold in both crucibles is argentiferous with small amounts of copper. Other crucibles indicate that high quality silver was being cast, but one crucible shows a mixture of brass and silver. Brass-silver alloys may not have been uncommon in the Viking Age; at Hedeby two objects out of 19 hacksilver objects tested contained comparable portions of brass. Substantial amounts of metal adhered to crucible **Cat. 216**, which turned out to be leaded brass. Occasionally silver and gold prills and drips of metal adhere to the ceramic on the interior of the crucible (**Figure 3a**).

Crucible **Cat. 226** contained two types of metal prills with no indication of mixing and seem to indicate at least two casting events: one with high quality silver and a second with nearly pure copper.

6.2 Heating Trays

Metallic prills range in size from sub-micron size up to 3 mm in diameter and were for the most part trapped in the glassy slag on the interior of the dishes. The prills of silver always contain amounts of copper. Five heating trays had gold prills adhering to slag and show a range of silver to gold ratios. Heating trays **Cat. 232** and **Cat. 242** have a wide range of ratios indicating either multiple use of the heating tray or that gold and silver were alloyed together in a single melt. For the most part, the alloys seem to reflect typical precious metal alloys used in the Viking Age (see Pernicka 2002 and Steuer 2003), but there are some alloys that stand out due to their high base metal contents. In one heating tray (**Cat. 240**) used for melting gold, all the prills analyzed contained significant amounts of lead. The silver prills of one heating tray (**Cat. 214**) contained major amounts of copper, and another heating tray (**Cat. 229**) contained prills of standard quality silver along with prills of a silver-brass alloy. If the heating trays truly represent the cupellation process, should there be precious metal prills with major quantities of base metals? Many of the gold alloys found in the heating trays are no purer than the Hedeby gold finds analyzed by Pernicka (2002), but the silver prills have a larger range from high purity (ca. 2 wt. % Cu) to alloys debased with copper or brass. This raises the question of what is actually going on in these heating trays, how were they used, and for what purpose?

7. Function of Cylindrical Crucibles and Heating Trays

What is clear from the analysis of prills is that both crucible forms were used for melting gold and silver alloys and that the purity of the alloys cannot be differentiated between the two crucible forms. The heating trays seem to only have been used for precious metal alloys, whereas the cylindrical crucibles were used for both precious metals and copper alloys. The two types of crucible differ in many other important ways. Morphologically they are different. The cylindrical crucible has a more restricted shape to help protect the metal from oxidation whereas the open form of the heating tray is designed for the opposite. The cylindrical crucibles were heated externally, and it is unlikely a coincidence that several cylindrical crucibles used for precious metals are made of imported high-alumina ceramic. The thin walls and dense ceramic of the imported ceramic help to transfer heat more quickly to the metal and the higher alumina provides better stability at casting temperatures. The closed form is also advantageous for use in charcoal hearths and for manipulation and casting. It is clear that cylindrical crucibles were used in casting, some showing clear tong impressions, but the one complete heating tray (**Cat. 217**) also shows the marks of a tong indicating that it was manipulated at high temperatures.

The heating trays were heated from above with little alteration to the bottom of the dish and relied on the insulating qualities of the ceramic to maintain structural integrity. Heat was probably applied with a single piece of charcoal and forced air from a blow pipe or bellow, which could quickly bring the metal to casting temperatures. The interior volume of the heating tray means that only small amounts of metal, approximately 20 to 80 grams, could be melted. The glazing of the exterior of cylindrical crucibles is presumably caused by the fluxing of fuel ash, while the glazing of the interiors of the heating tray is of a completely different character. Being caused by the reaction of lead with the ceramic under oxidizing conditions, it is reminiscent of the cupellation process.

7.1 Heating Trays and Cupellation

The association of heating trays with cupellation goes back to Drescher (1983, 182-3) and was further maintained by Bayley (1992). The process of cupellation is one that has been known for millennia and relies on the resistance of gold and silver to oxidation at high temperatures to separate them from lead, copper, tin and zinc, which do oxidize under these conditions. In the process, an excess of lead is added to the gold or silver and heated in a cupel or in a hearth, and litharge and base metal oxides are formed which can be skimmed-off or absorbed into a porous non-reactive material. Calcium phosphate, calcium-rich ash, and calcareous clay are preferred materials for this purpose due to their resistance to vitrification in the presence of lead oxide (Bachmann 1993, 493). Some of the sampled heating trays from Hedeby show that a thin calcareous layer was applied to the interior (**Figure 4**), however, the layer is too thin to absorb litharge; instead, it seems to be a protective coating to help keep the metal from sinking too deep into the ceramic at high temperature.

As we can see from the heating tray slag compositions, all contain elevated amounts of lead as well as other metal oxides (**Table 4** and **Figure 5**). What can be assumed is that small amounts of lead were added to the silver or gold and, through heating, some metallic and non-metallic impurities were drawn out of the metal into the lead-rich slag. For instance, the gold-silver prills of heating tray **Cat. 232** had zinc contents under one percent, but the lead-rich slag can contain up to several percent zinc. The same is true for heating tray **Cat. 219** where tin oxide phases are found in the slag, but the silver prills are nearly pure and are free of detectable amounts of tin (**Figure 3b**). There are clear indications that oxidation and purification occurred. Lead is detrimental to the working properties of precious metals and should have been completely removed by oxidation. The prills of one heating tray (**Cat. 240**) show that the separation of lead was not complete and the gold alloy must have been heated again to remove this impurity. A higher purity was achieved with the gold prills than with the silver. It appears that total purification of silver was dif-

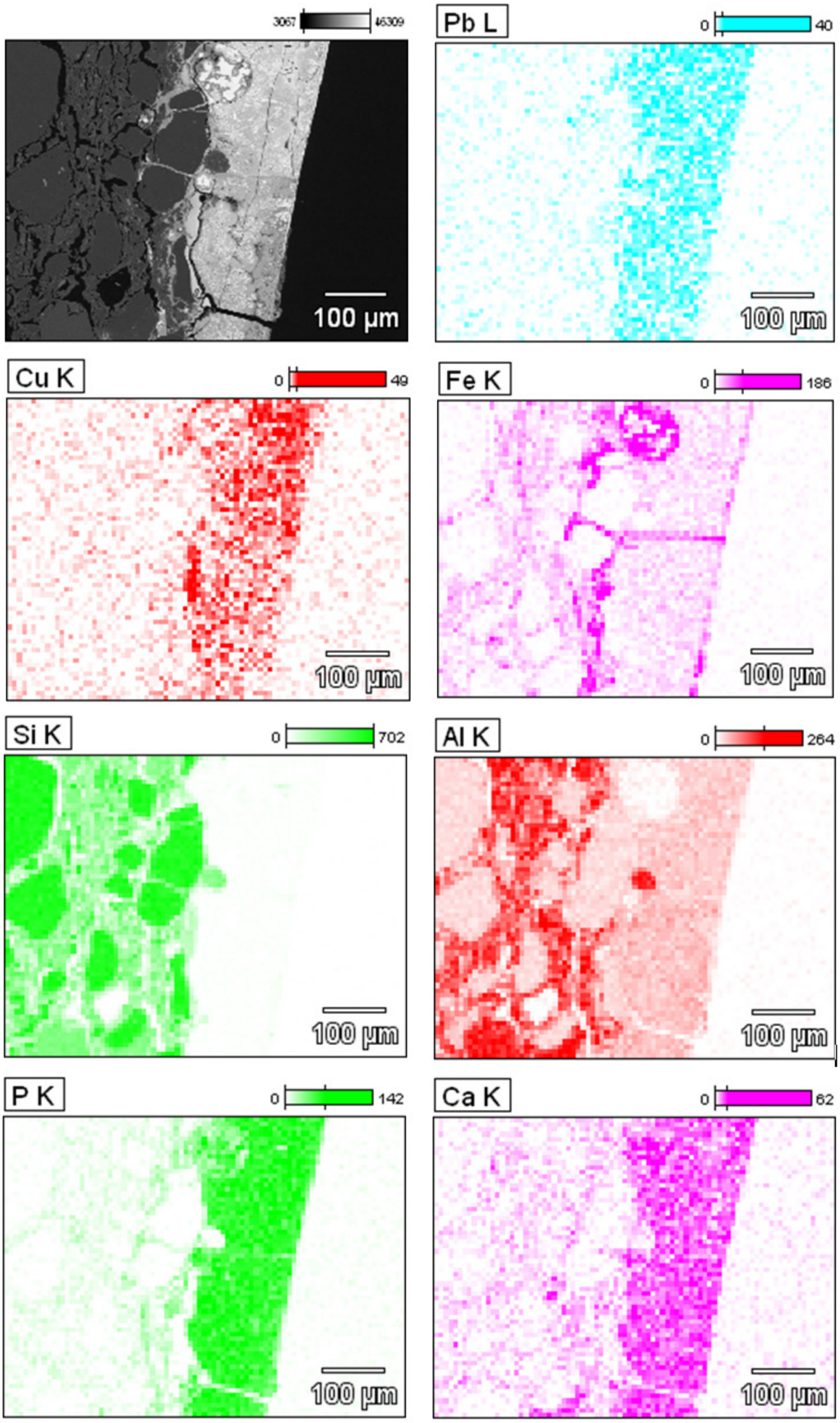

Figure 4 *SEM-EDS elemental scan of the interior of heating tray* ***Cat. 235.*** *The interior of the heating tray is coated with a 150-300 µm thick calcareous layer that is enriched in phosphorus, lead, and copper. The ceramic is demarcated with the zone higher in silicon and aluminum.*

Cat. Nr.	Metal	(n=)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Fe_2O_3	Cu_2O	ZnO	SnO_2	PbO	Ag	Au
240	Au	x11	-	0.5	5.8	54.3	4.4	1.7	-	-	3.8	1.8	-	-	27.2	-	-
215	Au	x5	2.7	-	6.3	35.7	7.3	1.7	3.1	-	27	1.6	0.5	-	11.8	-	1.5
227	Au	x13	2.1	1.0	6.7	50.5	2.4	5.0	6.7	-	5.4	-	-	-	19.6	-	-
232	Au/Ag	x4	-	0.7	6.5	47.4	2.0	1.8	3.6	-	3.2	7.9	9.5	-	14.3	2.7	-
242	Au/Ag	x3	1.3	0.5	6.0	50.8	0.7	-	1.8	2.0	4.7	3.2	-	-	28.7	-	-
219	Ag	x7	2.3	1.2	15.7	45.9	1.0	2.3	2.8	0.8	5.2	4.3	-	3.2	8.8	6.3	-
235	Ag	x3	2.1	0.8	10.4	32.6	12.1	1.8	2.3	0.7	4.2	7.2	-	0.7	21.0	3.9	-
218	Ag	x6	1.9	1.3	7.2	60.4	-	2.5	3.2	0.5	3.3	9.7	-	-	4.9	4.7	-
220	Ag	x8	3.7	1.2	6.7	56.6	1.6	3.6	4.8	0.6	3.8	7.3	-	-	8.5	1.6	-
214	Ag	x4	1.9	1.4	6.3	50.4	1.4	3.2	5.2	2.5	4.1	3.0	2.0	-	17.5	0.9	-
241	Ag	x4	1.6	0.9	6.5	49.5	1.8	1.0	2.2	1.1	1.9	9.3	-	-	16.1	8.1	-
229	Ag	x5	1.8	0.6	7.5	60.2	0.7	4.1	2.0	0.5	2.3	6.6	-	-	12.2	1.5	-
238	Ag	x9	0.7	0.7	7.3	39.7	5.7	2.7	3.3	-	6.0	3.0	1.1	2.1	23.4	3.9	-

Table 4 *Slag compositions from heating trays measured by SEM-EDS. The slag from the gold-containing crucibles was measured non-destructively, but the slag from the silver-containing crucibles was measured in polished section. All crucible slags are lead bearing and typically contain amounts of copper and other base metals. The "-" means below detection limit (< 0.5 %). Values are normalized to 100 % and given in weight percent.*

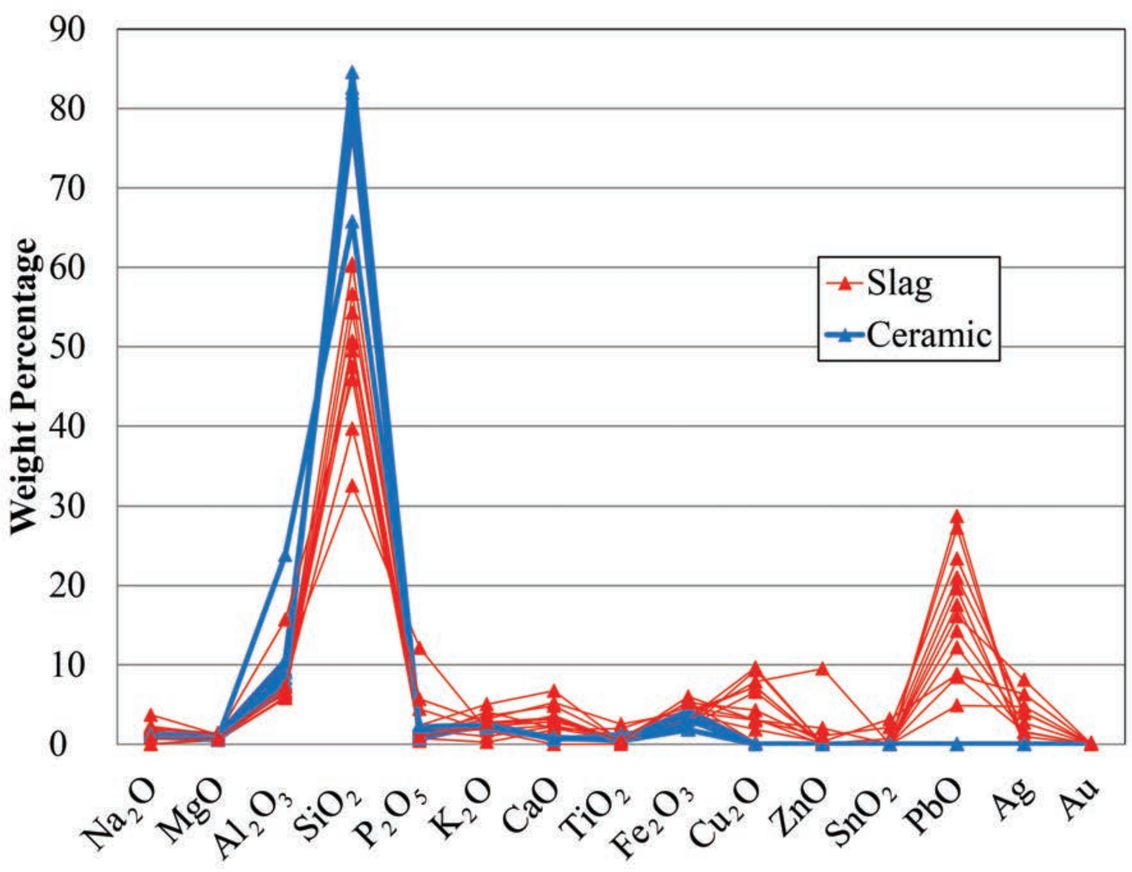

Figure 4 *This graph contrasts the ceramic composition and the slag compositions of heating trays where both ceramic and slag could be measured. It is clear that there is always an increase of lead oxide in the slag, and silver, copper oxide, zinc oxide, and calcium oxide show higher concentrations.*

ficult to attain or that the removal of all traces of copper was not the goal of the process.

It cannot be ruled out that heating trays were used to perform analytical cupellation; however, this technology is far from optimal for this purpose. Significant amounts of silver and gold are lost in the slag as prills up to several millimeters in size (**Figures 3c** and **3d**). Since silica-rich ceramic was used for all heating trays, litharge could not be absorbed but instead formed a lead-silicate glass. Only small amounts of lead could

***Figure 6 (a-b)** Modern crucibles for melting and refining gold from the open-air museum in Hagen, Germany and (c-d) visually comparable archaeological crucibles from Hedeby: **(a)** Cylindrical crucible used for melting larger quantities of metal and **(b)** a shallow dished-shaped crucible used for melting / cleaning scrap metal. The slag on the interior of the crucible is a glass produced by adding borax during melting. Prills of silver can be seen trapped in the slag. **(c)** Cylindrical crucible **Cat.223** and **(d)** heating tray **Cat. 217** **fr**om Hedeby. The sizes of the crucibles are approximately 5 cm rim diameter for the cylindrical crucibles and 4 cm diameter for the heating trays. (Photos: S. Merkel).*

have been added to the heating tray, no more than enough to make a thin slag layer. If lead was added in greater quantities it could destabilize the ceramic. The litharge produced would have often been cuprite rich, which may be responsible for the high loss of silver as micro-inclusions in the slag (see **Figure 3e** and **Table 4**). Bayley and Eckstein (1997, 108) describe an example of inefficient cupellation from Roman Britain and argue that silver was lost because of the high cuprite content and insufficient lead. The analytical cupellation process requires accurate weight measurements of the pre- and post-refined metal to calculate the original precious metal content. A combination of several factors prevents accurate calculation of gold or silver contents of the metal being 'tested' using the heating tray technology.

7.2 Heating Trays: Crucibles for Small-Scale Refining and Casting

An alternative interpretation seems to be more likely, and that is that the heating trays were used to purify small amounts of metal in a workshop setting for metallurgical purposes. Theophilus the Presbyter is often referenced in the discussion of heating trays because his 12th century account of silver purification mirrors the technology of the heating tray (Hawthorne/Smith 1979, 96-7). He describes the lining of an open ceramic crucible with ash and that metallic lead and impure silver are melted together, and the impurities of the silver are drawn out through the flames and blasts of the bellows. Theophilus warns about the possibility of zinc or tin in the silver and how this could be removed through the addition of glass and lead. The slag found in the Hedeby heating trays shows that only lead was added because the alumina to silica ratio is the same as the ceramic. The resulting slag was able to absorb some of the oxides of copper, tin, zinc, and iron.

The formation of a silicate slag, though detrimental to analytical cupellation, does have benefits for simple refining. If the silver or gold is impure and mixed with silicates, contamination of sand, clay, or ash, the high-temperature reaction with lead oxide can help to remove these materials. Small scraps, filings, spills, production debris, and metal recovered through the crushing of crucibles could be cleaned of its non-metallic impurities in addition to some metallic impurities. Al-Hamdānī, a 10th century Arabian geographer and metallurgist, describes a similar technology used to remove such impurities from gold. According to his ac-

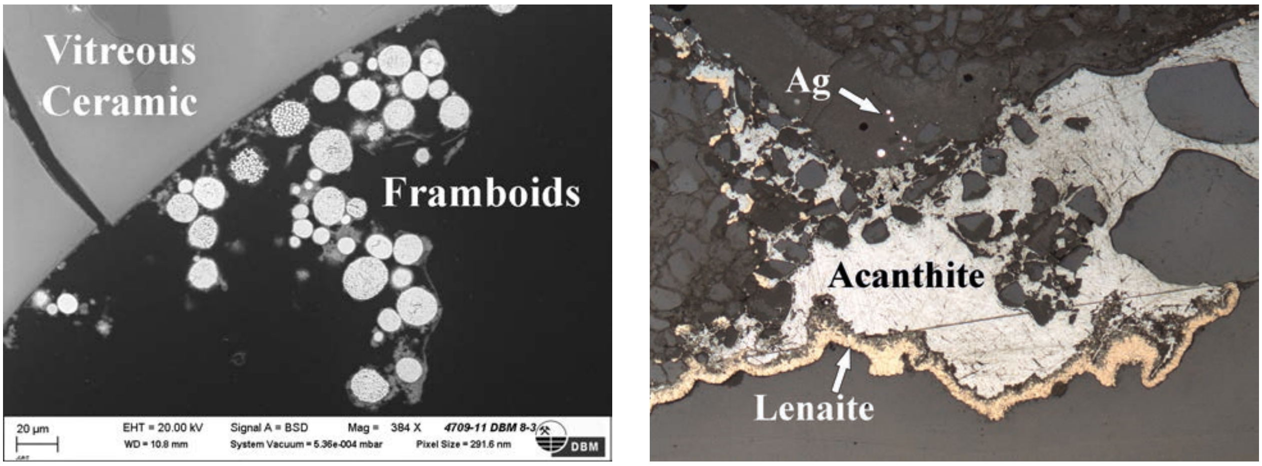

Figure 7 ***(a)*** *Pyrite framboids in the porosity of a crucible (****Cat. 222****, SEM-BSE),* ***(b)*** *Crucible fragment with silver prills trapped in slag and corrosion products: silver sulfide and silver iron sulfide. SEM-EDS analysis of the golden-colored mineral repeatedly produced the atomic ratio of* $AgFeS_2$*, which is similar to the mineral lenaite (****Cat. 246****, 5x magnification, frame 1.4 mm x 1 mm, PLM).*

count, impure metal is heated in an open crucible, and boric oxide[7] (instead of lead) is used to create a borosilicate slag to clean the gold of impurities and dust (Toll 1968, 158-60). The origins of the use of boric oxide, also known as borax, in gold metallurgy are obscure, but it is thought that borax was mined in Tibet or Azerbaijan and was used by the Arabic-speaking world long before it became available to northern Europe (Grieb 2004). The borosilicate glass formed would act in a similar way to a lead-silicate glass in its ability to remove base metal oxides as well as silicate material from the gold or silver. In addition to the mention of borax in refining precious metals, al-Hamdānī also mentions that heating silver in an open goldsmithing crucible with plenty of air can help to remove lead impurities in silver (Toll 1968, 172-174) and provides a close parallel to the early medieval heating tray technology.

The technology described by al-Hamdānī can still be seen today in the goldsmith's workshop in the open-air museum in Hagen, Germany.[8] In this gold-smithing workshop, cylindrical crucibles are used for melting large amounts of gold (**Figure 6a**), but a shallow dish-shaped crucible with a glassy slagged interior is used to melt lesser quantities of gold or silver (**Figure 6b**). Small amounts of metal or workshop debris could be melted quickly in the shallow crucible with borax to help remove contaminants, and, as in the account of al-Hamdānī, the gold is then cast into an ingot mould and the purified metal is used for smithing. According to the account of Theophilus, the silver was refined for this same purpose; that is for fine smithing (Hawthorne/Smith 1979, 96-7). According to the goldsmith of the Freilichtmuseum-Hagen, Mr. Kordon (pers. comm. 5.7.2014), these small dish-shaped crucibles are advantageous for several reasons: they are quicker and more fuel efficient for melting small quantities of metal, and the slag formation on the interior helps to trap impurities, but complete removal of all impurities, however, is not possible with this technique. This is done either by true cupellation in bone ash cupels or, even better, with modern acid treatments that were not available in the early medieval period.

7.3 Conclusions

The cylindrical crucible form is ideal for the melting of precious metals and copper alloys. They are multi-use and are well-suited for melting larger amounts of metals and heating in charcoal hearths. Regarding the heating trays, the evidence suggests that their function is for the melting and casting of small amounts of precious metals and that some impurities could be cleansed in the process. Whether it is production waste or silver / gold acquired through other means, the melting of metal in an oxidizing atmosphere with a small amount of lead can clean the metal of some unwanted metallic and silicate impurities that may be trapped inside. This process differs from true cupellation in that little lead was used; enough lead to produce a thin layer of lead-silicate slag, but not enough to create the excess of litharge needed to completely purify the gold or silver of all their base metal impurities. The use of small amounts of lead in a silica-rich crucible contribute to the inefficiency of the heating tray process in the recovery of noble metals, which is attested by the loss of metal, particularly silver, in the crucible slag. This fact, in combination with what is known about the testing of precious metals in the medieval period (see **Chapter 2 Section 2.5.2**), supports the conclusion that the function of the heating tray was not for testing of purity by analytical cupellation, but rather the recycling of small amounts of precious metals in a workshop setting to create clean alloys for fine smithing.

8. A Note on Corrosion and the Burial Environment

Upon the sectioning and examination of the cylindrical crucible and heating tray fragments the silver was

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[7] Boric oxide is also known as boric acid, borax, and in Arabic Būraq or Tinkār (see discussion by Grieb 2004, 449).

[8] LWL Freilichtmuseum-Hagen, NRW, Germany, visited on 05.07.2014.

often in sulfide form (Ag_2S). Niello, a black material made from silver sulfide, or copper-silver sulfide, was often used as an inlay for gold and silver objects in the early medieval period. At first it was thought that there may have been a connection and that these residues might reflect the manufacture of niello, but upon closer inspection, it was determined that the formation of sulfides was due to corrosion and the burial environment conditions. Two characteristic features support this conclusion and parallel features first identified in crucible fragments recovered from water-logged lake sediments from the Pfyn culture of southwest Germany and Switzerland (Rehren 2009). Pyrite (FeS_2) framboids were discovered in the porosity of many of the crucibles and heating trays just as they were found in the crucibles from water-logged burial environments of the Pfyn cultural layers (**Figure 7a**). Framboidal pyrite is known to form in anoxic marine and sulfur-rich environments, although it is still not clear exactly how they form (Wilkin/Barnes 1997). The second clue is that in addition to the silver sulfides, layers of silver-iron sulfides were discovered and form similar ‘cauliflower’-like corrosion patterns to those described with the Pfyn material (**Figure 7b**). The Pfyn crucibles however are linked to copper metallurgy and the corrosion products are thus copper sulfides and copper-iron sulfides like chalcopyrite, but the same transformation processes appear to have taken place with silver at Hedeby. The lower levels of the 1960s excavations were indeed waterlogged, but these distinctive corrosion features are found in crucible fragments from many of the excavation levels.

Appendix H
Elemental and Lead Isotope Analysis of Lead, Tin, and Refining Debris from Hedeby

Summary

Lead and tin objects and refining debris were analyzed as part of a larger study of the elemental and lead isotope composition of Viking-age non-ferrous alloys from the settlement of Hedeby. A total of twenty-three lead and tin objects ranging from ingots, scrap metal, tin coatings, and tin dirham imitations were analyzed to identify what types of lead-tin alloys were used at Hedeby and to potentially shed light on the source or sources of the metal. Additionally, lead-rich slag from three heating tray fragments and lead carbonate from a crucible were analyzed to compare to the lead objects and the silver finds from Hedeby to explore the possible consequences of refining on the lead isotope ratios of precious metals.

1. Introduction

As Ansprach (2010) explains, the lead and tin finds from Hedeby are a highly heterogeneous group of objects and the role of these objects in Viking society is far from understood. The relationship between metals like lead and tin to the more precious metals is complex and intricate. The use of lead and tin for jewelry can represent a low-cost alternative for the imitation of object archetypes produced in copper alloys and precious metals, but often lead and tin objects depart from the styles and forms of the metals deemed more prestigious and expensive (Ansprach 2010, 89). Although the relationship between the forms of lead / tin and precious metal objects is indirect, there are conceptual and metallurgical relationships between the metals. As gold is a contrast to silver,copper-alloy objects can be tinned or inlayed with tin to provide color contrast (example **Cat. 173**). The false dirhams from Hedeby's harbor are made mostly of tin, and this can be no accident because tin is the base metal most similar to the color of silver.

The distinctive forms of many lead and tin objects seems to be an indication for a metallurgical craft specialization, but there are clear indications that the use of lead and tin can be intimately tied to the manufacture of the most precious of objects. The low melting points of lead and tin make them ideal for soldering as is evident from a Carolingian-style gilt silver brooch (**Cat. 166**, **Appendix F: Figures 5** and **6**). Another practical application for lead and tin is for the construction of the core for the elaborately decorated Terslev / Hiddensee style brooches and pendants, which are the pinnacle of Viking-age gold smithing technology (Armbruster 2002). Lead was used in the technical process for the making of pressed sheets of gold and silver for this type of brooch, a process that is attested at Hedeby (Armbruster 2002, 239-45). At the Viking-age mint of Sigtuna, in Sweden, the die for the silver coins King Olof Eriksson was tested on a lead sheet (Eilbracht 2004, 35-40). The physical properties of lead such as its low melting temperature and malleability make it ideally suited for such applications, but the chemical properties of lead were also known and exploited by gold and silver smiths. As discussed in the previous appendix (**G**), the transformation of lead into litharge and / or lead-silicate glass is crucial for precious metal refining technologies and evidence is found in early medieval workshops and settlements over much of the Viking world.

The applications of lead and tin are manifold; not only were they used for the casting of simple objects like brooches, pendants, ornaments, and weights, but their use is also closely connected to the metallurgy of some of the most costly and exquisite objects of the Viking Age. Such a range of functions is rare in medieval metallurgy and demonstrates to the importance of the availability of these metals in non-ferrous metal workshops and settlements of all social and economic levels.

2. The Elemental Composition of Lead and Tin Finds

Four tin dirham imitations were analyzed by laser-ablation ICP-QMS and pXRF for major elements while the other miscellaneous lead-tin finds were analyzed by single-collector ICP-MS. The results are presented in **Appendix C**, **Tables 1** and **5** and the methodology for sample preparation and the instrumentation can be found in **Chapter 6**. The alloys range from nearly pure lead to above 90 percent tin (**Figure 1**). There are slight bends of the slope visible at 30:70 lead to tin and 70:30 lead to tin, but too few objects have been analyzed to get a representative picture. The alloying of lead and tin together considerably harden the metal (see Ansprach 2010, Figure 3), however the majority of objects tested are unalloyed lead.

The cast tin dirhams are all of slightly different alloys, although three of the four were cast in the same mould (Hovén 1990, 174; Steuer et al. 2002, 156-9).

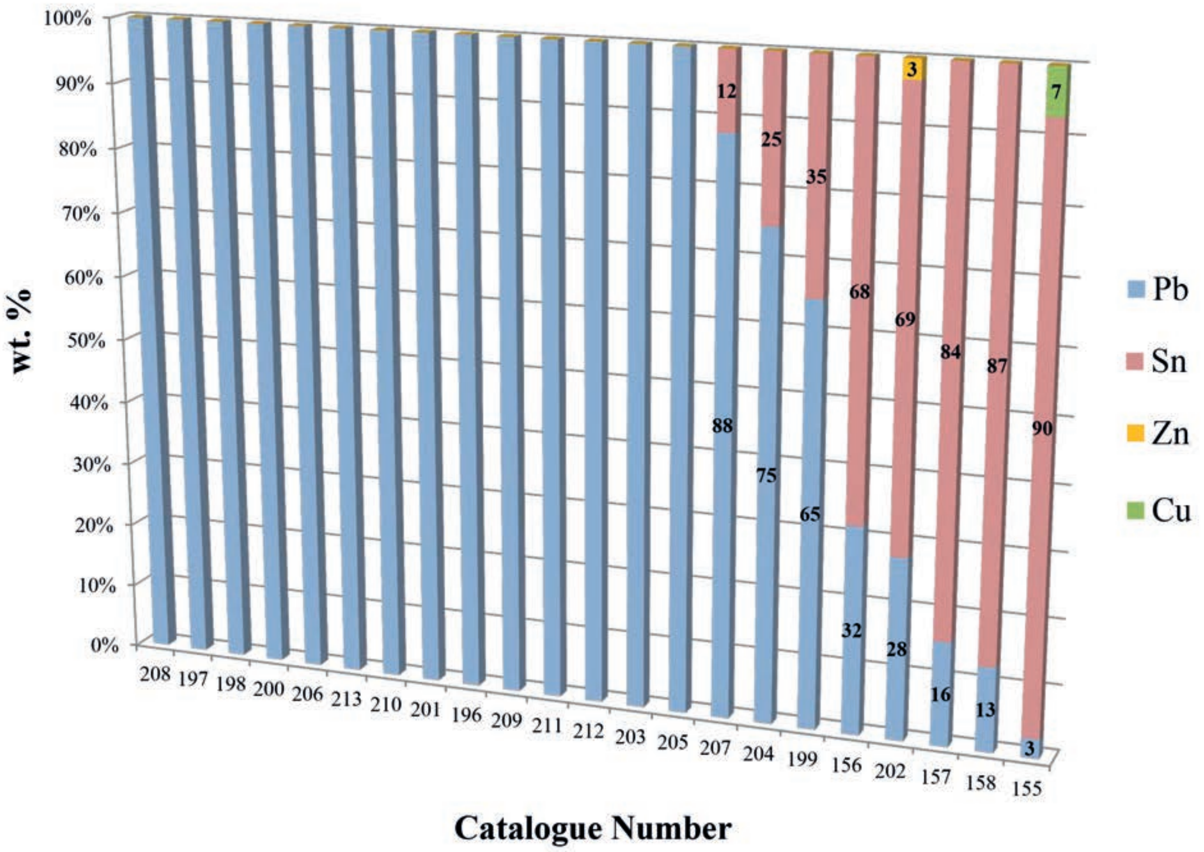

Figure 1 *The major and minor elemental composition of lead and tin find from Hedeby determined by SC-ICP-MS, ns-LA-ICP-QMS, and pXRF.*

The three cast ‘Abbasid’ dirhams belong to a larger set of 9 identical dirhams found in the Hedeby harbor, and the entire set has been analyzed by Steuer (2003, 149). The analyses are to a similar result with major elemental compositions differing by less than five weight percent from the analyses of Steuer.[1] They consist of alloys ranging from around 70 to 90 percent tin and 10 to 30 percent lead. A curious ‘Samanid’ dirham was also found in the harbor but was not previously analyzed. It was also found in the harbor, like the nine ‘Abbasid’ tin dirhams, and it has been suggested that it may also be a falsification making a complete set of ten dirhams (Kilger 2008a, 289; Steuer et al. 2002, 158). Elemental analysis confirms this supposition; however, the alloy of this tin dirham diverges slightly in that it contains a much higher copper content. The ‘Samanid’ tin dirham is made of a different material from the ‘Abbasid’ tin dirhams, and possibly at different times, but together the ten dirhams were probably used as a deceitful weight set to trick trading partners who trusted or relied on the weight standard of the dirham (see Kilger 2008a, 289-90).

The other finds, such as scrap metal, ingots, and weights, were destructively sampled and analyzed by mass spectrometry at the Deutsches Bergbau-Museum, Bochum. Six of the eighteen finds came from secure archaeological contexts (**Cat. 196**-**201**), and stratigraphic dating is still a work in progress. The rest were found while metal detecting in the Hedeby settlement area. Most of the metal-detected objects sampled are of forms comparable to finds from the plow zone of the Viking settlement of Kaupang (Pedersen 2010, 226-9, Figure 4.85) such as bar ingots with D-shaped cross-sections and trapezoidal-shaped ingot fragment. This lends some confidence in assigning a Viking-age date for many of the finds without secure contexts. Some of these ingots and ingot fragments seem to be weight adjusted. The complete bar ingot (**Cat. 205**) is certainly adjusted to a standard of approximately 50 grams, and other objects seem to reflect units of about 25 grams (**Cat. 208** and

Figure 2 *Lead ingot (**Cat. 213**) weighing 4 kilograms found at Hedeby (Maixner 2011, 163, Figure 186). Photo not to scale.*

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[1] **Cat. 156**-**158** are the same objects as Probe H08-H10 analyzed by Steuer (2003, 149).

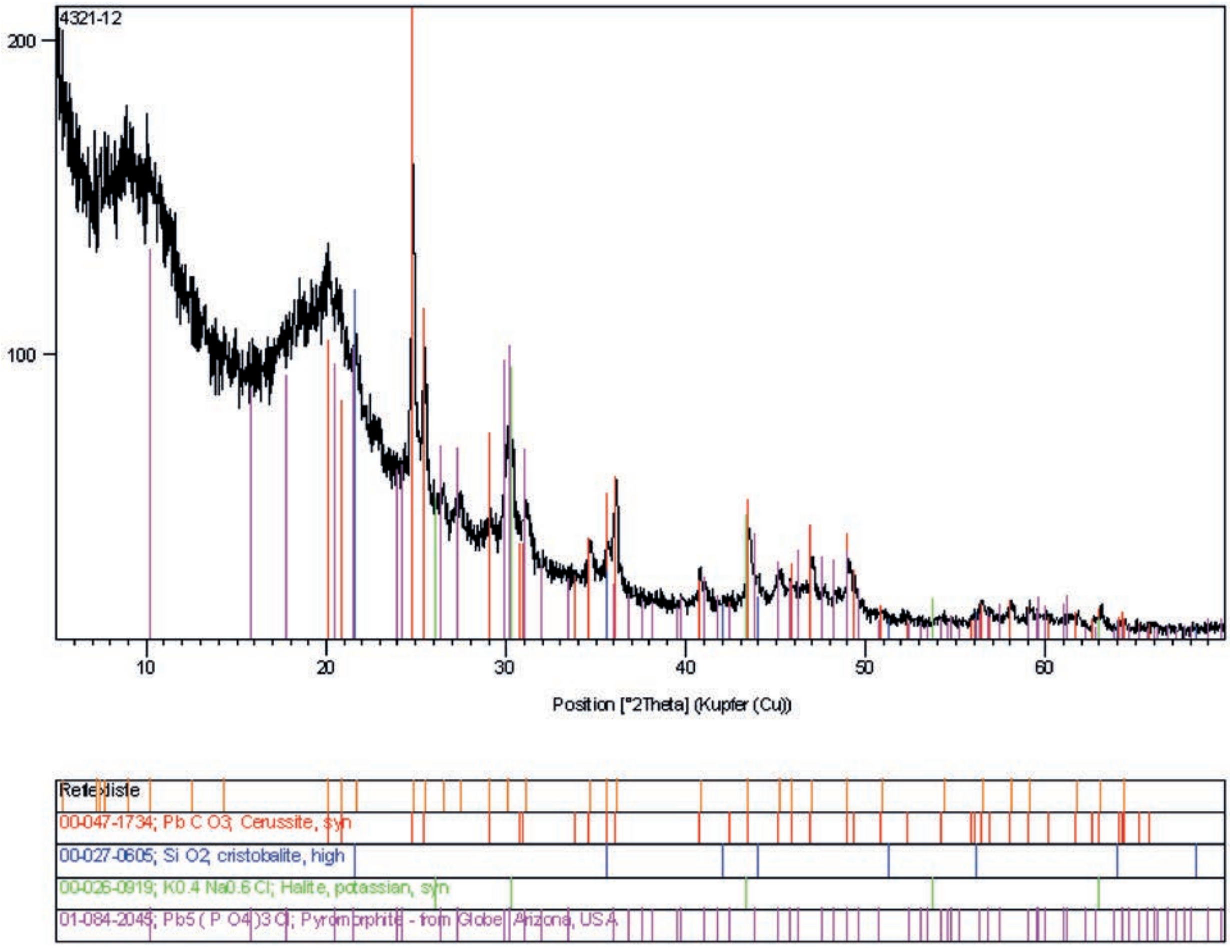

Figure 3 *X-ray diffraction spectrum from the contents of crucible* ***Cat. 247****. The crystalline minerals/phases are dominated by lead carbonate, chlorides, and phosphates. Cristobalite, a high temperature alteration of quartz, was detected.*

209) or larger units like 250 or 500 grams (**Cat. 200**, **211**, **212**). This seems to parallel the øre weight standard (24-26 grams) used for silver,[2] but a metric analysis of a larger sample of lead-tin finds would be necessary to prove any sort of weight adjustment conclusively.

Fourteen of the eighteen finds are pure lead with tin contents below 500 ppm. There seems to be no elemental relationships between copper, tin, antimony, arsenic, silver, bismuth, and phosphorus. The phosphorus level is highly variable, but this may be more related to the amount of corrosion and contamination from the burial environment. The silver content of the lead is also variable and in one case remarkably high (**Cat. 201**), to the extent that this lead must be related to some metallurgical process involving silver. This silver was probably incorporated into the lead at some point after the primary production because, with a content of nearly half a percent of silver, it would have been economical to perform cupellation at the site of production.

The thick slab ingots (**Cat. 200**, **209**, **211**-**213**) are all made of nearly pure lead with few trace elements (for example, Figure 2). The thin bar ingots with D-shaped cross-sections are more variable ranging from pure lead to lead-tin alloys. They can contain considerably more silver, copper and zinc, possibly indicating mixing and recycling. The lead sheet (**Cat. 196**) is made of high quality lead with very low copper, bismuth, antimony, arsenic, and tin contents. It could be called 'soft lead' due to the lack of impurities, and it was perhaps more malleable than other types of lead.

One metal-detected find stands out due to its zinc content in the percentage range (**Cat. 202**). Its form is irregular and not diagnostic to the Viking period. Due to the unusually high zinc content, this alloy possibly belongs to the post medieval or modern era when metallic zinc was available. ANSPRACH (2010, 17) points out that the area of Hedeby was part of a battlefield in the 19th century, which has left material traces in the artifact assemblage recovered through metal-detecting. For this reason, it is best to rely on material from sealed archaeological contexts or objects with distinctive and datable forms.

3. Evidence for Cupellation or Glass Working

Until now there has not been any evidence of true cupellation found at Hedeby. The heating tray technology discussed in the previous appendix (**G**) is techni-

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[2] See **Chapter 3** (**3.4.2.1**)

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl_2	K_2O	CaO	TiO_2	Fe_2O_3	CuO	PbO
Average Crucible Contents (x3)	0.7	0.1	1.4	3.4	7.8	6.8	0.7	4.0	-	1.5	-	73.1
Average Glass – Exterior (x8)	0.9	0.7	4.0	32.4	0.8	1.8	3.8	3.2	0.5	4.2	0.5	46.7
Average Ceramic – Exterior (x4)	3.4	1.9	13.2	34.1	5.2	1.7	11.7	9.9	1.1	11.7	-	4.9

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl_2	K_2O	CaO	TiO_2	Fe_2O_3	CuO	
Average Glass – Pb Excluded	1.7	1.4	7.5	60.9	1.5	3.4	7.1	5.9	1.0	7.8	0.9	
Average Ceramic – Pb Excluded	3.5	2.0	13.9	35.8	5.5	1.8	12.3	10.4	1.2	12.3	-	

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl_2	K_2O	CaO	TiO_2	Fe_2O_3	CuO	PbO
Average Glass w/o Ceramic	-0.2	0.3	0	44.8	-1.6	2.6	0.5	0.3	0.3	1.2	0.9	50.5

***Table 1** The corroded contents of crucible **Cat. 247** are in large part lead carbonates with phosphates and chlorides. To answer the question of whether crucible **Cat. 247** is a cupellation dish or a glass pot, drips of glass from the exterior surface of the crucible were analyzed and compared to the ceramic itself. If the vitreous drips on the exterior of the crucible were a result of pure litharge interacting with the crucible ceramic than the resulting glass would be compositionally proportional to the crucible ceramic if lead is excluded. However, this is not the case. The silica is disproportionally high, and this means that the droplets of glass on the exterior of the crucible are droplets of a separate, distinct silicate glass. When the contribution of the ceramic is subtracted (scaled to the alumina content), the resulting glass is primarily silica and lead oxide. This is an argument that the crucible is actually a melting pot for high-lead glass. Oxygen was calculated stoichiometrically and carbon was excluded. The "-" mean under the detection limit (< 0.5 %). Values are normalized to 100 % and given in weight percent.*

cally related to cupellation, but seems to have a slightly different goal. The production of litharge is crucial for the cupellation process as the litharge is the medium that absorbs and extracts impurities from the silver or gold. This litharge can either be tapped or skimmed off or the litharge can be absorbed into an unreactive porous material like bone ash or some other type of calcareous material. According to the 12th century account of Theophilus the Presbyter, vessels for cupellation were constructed of fired earthenware lined on the interior with ash to absorb the litharge (HAWTHORNE/SMITH 1979, 96-7). It is unclear what kind of ash is referred to; wood ash contains significant quantities of calcium oxide and could be used for a cupellation lining, but the alkali and amounts of silica present makes wood ash an inferior material compared to bone ash for this purpose.

A crucible fragment (**Cat. 247**) has been found at Hedeby that fits many of the characteristics of a vessel in which cupellation was performed. The ceramic itself is a relatively dense ceramic tempered with quartz and fired to an oxidized reddish-orange color. It is possibly wheel-made, due to spiral striations on the base of the vessel. It has a diameter of greater than 8 cm and the upper walls of the vessel are missing so the true form cannot be determined. Most importantly, there is a 1-2 mm thick layer of yellowish-white powdery substance on the interior of the dish. XRD analysis of this powdery residue (**Figure 3**) indicated the presence of lead carbonates, phosphates and chlorides, all possibly corrosion products of what was originally in the crucible. The ICP-MS results of this lining material show that lead is the most significant constituent, followed by lesser amounts of silica, phosphate, and calcium oxide (**Appendix C, Table 6**). The appearance of this powdery residue is similar to corroded glass, but the material primarily consists of lead carbonate and the amount of silica is too little for proper glass formation. The high level of phosphate may be from bone ash that was once present; however, there is proportionally too little calcium oxide for apatite, the main material of bone ash. Alternatively, the high phosphate level may be due to interaction with the burial environment.

There are difficulties in the interpretation that this crucible was used to carry out cupellation, but the interpretation of the crucible as a glass melting pot is also problematic. A potential solution to the interpretation of this crucible is that there are drips of lead-rich glass on the crucible exterior. Litharge is highly reactive with silica and forms in glass at the temperatures needed for cupellation. The drips of glass prove that the crucible was heated above the melting temperatures of lead glass (> 700°C) or litharge (> 888 °C), but are the drips of glass caused by interaction between liquid litharge and the crucible ceramic or is it an independent glass? SEM-EDS analysis of the glass drips and the crucible ceramic indicate that they are indeed independent because the glass contains too much silica to originate as a reaction of litharge and the crucible ceramic (**Table 1**). There is some contamination of the ceramic providing alumina to the glass composition, which acts as a stabilizer to prevent glass corrosion; this may be why these droplets were preserved when all other glass remnants are corroded. Therefore, the strongest argument is for the interpretation of crucible **Cat. 247** as a glass pot for melting high-lead glass and not a cupellation dish.

4. Lead Isotope Analysis of Lead, Tin, and Refining Debris

Lead is the major element for all objects except for the tin imitation dirhams and a piece of scrap metal (**Cat. 202**) which may not belong to the Viking assemblage due to its zinc content. Even with the lower lead contents of the tin imitation dirhams, it is clear that the lead isotope ratios probably do not reflect the source of the tin due to the low quantities of lead typically associated with tin ore (see Begemann et al. 1999). The one tin dirham with a notable copper content may be an exception, but otherwise the lead isotope ratios of the lead and lead-tin objects, the slag, and the lead-rich contents of crucible **Cat. 247**, should originate primarily from lead ore deposits. Lead was produced in large quantities in association with silver production, but lead was also a product sought on its own. Many galena deposits, for example in the British Isles and in the Rhenish Massif, were worked in the medieval period solely for their lead. The frequent occurrence of lead deposits and the ease with which lead can be produced without complex infrastructure mean that lead is often more difficult to source, but it also means that lead probably did not travel as far as other metals like gold and silver.

The lead isotope ratios of the lead-tin objects, refining waste and corroded glass are presented in **Appendix D** (**Tables 1**, **5**, and **6**) and are plotted in **Figures 4** and **5**. The span of lead isotope compositions of the lead and tin finds from Hedeby closely parallels the results of lead finds from Viking settlement of Kaupang, in Norway (see Pedersen 2010, 271-84, Figures 4.117 and 4.118). The lead and tin finds from Hedeby cover the same range, covering from Kaupang Groups 1 to 3 nearly to Group 4, however Group 5 is absent.[3] The similarity between the ranges of lead isotope compositions may indicate that the same sources of lead were used at the two settlements. This range matches many deposits in Central and western Europe. The several artifacts could come from deposits in England, as **Figures 6** and **7** indicate, but possible sources in France, like Melle, or in Germany cannot be ruled out (**Figures 8** and **9**). The entire variability of lead isotope compositions can be explained with ore of western and Central European origin,[4] and the analytical results provide little reason to argue that lead source other than these played any significant role in Viking-age northern Europe.

Concerning the tin dirham imitations, it is clear from the lead isotope ratios that the two ‘Abbasid’ dirhams able to be analyzed are isotopically nearly identical, despite the variation in lead content. The lead isotope ratios of the ‘Samanid’ tin dirham indicate a different lead source. Regarding the lead ingots, there seems to be no clustering of lead isotope compositions based on the ingot form or elemental composition. As to be expected, the lead isotope composition of the lead-silicate slag from the three heating trays and the lead carbonate from crucible **Cat. 247** are not distinctive from the lead metal available at Hedeby. Although the evidence is few and the sample size small, these first analyses indicate that any silver refined would be similar to lead isotope ratios of the crucible slag and residues which are, in turn, similar to the lead metal found at Hedeby.

5. Conclusions and Recommendations for Future Research

The elemental and lead isotope analysis of the lead and tin finds and the refining waste from Hedeby provide a basis for several conclusions. Most importantly, the lead isotope ratios of the lead and tin finds from Hedeby have close parallels to those analyzed from Kaupang, and the range of compositions is consistent with ore from several West or Central European lead deposits. Therefore, there is no indication that the lead was imported from regions further afield like the Mediterranean or the Islamic world. Unfortunately, it is not possible to positively identify the specific sources of lead. Lead, being a common metal, has too many possible sources and there are widespread overlaps in lead isotope ratios of numerous ore deposits. Unlike silver, the elemental compositions of the lead and tin finds provide no further clarification or possible solutions to the problem, and there are few elemental analyses of lead from the Viking period for comparison.

One area that has not been sufficiently explored is the difference between lead resulting from silver production and lead produced independently. As discussed in **Chapter 2** (**2.3.1**), lead was particularly valued in the medieval period for its softness and malleability, qualities that are directly related to the amount of metallic impurities in the lead. The higher temperatures required for silver production could potentially increase the amounts of impurities making the lead hard. Conceptually, this may provide a way to identify lead stemming from silver production. Conversely, lead with very few impurities of antimony, arsenic, copper, and bismuth, which are elements often associated with silver minerals, could result from lead production. Although this makes sense in theory, in application this is much more difficult to prove. To take examples from ore from two production sites in the Islamic world, Lashkerek in Uzbekistan (see **Appendix I**) and al-Radrād in Yemen (see Merkel et al. 2016), lead produced from the polymetallic ore of Lashkerek would be expected to be ‘hard’ with many trace elements whereas the ore from al-Radrād is practically free of many of these hardening elements and possibly produced a ‘soft’ lead, though the ore from al-Radrād does seem to have a certain cadmium content (compare **Appendix C**, **Tables 8** and Merkel et al. 2016). Therefore, one could conclude that the lead composition is a result of the ore used, and does not necessarily indicate if it was produced in association with silver. This question requires further investigation as well as experimental replication to be adequately explored.

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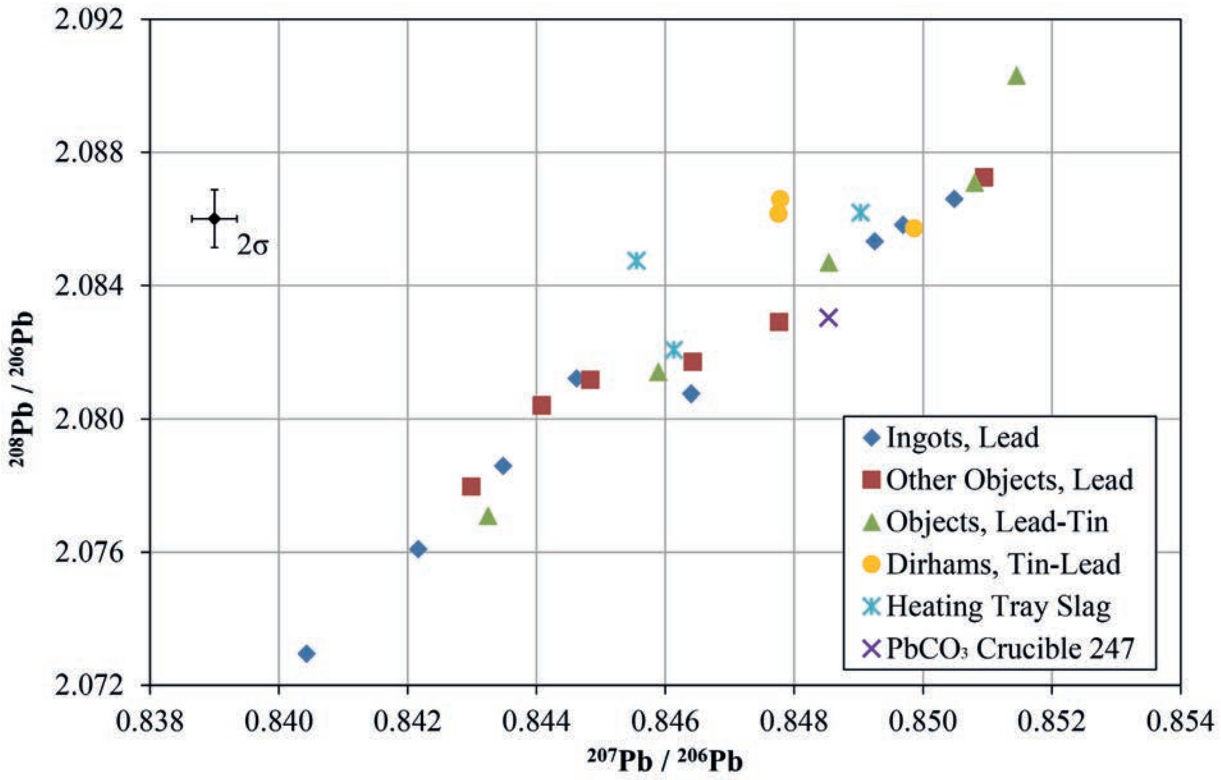
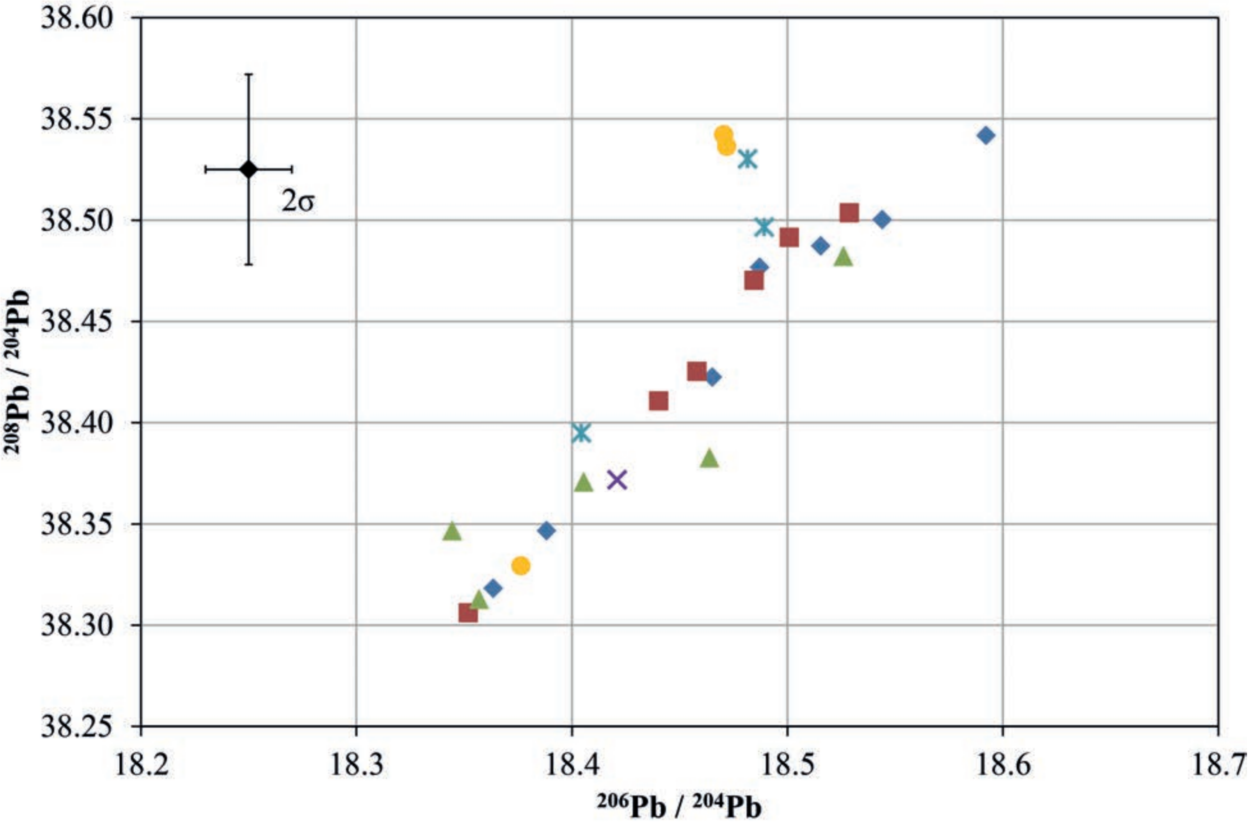
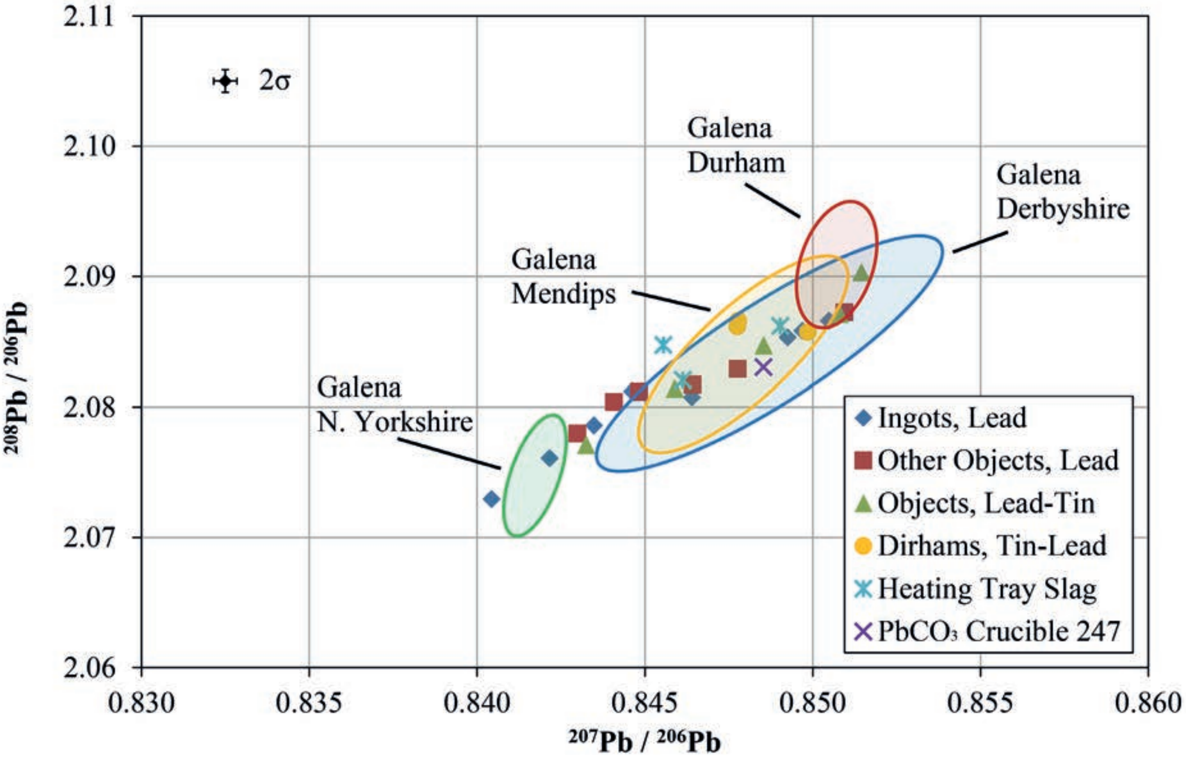
[3] Group 5 are of the Variscan geologic age. It possibly comes from Scotland, but many deposits in the Rhenish Massif, southern France, and Spain overlap with this field (Pedersen 2010, 280).

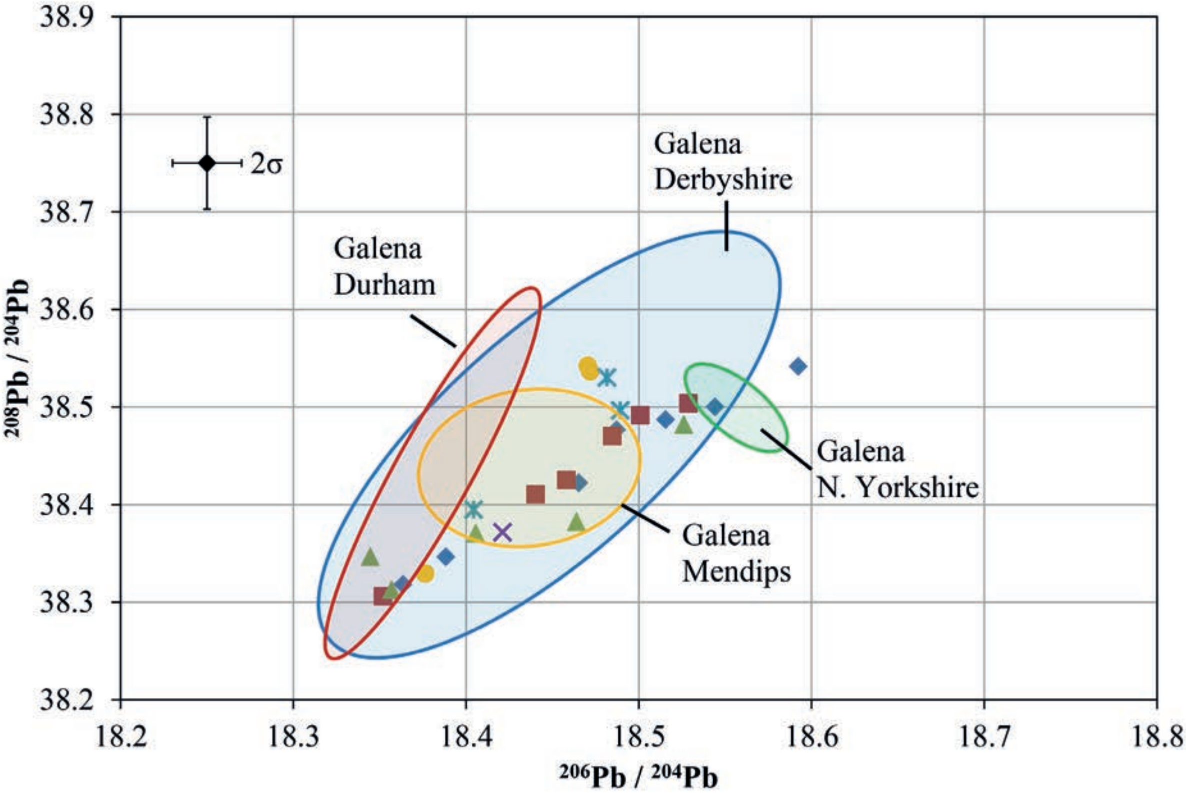
[4] Bielicki/Tischendorf 1991; Bode 2008; Brauns 1995; Durali-Müller 2005; Hatz et al. (1991); Krahn/Baumann (1996); Lehmann (2011); Lévêque /Haack (1993); Lévêque/Jakobus (1994); Rohl (1996); Schneider (1994); Schneider (1998); Téreygeol (2005); Wagner/Schneider (1999).



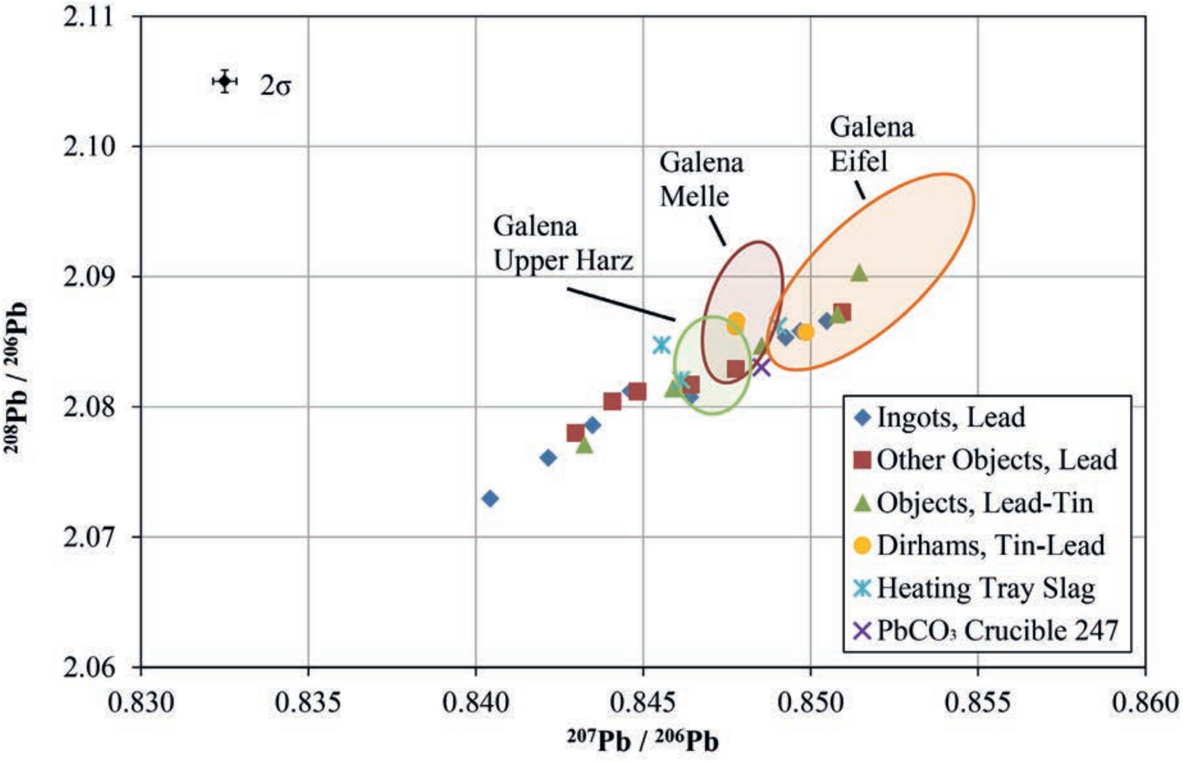


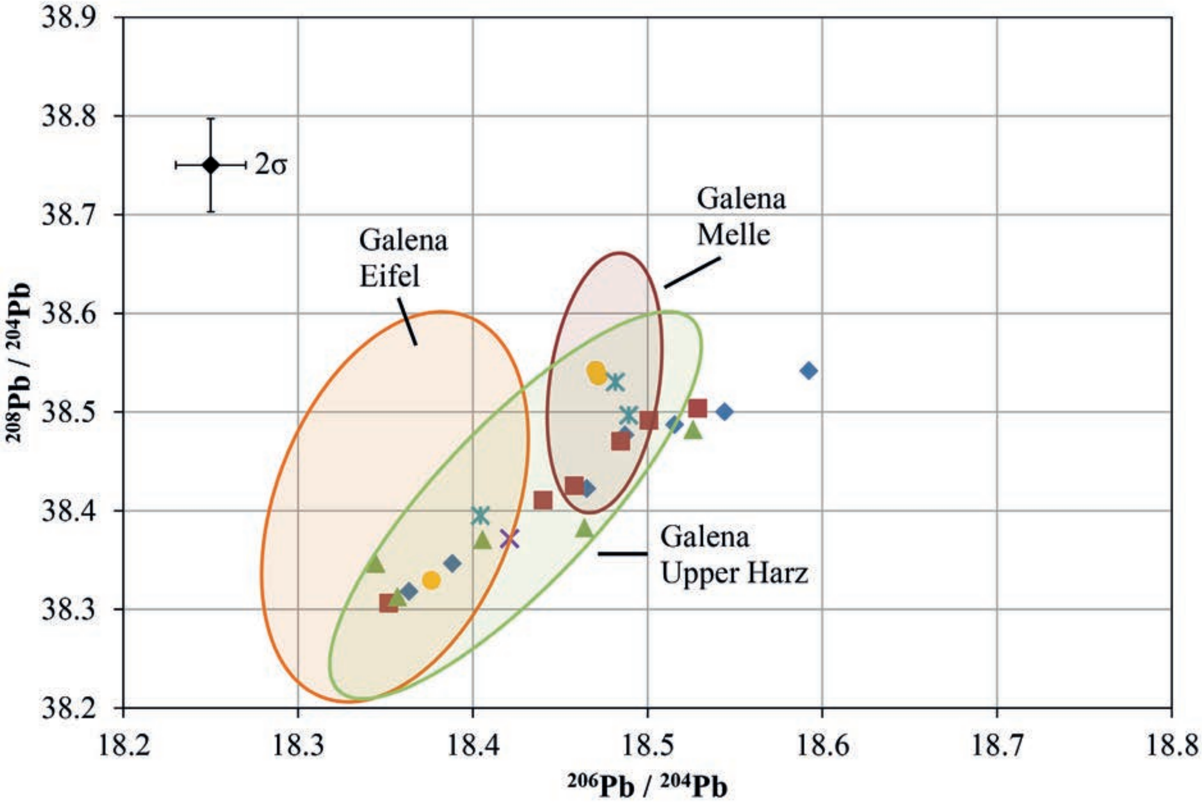
*Figures **4** and **5** Lead isotope diagrams showing the range of isotope ratios found in the lead and lead-tin objects and crucible slag from Hedeby.*





***Figures 6** and **7** Lead isotope diagrams comparing the lead and lead-tin objects and crucible slag to galena from the British Isles after Rohl (1996). Durham/Cumbria represented here by the deposits at Alston Moor and Alston Nentsberry.*





***Figures 8** and **9** Lead isotope diagrams comparing the lead-tin objects and crucible slag to galena of Continental European origin. In this case the Eifel is represented by ore from Mechernich (after Bielicki/Tischendorf 1991; Bode 2008; Krahn/Baumann 1996; Schneider 1994) and the Upper Harz is represented by Bad Grund (Hatz et al. 1991; Lehmann 2011; Lévêque/Haack 1993; Tischendorf et al. 1993). Analyses of galena from Melle are published by Téreygeol et al. (2005).*

Appendix I
Analysis of Slag and Ore from the Tashkent and Samarqand Areas: Medieval Silver Extraction and the Coinage of Samanid Central Asia

Summary

Samanid silver production in Central Asia was a driving force for the development of long-distance trading networks that stretched from Samarqand to as far as Scandinavia where dirhams are continually being found in hoards and Viking-age settlements today. The analysis of silver coins found at Hedeby is part of a study to look at the changing sources of silver in southern Scandinavia in the 10th and 11th centuries, and Samanid dirhams from Central Asia and Afghanistan make up a sizable proportion of the coin finds. The analysis of these coins not only forms a basis for studying the reuse of this silver in northern Europe in the Viking Age, but can give us valuable information about the inner workings of Samanid silver production at its height in the 9th and 10th centuries. To provide a comparison to the two major mints of Samanid silver dirhams, Samarqand and al-Shāsh, slag samples from two medieval silver production sites were collected and analyzed. In addition, ore samples from Lashkerek, one of the largest known medieval silver mine in Central Asia, and several deposits in the Nuratau Mountains near Samarqand were collected for analysis. The results show that polymetallic ore was smelted to produce copper, lead, and silver in the Īlāq region of Uzbekistan and that the smelting slags closely resemble the dirhams of al-Shāsh in lead isotope ratios. The coins of Samarqand seem to not be made from local silver resources but are possibly a mixture of silver from silver producing regions in the Shāsh Īlāq, the Pamir Mountains, and Afghanistan. This study utilizes optical and scanning electron microscopy, XRF, XRD, and mass spectrometry to shed light on the technology of silver production and the origins of Samanid silver. This appendix is the full and up-dated version of an abstract published in the conference proceedings for Archäometrie und Denkmalpflege 2013 (Merkel et al. 2013).

1. Introduction

Metal production was an important economic factor for the development and urbanization in medieval Central Asia and with connections via the Silk Road and over-land routes to India and north through Eurasia metal production helped to fuel long-distance trade routes that stretched from China to northern Europe. Dirham finds from 10th century settlements and hoards in Scandinavia clearly demonstrate the importance of the silver coins of Central Asia and Afghanistan for the economy and society of the Viking-age Baltic. The long-distance exchange networks of Eurasia are now well-known: Historical accounts indicate that expensive arctic furs and slaves among other goods were exchanged for an array of oriental goods including silver, glass, and textiles of which there are abundant archaeological finds to support (Noonan 2001; Richter-Bernburg 1987). The northern trade flourished between the Samanid heartland and the Baltic via Volga Bulgharia in the late 9th to the middle of the 10th century. The trading routes appear to falter as the quality of Samanid Central Asian silver began to diminish in the second half of the 10th century (Ilisch et al. 2003; Noonan 2001, 155). The causes for this decline in both trade and silver production remain unclear, but probably include political instability, disruption of trading routes, or the exhaustion of silver and other resources.

In order to look more in depth at the potential suppliers of silver for Samanid Transoxania[1] silver dirhams, polymetallic ore, and slag samples have been collected for archaeometallurgical analysis. This study uses a number of archaeometric methods to look at aspects of the production technology and to characterize the elemental and isotopic signatures of the ore deposits, slag, and silver artifacts (see Rehren/Pernicka 2008). Slag and ore samples were mounted for scanning electron and polarized light microscopy (SEM-EDS and PLM) to identify slag phases, ore minerals, and metallic inclusions, and X-ray diffraction was used in addition to confirm slag phase and ore mineral identification. Liquid solution mass spectrometry and laser ablation mass spectrometry were used to characterize lead isotope ratios and elemental composition of ore, slag, and silver coins.

2. Historical Background of Silver Mining and Production

2.1 Samanids and Mining

The founder of the Samanid state, Isma'il bin Ahmad, began as governor of Bukhārā, and between

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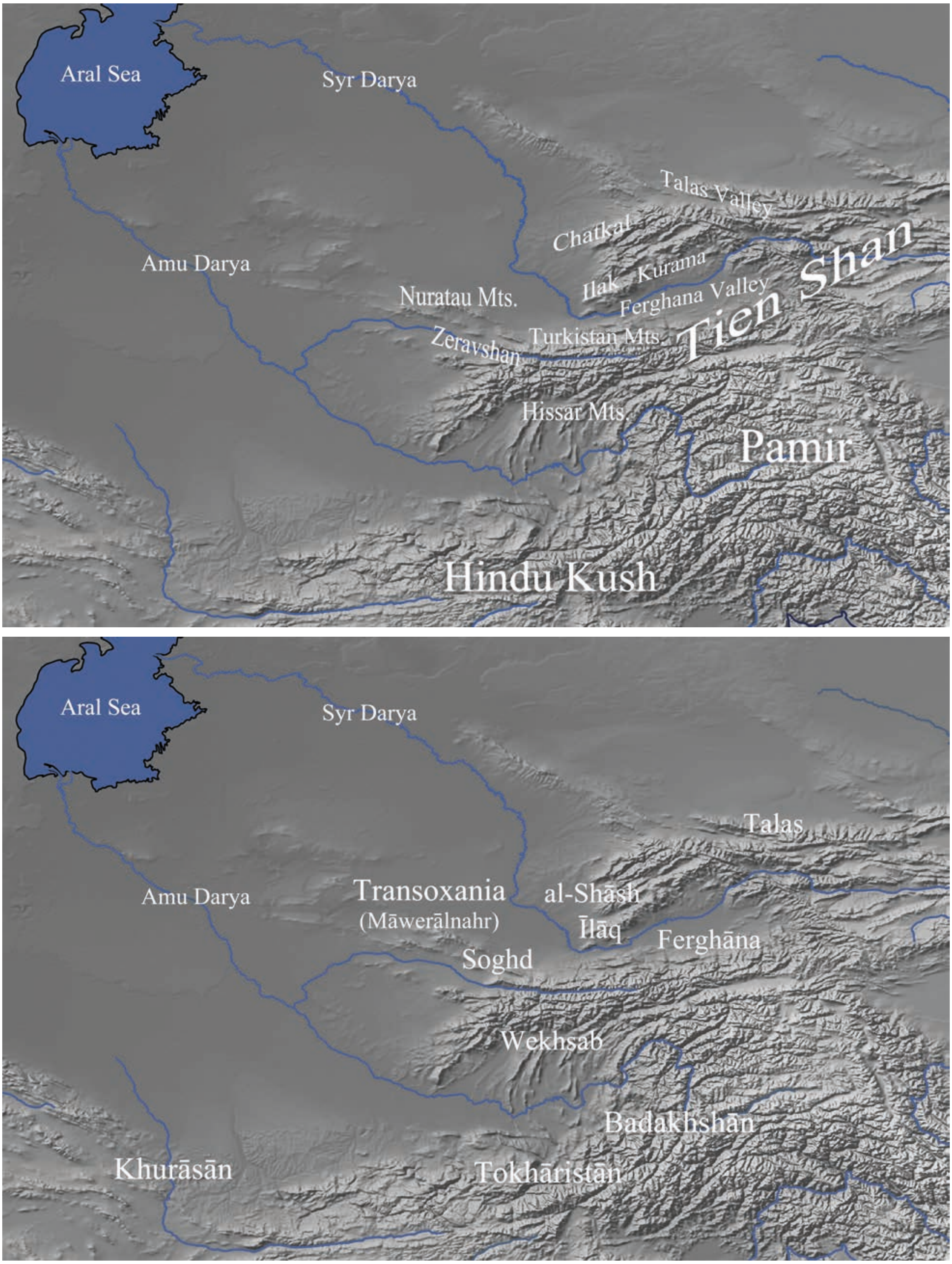
[1] Transoxania is defined as the land between the Amu Darya and Syr Darya in modern-day Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan.



***Figures 1** and **2** Natural and political maps of Samanid Central Asia with region names.*

***Figure 3** Samanid Dirham (**Cat. 15**) from al-Shāsh minted in 900-901 AD (288 AH) found at Hedeby (Identified by L. Ilisch, Photo: S. Merkel).*

the years 888 AD and 900 AD the empire expanded rapidly to include many smaller states in Transoxania, Tokharistān (northern Afghanistan-southern Uzbekistan), and Khurāsān (Negmatov 1998, 84-5). This expansion brought with it direct access to many mineral resources (**Figures 1, 2**, **4** and **5**). The Samanids campaigned aggressively for organization and economic development, which included mining and silver production (Buryakov 1974, 109). According to the 10th century geography of the Islamic world by Ibn Hauqal two regions stand out due to their scale of silver production: Panjhīr in the Hindu Kush Mountains of northern Afghanistan and in the region of Māwerālnahr (Transoxania). Ibn Hauqal describes the silver mines in what is now Uzbekistan as being the most productive of all with exception of Panjhīr (Ouseley 1800, 233). There are a number of different mining areas mentioned in his account: Īlāq (Ouseley 1800, 265), on the borders of Ferghāna (Ouseley 1800, 272), in the Turkestan Mountains between Samarqand and the Ferghāna Valley (Ouseley 1800, 264), and in Wekhshab in the Hissar mountains (Ouseley 1800, 239). Interestingly, he mentions that there are mines near Samarqand itself, which were no longer worked (Ouseley 1800, 254).

A major use of the mined silver was in the making of dirhams, which were used in local transactions and for export. Ibn Hauqal states that the minting of silver coinage in Transoxania was restricted to two mints: Samarqand and Deinket.

> *"In the mountains of Ailak there are mines of gold and of silver: these mountains are on the borders of Ferghaneh. Deinket is the largest of all the towns in Ailak. In all Maweranlahr there is not any mint, except at Samarcand and at Deinket."* (Ouseley 1800, 268)

Deinket is probably synonymous to Tunket located in the region of Īlāq in al-Shāsh and might be where the mint of the al-Shāsh dirham is located.[2] The numismatic evidence mirrors the account of Ibn Hauqal and indicates that dirhams of Samarqand and al-Shāsh (**Figure 3**) dominate conclusively. Of the important mints under the Samanids (al-Shāsh, Samarqand, Bukhārā, and Balkh), al-Shāsh makes up 54 percent and Samarqand makes up 38 percent of dirhams found according to a numismatic study of Eurasian and Baltic hoards (Kovalev 2003, 58). The fact that the dirhams produced at these two mints in Transoxania make up such a high percentage of Samanid coins (92 %), when the mines of Afghanistan were supposedly the most productive, shows that the productivity of mints may not be directly associated with the productivity of the nearest silver mines. Silver might not have only been minted into coins but could have been made into ingots of which there is one historical description; in regard to Samanid Central Asia, al-Muqaddasī mentions that all silver ingots were transported to Bukhārā, the capital of the Samanid state (Allan 1979, 15).

2.2 Mining in the Īlāq and the Metallurgical Center of Tunket

The archaeological evidence of mining in Uzbekistan and Tajikistan (**Figures 4** and **5**) in many cases confirms the accounts of Ibn Hauqal because traces of medieval silver mining have been found in several areas he described. Buryakov (1965; 1974) has documented mining sites in Shāsh Īlāq (Kurama and Karamazar Mountains), and it is clear that many of the mines of the Īlāq extracted polymetallic copper-lead-silver ore and / or gold (Sverchkov 2009, 145-6). Lashkerek, in the Īlāq, is one of the largest documented medieval silver mines in Central Asia and was exploited between the 7th and 10th centuries. Approximately 9,000 -14,000 tons of lead-bearing slag has been found near the mine (Buryakov 1974, 18; Eniosova/Mitoyan 2011, 582; Masson 1953). The mines of Lashkerek attest to a well-organized, centralized production and are unlike most mines in the region (Buryakov 1974, 20). The ore deposit is classified as polymetallic, and veins of native silver are associated with argentiferous fahlore (tetrahedrite), galena, sphalerite, and bornite; the galena is associated with bismuth-containing minerals, which increases in quantity with depth (Buryakov 1965, 288; Dunin-Barkovsky 1959; Eniosova/Mitoyan 2011, 583). Ore grades range from 100 to 14,500 g / ton silver and in some samples up to tens of kilograms per ton (Buryakov 1974, 20). During the 10th century the mine reached depths of around 300 meters and may have been abandoned for technical reasons (Buryakov 1974, 20; Eniosova/Mitoyan 2011, 583). Despite the fact that it is the largest mine in Īlāq, it was one of no less than fourteen silver mining areas located in the region (Buryakov 1974, 18-23, 110-1, 127).

Tunket was discovered in 1928 during a geologic survey by P. I. Rnjasev because of the two large slag heaps in the settlement (**Figure 6**) (Türik 1997, 1-2).

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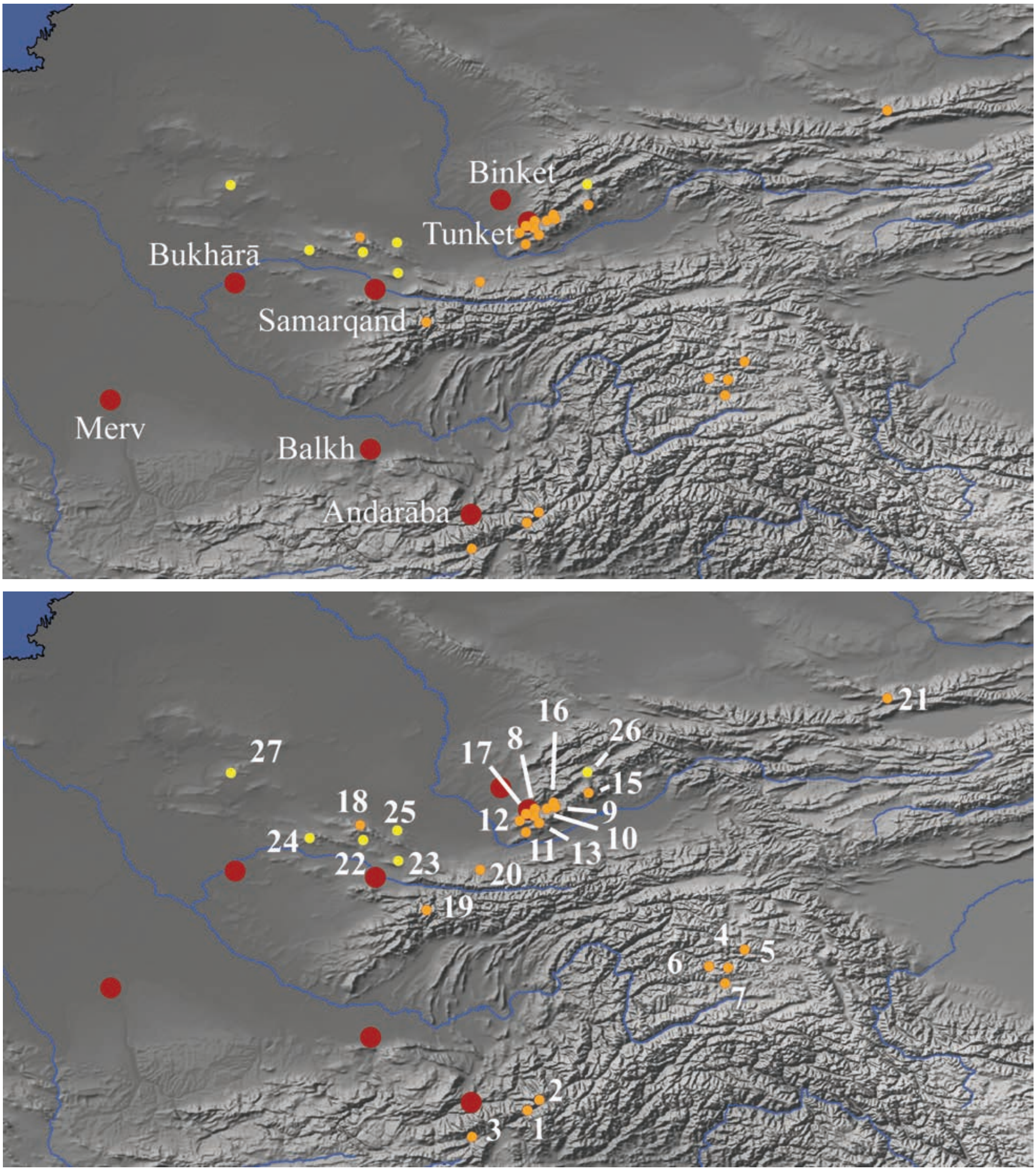
[2] In the account of Ibn Hauqal, he makes it clear that Deinket is distinct from Bounket and Boumeket, which are important administrative cities in the Shāsh-Īlāq region (Ouseley 1800, 266-8). However, it must be stated that it is difficult to match the place names referred by Ibn Hauqal with locations on maps due to the imprecise location descriptions and the numerous alternative spellings used on maps today.



***Figures 4** and **5** Maps of Transoxania and northern Afghanistan displaying important settlements/mints, medieval mines (lead-zinc and / or polymetallic) and selected polymetallic ore deposits with no known traces of ancient mining.*
*Hindu Kush: **1.** Panjhīr Valley, **2.** Chukri-Naw / Nukra-Khana, **3.** Farinjal. Pamir: **4.** Bazardara, **5.** Sasyk, **6.** Karadara, **7.** Alicur. Tien Shan: **8.** Kani Mansur, **9.** Lashkerek, **10.** Gul'duram, **11.** Kansai, **12.** Altyntopkana, **13.** Kandzhol, **14.** Aktashkan, **15.** Irisu, **16.** Koch-bulak, **17.** Kalmakyr, **18.** Sentjab, **19.** Koni-Nukra, **20.** Kurgashimkan. **21.** Aktyuz. Ore deposits: **22.** Zarmitan, **23.** Mardjanbulak, **24.** Sarmich, **25.** Uchkulach, **26.** Ustarasay, and **27.** Kosmanachi.*

The site was surveyed in 1929 by Sardzhaylyak and again in 1934 by Masson (Buryakov 1973, 93). The ruins of the city are more than 50 hectares with a citadel, city walls, and suburbs. The first archaeological excavations were undertaken by Buryakov and Fjodorovitch in 1959-1962 where stratified remains of houses, workshops, and metallurgical activities were found (Buryakov 1973, 93; 1974, 50-2). Ore beneficiation is attested by gigantic mill stones and smelting was performed at the settlement. More than 4,000 cubic meters (11,200 tons)[3] of slag were found at Tunket, which can be dated to the 9th and 10th centuries by ceramics (Buryakov 1974, 51).

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[3] Calculated with 3.5 g/cm^3 and 0.8 packing factor (Bachmann 1982, 5).

Figure 6 *Samples were obtained from a slag heap from the site of the medieval town of Tunket, near Almalyk in Uzbekistan. (Photo: L. Sverchkov)*

Another slag heap was found but not studied (Buryakov 1974, 52). Some preliminary investigations of the slag showed that it contains iron, copper, lead, and sometimes it contained silver and in one case gold. Buryakov (1974, 51) suspected that the polymetallic ore smelted at Tunket came from various mines in the region. Silver refining has also been attested with the use of calcareous cupellation dishes (Buryakov 1974, 124-5). The settlement itself can be dated between the 4th century and the 12th centuries AD (Buryakov 1973, 93). In the 10th century the minting of the al-Shāsh dirhams was particularly strong, which parallels the intensive mining of the Īlāq (Litvinsky 2012, 639-41), and the metallurgical remains at Tunket may have been connected to this development.

2.3 Pamir and Hindu Kush

Two other important mining regions supplying silver to the Samanids were the Pamir Mountains of Tajikistan and Panjhīr in Afghanistan. Medieval mining in the Pamir has been documented and researched by Bubnova (2001). Mining settlements have been found primarily dating from the 7th to the 11th century. The geology of the silver-antimony ore deposits of the southern-eastern Pamir has been analyzed, and remains to be an important supplier of silver today (Pavlova/ Borisenko 2009, 271-3). The Panjhīr silver deposit in the Hindu Kush Mountains in Afghanistan is mentioned in the 10th century geographies of both Ibn Hauqal (Ouseley 1800, 225, 233) and al-Hamdānī (Dunlop 1957, 40) who both attest to its importance amongst silver producers. According to Ibn Hauqal, no other mining area could match its productivity (Ouseley 1800, 253), but lack of archaeological investigations in this region has left the chronology and scale of production obscure.

So far no ore or slag from Panjhīr has been investigated. The only polymetallic ore and slag from the northern Hindu Kush region to have been analyzed comes from the site of Farinjal to the west of Chardeh in the Ghorbānd Valley. The mines and metallurgical sites of Farinjal were connected to the extraction of lead (and copper?) from the 3rd century BC to the 13th century AD (Tylecote 1968a, 1-2). Although litharge was found in association with the smelting remains, analyses of the galena show low silver concentrations, and hence the litharge is interpreted as production waste from the smelting of secondary ores and not from cupellation of silver. The slag investigated was primarily glassy with quartz, fayalite, magnetite, and inclusions of lead and copper phases (Tylecote 1968b, 9). Although silver was not found in the galena, it cannot be excluded that the ore found in recent times matches the type or quality of ore used in the past, nor can it be assumed that galena would have been the main silver carrier. Litharge is typically a by-product of silver refining and the finding of litharge is indeed curious if lead was the intended product. Lead isotope analyses of three pieces of galena and one slag specimen from this site are presented by Brill et al. (1997).

2.4 The Samarqand Area, Talas, and other Mining Areas

Mining in the area around Samarqand is less well-known and was perhaps less active. The mining of polymetallic ore (Au-Ag-Cu-Pb) has been attested in the Nuratau Mountains at the site of Sentjab, to the north of Samarqand (Buryakov 2001, 55-7; Sverchkov 2009, 155), but research into the mining history of this region in general is unsatisfactory (Sverchkov 2009, 155).

Besides the Nuratau area, there are ancient mines of silver-lead ores in the upper Zeravshan River valley at the pass from the Nignot in the Hissar Mountains; the largest mine is called Koni-Nukra (Islamov 1976, 50-1; Ivanova 1934, 202-5; Sverchkov 2009, 150). On the north side of the Turkestan Mountains[4] is the lead-silver mine called Kurgashimkan with accompanying slag fields (Sverchkov 2009, 147). There are a number of known mines in the Chatkal Valley, north of the Īlāq, but the mines of the Chatkal Valley are not well studied. Some of these might have produced silver, but others certainly supplied a diverse array of raw materials (Sverchkov 2009, 145-6).

The mines and smelting sites of the Talas have been published by Bubnova (1963). The Talas is hardly mentioned by Ibn Hauqal as it was at the border of Islam at the time of his account (Ouseley 1800, 274). Apparently the beginning of large scale production in the Talas region began in the middle of the 10th century as the Shāsh-Īlāq declined. Its peak of production is in the 11th century, which may have been a result of the expansion of the Qarakhanids at the end of the 10th century and the later Ghaznavids (Bregel 2003, 25-7). After the closure of the trade route to the Volga in the second half of the 10th century, it is thought that much of the silver produced in the Talas region went south into India under the Ghaznavids (Blanchard 2001, 360-2).

Despite the archaeological evidence and the broad chronological and regional developments in the 10th century, the Talas region should be examined more closely as a potential silver producer for the Samanids. The

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[4] In the region of Setroushteh described by Ibn Hauqal (Ouseley 1800, 264).

region further east of the Talas also provides evidence of mining in the 10th century, such as in the Aktyuz polymetallic deposit in Kyrgyzstan.[5] We have anything but a clear picture of the role of mining in these border regions.

3. Geological Survey: Tien Shan, Pamir, and Panjhīr

3.1 Introduction

The geology of the mining regions is important in the provenancing of metal artifacts particularly in light of lead isotope composition and geologic ages (Gale/Stos-Gale 2000). A brief survey of the ore geology of the Tien Shan, the Pamir, and the Panjhīr is presented in the following section.

3.2 Geology and Ore Deposits of the Tien Shan (including the Īlāq)

The Tien Shan belt is part of the much larger Altaid orogenic collage, which ranges from eastern Europe to Siberia and mostly formed between the Late Proterozoic and the Early Mesozoic Age and consists of accretions associated with subduction, island arcs, ophiolites, and micro-continents (Chiaradia et al. 2006, 412). The Tien Shan is very complex with faults, magmatic intrusions, and mountain building events of differing ages. The Kurama Mountains, where the Shāsh-Īlāq is located, is in the Middle Tien Shan, the main component of which is the Hercynian Beltau-Kurama volcano-plutonic belt (Chiaradia et al. 2006, 413; Moralev/Shatagin 1999). The Īlāq is in the southwest part of the Kurama Mountains and is dominated in the south by a Paleozoic acid-intermediate intrusion and in the north by rock of Carboniferous age (Haghipour 2009). The mountains of Navoi and around the Samarqand area show similar geology with paleozoic acidic-intermediate intrusions alongside rock of Carboniferous to Ordovician age (Haghipour 2009).

Epithermal volcanic-hosted Au-Ag-Te, porphyry Cu-Mo-Au, and base metal deposits are associated with Carboniferous and Early Permian subduction-related calc-alkaline magmatic rocks of the continental Beltau-Kurama arc[6] (Chiaradia et al 2006, 414). The lead isotope signatures of the Beltau-Kurama belt reflect a derivation of lead from a homogeneous reservoir, typical of continental arc magmas. The lead isotope ratios indicate a mixing of mantle-derived magmas with the continental crust rocks (Chiaradia et al. 2006, 423).

3.3 Geology and Ore Deposits of the Pamir

The geology of the silver-antimony deposits in the southern Pamir range is described by Pavlova and Borisenko (2009, 171-3) with accompanying lead isotope ratios of ore specimens. Archaeological mining sites and settlements dating from the 7th to 10th centuries can be found in the regions of Bazar-Dara, Mardjanay, and Tokuzbulak silver-antimony deposits, the mining sites at Tokuzbulak tend to date earlier than Bazar-Dara (Bubnova 2001, 178). The geology of the region is complex with metamorphic rock of Proterozoic age in the west (Tokuzbulak ore deposit) and unmetamorphosed carbonaceous sedimentary rock in the east (Bazar-Dara ore deposit). The region has granitic intrusions of various ages from the Early Mesozoic to the Cenozoic (Pavlova/Borisenko 2009, 171). The Bazar-Dara ore deposit is centered on Cretaceous granitoids that intruded carbonate sediments of Carboniferous to Triassic age. Several mineralizations formed, the latest being Ag-Sb fluorite mineralizations. The silver is found in quartz-siderite-fluorite veins hosted in carbonaceous and granitic rock. Ore minerals include tetrahedtrite, sulfosalts containing copper, lead, and silver, and primary sulfides like chalcopyrite, galena, bismuthinite, and pyrite. Most of the primary ore minerals contain antimony, but, with the granite hosted veins, native bismuth and bismuth minerals are found in high percentages. There is a tendency for bismuth to replace antimony in many of the minerals, which also includes tetrahedrite. The Ag-Sb mineralization is relatively young dating around 44 Ma according to isotopic and geological data (Pavlova/Borisenko 2009, 171-3). The Mardjanay ore cluster is characterized by antimony-silver and lead-silver bearing barite-quartz-siderite veins hosted in Late Cretaceous intrusions, Jurassic limestone, and older metamorphic rock. Tetrahedrite and galena are common minerals and are associated with chalcopyrite, stibnite, and many other hypogene sulfides (Pavlova/Borisenko 2009, 173).

3.4 Geology and Ore Deposits of Panjhir

Andarāba is located near the Khāwak Pass to the Panjhīr valley on the route that crosses the Hindu Kush south to Kabul and towards India. Ibn Hauqal describes the location of the mining region of Panjhīr as being situated in a mountain pass between the towns of Jāriāna and Panjhīr, three to four days travel from Andarāba (Ouseley 1800, 231, 233). Although there are a few documented unnamed lead-zinc, silver-fluorite, and copper deposits of late Triassic age in Baghlan province in the area of Andarāba (Doebrich/Wahl 2006; Orris/Bliss 2002, 80), as of yet no silver ore deposits of modern economic importance are documented in the region around or below the Khāwak Pass into the Panjhīr Valley. In the Panjhīr Valley below the Khawak pass there is the Chukri-Naw mineralization, which may be enriched in silver (Peters 2011, 1010), but it is primarily known as a hematite-siderite mineralization. The Nukra-Khana iron occurrence in the Panjhīr Valley has no known association with silver. The hematite ores of this area are enclosed in Proterozoic carbonate strata and can occasionally contain minerals with minor amounts of non-ferrous metals, like silver, copper, lead, and zinc. (Peters 2011, 1010). Ancient slag and tuyères have been found in conjunction with these deposits (Peters

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[5] http://www.stansenergy.com/projects/kutessay-ii-ol/kutessay-ii-history/ accessed 04.06.2013.

[6] Kalmakyr, Kochbulak, and Ustarasay deposits in the Īlāq area and Pb-Zn deposit at Uchkulach.

2011, 1012), but so far no archaeometallurgical or geochemical studies have been undertaken in the Panjhīr region.

4. Methodology

4.1 Samples and Methodology

Samanid dirhams from Transoxania and Afghanistan were analyzed in part of a larger study to analyze the silver finds from Hedeby, a Viking settlement in modern day Schleswig-Holstein. The Islamic silver coins (Abbasid and Samanid) form one of the largest coin groups found at Hedeby. The majority of coins analyzed in this study came from the recent metal-detecting campaigns (see Hilberg 2011). The new dirham finds were identified by Lutz Ilisch in Tübingen. Fifteen coins from al-Shāsh (894-954 AD), twelve coins from Samarqand (892-961), and ten coins from northern Afghanistan (875-933 AD)[7] were selected for analysis (**Appendix A, Cat. 13-49**).

Slag and ore samples were also collected and sampled for analysis. A total of 13 ore samples were obtained for this study. Five samples from the mine of Lashkerek and one sample from the ancient mine of Aktepe were curated in the Geological Museum in Tashkent. A further seven samples from four ore deposits around Samarqand were also included (**Appendix A, Cat. 261-264** and **274-281**).

Due to the importance of Tunket as a metallurgical center and potential production site of the dirhams of al-Shāsh, an expedition to Tunket was undertaken by Dr. Leonid Sverchkov in 2012 and seventy slag samples were collected. In addition, six slag samples were taken from the Geological Museum and the Museum of History in Tashkent and come from slag fields near Lashkerek, Apantepe, and Tunket. Dr. Utkur Islamov collected these samples in the 1960s and 1970s. In all, 20 slag fragments were prepared for analysis (**Appendix A, Cat. 248-259** and **265-273**).

4.2 Method for the Analysis of Silver Dirhams

The dirhams were analyzed at the Leibniz Universität Hannover Institut für Mineralogie / Anorganische Chemie with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). A Neptune multi-collector fs-LA-ICP-MCMS was used to obtain lead isotope abundances and ns-LA-ICP-QMS was used to characterize the major, minor and trace elements (see **Chapter 6** and Lehmann 2011 for methodology). All silver objects were analyzed by portable X-ray fluorescence spectrometry (pXRF) to compare the elemental results of the LA-ICP-MS. The LA-ICP-MS data are presented in **Appendix C**, **Table 1** and **Appendix D**, **Table 1**. Two laboratories were used to analyze the silver coins and the ore / slag. In order to insure the data compatibility between the two laboratories the same lead isotope standards were used (NIST981) and, additionally, two silver objects were analyzed in all labs with all methods (**Appendix D**, **Table 8** and **Chapter 6**, **Tables 6.2-6.3**).

4.3 Methods for the Analysis of Ore and Slag Samples

Samples were analyzed macroscopically and microscopically. Both optical microscopy and scanning electron microscopy (SEM) were used to identify minerals and phases present.[8] Polarized light microscopy (PLM) was performed on thin-sections and polished sections. A Zeiss Gemini scanning electron microscope with a Thermo UltraDry Silicon Drift X-ray Detector was used in conjunction because of its capability to obtain elemental data on the phases and minerals. The compositions obtained by energy dispersive X-ray spectroscopy (EDS) are semi-quantitative (**Tables 1-2**).[9] Additionally, the crystallography was determined with XpertPro Panalytical X-ray diffraction (XRD) at the Deutsches Bergbau-Museum, Bochum (**Tables 3-4**). The bulk chemistry was determined initially with a Thermo Scientific, NITON Analyzer pXRF device and followed by single collector inductively coupled plasma mass spectrometry (SC-ICP-MS) with a Thermo Scientific Element XR (**Appendix C**, **Tables 7-8**). The lead isotope ratios were determined with a Thermo Scientific Neptune ICP-MS at the Goethe Universität Frankfurt am Main Institut für Geowissenschaften. For sample processing and analysis methodology see Klein et al. (2009, 62) and **Chapter 6**. The data collected are presented in **Appendix D**, **Table 7**. A list of the minerals and phases discussed in the text along with their chemical formula can be found in **Appendix E**.

5. Results and Discussion of the Analysis of Ore and Slag

5.1 Ore Samples

Although the five samples from Lashkerek came from the ancient gallery, care must be taken because they may not be representative of the ore that was extracted in the past. They belong to material left behind or rejected by the medieval miners. Four of the five samples from Lashkerek are samples of metasomatic[10] primary sulfides consisting of chalcopyrite, bornite, tetra-

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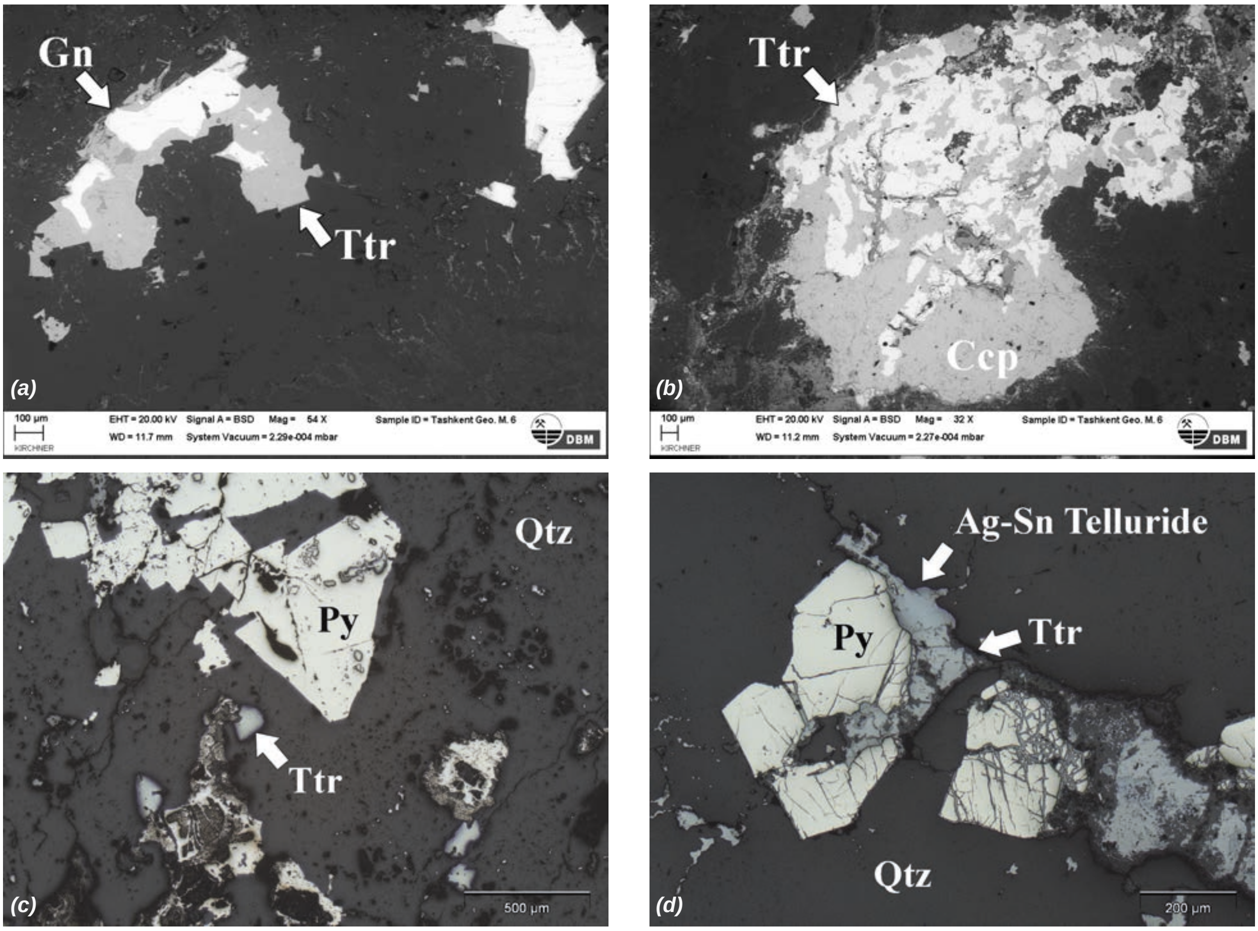
[7] This includes one Abbasid dirham minted at Panjhīr, which was included because it likely was made from ore from the hitherto unstudied Panjhīr mines.

[8] The phase and mineral identification through optical and SEM microscopy relied on the work of Anguilano (2012), Asmus (2012), Bachmann (1982), Ettler et al. (2009), and Manasse and Mellini (2002), and with the help of www.webmineral.org and www.mindat.org accessed in June 2013.

[9] Some problems occurred due to peak overlap between lead (Pb Lα) and arsenic (As Kα) and magnesium (Mg Kα) and arsenic (As Lα1). The separation of the peaks should be possible (Ward 1987), but the EDS software could not reliably do this. The presence of arsenic was checked with the Kβ1 peak which has no overlap with any other peaks. When the peak was not visible above the background, the arsenic content was not measured. Therefore, discussion of the arsenic content in phases is unfortunately limited.

[10] According to the Tashkent Geologic Museum sample label.



Figures 7 ***(a)*** *Ore from Lashkerek (****Cat. 262****) containing galena (Gn) and argentiferous tetrahedrite (Ttr) in a dolomite-ankerite-kutnohorite matrix (SEM-BSE).* ***(b)*** *Ore from Lashkerek (****Cat. 262****) containing tetrahedrite (Ttr) and chalcopyrite (Ccp) in a dolomite-ankerite-kutnohorite matrix (SEM-BSE).* ***(c)*** *Sarmich ore (****Cat. 278****) containing pyrite (Py) and argentiferous tetrahedrite (Ttr) in a quartz matrix(Qtz) (PLM).* ***(d)*** *Kosmonachi ore (****Cat. 281****) containing pyrite (Py), argentiferous tetrahedrite (Ttr) and silver-tin-telluride in a quartz matrix (Qtz) (PLM).*

hedrite-tennantite-freibergite, galena, barite and silver sulfide with quartz and carbonates of the dolomite-ankerite-kutnohorite system (**Figures 7a-b**). The fifth sample was chemically weathered and consisted of secondary ore minerals like malachite and azurite with clay minerals and quartz. Microscopic analysis revealed that the primary ores contained fahlore minerals and copper-iron sulfides containing silver or were inter-grown with native silver or acanthite. One ore sample (**Cat. 262**) contained several acanthite inclusions up to 300 µm in size. In the specimens small amounts of barite and galena were found, but all the samples are overall low in lead and barium (<0.5 wt. %).

SEM analysis of the ore sample from Aktepe (**Cat. 274**) shows it is a high arsenic-nickel-cobalt-iron ore with amounts of lead and silver. The main ore minerals are low in sulfur and consist primarily of arsenic minerals with lesser amounts of magnesium, cobalt, nickel, and iron. Silver is associated with lead-arsenic sulfides in varying concentrations (2-5 wt. %). The gangue is quartz, calcite containing amounts of iron and manganese, and iron calcium aluminosilicates. The amount of arsenic, cobalt, nickel, and iron would produce speiss during smelting making silver recovery difficult if not impossible (Kassianidou 1998). The ore is extremely rich in arsenic and its extraction in prehistory evidenced by ancient traces of mining and stone hammers (Sverchkov 2009, 146) may have been for the extraction of arsenic ores for arsenical bronze production and not for silver production (example Rehren et al. 2012).

The six samples from the Samarqand and Zarafshan areas come from the Sarmich, Zarmitan, Mardjanbulak and Kosmanachi ore deposits. The samples were first screened with XRD and pXRF to determine their mineral composition and their silver, copper, and lead contents. The two samples from Zarmitan were not analyzed further due to low lead, silver, and copper contents. Three samples proved to contain silver above 100 ppm. In **Cat. 278** from the Sarmich deposit, the XRD showed galena, arsenopyrite, and chalcocite in a quartz matrix, and SEM analysis revealed argentiferous tetrahedrite (**Figure 7c**) and a silver-tellurium-tin-sulfosalt. **Cat. 279** from Mardjanbulak is a of silver-containing lead-zinc ore in a quartz and calcite matrix. The ore (**Cat. 281)** from Kosmanachi contains galena, pyrite, argentiferous tetrahedrite, tennantite, and a similar silver-tellurium-tin-sulfosalt to sample **Cat. 278** (**Figure 7d**). The gangue material is quartz and orthoclase feldspar.

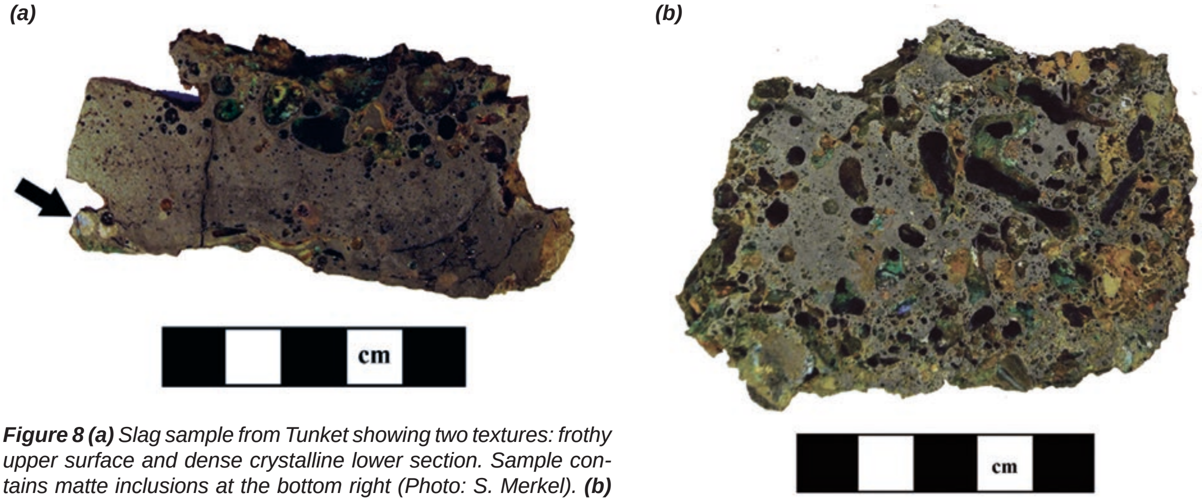


__Figure 8 (a)__ Slag sample from Tunket showing two textures: frothy upper surface and dense crystalline lower section. Sample contains matte inclusions at the bottom right (Photo: S. Merkel). ***(b)*** *Frothy slag sample from Tunket containing rock fragments, charcoal, and sulfide inclusions. Corrosion of iron and copper phases are visible by the blue, green and orange colors (Photo: S. Merkel).*

5.2 Slag from Lashkerek and Tunket

Once at the Deutsches Bergbau-Museum Bochum, the slag samples were macroscopically sorted and screened with pXRF to determine their character. Four slag groups were identified by their physical characteristics: 1. Frothy slag, 2. Dense crystalline, 3. Dense microcrystalline and 4. Glass-rock slag. The terminology will be discussed in detail further on. All of the slag from the Lashkerek area and from Tunket proved to be polymetallic with concentrations of lead, copper, and iron. The sample from Apantepe (**Cat. 249**) and one from Lashkerek showed high silica and alumina and were determined to be molten ceramic and were excluded from further analysis. Other samples of molten ceramic or furnace material were identified in the material from Tunket and were not studied further. Four polymetallic slag fragments from Lashkerek were sampled for analysis. Three are tap slags with characteristic flow marks and are macroscopically similar: dense, black-dark gray, and crystalline. The fourth sample (**Cat. 250**) is a slag with large inclusions of quartz and feldspar suspended in a black glass.

All samples from Tunket exhibit green and blue copper corrosion products on exterior surfaces, but slag textures range from frothy with large quartz inclusions, charcoal fragments, bubbles, and ore and matte inclusions, to the other extreme, a very dense tap slag with small prills of sulfides and metal. The differentiation of slag into clear-cut groups is made difficult because some of the larger slag samples have dense lower sections becoming frothy at the top indicating that two visually dissimilar slag pieces could belong to the same process (**Figure 8a**). Very few samples show signs of flow on both sides, but they do occur. Flow marks have been found on some dense crystalline and microcrystalline slag pieces. Many of the crystalline slag samples have smooth, pitted surfaces with inclusions of dirt and sand as if the molten slag was in contact with the ground, indicating tapping. Without a closer examination of the furnaces and larger pieces of slag, it is difficult to say how the different types of slag relate to each other based solely on their macroscopic appearance. As opposed to technological categories like tap and furnace slag, the slag will be described primarily by its texture: Frothy, crystalline, microcrystalline, or glassy.

Eleven slag samples were mounted in resin for polishing and nine samples were mounted for thin-sectioning. Coincidentally, many of the slag samples sectioned contained ore restites, gangue, matte, and metallic inclusions, which provide invaluable information about the raw materials, the technological processes, and the probable end-products.

The dense crystalline slag from Lashkerek and Tunket seem to be similar and can be regarded as belonging to the same technological tradition with similar or identical raw materials and will be discussed together. As mentioned earlier, the difference between the frothy slag and the dense slag is not straightforward. There is a range of slag textures from slags that were fully liquid to viscous and incompletely molten. The glassy slag piece (**Cat. 250**) from Lashkerek might belong to a different technological process and will be discussed separately.

5.2.1 *Slag Type 1: Frothy Slag*

The frothy slag fragments contain ore restites, gangue / flux, and charcoal inclusions (**Figure 8b**). The slag commonly contains large inclusions of heat fractured quartz, which are often banded with iron oxides. Unreacted ore minerals and matte are found enveloped in slag and consist of iron-rich chalcopyrite, bornite, and galena. The slag phases are mostly fayalite and hedenbergite, but leucite is also present. Charcoal inclusions are quite common and were all determined to be coniferous based on the plant cell structure (Nicole Boenke pers. comm. 22.04.2013). Charcoal fragments are small and thin, no greater than 1 cm in size, and one fragment of a carbonized twig has a cross-section diameter of 8 mm.

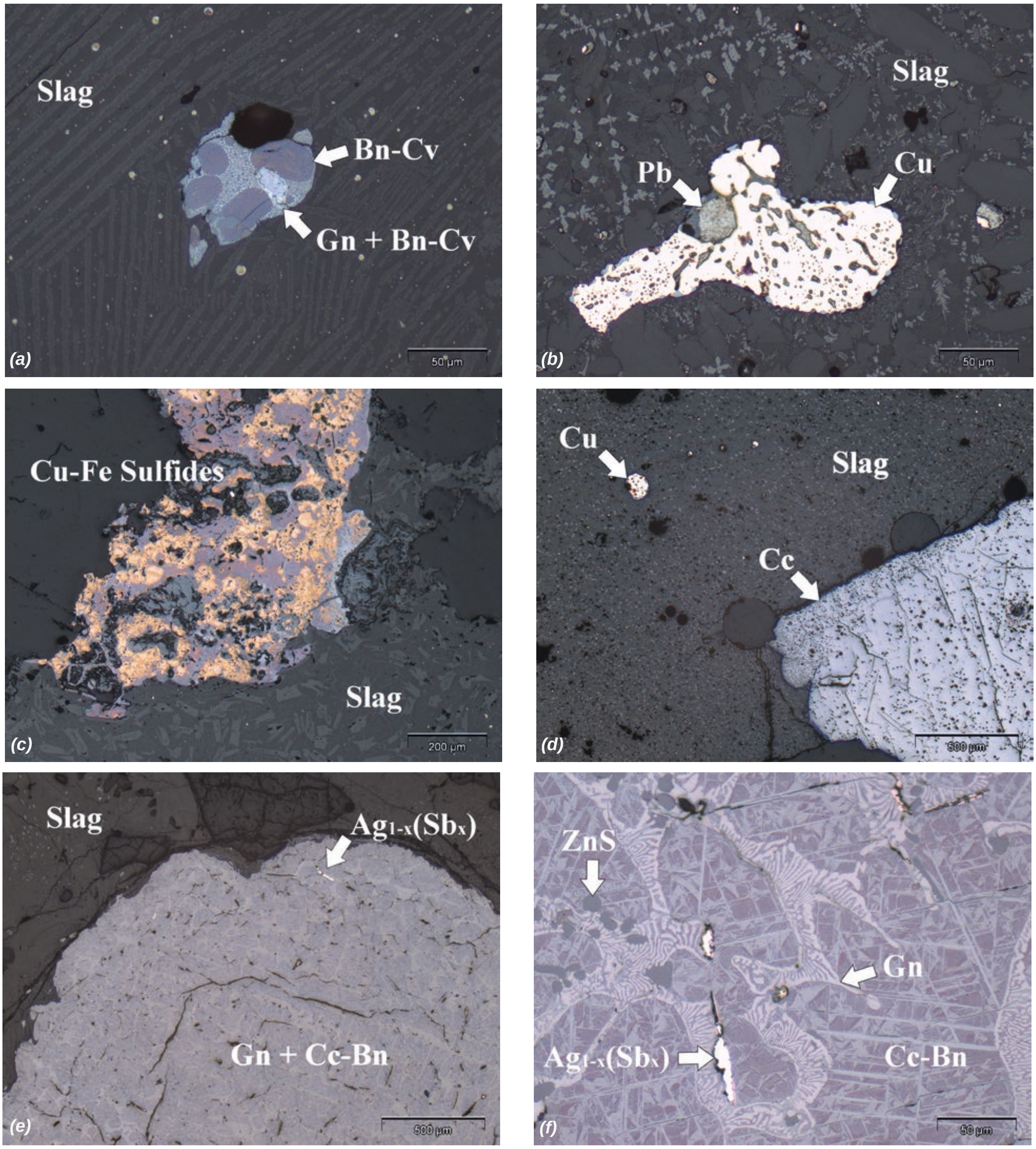
Microscopy revealed that metallic phases of copper and lead could be found next to oxides and sulfides. In general, the morphology of the sulfide inclusions indi-

Table 3 (left) *Phases and minerals in slag identified through XRD (x) and microscopy (+).*

		Type 1	**Type 2**	**Type 3**	**Type 4**
	Phase	**Frothy (n=5)**	**Crystal-line (n=11)**	**Micro-crystal-line (n=2)**	**Glassy (n=1)**
Silicates	Fayalite	x+	x+		
	Pigeonite	x+	x+	x+	
	Augite	x+	x+	x+	
	Leucite	+			
	Quartz	x+	+		x+
	Orthoclase				+
Oxides	Magnetite	x+	x+	x+	
	Wüstite		x		
	Litharge	+	+	x+	
Sulfides	Galena	x+	x+	x+	x+
	Sphalerite/Zinc Sulfide	+	+	+	+
	Pyrrhotite	+	+	x	
	Argentopyrite				x
	Cubanite	+	+		
	Chalcopyrite	+	+		
	Bornite	+	+	+	+
	Chalcocite	+	+	x+	
	Skinnerite				x
	Anglesite-Barite		+		+
Metals	Lead	+	x+	x+	
	Copper		+	+	
	Silver Antimonide	+	+		+
Speiss	Copper Antimonide	+	+		
	Other speiss		+		

Table 4 (below) *Minerals in ore identified through XRD (x) and microscopy (+).*

	Phase	**Lashkerek**	**Aktepe**	**Sarmich**	**Mardjanbulak**	**Zarmitan**	**Kosmonachi**
Silicates	Quatz	x+	+	x	x	x	x+
	Orthoclase	x+					x+
Other	dolomite/ankerite/ kutnohorite	x+	+	x	x		
Oxides	Hematite	+					
	Malachite	+					
	Azurite	+					
Sulfides	Galena	+		x	x		x+
	Zinc Sulfide			+	x		
	Pyrrhotite						
	Pyrite			+		x	x+
	Arsenopyrite			x			
	Cubanite						
	Chalcopyrite	x					
	Bornite	+					
	Chalcocite	x		x			
	Skinnerite						
	Anglesite-Barite	+					
	Fahlore	x		x			x+
	Silver Sulfide	+					
	Silver Sulfosalt			+			x+
	Guitermanite	x	+				
Metals	Native Silver	+					
	Native Arsenic		+				



***Figures 9 (a)** Tunket fayalite-hedenbergite slag (**Cat. 254**) with polymetallic sulfide inclusion. The sulfide inclusion contains several phases but are chiefly bornite-covellite (Cv-Bn) with a galena and bornite-covellite eutectic phase (Gn + Bn-Cv) (PLM). **(b)** Tunket slag (**Cat. 255**) with metallic copper prill (4% Sb) and metallic lead in a slag containing magnetite and hedenbergite (PLM). **(c)** Tunket fayalite-hedenbergite slag (**Cat. 257**) with sulfide inclusion. The sulfide inclusion contains chalcopyrite, bornite, chalcocite, silver antimonide, and corrosion products (PLM). **(d)** Tunket fine-grained hedenbergite slag (**Cat. 258**) with magnetite and inclusions of porous (blister) copper and chalcocite. The large sulfide inclusion is mostly chalcocite (Cc) with a small amount of bornite (PLM). **(e)** Tunket fayalite-hedenbergite slag (Cat. 259) with large polymetallic sulfide inclusion containing mostly chalcocite-bornite with a galena eutectic phase (Gn + Cc-Bn), zinc sulfides, and inclusions of silver antimonide (PLM). **(f)** Tunket slag (**Cat. 259**) detail of large polymetallic sulfide inclusion. White phase is silver antimonide and the dark gray inclusions are zinc sulfides. The exsolution texture of bornite and chalcocite can be seen (Cc-Bn) as well as galena-bornite-chalcocite eutectic phase (PLM).*

cates that chalcopyrite was decomposing to form iron oxides and copper-iron sulfides similar to bornite (**Figures 9a** and **9c**). The slag often contains prills of matte such as with **Cat. 259** where there are prills of bornite-chalcocite-galena. Metallic silver prills containing small amounts of antimony can be found in some of these matte inclusions (**Figure 9f**).

Litharge, cerussite, and anglesite were found in many of the slag samples of this type (**Figure 13**).[11]

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[11] Asmus (2012, 212-3), Pernicka et al. (2011, 662, Figure 31).

Litharge and cerussite were often found in association with copper-iron sulfides, metallic lead, speiss, and silver antimonide. In all cases the litharge and cerussite seemed to have formed during the corrosion of metallic lead, which is usually argentiferous. Inclusions of silver antimonide were found in nearly every example of metallic lead and its corrosion products. Silver antimonide forms small prills (1-20 µm) or chains possibly demarcating grain boundaries formed during the crystallization of lead. The corrosion of metallic lead into litharge and cerussite can be seen by the fact that these dissolution chains of silver antimonide inclusions cross from the metallic lead into the oxide and carbonate minerals without interruption. The high viscosity of the slag was caused by insufficiently high temperatures, which prevented complete separation of matte and metallic lead from the slag.

5.2.2 Slag Type 2: Dense Crystalline Slag

The dense crystalline slag is characterized by less bubbles, fewer and smaller quartz inclusions, and larger (macroscopic) crystals of olivine and clinopyroxene (**Figure 12a**). Some slag fragments appear to have flowed, but others seem to be furnace slag grading into a frothy texture. Microscopy revealed that the primary slag phases are fayalite and clinopyroxenes like hedenbergite. Matte inclusions appear throughout the slag. The copper matte inclusions range from compositions similar to cubanite and chalcopyrite to chalcocite but most are around the composition of bornite (**Figures 11b** and **12d**). Sulfides similar to bornite (**Figure 10**) are the primary sulfide phases in the matte and are often together with galena in eutectic phase (**Figure 9a, 11b,** and **11d**). Occasionally small ore restites can be seen, for instance in **Cat. 253**, where angular cubanite and galena crystals are inter-grown (**Figure 11c**). A few of the slag samples have metallic copper and lead, but metallic lead is far more common. The metallic lead can have high concentrations of silver-rich inclusions, which can be seen in **Cat. 257** (**Figures 13c-d**). It is clear that there is immiscibility between the metallic argentiferous lead and the copper matte, but the surface tension of bubbles prevented some of the phases from sinking.

5.2.3 Slag Type 3: Dense Microcrystalline Slag

Macroscopically, two slag pieces analyzed have a very fine texture (**Cat. 255** and **257**). They are both tap slags because they have rope-like flow textures on their upper surfaces. Microscopically, fayalite was not detected nor was it detected by XRD. The main slag phases are clinopyroxenes like hedenbergite and pigeonite (**Figure 12b**). Magnetite was also found in both slags, and iscorite can be found in this slag type indicating mildly reducing conditions (Meyerdirks et al. 2004, 655). Metallic lead prills, copper prills containing antimony (4-7 wt. %), and chalcocite dominate (**Figure 9b**). Galena and chalcopyrite were not detected. The inclusions show that much of the iron and antimony has been drawn into the slag and the overall sulfur content of inclusions is lower. **Cat. 257** has a large piece of copper matte (1.5 cm) that is nearly free of iron and lead, and nearby there is a prill (1.5 mm) containing argentiferous lead, metallic copper, and chalcocite (**Figure 9d**). These slags clearly represent the most advanced step of the smelting process and stem from the production of copper sulfide (chalcocite), metallic copper, and some argentiferous lead.

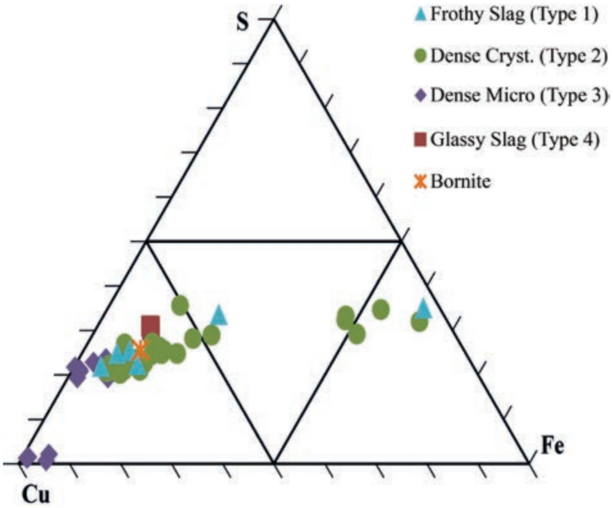
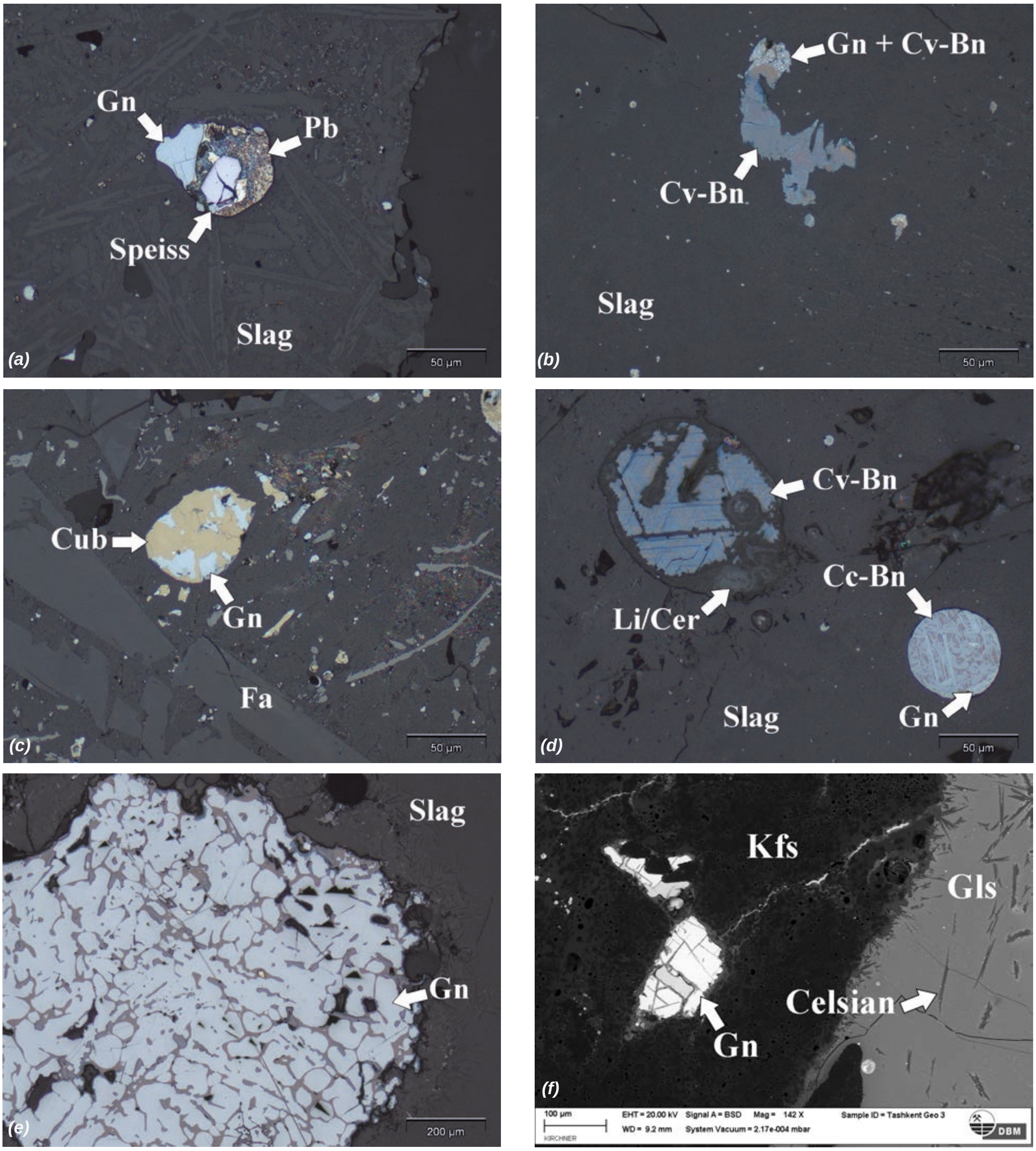


Figure 10 *The range of copper, copper sulfide, copper-iron sulfide inclusions found in the four slag types determined by SEM-EDS. The slag types 1, 2, and 4 tend to cluster around the composition of bornite, but the inclusions of type 3 have lower iron contents and metallic copper. Some inclusions in slag type 2 are similar to cubanite in composition. Speiss phases like copper antimonide were excluded, but all metallic copper prills had small amounts of antimony. The compositions are semi-quantitative and normalized to 100 percent.*

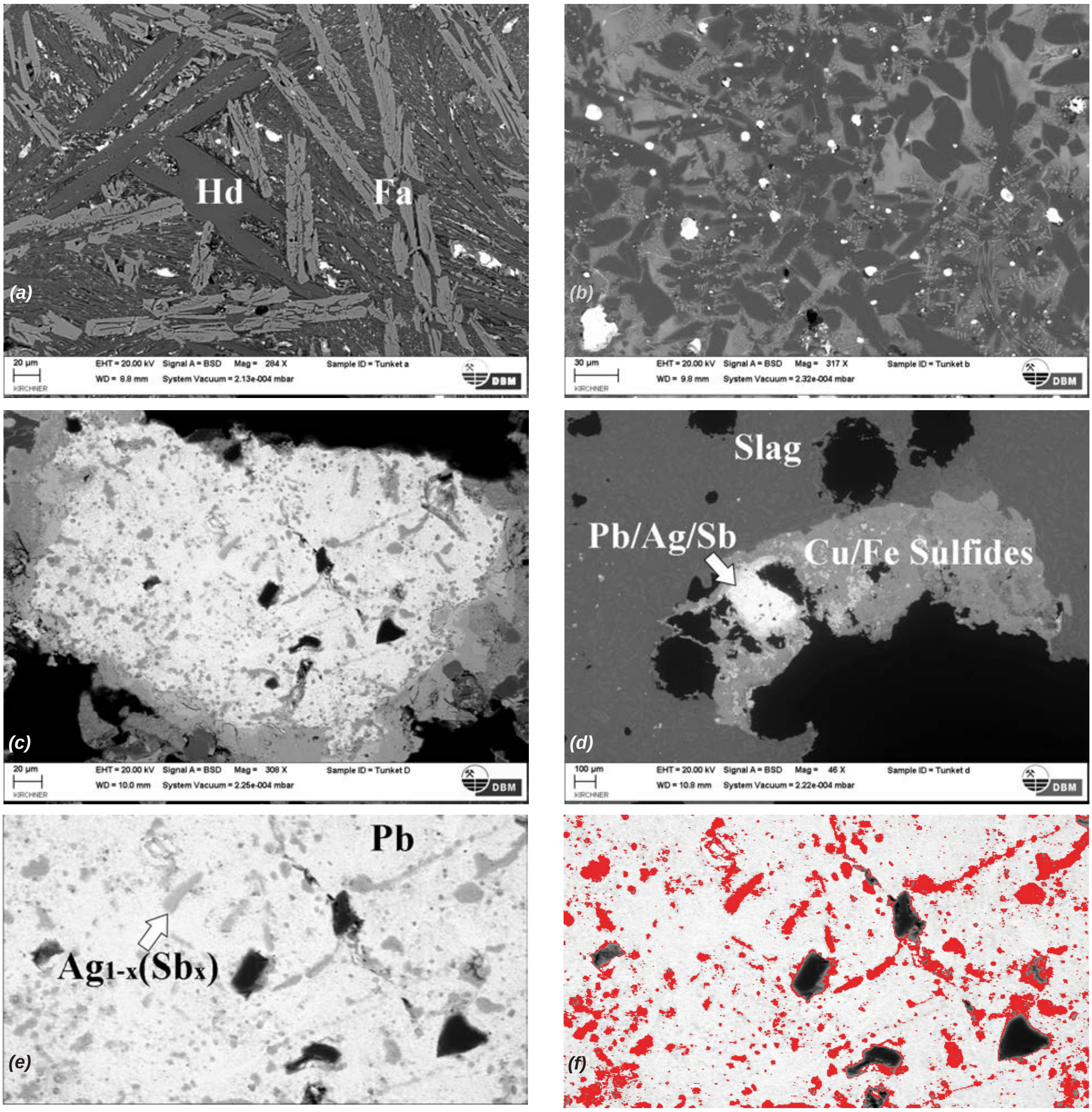
5.2.4 Slag Type 4: Lead-Barium Glass from Lashkerek (Cat. 250)

This slag is dissimilar to all other samples by its macroscopic texture. It also diverges in its composition and morphology, and this is the only slag where galena is the main sulfide phase. This slag from Lashkerek is glassy with large inclusions of quartz, orthoclase, and galena, and the glass itself is high in barium and lead. Upon cooling small celsian crystals had begun to precipitate from solution (ca. 50 µm). There are lead sulfide inclusions throughout the slag. One large sulfide inclusion (1 mm) appears to be a partially reacted ore fragment and contains many phases / minerals (**Figure 11e**). The inclusion is mostly galena, and between the grains of galena are copper-iron sulfides (composition similar to bornite) containing 5-10 weight percent silver. There are zinc sulfides and barium-lead sulfate inclusions (barite) and a number of silver antimonide grains (centering on $Ag_{0.84}$ $Sb_{0.16}$). The inclusions in the slag are all high in silver, which supports the interpretation that the slag was produced with the aim of argentiferous lead production. The high quantity of sulfides with few metallic phases indicates that this slag probably belongs to a first-stage smelting process. Because of the inclusions



Figures 11 (a) *Lashkerek fayalite-hedenbergite slag* ***(Cat. 251)*** *polymetallic inclusion containing galena (Gn), metallic lead, and speiss (copper antimonide ≈ Cu_2Sb) (PLM).* ***(b)*** *Lashkerek hedenbergite slag* ***(Cat. 252)*** *sulfide inclusion. The sulfide inclusion contains several phases. There is a galena and covellite-bornite eutectic phase (Gn + Cv-Bn) and the rest of the inclusion consists of covellite and bornite (Cv-Bn) (PLM).* ***(c)*** *Lashkerek slag (****Cat. 253)*** *containing sulfide inclusions and fayalite (Fa). The copper-iron sulfide mineral / phase is similar to cubanite (Cub = $CuFe_2S_3$) and the pale mineral / phase is galena (Gn) (PLM).* ***(d)*** *Tunket fayalite-hedenbergite slag* ***(Cat. 248)*** *sulfide inclusions. The upper prill contains copper sulfides and copper-iron sulfides (Cv-Bn) and lead oxide and lead carbonate (Li / Cer). The other prill is made of copper-iron sulfides (Cc-Bn) with a galena eutectic phase (Gn) (PLM).* ***(e)*** *Lashkerek slag* ***(Cat. 250)*** *large silver-rich polymetallic sulfide inclusion mainly consisting of galena (Gn), but also contains copper sulfide, zinc sulfide, and barite. Silver is found in the galena at around 1 wt. %, but in the darker phase between the galena (probably copper-iron sulfides) there is more, averaging around 6 wt. %. Small inclusions of silver antimonide (Ag 0.84 Sb 0.16) can also be found (10-20µm) (PLM).* ***(f)*** *Lashkerek slag (Cat. 250) potassium-rich feldspar (Kfs) with imbedded galena (Gn) in a barium-lead-silicate slag (Gls). The slender prism phases in the slag are enriched in barium and aluminum in regard to the slag and are probably celsian (SEM-BSE).*

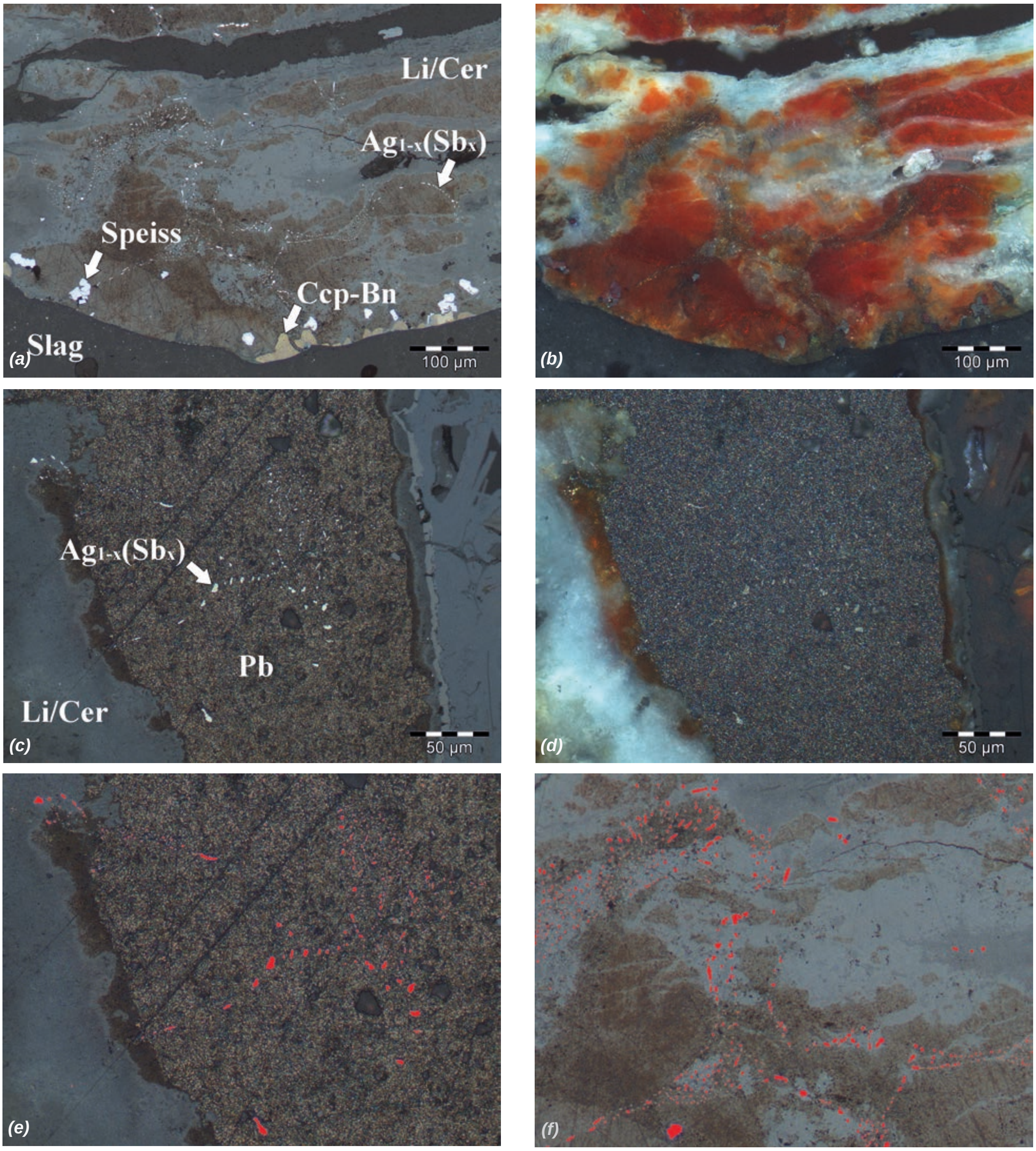
of unreacted galena within the large siliceous rock fragments they are interpreted as ore and gangue material, parts of the furnace charge that did not have time to fully react (**Figure 11f**).



***Figures 12 (a)** Tunket slag **(Cat. 254)** fayalite (Fa) and hedenbergite (Hd) phases (SEM-BSE). **(b)** Tunket slag **(Cat. 255)** with clinopyroxenes, iron oxides, and metallic lead and copper inclusions in a lead-silicate glass (SEM-BSE). **(c)** Tunket slag **(Cat. 257)**: Lead-rich inclusion (white) with silver antimonide inclusions containing approximately 6 wt. % antimony (gray) (SEM-BSE). (d) Tunket slag **(Cat. 257)** large mixed sulfide-metallic inclusion trapped between bubble and slag. The inclusion contains copper sulfides and copper-iron sulfides (medium gray) and argentiferous lead (white) (SEM-BSE). **(e-f)** Tunket slag **(Cat. 257)** with silver antimonide inclusions in metallic lead and the quantification of inclusions using imaging software, area of field 250 µm x 150 µm (SEM-BSE).*

5.2.5 Speiss

Speiss phases were encountered in most of the slag samples of the first two types. Speiss formation due to the smelting of ore with group 15 elements (As, Sb and Bi) has often been documented in archaeological slags particularly associated with silver production from polymetallic ore (Asmus 2012; Craddock 1995, 219-21; Kassianidou 1998; Keesmann 1993; Rehren et al. 1999). The minerals tetrahedrite and tennantite are often important components of silver ore and contain substantial amounts of antimony and arsenic. For the silver to be successfully and efficiently recovered the antimony and arsenic must be either oxidized and incorporated into the slag or drawn out through vaporization because if they are reduced they will bind with metallic copper, iron, nickel, and precious metals to form speiss (Keesmann 1993, 114; Peterson/Twidwell 1985, 225; Rehren et al. 1999, 76-7). The silver in the speiss is trapped and is thought to have been unrecoverable to the smelter (Kassianidou 1998). Even in modern metallurgy antimony and arsenic pose problems during smelting, but they can be removed by careful roasting and during the matte smelting stage (Hino/Toguri 1987, 193).



***Figures 13 (a-b)** Tunket slag **(Cat. 268)** with lead corrosion (Li/Cer) with silver antimonide eutectic phase, speiss inclusions and chalcopyrite-bornite (Ccp-Bn) (PLM+XPLM). **(c-d)** Tunket slag **(Cat. 267)** with metallic lead inclusion with silver antimonide eutectic phase. The silver phase is also found in the litharge and cerussite probably indicating that this is the corrosion of the metallic lead (PLM+XPLM). **(e-f)** Imaging software used to quantify the amount of silver antimonide inclusions in lead-litharge in **Cat. 267** and **Cat. 268**. Images are approximately 300µm x 200µm.*

The most often encountered speiss phase analyzed by SEM-EDS has the composition of Cu_2Sb, which has also been found in high medieval copper-lead-silver slag from the Harz (Asmus 2012, 204). Various ratios of copper to antimony have been identified in the slag from Lashkerek and Tunket. Most common is Cu_2Sb, but others occurred, such as Cu_4Sb or Cu_3Sb_2. No iron arsenide phases were observed. The speiss phases tend to contain a small amount of iron, nickel, and arsenic, and are always a part of multi-phase polymetallic matte and/or metal prills. Frequently the combinations of galena, metallic lead, and speiss (**Figure 11a**) or bornite, galena, and speiss were observed in prills smaller than 100 µm. Occasionally speiss inclusions contain high percentages of antimony and bismuth and some have silver contents as high as 30 weight percent, but, more typically, the silver content of the speiss is at or below the detection limit of the SEM-EDS system (< 0.5 wt. %).

	Augite/Hedenbergite								Pigeonite				Fayalite		
	Cat. 254	Cat. 255	Cat. 256	Cat. 258	Cat. 259	Cat. 248	Cat. 251	Cat. 252	Cat. 256	Cat. 258	Cat. 259	Cat. 251	Cat. 254	Cat. 257	Cat. 253
Analyses	(x2)	(x1)	(x3)	(x4)	(x5)	(x4)	(x1)	(x2)	(x2)	(x2)	(x2)	(x1)	(x2)	(x6)	(x5)
Na_2O	-	-	-	0.6	-	-	0.7	-	0.5	1.4	-	0.7	-	-	-
MgO	2.3	3.8	5.5	3.7	4.4	5.2	3.7	3.0	3.8	1.0	2.7	10.0	3.7	4.4	2.3
Al_2O_3	1.8	7.7	6.7	8.1	4.6	6.7	9.0	2.3	4.7	8.5	5.6	5.2	2.0	2.0	1.1
SiO_2	47.9	41.8	49.1	44.8	47.4	46.6	44.8	48.6	40.0	39.4	37.3	40.1	35.9	34.9	33.3
K_2O	-	0.7	1.2	1.5	0.5	1.1	0.6	-	1.1	3.9	1.1	1.2	-	-	-
CaO	12.3	19.0	12.9	16.7	14.4	18.0	16.6	20.5	4.3	5.6	6.6	3.6	3.5	2.4	3.2
TiO_2	-	-	-	-	-	0.6	0.5	-	-	-	-	-	-	-	-
MnO	16.6	1.2	5.8	1.2	10.4	2.7	-	11.4	10.7	1.7	11.6	0.3	19.8	13.5	7.9
FeO	17.7	25.1	17.8	22.8	15.5	18.6	20.7	12.4	33.7	37.7	29.5	33.8	32.7	41.9	51.8
ZnO	1.1	-	-	-	2.4	-	3.1	1.3	1.1	0.5	4.7	4.8	1.8	-	-

***Table 1** Semi-quantitative elemental compositions of clinopyroxenes and olivine phases in slag samples determined by SEM-EDS area analysis. Oxygen was calculated stoichiometrically and carbon was excluded. The "-" means not detected or the value was under 0.5%. Values are normalized to 100 % and given in weight percent.*

	Cat. 251	Cat. 252	Cat. 253	Cat. 250	Cat. 248	Cat. 254	Cat. 255	Cat. 256	Cat. 257	Cat. 258	Cat. 259	Cat. 268
Na_2O	1.6	-	-	1.0	0.5	-	0.7	0.7	0.7	1.1	0.5	0.9
MgO	4.0	2.0	0.9	1.0	2.8	1.1	2.2	2.0	0.9	2.3	2.3	2.3
Al_2O_3	9.1	5.8	3.5	5.9	8.1	5.4	8.4	7.8	7.4	8.6	6.2	9.3
SiO_2	42.1	43.2	37.9	47.3	44.6	42.5	41.6	53.4	41.4	42.1	45.1	45.6
SO_3	0.5	0.5	1.9	-	0.5	1.0	-	1.6	1.1	n.m.	n.m.	n.m.
K_2O	1.7	1.1	0.9	1.9	2.3	1.4	2.7	1.9	1.6	2.8	1.3	2.5
CaO	8.0	16.5	8.6	9.8	13.3	8.9	10.9	6.9	6.6	11.3	11.1	11.9
MnO	-	10.1	5.0	0.5	3.1	12.6	1.6	4.6	8.3	1.3	9.8	2.2
FeO	21.5	16.5	39.5	12.4	21.5	22.8	28.0	17.3	28.1	27.3	17.1	21.7
Cu_2O	-	-	-	-	0.6	-	0.9	0.8	-	0.7	-	-
ZnO	5.1	2.3	-	4.6	0.5	2.4	-	0.5	0.6	-	3.5	-
BaO	0.9	-		8.7	0.7	0.8	-	1.9	2.2	-	0.8	-
PbO	3.0	1.1	-	6.7	1.4	1.0	2.1	0.4	0.5	1.8	1.6	1.3
As	1.0	-	-	-	-	-	-	-	-	-	-	-
Ag	-	-	-	-	-	-	-	-	-	-	-	-
Sb	1.2	0.6	0.9	-	-	-	0.4	-	-	-	-	0.9

***Table 2** Semi-quantitative elemental compositions of slag samples determined by SEM-EDS area analysis. The results represent areas of 2-4 mm2 free of large quartz, metal, or sulfide inclusions. Oxygen was calculated stoichiometrically and carbon was excluded. The "-" means not detected or the value was under 0.5%, and n.m. means not measured. Values are normalized to 100 % and given in weight percent.*

5.2.6 Silver Antimonide

Pure silver was not found; nearly all silver-rich phases found in the slag samples are silver antimonides. Antimony and silver form phases between dycrasite (Ag_3Sb) and allargentum ($Ag_{1-x}\ Sb_x$)[12], which show a range of solubility (Lee et al. 1994, 294). The silver antimonide phases in the slag from Lashkerek and Tunket have the formula $Ag_{0.94}\ Sb_{0.6}$ to $Ag_{0.84}\ Sb_{0.16}$. This phase is found in three of the four slag types and is associated with matte, metallic lead, and lead corrosion products. In the metallic lead, they form a eutectic phase and form very small crystals (1-20 µm) (**Figures 12e** and **13a**-**c**), but in the matte inclusions they can be larger (**Figures 9e-f**). In one instance a silver antimonide inclusion of 100 µm was found, but most are 50 µm and smaller. The presence of silver antimonide or antimonial silver in slag samples has been documented at many silver production sites (Anguilano 2012, 175, 181; Asmus 2012, 275; Eggers/Kronz 2000, 40; Ettler et al. 2009, 842). Silver antimonide can be found in conjunction with speiss, which would have been lost to the smelter (Rehren et al. 1999, 77), but the silver antimonide found in the lead and matte is more indicative of the richness of the end-product, the argentiferous lead and matte that would have been further processed and refined to produce metallic silver.

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[12] http://www.mindat.org/min-128.html accessed 29.04.2013.

5.3 Polymetallic Smelting Technology and Silver Production

All slag samples analyzed belong to processes involved in the smelting of sulfidic polymetallic ore. The process of separating copper, lead, and silver in complex ores is difficult and relies on the preferential bonding of silver with lead and copper with sulfur on the one side and silica with the oxides of iron, manganese, and calcium on the other (Bachmann 1993, 491-2). Metals are immiscible with matte, as is matte and slag (Asmus 2012, 56). During smelting liquid phases separate according to their density (Keesmann 1993, 114; Rosenqvist 2004, 268). Lead metal is the densest (10.66 g / cm^3), then speiss / copper antimonide (8.4 g / cm^3), matte (7.6-4.9 g / cm^3) and finally the slag (4-3 g / cm^3).

If we take the reconstruction of medieval smelting of the Rammelsberg as an example (Asmus 2012), the process of smelting polymetallic ore is not straight-forward, but is a repeated process of gradual enrichment and continual separation of copper-rich and lead-rich (argentiferous) phases in multiple smelting steps. This seems to have parallels in the slag from Tunket, which also appears to be a multi-step process.

The ore was possibly roasted before the first smelt to fracture and partially oxidize it, but oxidation was not carried out to completion as shown by the abundant sulfides found in the slag. The frothy slag and dense crystalline slag (Types 1 and 2) likely belong to the same smelting process, despite differences in appearance and texture. These slags reflect the two ends of a range of variability of viscosity, composition, and working temperatures. Galena and metallic lead are found trapped in the viscous frothy slag, but in the slag that was more fluid the prills tend to be much smaller and are dominated by copper-iron-sulfide phases showing that most of the lead was effectively separated. Because sulfur has a stronger affinity to copper than lead, under reducing conditions lead sulfide is more easily reduced to metal than copper sulfide (Rehren et al 2012, 1724; Willis/Toguri 2009). The reduction of most of the lead seems to have taken place in the first smelting step. The argentiferous lead would have been refined through the cupellation process to produce silver.

The matte produced in the first smelt would still have contained iron, lead sulfide, and some silver and would have needed a second smelt, probably after a roasting step to further oxidize the copper-iron sulfides. The dense microcrystalline slag (Type 3) appears to represent the second smelting process. The two slag samples of this type were fluid and quickly cooled and contain inclusions of metallic copper, lead, and copper sulfide (chalcocite) nearly free of iron. The two main groupings of slag types, (1/2 and 3), indicate that at least two smelting steps occurred: a lead smelting step, which produced argentiferous lead, speiss, and iron-bearing matte, and a second step to fully remove the iron from the matte to produce chalcocite, copper and small amounts of argentiferous lead.

Silver was at the center of production. Four of the five frothy slag sampled contain microscopic inclusions of silver-rich phases. These inclusions in the frothy slag are most visible in the metallic lead and its corrosion products. In slag samples **Cat. 259** and **Cat. 250,** the silver has concentrated as discrete silver antimonide crystals in the galena-bornite matte (**Figures 9e-f**) but also may appear as a solution in some of the sulfide phases. Therefore, silver was concentrated in both the metallic lead and the matte, which would need to be separated through further metallurgical processes.

The concentration of silver in the metallic lead and its corrosion products is variable. Two methods were used in determining the silver content of lead-litharge inclusions. SEM-EDS area analysis can be used to get an average silver content of a field, but the results are much less reliable when they are under one percent. The second method is described by Asmus (2012, 68-72) where imaging software[13] is used to quantify the surface area of silver-rich inclusions in metallic lead. To calculate the weight percentage of silver in the silver antimonide inclusions the formula $Ag_{0.9}$ $Sb_{0.1}$ is used and the weight percent of silver is therefore 89 percent. To find the weight percent of silver antimonide a density of 10 g / cm^3 was used and for lead 11.3 g / cm^3. With this software and the equations provided by Asmus (2012, 70) areas from two slag samples (**Cat. 268** and **Cat. 267**) were calculated to contain 1.3 and 0.6 weight percent silver antimonide (**Figures 13e-f**), 1.1 and 0.5 silver in weight percent respectively. If these areas are indeed representative, then a silver content of the argentiferous lead of around 0.5-1 percent is to be expected. This value is in gross contrast to the silver rich slag **Cat. 257**, which was analyzed by both techniques (SEM-EDS and imaging software). A 200 x 300 µm argentiferous lead inclusion found in this sample has numerous silver antimonide inclusions and gives an overall average normalized value of 10 weight percent silver by SEM-EDS and with the imaging software and subsequent calculations the silver content was determined to be 11 weight percent (**Figures 12c-f**). The variability of the three samples is too large to form a basis for wider discussion of the silver content of the lead produced through smelting. The high silver contents found in the slag (**Cat. 257**) are well above the normal range of argentiferous galena, which without additional silver-rich minerals is in the range of 0.1 to 1 weight percent (Bachmann 1993, 492-3; Ramdohr 1980, 646) and indicates that minerals like argentiferous tetrahedrite, silver sulfide, or native silver were also present.

Bismuth was not found in detectible quantities in the lead phases although this is where it should be concentrated (Craddock 1995, 221; Pernicka/Bachmann 1983). Bismuth is found in speiss phases containing antimony and occasionally silver. In the slag Types 1-2 from Tunket and Lashkerek, there seems to be a weak correlation between the silver and bismuth contents in that silver above 100 ppm tends to have higher bismuth contents than the samples with less than 60 ppm silver. The primary ore samples from Lashkerek and from the Nuratau mountains all have very low bismuth concentrations. Only the oxidized ore from Lashkerek (**Cat. 264**) had more.

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[13] ImageJ open source software from http://rsbweb.nih.gov/ij/ accessed 04.06.2013.

Lastly, the abundance of frothy slag pieces found in the slag heaps seems to confirm that this slag was indeed a waste product and was not re-smelted to recover the trapped lead and silver. However, the slag was found fragmented indicating that there may have been an effort made to manually beneficiate larger matte and metal inclusions from the slag.

6. Lead Isotope and Elemental Analyses: Results and Discussion

The use of lead isotopes analysis in archaeology is still a developing field (Gale/Stos-Gale 2000; Pollard/Gale 2009), and increasing application of multi-collector ICP-MS in archaeology (Niederschlag et al. 2003) and newly established laser ablation techniques (Lehmann 2011; Ponting et al. 2003) have led to great improvements to the instrumental precision, speed of preparation, processing time, and cost of analysis. With the advances in laser ablation in particular, the restricted access to sample precious metal objects is gradually becoming less of an obstacle. Lead isotope analysis was carried out to determine how the slag, ore, and silver coins relate to one another. As mentioned earlier, the ore and slag samples were prepared at the Deutsches Bergbau-Museum, Bochum, and analyzed in Frankfurt am Main by MC-ICP-MS while the coins were analyzed in Hannover by laser ablation. The data collected in this study are also compared to what is known about the regional ore geology and to published lead isotope data from archaeologically relevant ore deposits, namely in the Tien Shan (Chiaradia et al. 2006), the Pamir (Pavlova/Borisenko 2009) and the Hindu Kush Mountains (Brill 1997). Ore and slag samples from published literature were used to augment the data collected in this study.[14]

In general, the lead isotope ratios from the Pamir, Hindu Kush, and the Īlāq show good agreement with the range of isotopes found in the Samanid coins from al-Shāsh, Samarqand, and northern Afghanistan (**Figures 14-17**). The coins from northern Afghanistan are distinctly different from those of al-Shāsh, which reflect younger and older geologies respectively. Model ages determined by Stacy and Kramers (1975) show younger dates for the coins of Afghanistan, and the coins of al-Shāsh are much older, centering on 600 million years. In Afghanistan, the cluster of ore / slag from Farinjal matches with one dirham from Balkh, but most of the dirhams of northern Afghanistan form a cluster that centers on the one coin analyzed from the mint of Panjhīr and likely reflect the isotopic signature of this mining region. Unfortunately, the coin from Panjhīr fits within the field of silver ore from the Pamir Mountains, which makes the differentiation of these two sources at the moment impossible.

The isotope ratios of the slag from Tunket and Lashkerek show a similar range of compositions and, as to be expected, the polymetallic slag show close agreement to the coins of al-Shāsh. This supports the hypothesis that production centers in the Īlāq provided the silver for the making of al-Shāsh dirhams. But difficulties arise when the ore and the slag are compared. The slag often show significantly older geologic ages than the analyzed ore from the Īlāq, including that from mine of Lashkerek. Only two slag samples (**Cat. 250** from Lashkerek and **Cat. 254** from Tunket) fit well with the ore specimens from the mine of Lashkerek, the other nine slag samples point towards older geologic origins. The isotope ratios of the ore from the Īlāq analyzed in this study conform to the published analysis of other ore deposits in the Īlāq region, and it cannot be argued that there was an error in their attribution. Some ore samples from the North Tien Shan east of the Ferghana fault have more comparable isotope ratios to the Īlāq slag, such as from the Aktyuz ore deposit (Chiaradia et al. 2006), which also has evidence of 10th century mining and extractive metallurgy.[15] However, it must be stated that too few samples have been analyzed to draw firm conclusions.

The slag from Lashkerek and Tunket do not entirely match the ore specimens from Lashkerek mine in other regards. Although the slag from Tunket reflects a standardized technological process, the slag compositions show variable amounts of magnesium, zinc, calcium, iron, and manganese and reflect a variety of raw materials. For example, the gangue minerals from the Lashkerek ore (quartz and carbonates containing magnesium, manganese, iron, and calcium) do fit well with most slag, but in two slag samples there is very little manganese.

The four primary ore samples may not be representative of the ore extracted in the medieval period because the chalcopyrite to galena ratio is incompatible with what is found in the slag. The silver ore specimens from Lashkerek contain very little galena in relation to copper and silver-containing minerals. It is clear from the analysis of the slag that galena and chalcopyrite-bornite were smelted together and that at least some of the ore fragments contained both types of minerals. It cannot be ruled out that additional galena was added during the smelting process. As it has been mentioned previously, the galena from Lashkerek contains bismuth especially in the deeper parts of the mine, and it may have been beneficial to add galena free of bismuth perhaps from another source during smelting. Bismuth is an unwanted impurity because it causes complications during silver refining and it makes the silver hard and brittle, even in small quantities (Pernicka/Bachmann 1983, 595-6; Zwicker et al. 1991, 72-3). Another possibility is that the smelting of the copper-silver fahlore from Lashkerek required additional galena for other technical reasons. Perhaps the ore from Lashkerek had insufficient quantities of lead to efficiently collect the precious metals to prevent them from being trapped in the slag and in copper and speiss phases. Examples of ‘dry’ or lead-poor silver ores are not rare: Rio Tinto, Saxonian Erzgebirge, etc. (Anguilano 2012; Bartels 2008, 30;

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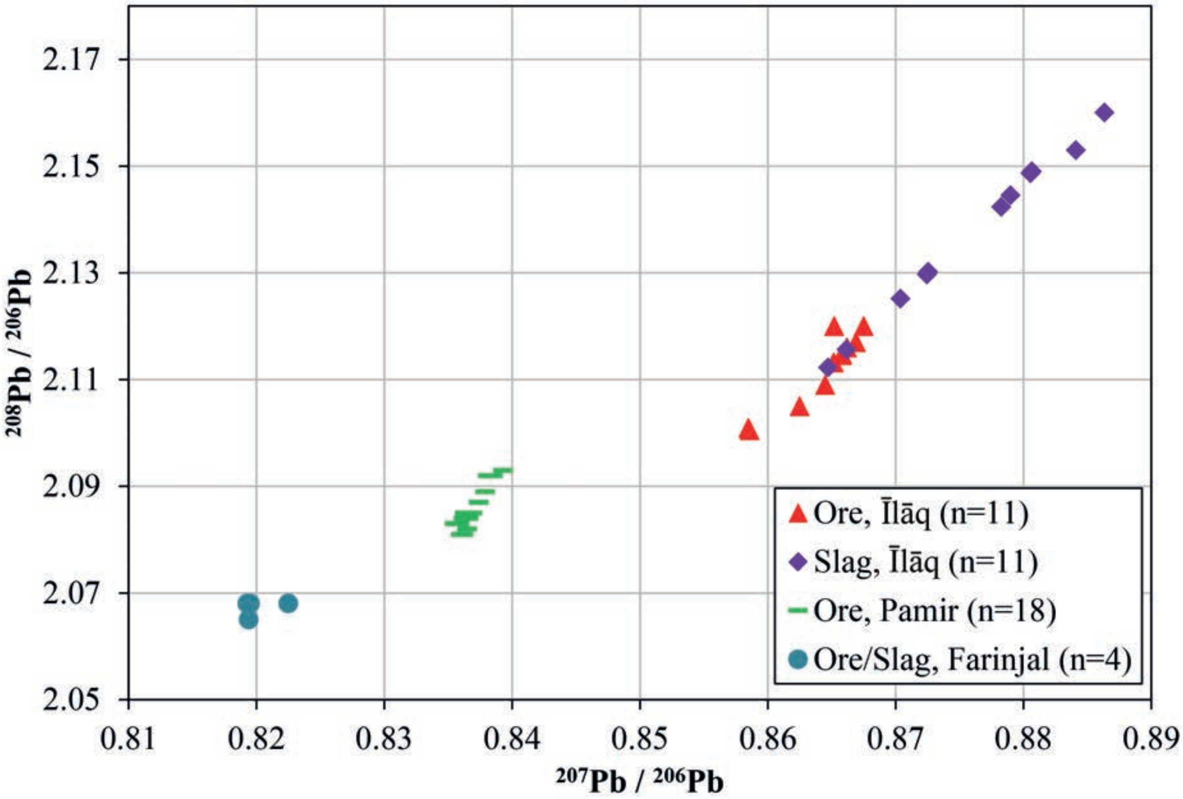
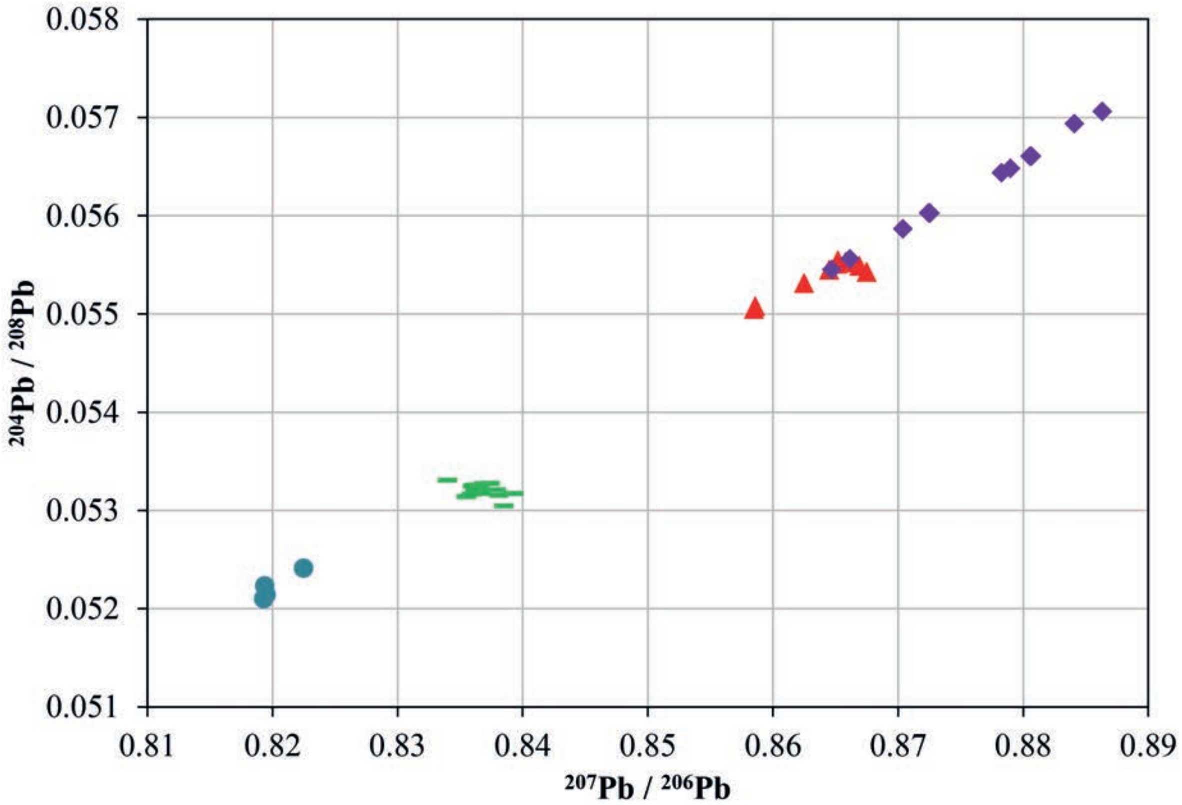
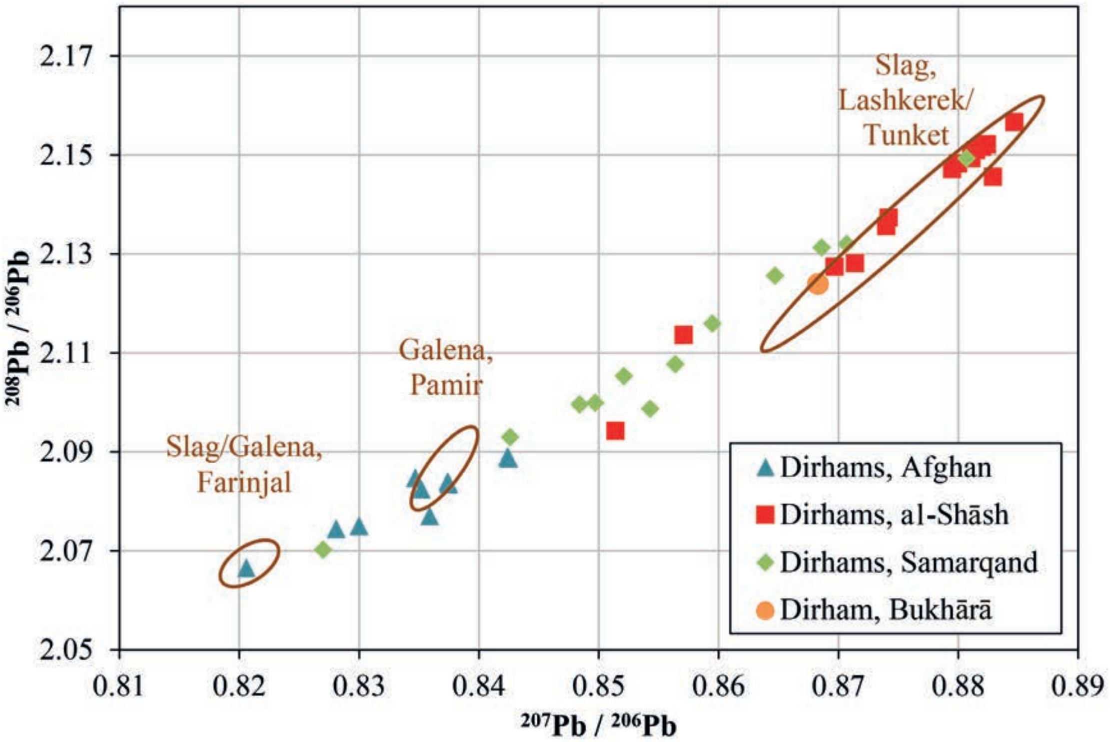
[14] Chiaradia et al. (2006): Kalmakyr, Kochbulak, Uchkulack, Ustarasay, Mardjanbulak, Sarmich, Zarmitan; Aktyuz; Pavlova/Borisenko (2009): Bazar-Dara, Mardjanay; Brill et al. (1997): Farinjal.

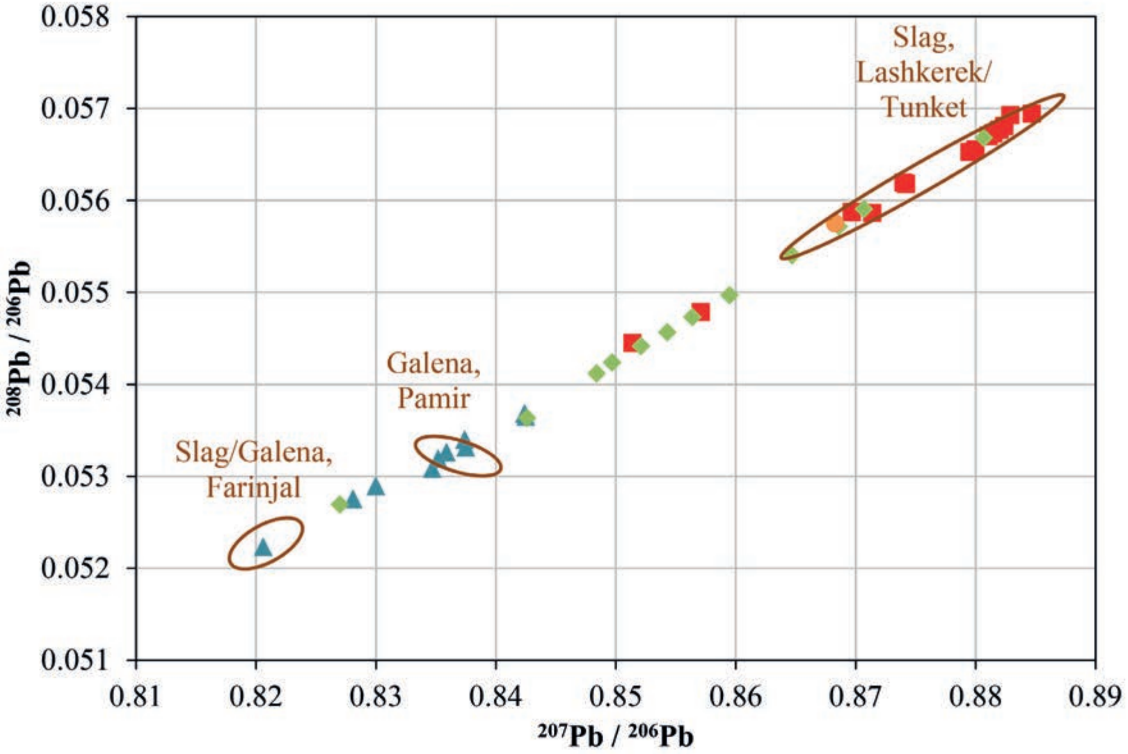
[15] http://www.stansenergy.com/projects/kutessay-ii-ol/kutessay-ii-history/ accessed 04.06.2013.



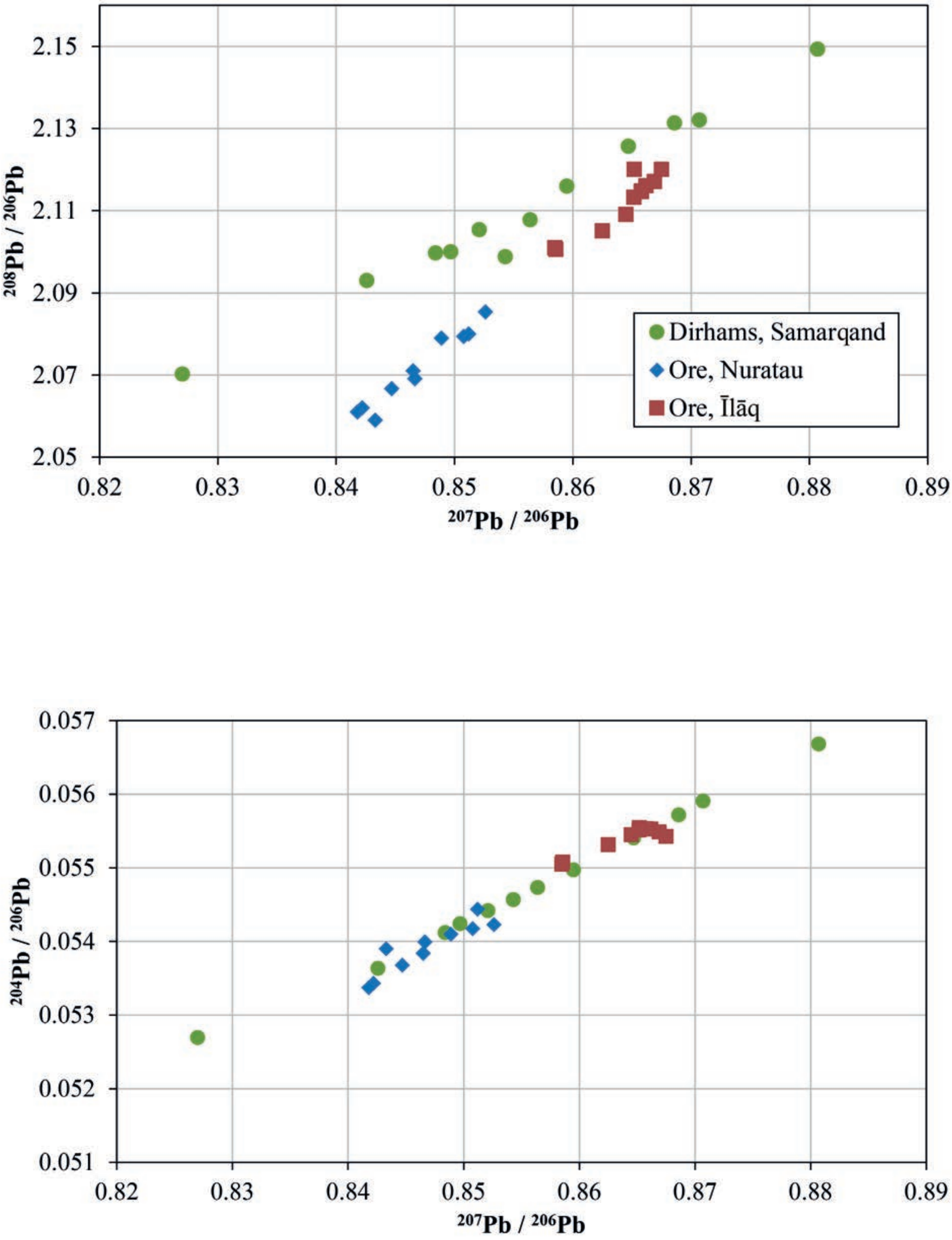


Figures 14 *and* ***15*** *Lead isotope ratio diagrams of a selection of ore and slag from the Pamir (PAVLOVA/BORISENKO 2009), Farinjal (BRILL 1997), ore from the Īlāq (CHIARADIA et al. 2006) and ore and slag from Lashkerek and Tunket (this study).*





***Figures 16** and **17** Graphs showing relationship of coins to selected ore and slag. The slag from Lashkerek and Tunket closely match the majority of coins from al-Shāsh and a few coins from Samarkand. The coins from Samarqand have the broadest range of isotopic composition and may reflect a mixture of several sources. The ore from the Pamir and the slag and ore from Farinjal fit well with many coins from northern Afghanistan, but the one coin from the Panjhīr mint is within the field of Pamir ore showing that there might be an overlap between the Pamir and the Panjhīr deposits.*



***Figures 18** and **19** These graphs contrast the ore from the Nuratau Mountains in the Samarqand area, the ore from Lashkerek and published analyses of ore from the Īlāq area with the coins of Samarqand. The ore from the Nuratau do not match the coins, but ore from the Īlāq fit only with one Samarqand coin.*

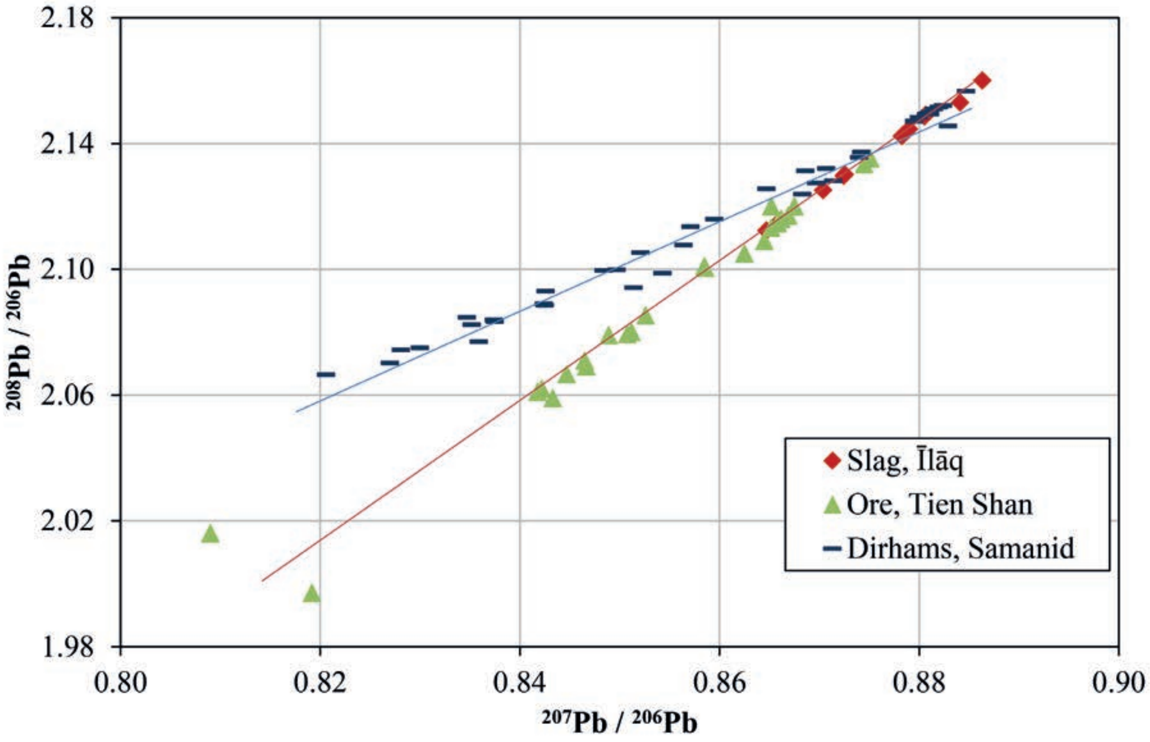


Figure 20 *The Samanid silver coins and the ore / slag from the Tien Shan form two trend lines that converge above 0.87 ^{207}Pb / ^{206}Pb. The younger deposits of the Tien Shan, here represented primarily by the Nuratau deposits near Samarqand do not correlate to the Samanid silver line. The Samanid silver line can better be explained as a mixing line between silver stemming from older deposits in the Tien Shan and the younger deposits in the Pamir and Hindu Kush Mountains.*

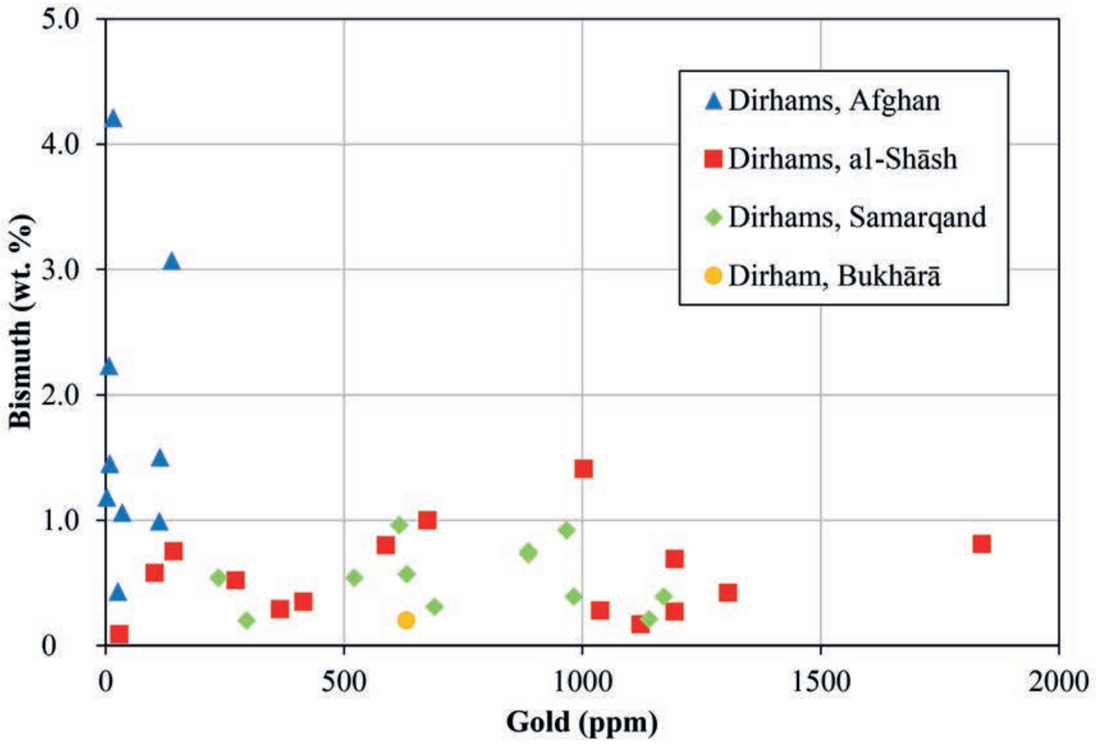


Figure 21 *This graph contrasts the gold and bismuth contents of the silver coins from the various regions. It is quite clear that Samarqand and al-Shāsh are similar whereas the coins from Afghanistan are different. There is no indication that the Samarqand coins are a mixture of Afghan and al-Shāsh silver, but closely aligns only with al-Shāsh.*

Craddock 1995, 217). A conclusive solution to the problem remains elusive, and it would require more sampling to answer.

The mixing of different types of ore from various origins is definitely possible for Tunket, but seems less plausible at the mine of Lashkerek itself. If the account of al-Hamdānī, a 10th century Arab metallurgist and geographer, can be deemed applicable, the taxation of the miners' yields may have been an important way of supplying the state with ore / metal (Dunlop 1957, 41). Both the owner of the property and the government each received a portion of the ore collected by miners. It is altogether reasonable to assume that the ore would have been collected and smelted in central locations like Tunket. In any case, it is certainly possible that the silver production at Tunket was based on the supply of ore from the many mines of the Īlāq and perhaps further afield.

The dirhams from Samarqand do not fit with the ore from the deposits of Sarmich, Zarmitan, Mardjanbulak and Kosmanachi in the Nuratau and Navoi Mountains; an argument for a local supply of silver is not supported by the isotopic evidence. The $^{207}Pb / ^{206}Pb$ to $^{208}Pb / ^{206}Pb$ slope from the Tien Shan ore diverges clearly from the isotopic slope of the coins from Samarqand (**Figures 18** and **19**). If the mint of Samarqand was not supplied with local silver resources then it is likely they got their silver from the silver supplying regions such as the Pamir, Hindu Kush, and the Īlāq (**Figure 20**). The lead isotope analysis supports the possibility that the silver of Samarqand is a mixture because there is a mixing line between geologically old Īlāq slag and the younger Pamir and Hindu Kush deposits.

For this argument to be sound, it must also be confirmed in the elemental signature of the coins. Gold and bismuth have been identified as the most important trace elements for the study of silver provenance because gold remains unchanged in the refining process and bismuth is difficult to completely remove from the silver (McKerrell/Stevenson 1972, 198; Pernicka/Bachmann 1983, 595-6). As has been long known, the silver from the Hindu Kush is unusually high in bismuth and very low in copper and gold (Cowell/Lowick 1988, 65). The trace elements of the coins from Afghanistan determined by LA-ICP-MS also comply with this observation. With the exclusion of one coin with an extraordinarily high bismuth content (14 wt. %) the average value is 1.7 weight percent whereas the coins from Samarqand and al-Shāsh are 0.54 and 0.56 weight percent, respectively. The coins from al-Shāsh and Samarqand have similar gold contents, both 750 ppm, while the coins from Afghanistan have only 50 ppm on average. There are clear differences between the Samarqand coins and those of northern Afghanistan (**Figure 21**). It is true that the Samarqand coins with the younger isotope ratios also have the lowest gold contents, but, in general, the coins from al-Shāsh are much more similar to Samarqand in elemental composition and clear signs of mixing between Īlāq and Panjhīr are not visible elementally. Several pieces are still missing from the discussion. The ore from the Pamir Mountains probably overlaps isotopically with Panjhīr, but neither the slag nor the silver from this region have been characterized. Slag and silver from other deposits in the Ferghāna Valley, Hissar Mountains, and Turkestan Mountains have not been studied and may have helped to supply Samarqand with silver. The role of refining at Samarqand must also be considered because if imported lead was used for refining at the mint then this would have important impacts on the lead isotope signature of the coins produced there.

7. Conclusions

In the early 10th century, the Samanids of Khurāsān and Transoxania were at the center stage of silver production, and they can be regarded as a vital silver supplier to the early medieval world. Not only is the study of silver production important in understanding the inter-regional trade of metal in the Samanid Empire and neighboring regions, the impact of Central Asian silver production in the economy of northern Europe in the Viking Age is a particularly current subject, and a direct look at the material evidence is required to push the discussion forward. It is clear that there was more than one supplier of silver in the Samanid Empire, but the significance of the various mines and production centers and their chronology is still an open discussion in need of further research.

The slag from Lashkerek and Tunket can be characterized as polymetallic with an emphasis on silver, copper, and lead production. The isotope ratios of the slag from the Īlāq mirror the isotope ratios of the Samanid silver dirhams minted at al-Shāsh, which through historical reference can be linked to the medieval city of Tunket, near modern-day Almalyk in Uzbekistan. The silver ore samples from Lashkerek partially fit with the isotope data, but for the majority of slag samples the isotope ratios are geologically older. The sample size of the ore is limited and may not be representative of the ore used in the past. More samples are needed and other deposits and mines should be tested before further conclusions can be drawn.

The smelting technology is based on smelting primary sulfides of iron, copper, lead, and silver. Antimony-containing ore seems to have played an important role and indicate that, in addition to galena, fahlore minerals like tetrahedrite were smelted. The slag shows silver contents between 300 and 20 ppm, and the silver concentration of the argentiferous lead found in three samples was determined to be between 0.5 and 10 weight percent, although more samples should be tested to get a truly representative result. The slag composition itself is very heterogeneous with varying concentrations of iron, calcium, and manganese indicating that the raw materials for smelting were not standardized. Despite the differences in slag compositions, the technology appears to be a standardized process. Three types of slag were identified from Tunket, which could represent a two-stage smelting process for the producing: 1. Argentiferous lead and iron-bearing matte, and 2. Iron-poor matte, copper, and argentiferous lead.

Ore samples from the mountains around Samarqand do not fit with the isotope ratios of coins from the mint of Samarqand, which according to an historical account was not supplied by local mines (Ouseley 1800, 254). Too little information is known about the sources that may have supplied the mint of Samarqand, but due to its broad isotope field a mixture from the Pamir, the Hindu Kush and from the Īlāq is possible. Ibn Hauqal also describes other regions that were actively mining silver in the 10th century, which may have played a role. The regions beyond the Samanid heartland like the Talas, Chatkal, Pamir, and northern Tien Shan also need further consideration. As more ore, slag, and silver from these regions are studied our understanding of Samanid silver production will become clearer.

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