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Late Medieval bone-ash cupels from the archbishop’s mint in Trondheim

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During the excavations in 1991–95 of three successive mints in the Archbishop’s Palace in Trondheim, Norway, 174 bone-ash cupels and fragments from AD 1500–37 were unearthed. Four used cupels have been cut in half in order to study their inner microstructure. Analyses show that the cupels were made from pure bone-ash from animals, as described in contemporary literature. The cupels form five groups according to size: the small ones are likely to have been made for assaying metal with a high concentration of silver and the larger ones for alloys with lower silver content. During cupellation lead oxide fills the cupels from the top. The bottom of the cupels may not become impregnated with lead oxide. For this reason most of the excavated cupels have a ball-shaped bottom. Impurities in the assayed material, like copper, were also found as copper-rich precipitates inside the bone-ash particles. The bowl-shaped tops of the cupels have a fine-grained surface layer.

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The Archdiocese of Nidaros was founded in the period AD 1151–54. Nidaros was chosen due to the cult of St. Olav, which had made the town an important pilgrimage destination. Although the royal court subsequently moved south to Bergen, and later to Oslo during the 13th and 14th centuries, the Church remained firmly situated in Nidaros, now Trondheim, Norway. In 1449 the king delegated tax collection and supervision of the local courts to the archbishop. Being both a major economic player and the country’s superior spiritual supervisor, the archbishop was a potent authority in local as well as national affairs.

In 1397, Norway joined the Kalmar Union along with Sweden and Denmark. According to the agreements establishing the union, the king was supposed to rule under the supervision of national councils from each of its membership countries. During the 15th century, it became the rule that the Norwegian Council of the Realm was led by the archbishop. This council exercised its greatest influence at the moment of the election of new kings, especially from 1448 onwards, when Norway was officially recognised as an electoral kingdom (Benedictow 1977).

One notable result of this influence is found
in the Halmstad Recess of 1483, a charter setting out the conditions of King Hans’ election as king of Norway (NgL 2 R, #1). Among several concessions, Hans had to reconfirm the Archbishop of Nidaros’ privilege to strike coins. This privilege had originally been accorded in 1222 by King Haakon Haakonsson but was withdrawn by King Eirik Magnusson in 1281 (NgL I: 446; DN III, #30; Skaare 1995, p. 108; Risvaag 2000).

The Reformation of the Church imposed by King Christian III in 1536, and Archbishop Olav Engelbrektsson’s flight from Nidaros on April 1st 1537, brought an end to the Catholic Church in Norway. The Archbishopric of Nidaros’ coin-issuing privileges also ceased.

Aims of the investigation
Archaeological excavations took place in the Archbishop’s Palace of Nidaros between 1991 and 1995 following a fire in 1983 that ravaged the eastern and southern wooden ranges (McLees 1996; Saunders 2001; Walaker Nordeide 2003).

The excavations identified three successive mint complexes, one above the other, in the northern part of the eastern wing. They were all near the palace’s perimeter wall. Their structure and layout with workbenches, tiled floors and hearths clearly indicate the purpose of the buildings as workshops of Late Medieval moneyers, corresponding to illustrations of minting in contemporary treatises. The archaeological evidence further corroborated this interpretation of the buildings as mints, with important finds of debris from coin production such as cupels, crucible fragments, hammered rods, blanks and coins. The finds are mainly from the site’s period 6, phase 1–3, i.e. the years AD 1500–32, plus period 7 phase 1, 1532–37. Judging from dendrochronology, the oldest mint complex was established about AD 1500 (Olsson 2000).

Although coins were struck by the archbishops of Nidaros between 1222 and 1281 (Risvaag 2006, p. 239), the excavations uncovered no indication of a mint within the palace precinct prior to the late 15th century (Saunders 2001). The excavations of the mint complexes revealed coin production under the offices of three archbishops: Gaute Ivarsson (1475–1510), Erik Axelsson Valkendorf (1510–22) and Olav Engelbrektsson (1523–37).

During the excavations a total of 143 bone-ash cupels and 31 cupel fragments were unearthed (Bergstøl & Nordeide 1992–93; Saunders 2001, pp. 27–33). The use of bone-ash cupels was a standard technique in the assaying of precious metals at the time. The cupels have an inherent capacity to separate precious metals from others, thereby permitting calculations of the fineness of a sample. The heaviness of the finds indicated that all contained lead oxide (PbO), litharge, as a result of having been used. As the archbishops in Medieval Trondheim had no silver mines, bone-ash cupels were used to measure the fineness of precious metals being paid to the archbishops or to establish the correct alloy composition when making bullion for use in coin production.

To obtain correct results high quality cupels were needed. Detailed guidelines on how to make them are given in several contemporary treatises, e.g. Biringuccio 1540 (1966), Agricola 1556 (1950) and Ercker 1574 (1951). Modern investigations of 16th century cupels from the Tower of London (White 2010) show that these were made from bone-ash, while cupels from Oberstockstall (Rehren 1998; Martinon-Torres & Rehren 2005) were made of about two-thirds bone-ash and one third clay mixed in as a binding agent. Mid-14th century cupels from Pymont (Rehren & Eckstein 1998) contain about 10% by weight of other materials. Investigations have also provided information about testing details (e.g. Bayley 1991; Sieblist 2006). A modern standard description of how to assay precious metals is available as ASTM-E1335-08. However, papers dealing with the micro-structure of cupels in general are few.

An unpublished paper (Bergstøl & Nordeide 1992–93) presents the results of X-ray fluorescence (XRF) investigations of eleven bone-ash cupels from the Archbishop’s Palace in Trondheim. These show that lead and copper dominate the metal impurities in the discarded cupels, with traces of zinc and nickel. However, as XRF was used as a non-destructive technique, no micro-structure of the cupels was revealed. The main objective of the present study has been to record the cupels from the archbishop’s mint. Specifically, to document their size, shape, and the materials used to produce them; and to study the micro-structure of a small number of cupels in order to
discern how they were made, and – when used – to determine what materials were assayed by cupellation at the mint.

**Assaying process and microstructures**

Bullion for silver coins had to be refined before being mixed with a controlled amount of base metal, here copper, to obtain an alloy with the intended degree of fineness. Investigations of fineness, called assaying, were done by cupellation. Typically, a small piece of the material to be assayed would be melted in the cupel with ten times as much lead. Hot air was circulated above the cupel to produce oxidizing conditions. If the cupel is pre-heated to 900 °C, as ASTM E-1335-08 recommends, and is kept at this temperature after charging, several reactions may take place:

1) Lead melts at 327.5 °C and may at 900 °C dissolve the silver to be assayed (fig. 1).

2) \( \text{2 Pb}_{\text{Liq}} + \text{O}_2 \rightarrow \text{2 PbO}_{\text{Sol}} \) which melts at about 888 °C: \( \text{PbO}_{\text{Sol}} \rightarrow \text{PbO}_{\text{Liq}} \)

This is an important reaction since molten lead oxide wets bone-ash and may be sucked into the cupel body without reacting with the bone-ash itself (Bayley 1991; Rehren & Klappauf 1995; Tereygeol & Thomas 2003; Martinon-Torres et al. 2008). Liquid lead, however, does not wet the bone-ash and will stay on the surface of the cupel. The impurities in the alloy to be assayed will not be dissolved in the molten lead or molten lead oxide:

3) At about 750 °C: \( \text{CuO}_{\text{Sol}} + \text{PbO}_{\text{Sol}} + \text{Ag}_{\text{Sol}} \rightarrow \text{liquid (eutecticum; fig. 1; phase eq. diag. 2001, fig. 10300), and} \)

4) At temperatures between 750 and 780 °C impurities like copper, iron and others may enter the liquid lead oxide:

\[
\text{CuO}_{\text{Sol}} + \text{PbO}_{\text{Sol}} \rightarrow \text{liq. (eut.)}, \\
\text{Fe}_2\text{O}_3(Sol) + \text{PbO}_{\text{Sol}} \rightarrow \text{liq. (eut.)} \text{ and} \\
\text{NiO}_{\text{Sol}} + \text{PbO}_{\text{Sol}} \rightarrow \text{liq. (eut.)}
\]

At 900 °C the impurities in the alloy to be assayed are dissolved either in liquid lead oxide or in liquid lead which is being gradually oxidized. A minor part of the silver (1–2%) is also dissolved in the liquid lead oxide. As liquid lead oxide is being sucked into the cupel wall and more and more lead is being oxidized, the rest of the liquid lead becomes richer in silver. Solid silver (at about 98% Ag) is formed when the concentration of silver in liquid lead reaches the liquidus line (at

![Figure 1. Phase diagrams of Ag-Pb and PbO-CuO-Ag. Impurities may alter these diagrams.](image-url)
Fig. 2. a) Three bone-ash cupels with an upper outer rim diameter of 30 mm (N124857). Note the depression at the bottom of N124857. In b) the cross-section of another cupel, N124860, is shown from two angles. Upper rim diameter 35 mm, height 23 mm. Note the surface layer at the bottom of the bowl. c) Sketches of two cupels with upper rim diameters of 35 and 40 mm. The dotted lines indicate where most of the cupels are broken (ball-shaped). Emphasised lines illustrate the fine-grained surface layer. Photographs Bruce Sampson, NTNU Vitenskapsmuseet. Drawings Pål Ulseth.

about 90% Ag and 10% Pb). Near the end of the process the liquid (Pb + Ag) may have a near spherical shape. At the end of the cupellation process, when the last liquid lead is oxidized and leaves the spherical bead, the surface of the bead may visibly brighten or “flash”. This has been said to result from a sudden release of the latent heat of fusion upon the phase change as the lead-free bead solidifies (ASTM E-1335-08).

During cooling the liquid lead oxide containing copper oxide (and other impurities) inside the cupel solidifies and splits into solid lead oxide and solid copper oxide. At a temperature around 700°C a solid state reaction (peritectoid) may take place where

\[
\text{Cu}_2\text{O}_{\text{Sol}} + \text{PbO}_{\text{Sol}} \rightarrow \text{Cu}_2\text{PbO}_2(\text{Sol})
\]

after prolonged aging (Čančarević et al. 2005).

By comparing the weight of the clean silver bead at the end of the process with that of the starting object, the fineness is determined. The correct purity may be a bit higher than this measured result since only the weight of the large silver bead is counted, and the minor losses to the liquid lead oxide in the body of the cupel or silver particles in flaws of the cupel surface are not considered (Téreygeol & Thomas 2003).

In a used cupel, CuO and PbO will be the most likely components to be found in addition to bone-ash particles as there may not be sufficient time to produce particles by the peritectoid reaction to \(\text{Cu}_2\text{PbO}_2\). Silver particles precipitated from CuO and PbO are expected to be tiny and therefore difficult to register.

**Experimental procedure**

The goal of the sample preparation was to reveal the microstructure and chemical composition of the cupels from top to bottom in order to understand how the cupels were made and used. With permission from the NTNU University Museum, we cut four cupels in half vertically with an Accutom saw (fig. 2b). It has a 0.5 mm thick metallic diamond-bound cutting wheel with a diameter of 125 mm. With a low cutting speed and slow feeding we accomplished the cutting without adding any cooling liquid. Next, we embedded one of each of the halves in resin to facilitate further preparation and handling. After grinding on SiC paper
down to grid 4000 without cooling liquid, and diamond polishing with 3 and later 1 μm particles on soft cloths with alcohol as polishing medium, we investigated the plane surfaces under a light microscope.

Later we coated the surfaces with carbon and investigated them in a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). We used backscattered electron (BSE) images to reveal element contrast.

To document the mean chemical composition, we prepared specimens of about 0.5 g by vertical cuts of the small cupel N124918. We dissolved one specimen in nitric acid (HNO₃) and another in hydrofluoric acid (HF) at 80°C under ultrasonic vibration for two hours, to make sure that silicates were dissolved. We then used a high-resolution inductively coupled plasma mass spectrometer (ICP-MS) to analyse the solutions.

The cupels are presented according to their museum numbers.

**Surface description of the cupels**

Fig. 2 shows the principal parts of three bone-ash cupels typical of the 132 excavated cupels investigated in this study. They have a conical outer surface, showing that they have been produced in moulds. The shape, height and upper rim diameters vary (tab. 1).

The outer rim diameter of the “upper bowl” can be divided into five groups according to size, from 25 to 45 mm, each group within ±1 mm (tab. 1). Most of the cupels belong to the 35 mm group. As seen in fig. 2 and tab. 1 most lack their lower part and have a ball-shaped bottom. Only a few retain their full height preserved with a flat bottom after cupellation. Many cupels also lack a complete upper rim.

Of the 77 cupels with an upper rim diameter of 35 mm, 20 retain their full height which varies from 17 to 25 mm. Most of the largest cupels, 40 and 45 mm in diameter, have a depression at the bottom of the bowl (fig. 2c; Rehren & Eckstein 1998).

**Cross-sectional structures**

In the four halved cupels we made the following observations, starting from the upper bowl-shaped surface and going downwards (figs 3–10).

a) On the upper side of the small cupel N124918, a rough layer of lead oxide is found on the surface at the bottom of the bowl (figs 3, 4a). This is not typical, but gives information about the conditions at the end of the assaying process. The spherical pit in the lead oxide skin corresponds to the seat of a silver bead measuring about 2–2.5 mm in diameter. The shape of the lead oxide’s surface towards the silver bead tells us that the liquid lead oxide did not fully wet the silver bead. On N125125, another small cupel, the lead oxide forms just a thin layer at the bowl surface. At the bottom of the bowl some scratches are seen which may be due to picking out the silver bead.

b) Beneath the lead oxide a smooth, uniform surface layer of fine particles consisting of phosphorous, calcium and oxygen can be observed on the cupels N124918, N125125 and N124860. Veins of lead oxide run through the fine-grained layer

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**Tab. 1. Size and shape of the 132 crucibles included in this investigation. “Ball” refers to ball-shaped bottom.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Number and (%)</th>
<th>Shape Number and (%)</th>
<th>Bottom thickness (mm)</th>
<th>Height (mm)</th>
<th>Depressed bottom Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up. rim diameter</td>
<td></td>
<td>Ball</td>
<td>Full height</td>
<td>Ball</td>
<td>Full height</td>
</tr>
<tr>
<td>25 mm</td>
<td>10 (8%)</td>
<td>10 (100%)</td>
<td>0 (0%)</td>
<td>7-10</td>
<td>-</td>
</tr>
<tr>
<td>30 mm</td>
<td>16 (12%)</td>
<td>16 (100%)</td>
<td>0 (0%)</td>
<td>8-11</td>
<td>-</td>
</tr>
<tr>
<td>35 mm</td>
<td>77 (55%)</td>
<td>57 (74%)</td>
<td>20 (26%)</td>
<td>7-14</td>
<td>17-25</td>
</tr>
<tr>
<td>40 mm</td>
<td>22 (20%)</td>
<td>21 (100%)</td>
<td>1 (5%)</td>
<td>6-14</td>
<td>17</td>
</tr>
<tr>
<td>45 mm</td>
<td>7 (5%)</td>
<td>7 (100%)</td>
<td>0 (0%)</td>
<td>9-15</td>
<td>6 (84%)</td>
</tr>
</tbody>
</table>

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Fig. 3. The small cupel N124918. SEM-BSE image of the cross-section of the same cupel after grinding. Top: a white lead oxide skin. Middle dark ribbon: a 250 μm thick fine-grained bone-ash layer (black) with lead oxide veins running through (white). Bottom: a mixture of coarse and fine bone-ash particles (black / grey) embedded in lead oxide (white background).

Fig. 4. EDS analysis of a) lead oxide skin, b) black particles in the thin layer with peaks of P, Ca and O, and c) veins of lead oxide running through the thin layer in fig. 2. Carbon (C) stems from the specimen preparation coating. These spectra are used to illustrate the differences in chemical composition without a detailed quantitative analysis of each component.
Fig. 5. EDS analysis of the small cupel N124918. a) A bone-ash particle with main peaks from P, Ca and O. b) Material surrounding the particles: main peaks Pb and O.

Fig. 6. SEM-BSE. N124918. a) The arrows point to two silver particles in surface flaws in the fine-grained layer. b) A magnified picture of the silver particle to the right. The grey structures below the particle are bone-ash particles surrounded by lead oxide (white).

The presence of phosphorous, calcium and oxygen shows that this thin layer, about 250 μm thick and about 15 mm wide (as seen in the cross section), consists of fine-grained bone-ash particles. This thin, compact surface layer is what Ercker (1574, p. 31) named “cupel facing”. On cupel N121965, with a rim diameter of 35 mm, no fine-grained surface layer is observed. By visual inspection of 132 cupels, only two seem to lack this facing layer. If a detailed analysis could confirm this number, it means that about 98% of the cupels have a fine-grained surface layer.

In a few places silver particles fill flaws in the fine-grained layer (fig. 6). These particles have an irregular shape and their size is typically 20–30 μm across.

c) Further down, the material consists of porous bone-ash particles of various sizes mixed in lead oxide (fig. 7). Note the low number of pores. The particles vary from small to 300 μm in diameter. EDS analyses show that here too their main chemical constituents are P, Ca and O, indicating bone-ash. These particles contain cylindrical canals. Some of the canals may be open (fig. 8a), others are filled with lead oxide (fig. 8b). Many porous particles are filled up with lead oxide throughout their whole volume (figs 7–9; Marti-Non-Torres et al. 2008). Near the bottom of the cupel (fig. 7), the structure is more or less the same as described above.

The results from the chemical investigations of dissolved cupel materials by plasma mass spec-
Fig. 7. SEM-BSE. Typical structures near the bottom of the small cupel N124918. Coarse bone-ash particles are embedded in a mixture of fine bone-ash powder (black) and lead oxide (grey) with only a few pores.

Fig. 8. SEM-BSE images of two coarse bone particles embedded in a mixture of fine bone-ash powder and lead oxide in the small cupel N124918. a) Bone-ash particle (centre) with cylindrical holes. b) Porous bone-ash particle (centre) filled with lead oxide all through its volume (white spots). Note that the magnification here is higher than in fig. 7.

toscopy show the presence of phosphorous, calcium, lead and small amounts of magnesium, aluminium, silicon, manganese and iron. No debris remained after the dissolution of the specimens from the small cupel in acids.

Looking at the EDS spectra from the two small cupels where lead dominates, we saw only traces of other metallic impurities, viz iron and/or copper. This indicates that the material assayed in the cupels N124918 and N125125 was high purity silver. In the large cupel N121965 we also found copper in the bone-ash particles, not homogeneously distributed, but mainly as precipitates of a size of about 5 \( \mu m \), see element map in fig. 10.

Production technique

The macropictures and microstructures of the cupels, as shown in the figures, provide a clear idea of how the bone-ash cupels were made. In each case the main body consists of a mixture of fine and coarse bone-ash particles. The upper fine grained layer, covering about half the area of the bowl, has a uniform thickness and a smooth surface. On the large cupels, however, there is a small depression at the bottom where the silver bead would be expected to be found. To obtain the even thickness of the fine-grained layer, the main body was probably pressed first before a certain amount of fine bone-ash powder was added and finally pressed with a pestle with a convex bottom, to obtain the bowl-shaped top.
Fig. 9. SEM-BSE of a bone-ash particle showing Haversian canals (see arrows) surrounded by a network of finer canals, all filled with material containing lead oxide (and impurities).

Fig. 10. SEM image of the large cupel N121965. a) BSE image. Dark areas show Cu (inside the circles). b) Elemental map showing the distribution of copper. Samr magnification as in a). These micrographs at high magnifications show that copper is present as agglomerates / precipitates in a nearly pure lead / bone-ash structure (light area).

This interpretation of the examined material corresponds with the descriptions found in the Pirotechnia by Vannoccio Biringuccio (1540, p. 138) and the Treatise on Ores and Assaying by Lazarus Ercker (1574, pp. 26–31). Ercker describes the process in the following manner:

“Then pack the cupel mold full of ashes, scrape or wipe off the excess, and with one to four blows of the wooden mallet drive the monk into the mold. Wipe the monk clean and with a little wooden spoon sprinkle good facing ashes on the cupel while it is still in the mold. Spread the facing ashes with one of your fingers, then put the monk back in again, fit it on straight, and with two or three straight blows, whichever the case may require, beat the facing in the cupel so that it adheres very evenly. Then lift out the monk and over some more ashes press the cupel from the mold. The cupel will then be ready”.

About 98% of the cupels look like they have this facing layer, and so the cupels in the archbishops’ mints seem to have been made according to recommendations.

Cupel shape
No unused cupels were identified from the excavations. They are all heavy, showing that they have been used. This is hardly surprising since pure...
bone-ash cupels appear to be too fragile to be preserved archaeologically. Used cupels survive because they contain absorbed lead oxide which binds the bone-ash particles together. Portions without any lead oxide easily break off (Tèreygeol & Thomas 2003, fig. 10). If a cupel is not fully penetrated by lead oxide during cupellation only the penetrated mass will be preserved (Martinon-Torres et al. 2008). This may explain why most of the cupels have lost their bottom part and part of their upper rim, and only about 15% retain their full height. Lead oxide fills the cupel from the top and to a certain depth, as long as there is liquid lead oxide left in the bowl and the temperature is above the solidification point of the impure litharge. (Pure litharge solidifies at about 888°C). The rest of the cupel receives little or no lead oxide and thus remains fragile. Also, the assayer did not want to use more lead than necessary, but needed to be sure that all liquid lead oxide left the bowl. Not filling the entire cupel body with lead oxide may thus have been deliberate. Could the bone-ash in the lead-free fragile bottom be reused? If so, then the bottom part may be lost, not by rough handling during the excavation, but to reuse.

Lead oxide layer on the surface of the cupel
As already noted, on top of cupel N124918 is a layer of lead oxide around a spherical pit corresponding to the outline of the silver bead. The bottom of this cupel is ball-shaped which shows that the cupel could have absorbed more molten lead oxide. This means that the processing time at high temperature was too short for all the lead oxide to enter the cupel body. But as the molten lead oxide does not wet the silver, the bead was visible even though not all of the lead oxide was sucked into the cupel. Upon visual inspection of all the cupels, we have only found this “thick” lead oxide skin on two other cupels.

Cupel surface layer
To obtain reliable assay results it is important that all silver coalesces into one liquid droplet before solidification. The surface of the bowl must therefore be smooth and slope towards the centre, so that when the liquid lead contracts due to oxidation, droplets are not left on the surface of the cupel. Flaws in the surface layer may obstruct the contraction and create droplets which are left behind and result in a low assay result. Except for in a few small flaws in the fine-grained surface layer (fig. 6), we found no silver particles on the surfaces of the cupels that we investigated. Most of the silver therefore seems to have been collected into single beads. Both the smoothness of the thin surface layer and the depression in the centres of the large cupels may have been extra precautionary measures to collect all silver in one droplet. Ercker (1574, p. 31) maintains that a good facing layer of ashes is an essential requirement for cupels, and explains ways to prepare the ashes. He recommends using bones from the heads of calves or large fish bones. The fine-grained surface layer also corresponds to descriptions of cupels from other sites, e.g. the Tower of London (White 2010).

However, when investigating the cupel N-121965 (rim diameter 35 mm) we saw no traces of a facing layer in the cross-section, and the bowl surface looked rougher than on the small cupels. We found no silver particles on the bowl surface or inside this cupel body. Therefore, only three out of four cupels that we cut in half and investigated had a facing layer. As noted above, visual inspection of the 132 cupels suggested that about 98% have this layer. A facing layer therefore seems to have been part of normal manufacturing procedure at the archbishops’ mints.

Cupel body
Agricola (1556, pp. 229–231) and Ercker (1574, p. 31) offer several recipes for preparing the material for the body of the cupels. Both seem to agree that unmixed fine-grained bone-ash from the horns or skulls of animals is best. Agricola also recommends fish vertebrae. Never the less, both authors also mention that mixtures of bone-ash and wood-ash are used. This suggests that there was some variety in how the cupels were made at different mints.

During the Trondheim excavations, as at practically all stratified sites of this period, quantities of bones were found in the area around the mint, both from animals and fish. A large number of coarse bone-ash particles in the cupels have been investigated. They all consist of Ca, P and O (calcium phosphate) and possibly a bit of magne-
sium (Mg). As seen in figs 8–9 the particles have a spongy appearance. Their structures vary from an open canal structure (Haversian canals and canaliculis) to more compact bones (only Haversian canals). This is typical for large bones from animals. The bone-ash particles are therefore from bones of animals and not from fish.

Only a few small microstructure elements which may point to reactions between bone-ash particles and particles of clay or sand during cupellation were observed by SEM on the cross-sections of the four cupels investigated. These may be due to the presence of dust particles. And as the chemical analysis (tab. 2) shows, neither silicon nor aluminium, the most common elements in sand and clay, are present in substantial amounts. Thus these materials were not a common addition to these cupels. Although only one cupel has been investigated by plasma mass spectroscopy, the results indicate that the moneyer at the Archbishop’s Palace used only bone-ash in his cupels. This parallels the results from cupels from the Tower of London (White 2010), but contrasts with the chemical analysis of cupels from Oberstocktall, Kirchberg am Wagram, Austria (Rehren 1998; Martinon-Torres & Rehren 2005).

Note that the internal structures of the bone-ash particles vary and therefore may have varied in their ability to absorb lead oxide. However, as the lead oxide is evenly distributed throughout the body of the cupels, from top to bottom, the varying absorption qualities of each bone particle does not seem to have influenced the efficiency of the cupels. This shows that the cupels used were of a high and uniform quality.

No silver particles were found inside the cupels. Nevertheless, tiny particles of silver from the solidification of lead oxide and copper oxide may be present, but too small to be identified using SEM. Tab. 2 shows that the body of the cupel contains about 0.004% silver by weight. As cupel N124918 weighs about 16 g, this means that the amount of silver lost to the body of the cupel is of the order of 0.0006 g. This may be about 1.5% of the weight of the 2–2.5 mm silver bead taken out for affirming the fineness of the material. This corresponds with results presented by Téreygeol & Thomas (2003). Without knowing more about the size and the purity of the silver bead and small particles left in flaws in the fine-grained layer, it is difficult to evaluate the accuracy of the assaying technique used.

We did not investigate copper content in relation to depth.

The copper-rich precipitates inside the bone-ash particles in the large cupel are coarse: typically 5 μm across. These particles may come from the eutectic solidification of the CuO-PbO melt, as the cooling can be expected to have taken place too fast in order to make any peritectoid-formed particle, Cu₂PbO₂, become 5 μm across.

### Cupel size

When evaluating the fineness of silver alloys, the ability to accurately weigh small objects is crucial. To obtain a result of high precision when performing the cupellation process, the resulting silver bead must have a certain weight corresponding to the accuracy of the balance being used. For high-grade silver a small test piece may be enough. Mixed with the prescribed amount of lead, the resulting silver bead will give a reasonably precise result. In such a case a small cupel would be suitable. For a material expected to have a low concentration of silver though, a larger sample must be taken and mixed with a much larger amount of lead, and so a larger cupel must be used. Ercker (1574, p. 33) shows examples of cupel sizes used for different purposes. The small ones are used for silver of a high purity while the larger ones are used for low-grade silver. Judgments like this may also have been made in the
archbishop’s mint. Although the number of cupels investigated is relatively small, the fact that five different size classes have been identified, and that copper is apparent in the large cupel and only traces of impurity elements in the two small ones, supports such a hypothesis.

Where were the cupels made?
Were the cupels imported or made at the mint? No mould for making cupels was found. During the excavations, however, a large quantity of animal and fish bones was found in the vicinity of the mint. Such bones were also used for other purposes, e.g. to make glue. However, it is not unlikely that animal bones were also used by the moneyer to make bone-ash cupels.

The microstructure of the cupels shows that their maker followed the recommendations in 16th century handbooks, published years after the mint in the Archbishop’s Palace ceased operations. This indicates that the knowledge of how to make good cupels must have been common among moneyers long before the well-known treatises were published. Nothing suggests that the cupels were made in the Archbishops Palace, but finished cupels would have been fragile and difficult to transport over long distances without breaking. We are not aware of any workshops that specialised in making and selling cupels, and the fact that quantities of bones were found near the mints shows that the cupels could have been made locally. Or perhaps bone-ash of two grain sizes was imported and only the final manufacturing was done locally.

The large number of bone-ash cupels found shows that the testing of silver-rich alloys was a common practice at the mint in the Archbishop’s Palace. The larger cupels found indicate that less pure silver was also tested.

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Summary

1. 174 used bone-ash cupels, intact or as fragments, were found in connection with the mint in the Archbishop’s Palace in Trondheim during archaeological excavations in 1991–95. Judging from stratigraphy, the cupels date from the period of the last three archbishops, AD 1500–37. In this investigation 132 cupels have been measured and visually inspected. Of these, four were prepared for microstructural investigations. The following may be said:

2. The microstructures of the bone-ash cupels show that they are manufactured in accordance with the recommendations in Lazarus Ercker’s Treatise on Ores and Assaying published in 1574, about 40 years after the mint in the Archbishop’s Palace ceased to produce coins.

3. The pore structure of the bone-ash particles shows that the cupels were made from animal bones and not from fish bones.

4. Only a few traces of reactions caused by sand or clay particles were observed in the cross-sections of the cupels. In the chemical analysis silicon and aluminium are present only as trace elements. Sand or clay were therefore not a standard addition to the cupel material.

5. The cupels can be divided into five size groups, where the small ones may have been used for assaying alloys expected to be rich in silver and the larger ones for low-grade silver. The most common cupel size had an upper rim diameter of 35 mm and a mean height of 20 mm.

6. As the cupels are very fragile they were most likely made locally at the mint.

7. Even though the mints were small, situated at the periphery of Christendom and far from the capital of Copenhagen, the assaying work was performed to a high technical standard.