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RESEARCH ARTICLE

First evidence of lime burning in southern Scandinavia: lime kilns found at the royal residence on the west bank of Lake Tissø

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In connection with investigations of the aristocratic residence at Tissø from the Viking Age, the earliest evidence so far of lime burning in Denmark has been excavated. The excavations unearthed traces of up to five lime kilns which were subsequently dated to the end of the ninth century. This corresponds well with the dating of the erection of the hall in the third construction phase at Fugledegård. Finds of mud-and-wattle with whitewashing show that the lime was used to whitewash the halls at Tissø in both the Germanic Iron Age and the Viking Age. Analyses of lime from the lime kilns and the whitewashed mud-and-wattle demonstrate that the raw material for the lime burning was mainly travertine deposited in spring water, but that bryozoan limestone was also used. The lime kilns were just under 2 m in diameter with stone-built edges, and there are indications that the superstructure may have been built up with clay. This resembles the corresponding parallel finds from the Iron Age in the German area.

Keywords: lime burning; lime kilns; whitewash; Viking Age; Iron Age; aristocracy; Tissø

Introduction

In Danish archaeology, lime burning has always been dated to the Early Middle Ages, when the first stone churches were built with fieldstone masonry, calcareous tufa and mortar. The present finds of lime kilns from the Viking Age are the first in the southern Scandinavian context where lime-burning units from prehistoric times have been excavated. The find has afforded us the opportunity to gain insight into the constructional aspects and processes that lie behind the final product: whitewash. What follows below is a review of the function and construction of the lime-burning units and the perspectives of the find.

The archaeological investigations

Excavation history

In the mid-1990s, archaeologists from the National Museum of Denmark and the Kalundborg Museum (today the West Zealand Museum) conducted excavations of what was later to turn out to be one of northern Europe's richest sites from the Late Germanic Iron Age and the Viking Age (Jørgensen 2013). The excavations took place on the western bank of the Lake Tissø in western Zealand (Figure 1). Two presumed royal residences with related ritual areas as well as workshops and gathering places were investigated there (Jørgensen 2009, 338 ff.). The first royal residence lay at Bulbrogård (*c.* 550–700) and when it was closed down a new residence was built 600 m further south at Fugledegård (*c.* 700–1050). The latter site is contemporary with the lime kilns. The royal residence at Fugledegård could be traced through four phases, and in all phases consisted of a hall building, a smaller fenced-in area with a cult building, a smithy in the northern part of the residence and a larger enclosure of the whole complex (Figure 2). When the smithy area was investigated in the 1990s intact culture layers were identified, only some of which were excavated; at the same time the topsoil was drawn off down to the subsoil around the preserved culture layer, and towards the east there emerged a large irregular ash-grey fill-layer with an area of 4 × 6 m. At the time it was interpreted as an ash layer and was not investigated in more detail.

In the spring of 2013, the National Museum returned with assistance from the Kalundborg Archaeological Society to the smithy at Fugledegård, and opened up the intact culture layer once more. The aim was to clarify the relationship of the culture layer with the smithy through their various phases. During clearance, parts of the large ash-grey fill-layer came to light, partly beneath the culture layer. In connection with the excavation, the overlying culture layer was water-sifted to find any objects and here emerged small lumps of cemented-together material with solid-fired charcoal and bone fragments in the sieve residue from the top of the grey layer (Figure 3). Because

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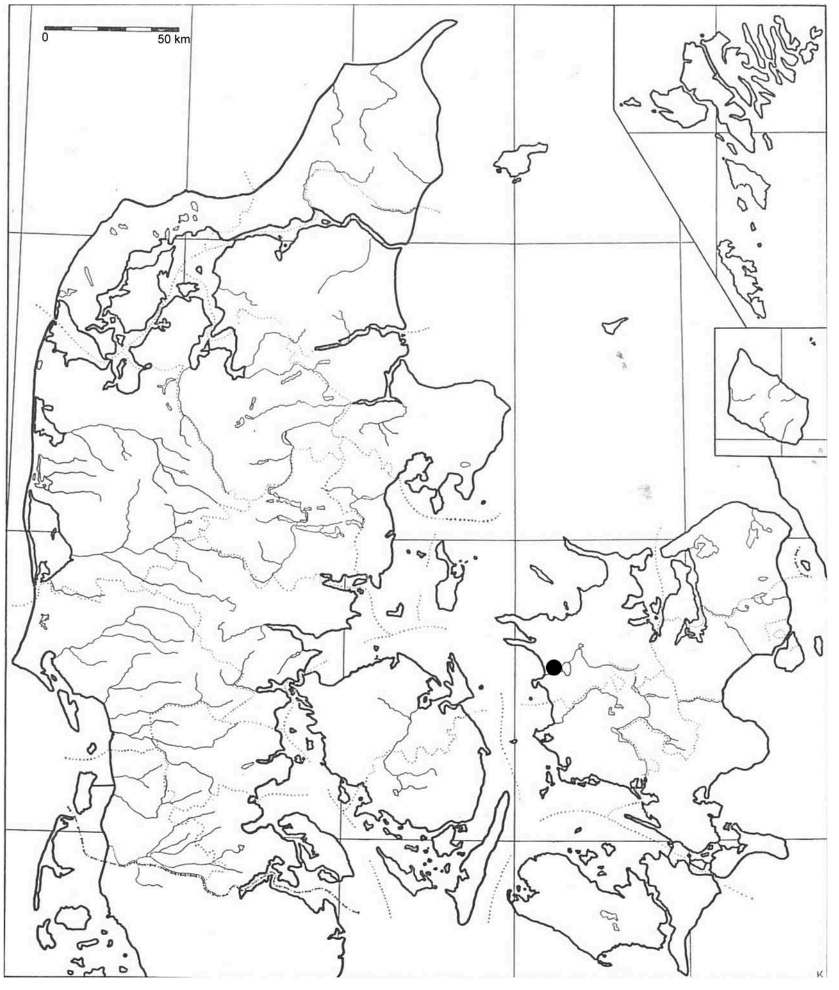

Figure 1. Location of the Tissø-complex in Western Zealand.

of the solid-fired material, the cemented lumps were examined in the microscope and it now became clear that they could be pieces of lime. In a subsequent test with hydrochloric acid, it was confirmed that the lumps did consist of lime.[1] At this time, the fill-layer was only partly uncovered, and an interpretation based on the character of the layer and a profile of the excavation boundary to the east was that this might be the bottom of a lime kiln – in that case, the earliest known lime kiln in the southern Scandinavian area.[2] Later the layer was radiocarbon-dated to the ninth century. Because of the special nature of the find, the remains of the layer were subsequently uncovered and excavated. This resulted in the find of three round-to-oval lime kilns as well as what are thought to be the remains of a further two to three kilns.

Construction of the lime kilns

Three of the lime-burning units were so well preserved that their original size and contour could be observed, as can be seen on the excavation plan (Figure 4). However, only the bottom 5–15 cm of the units was preserved. The units were 170–190 cm in diameter and almost circular. Before the establishment of the kilns the whole area had been dug down to pure subsoil sand, and the kilns were then dug down a further 5–10 cm. No stratigraphic distinctions could be observed between the various kiln units. In two of the kilns, remains were found of a stone-built ring around the edge of the unit, which indicates that the kilns were built with a stone-built mantle at the top. In the westernmost part of the lime and ash layer, this is overlaid by a *c*. 6 cm thick layer of clay. By two of the kilns, FG-A117 and FG-A119, possible stoking holes and/or flues were found in the form of small buried channels coming out of the circular units.

In the feature FG-A118, which was the best preserved, two layers of lime were found in the kiln (Figure 5). Just above the sand subsoil there was a thin greyish-brown layer of ash and charcoal overlaid by an almost white lime layer, which was up to 5 cm thick and surface-covering. Above this was

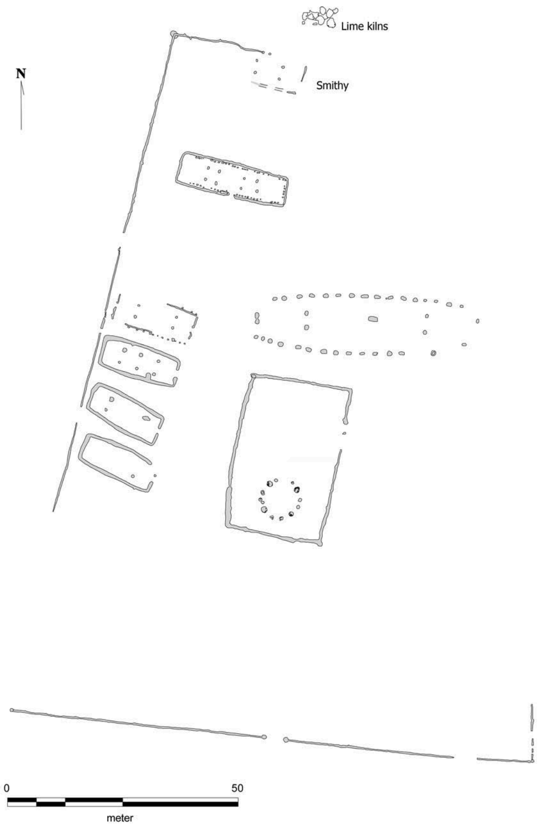

Figure 2. The royal complex in phase 3 with the lime kilns marked to the north.

Figure 3. Lump of lime from kiln FG-A118 with charcoal and bone fragments. Photo: P.S. Henriksen.

found yet another layer of ash and charcoal which was in turn overlaid by a more reddish lime layer, similarly several centimetres thick, but not present throughout the area of the kiln.

The subsoil sand beneath and around the kilns was particularly hard as a result of the precipitation of slaked lime after the lime burning. This shows that the whole kiln area was covered by burnt lime, presumably in the form of crumbled lime scattered in connection with the emptying of the kilns after the lime burning.

In the area around the lime kilns, the excavations of the 1990s registered a number of post-holes at the edges of the two lime kilns. The excavation of the two lime kilns FG-A118 and FG-A119 registered a further two post-holes around the edges which may have belonged stratigraphically to the kiln units.

Datings

From the three best preserved kilns, charred material embedded in the lime was AMS radiocarbon dated. From each of the three features FG-A117, FG-A118 and FG-A119, a grain specimen and small pieces of charcoal were dated; the results of the datings can be seen in Figure 6.

All the datings fall within the Viking Age, unfortunately with a high degree of uncertainty because of wiggles in the radiocarbon curve. If the lime kilns are more or less contemporary, as the stratigraphy suggests, the most likely dating is at the end of the ninth century, which corresponds to the start of phase 3 of the royal residence at Fugledegård.

Finds of mud-and-wattle and pottery with whitewashing

During the excavations of the Tissø complex in the 1990s and at the beginning of the 2000s, mud-and-wattle with whitewashed surfaces was found in both Germanic Iron Age and Viking Age structures. From the halls at Bulbrogård, kilograms of mud-and-wattle with whitewashing emerged. This find has been dealt with in detail by Bican (2007). At Fugledegård, only smallish pieces of mud-and-wattle with whitewashed surfaces were found in the hall area, but it is assumed that there too the halls had whitewashed walls. Moreover, in the phase 2 hall, a single potsherd was found with painting on the outside, and investigations and microscopy demonstrated that burnt lime had been used there too.

The lime-burning process

The process of making slaked lime that could be used to whitewash mud-and-wattle walls began with the burning of limestone in a lime kiln. The limestone could come from many different sources. Lime in the form of chalk, bryozoan limestone and coral limestone exists in the Danish and Baltic subsoil and in certain places the limestone layers are exposed in cliff formations such as those at Stevns and Møn. During the Late Baltic Glacial at the end of the last Ice Age, limestone from these layers was deposited in the moraine of the whole eastern Danish area

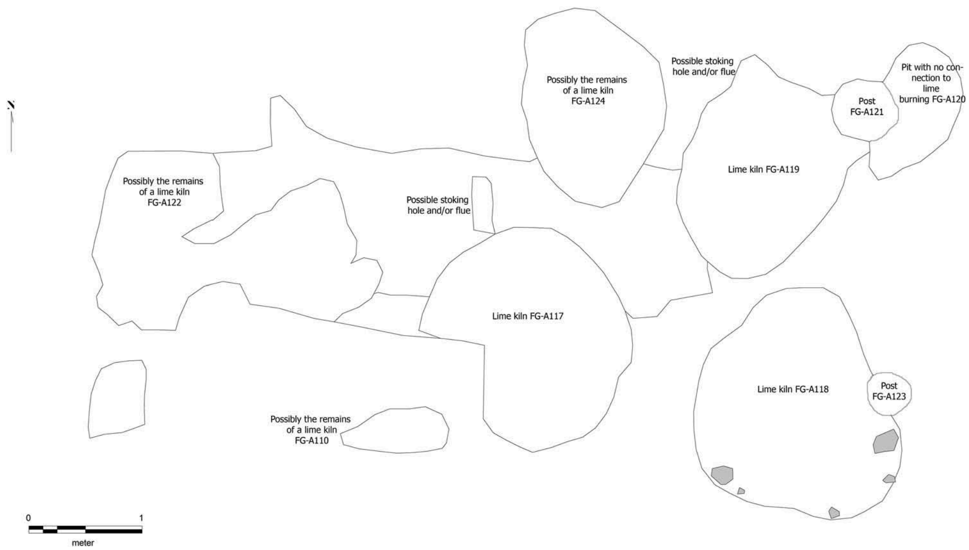

Figure 4. Excavation plan.

Figure 5. Profile of lime kiln FG-A118 (note that the A-number on the blackboard has later been changed), showing two lime burning layers. Photo: S. Holst.

(Houmark-Nielsen and Sjørring 1991), where it can now be gathered from fields and along the coasts.

In many parts of the country, lime can also be found as travertine, which can form metre-thick layers (Nielsen 1967). The deposits are formed in springs where CO_2-rich groundwater that has dissolved lime in the soil comes up to the surface, where the carbon dioxide evaporates and the lime is re-precipitated, usually together with iron and manganese (Larsen and Surlyk 2012).

Other possible sources of lime are oyster shells and other seashells since the mineral elements of these consist exclusively of calcium carbonate (Petersen 1971). The shells can be gathered along the coast, often washed together in large concentrations.

In lime burning the limestone has to be heated to above 850°C. At this temperature, the limestone, which

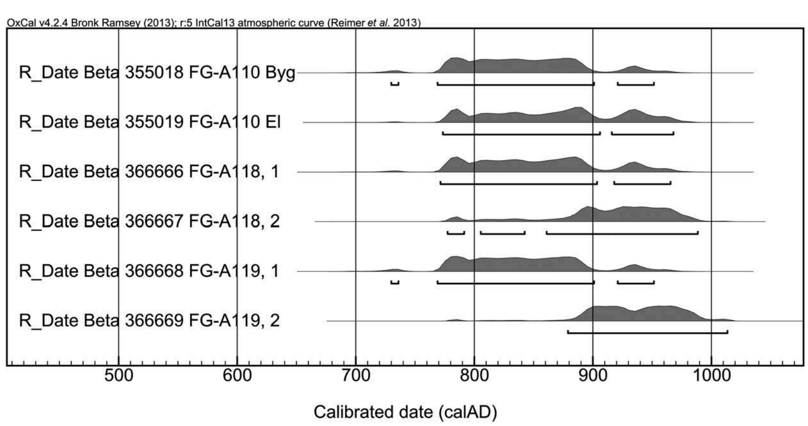

Figure 6. AMS radiocarbon dates of the lime kilns calibrated with OxCal v4.2.3 (Bronk Ramsey 2013) and IntCal13 (Reimer *et al.* 2013).

$$CaCO_3 \xrightarrow{\text{Heat}} CaO + CO_2 \xrightarrow{H_2O} CaO + H_2O \rightarrow Ca(OH)_2 \xrightarrow{CO_2} CaCO_3 + H_2O$$

Figure 7. The chemical process of lime burning and slaking.

consists of calcium carbonate, sheds carbon dioxide to become calcium oxide (see Figure 7). Subsequently, the calcium oxide is mixed with water. This is called slaking, and forms calcium hydroxide, also called slaked lime. When the slaked lime comes into contact with air, for example when used to whitewash house walls, it re-absorbs carbon dioxide and then becomes calcium carbonate/limestone again.

Scientific investigations

Microscopic investigations of lime from the lime kilns

A number of specimens were taken (3–4 l/specimen) from the lime layers in the various kilns for more detailed analysis. The composition of the layers varied from almost pure lime to layers with equal proportions of lime, ash and sand. From the kiln FG-A118, two specimens were analysed in more detail; one specimen from the lower, almost white lime layer, and one specimen from the upper, reddish lime layer. Parts of the specimens were passed through a sieve with a mesh size of 0.5 mm to remove fine sand prior to the microscopic examination.

Microscopic analysis of the specimens at a magnification of 8–100× showed that they mainly consisted of lime in which many pieces of charcoal were embedded, as well as some sand, fragments of bones and shells of swollen river mussel (*Unio tumidus*) and a few cockle and snail shells.

The lime took the form of a cemented mass of micro-crystalline grains around 1–10 µm in size. In among the lime grains were varying amounts of reddish-brown particles of iron of 1–5 µm. In the lower lime layer from FG-A118, the percentage of iron particles was low, while the upper lime layer contained so many iron particles that the layer looked reddish-brown (see Figure 5).

XRF analysis

Specimens from the lower and the upper lime layer in FG-A118 were investigated at the National Museum's Environmental Archaeology and Materials Science Unit with an XRF scanner.[3] This scanning analysed the material for element composition; however, small elements such as oxygen and carbon cannot be demonstrated with XRF. The scanning showed that the specimens were dominated by calcium, as expected, since calcium is the main element in lime. The specimen from the lower layer also contained iron, while the specimen from the upper layer

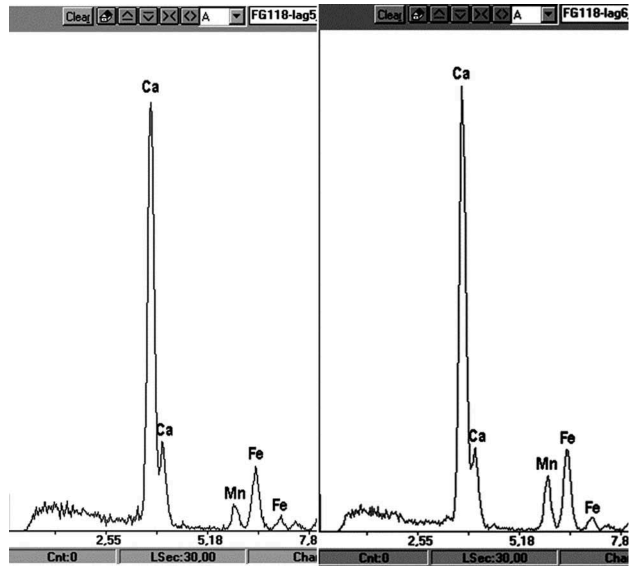

Figure 8. Results of XRF analysis of the lime layers from FG-A118. Left: the lower lime layer. Right: the upper lime layer. Both layers contain iron and manganese.

contained both iron and manganese (see Figure 8). The XRF analysis shows that travertine was used as raw material in the lime burning since travertine is rich in iron and manganese, whereas bryozoan limestone and seashells, the other locally occurring lime types, do not contain these elements.

Thin-section analysis

A specimen from the bottom layer of the feature FG-A117 was subjected to thin-section analysis[4] (Seir 2013). Around 70% of the specimen consisted of lime crystals formed by the slaking of burnt lime. The remainder of the specimen consisted of sand and a small amount of unburnt lime, most of which was a very fine-grained sedimentary limestone without impurities and in places with structures from bryozoa-like fossils. This suggests that the point of departure for this specimen was Danian lime, which is the limestone found at the cliffs of Stevns Klint, but which can also be found as loose blocks in the moraine of among other places Zealand. In the specimen, there were at one point clearly contoured traces of hexagonal calcite crystals, which may indicate that there was also travertine in the specimen analysed (Seir, personal communication).

Microscopic analyses of the whitewash

A piece of mud-and-wattle with lime from Bulbrogård was analysed at the National Museum's Conservation Department. The analysis showed that this was whitewashing done with slaked lime. The lime layer was 0.2–0.5 mm thick and in a few places layers from two whitewashings

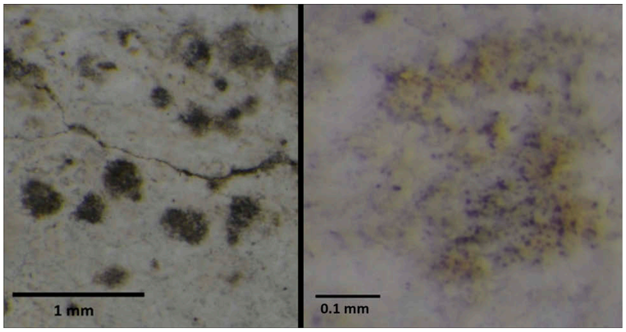

Figure 9. Microscopic images of the lime layer with the many black areas 0.2–1 mm in size identified as manganese (left), along with scattered 2–5 μm red spots of iron (right). Photo: P.S. Henriksen.

could be observed. Beneath the lime layer, a layer of a similar thickness was found, consisting of a mixture of lime and clay. This may have been formed when the first whitewashing was done on the still-wet mud-and-wattle (Christensen and Schnell 2006).

On other pieces of whitewashed mud-and-wattle from Bulbrogård, a layer of clay up to 5 mm thick was found with lime mixed in between the mud-and-wattle and the outer lime layer. This suggests that a plaster layer of clay mixed with lime was added before the final whitewashing, presumably to get better adhesion of the lime to the underlay.

XRF analysis of whitewash from Bulbrogård showed that the lime layer, besides calcium, also contained iron and manganese, which shows that travertine was used as a raw material. The iron could also be examined microscopically since innumerable small red grains were found scattered through the white lime layer.

The mud-and-wattle with lime from Fugledegård resembled the find from Bulbrogård; here too there was a plaster layer of lime, clay and sand as an underlay for the whitewash. On one of the preserved pieces of whitewashed mud-and-wattle, the plaster layer was around 2.5 mm thick.

The lime layer appeared as a white groundmass with many black areas 0.2–1 mm in size, which XRF analysis was able to identify as manganese, as well as scattered, 2–5 μm red spots of iron, very numerous in some places, corresponding to what was also seen in the lime from the lime kilns (see Figure 9).

Experimental lime burning

In order to test how different lime types are suited to the production of whitewash and what the lime looks like, bryozoan limestone, mussel shells and travertine with different iron contents were heated to 1000°C in a muffle kiln and then slaked. The lime was then painted on clay slabs that could be compared with the original whitewashed mud-and-wattle from Bulbrogård and Fugledegård.

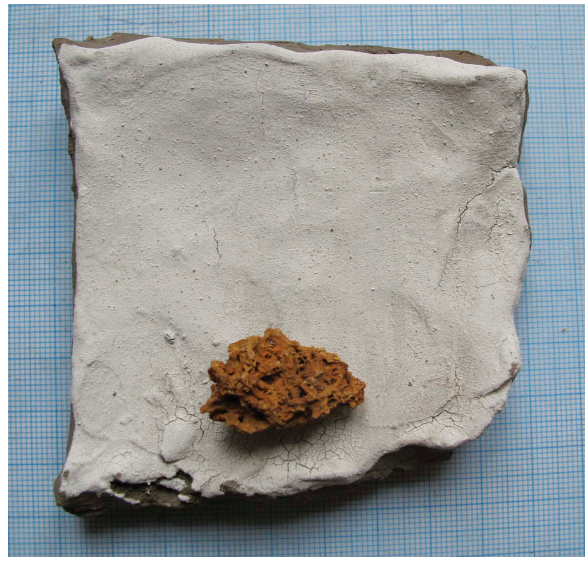

Figure 10. The result of experimental whitewashing based on lime with high content of iron as described in the text. A piece of the iron rich lime is placed on top of the whitewashed clay slab. Photo: P.S. Henriksen.

All the whitewashing appeared more or less white – even the lime that was made on the basis of dark, rust-red travertine (see Figure 10). Under the microscope, small red and black iron and manganese particles could be observed embedded in the lime made on the basis of travertine, while the lime made of bryozoan limestone and seashells did not contain any of these impurities. The lime made from travertine thus corresponded best to the lime found on the mud-and-wattle.

Parallels from abroad

The early development of lime-burning technology

The earliest signs of the use of burnt lime come from pre-pottery Neolithic settlements in the Middle East dated to the 7th century BC (Garfinkel 1987); the earliest known lime-burning unit was found in the Mesopotamian city of Khafaje, and has been dated to the middle of the third millennium BC (Williams 2004, p. 3). However, it was not until later, for example in the Middle Minoan period on Crete around 1800 BC, that lime in the form of mortar was used as a construction material. And not until the Roman Empire did lime mortar come into common use in construction (Dix 1982, p. 339, Harrington 2000, 4 f.). The Romans' use of lime for construction and other purposes is particularly well known since besides the archaeological finds there are several contemporary written sources that describe in detail the processes leading from limestone to usable construction materials. A detailed account was written by the Roman statesman Cato[5] in the work *De agri cultura*, in which he reviews everything from the construction to the operation of various kilns (Uschmann 2006, p. 95).

In the northern European area, the first reliable find of lime burning is a chalk layer at the bottom of a kiln dated to the Late Bronze Age and found in eastern Pomerania around 1880 (Uschmann 2006, p. 12). Since it is likely that the lime-burning technology came to the Scandinavian area from the south, it seems reasonable to look at the parallels from there.

Northern European parallels

A large number of lime kilns from the period around the 3rd century BC until the 4th century AD have been found in the present-day German area, with concentrations around Hamburg and in the lower Elbe area (Uschmann 2006). The early kilns, dated to the Pre-Roman Iron Age, were typically round with a diameter of 1–2 m, but in the course of time the shape of the kilns changed to oval. Most kilns had a stone-built funnel-shaped bottom with a depth of 0.5–1 m, in some cases a stoking duct in the side, and in connection with many of the kilns one could see remains of a clay superstructure that was broken down after each burning. At many of the kilns, traces have also been found of covering constructions (Uschmann 2006, 38 f. & 75, diagrams 25 & 26). In the German material, several kiln units occur which are very similar to the Fugledegård kilns, round-to-oval constructions with traces of stone rings around them (Figure 11). This applies, for example, to finds from Printzen and Herzsprung II as well as Osterrönfeld from Brandenburg and Schleswig, respectively (Jöns 1993, Abb. 3, Schuster 2000, 96 f., Uschmann 2006, plate 4, 1).

In the transition to the Early Middle Ages in the German area (*c.* AD 490), lime burning changed its character. This happened when the need for burnt lime for mortar increased dramatically in connection with the spread of monasteries and other stone-built houses. Large stone-built lime kilns were set up at monasteries and in towns, while small-scale production in the countryside took place in simple charcoal stacks covered with turf, built directly on the ground surface (Uschmann 2006, 111 ff.).

In the northwestern German area, the raw material for the lime burning was mainly lake and bog lime, found there in layers up to several metres thick at the bottom of lakes and under the peat in some bogs (Uschmann 2006, p. 20). Lake and bog lime are lime layers precipitated in lakes with highly calciferous water (Galsgaard 1998, p. 32). In many German lime kilns, there are also remains of burnt bones (Jöns 1993, p. 68), as was the case in the find at Fugledegård.

Discussion

Construction and placing of the lime kilns

The lime kilns from Fugledegård recall the German kilns with stone-built edges and stoking ducts. However, the Fugledegård kilns were not constructed with a depression in the middle as most of the German kilns were. There was only a small layer of clay which could be the remains of a superstructure of the kind known from Germany. However, since only the very lowest layers were preserved, it is not possible to establish how the superstructure looked. In the kiln unit FG-A118, there were two separate layers of burnt lime, which indicates that the kiln was used for at least two burnings. It could not be ascertained whether the other kilns had been used several times since only a thin bottom layer was preserved in them.

At Fugledegård the lime kilns were situated just outside the large paddock enclosure in phase 3, associated with the smithy, which was situated close to the fencing with an outlet through the fence (see Figure 3). In a number of German cases, the lime kilns were also associated with smithies, but isolated from the built-up areas (Jöns 1993). It is thus likely that it was the smith that was responsible for lime burning. Whether the lime burning was isolated from the surroundings with a covering, as described from the German area, is hard to say, since the post-holes around the lime are so irregularly placed that one cannot directly distinguish a structure.

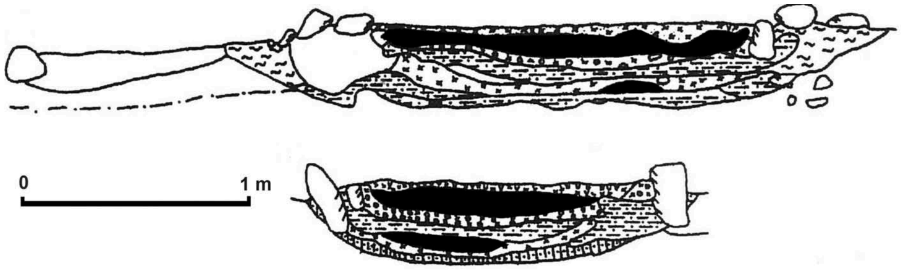

Figure 11. Profile drawings of a lime kiln from Printzen, Germany, which are very similar to those at Fugledegård. The lime layers are marked with black. (Redrawn after Uschmann 2006).

At Fugledegård, the kilns were placed less than 70 m from the hall building despite the fact that the lime-burning process would have created a nuisance in the form of smoke and highly corrosive lime dust. One explanation may be that the kilns only functioned during the establishment phase of the hall from phase 3, which is supported by the datings to the end of the ninth century, when this hall phase was built.

Raw materials for the lime burning

The analyses show that the primary raw material for the lime burning was travertine, but that bryozoan limestone was also used. The closest travertine deposits are found just a kilometre west of the royal residence at Fugledegård in the former bog area Maderne. Drillings in the low-lying surfaces in this area showed signs of removal of the lime since thin lime layers could be observed at a depth of 40–50 cm, overlaid by re-dug layers. On slightly higher-lying surfaces, there are moreover areas of up to several hundred square metres with ploughed-up travertine layers. On the surface there one can see many travertine fragments up to 15 cm thick. Drillings have further shown that beneath the plough layer travertine can be found down to a depth of at least 70 cm.

The bryozoan limestone could be gathered in small quantities from the surface in the landscape and along the banks of Tissø and at the Great Belt coast. However, it is not possible to ascertain how much of the raw material for the lime burning consisted of bryozoan limestone.

To a lesser extent, shells were also used, primarily from swollen river mussel, a freshwater species that could be gathered in Tissø and Halleby Å.

In the lime layers, there were also many fragments of burnt bones, which indicate that there were also attempts to exploit the lime in the bones. However, only a small part of the lime can be used since only a few per cent consists of calcium carbonate (Biltz and Pellegrino 1969), while by far the greater part is calcium phosphate, which cannot be converted into calcium oxide by burning. Despite this, it was apparently common to add bones in the lime burning, as can be seen in the German material (Uschmann 2006). Whether it was believed at the time that lime from bones could be exploited or whether there were ritual reasons behind this can hardly be determined. Some researchers do think, however, that lime burning in prehistoric times was used as a means of consolidating social and cultural identity, and that lime burning was therefore assigned a ritual meaning (Dillehay *et al.* 1997, 46 f.). Since travertine is easily accessible in large quantities close to Fugledegård, it was not because of a scarcity of raw materials that bones were used. This may suggest that bones were added for other reasons, for example, ritual ones. Unfortunately, the bone remains from Fugledegård are much fragmented and it is not possible to identify their species.

Whitewashing in prehistory

It is uncertain how long whitewashing with burnt and slaked lime was practiced in the Danish area. Finds of mud-and-wattle with whitewashed surfaces have earlier been traced all the way back to the Bronze Age with the finds from Voldtofte, Skamlebæk and Ledreborg Golfbane[6] (Lomborg 1979, Thrane 1979, Jensen 2002, p. 351, Andersen 2012) and to the Early Iron Age with the find from Ginderup (Kjær 1928, Høy and Kaul 1995), but analyses of the 'whitewashed' mud-and-wattle pieces from the four sites in connection with these investigations have shown that on the whole there was no lime in the light-coloured coatings of the mud-and-wattle. It is instead likely that this was painted with a layer of very light-coloured clay with a small lime content. From Voldtofte we know of early painting with red and black colours (Berglund 1982). From Fosie IV in Scania, there is a similar find of mud-and-wattle painted with chalk in a pit in a Bronze Age house (Björhem and Säfvestad 1993, p. 86) and in the present-day German area painting of the Bronze Age houses was also widespread (Knoll *et al.* 2013).

Painting with lime has also been described on a number of house-shaped urns from the Bronze Age (Broholm 1946, pp. 129 & 132–133, 1949, pp. 146–148). Investigations of these house-shaped urns showed that burnt lime was not used to colour these urns either, but that they were painted with a greyish-white clay. On a few house-shaped urns, the light-coloured coatings were not painted at all, they were mineral precipitation found both on the inside and the outside. The oldest known occurrences of whitewashing with burnt lime are therefore in the find from the Late Germanic Iron Age from Bulbrogård as well as a contemporary find from Fredshøj in Lejre (Tom Christensen, personal communication). The structures at this site (Christensen 2010) were presumably parallel in status to those at Bulbrogård. From Scania we also know of a contemporary find since mud-and-wattle with whitewash was found around the burnt-down cult house at Uppåkra (Karl Magnus Lenntorp, personal communication, 24 April 2014).

Finds of mud-and-wattle with whitewash are very few in the Danish archaeological material. However, it can be hard to tell whether this is because whitewashing was uncommon or whether it was due to the preservation conditions. If mud-and-wattle with whitewashing is to be found preserved, it has to have been subjected to strong heat so that the clay has been fired, but the lime must not have been heated to over 850°C, at which point the carbon dioxide is split off.

Whitewashing: practical and social function

The whitewashing of mud-and-wattle walls has been widespread until recent times. The whitewashing was absolutely necessary to the durability of mud-and-wattle outer walls since without whitewashing they would very quickly be destroyed by driving rain, which can soften the clay surface, making it fall down. Whitewashing forms a thin film of waterproof limestone on the outside of the wall, which thus becomes more weatherproof.

In several of the phases of the royal residence at Tissø, the posts were of such large dimensions that we must presume that the buildings had more than one floor (Lars Jørgensen, personal communication, 3 July 2014). This means that the walls must have been so high that the roof construction was unable to protect the walls, so whitewashing would have been essential to the preservation of the mud-and-wattle.

It is also possible that the inside walls were whitewashed since white walls reflect light better than clay walls, which would have considerably improved the benefit of the poor lighting of the period. The very widespread use of mud-and-wattle with whitewashing at Bulbrogård makes it likely that the walls there were whitewashed both outside and inside (Bican 2010, p. 152). Whitewashing of inside clay walls was certainly known as far back as the 1500s (Steensberg 1974).

Besides the practical function, whitewashed walls may also have had a social function. The halls at Fugledegård were situated on a plateau down towards Tissø and given the sizes of the halls, both at floor level and at the presumed heights, whitewashed walls would have been highly visible in the landscape, whether one sailed into the complex or arrived by land. It has therefore earlier been suggested that whitewashed walls were in fact an element in the manifestation of social power, and that they should be seen as part of the demonstration of power by the elite (Bican 2010). This may be supported by the fact that the finds from the Iron Age and Viking Age so far all come from the buildings of the elite. This gives us a picture of lime burning as something associated with the higher levels of society, suggesting that the actual lime-burning technology was perhaps reserved for the aristocracy.

Summary and perspectives

Lime burning and whitewashing with burnt and slaked lime appears with certainty from the Germanic Iron Age in Denmark since older finds of presumed whitewash have proved not to be lime based. Instead, they are examples of painting with light-coloured clay. The present finds of whitewash in prehistory are all from high-status sites – whether this is the true picture of the occurrence of whitewashing or whether it was more common cannot be established with certainty with the present small amount of data.

The kiln structure found at Fugledegård in many ways recalls parallels from the present northern German area during the Iron Age, but also differs from most of these in not having a sunken middle. This is probably because kiln construction changed over the centuries from the type of kiln developed in the German area to the type used in the Danish area in the Viking Age.

The analyses of lime from the lime kilns and of whitewash on mud-and-wattle show that in the Germanic Iron Age and Viking Age a number of raw materials were used in the production of whitewash. The main ingredient was travertine or bryozoan limestone, but to a lesser extent shells and bones were also used.

The lime kilns were placed just outside the fencing, associated with the smithy, which may indicate that the lime production was connected with the smith, a situation we also know from many German finds from the Iron Age (Jöns 1993, p. 75).

Lime kilns have hitherto been a neglected find group in Danish archaeology. The feature type can however easily be identified by simple means: one has to pay attention to round or oval stone-surrounded features with ash layers with possible white or reddish lime layers, which can be identified with diluted hydrochloric acid. One must moreover be alert to hardened subsoil layers in connection with the features. By many of the lime kilns from the German area, traces of coverings were found. With future finds of lime kilns one must therefore be very aware of post-holes which may come from such covering structures.

Notes

1. The presence of lime can be demonstrated with hydrochloric acid. When one pours diluted hydrochloric acid (10%) on lime, it fizzes powerfully since the acid decomposes the calcium carbonate, emitting CO_2.
2. On Gotland, a possible Viking Age lime kiln has been excavated in 2013. The interpretation as a lime kiln is however uncertain since the kiln itself is built of limestone. The burnt lime at the bottom of the kiln may therefore come from the actual casing of the kiln, without having anything to do with the function of the kiln (Carlsson *et al.* 2014).
3. The XRF analyses were conducted at the Environmental Archaeology and Materials Science, National Museum of Denmark by Conservation Scientist Michelle Taube using a Bruker Tracer III-V+ hand-held X-Ray Fluorescence apparatus. With XRF one bombards a specimen with an X-ray. This boosts some of the atoms to a higher-energy level, after which they decay again while an X-ray characteristic of each element is emitted. From an X-ray spectrum, one sees the elemental composition of a specimen since the position of the peaks shows which element they come from and their areas indicate the amount of the element in question. With the National Museum's XRF, all elements with a higher atomic number than magnesium (no. 12 in the periodic system) can be detected. The X-ray tube in the apparatus contains rhodium (Rh), which means that peaks for Rh are shown in the spectrum.
4. In thin-section analysis, the specimen is first impregnated with epoxy treated with fluorescent pigment. Then a 0.02 mm thick slice of the specimen is made. At this thickness, mineral grains and other components are translucent and can thus be identified with so-called refraction or polarization microscopy.
5. Cato lived from 234 until 149 BC and was a Roman statesman and theoretician of science (Uschmann 2006, p. 95 note 450).
6. Thanks to Roskilde Museum and Ole Thirup Kastholm for kindly making the Ledreborg Golfbane material available for detailed investigation.

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