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The use of radiography and GIS to assess the deterioration of archaeological iron objects from a water logged environment

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Abstract

Pollution, acid rain, and modern agricultural practise are often blamed when archaeological metal objects are heavily deteriorated. However, looking at a deteriorated object, it can be difficult to differentiate whether the deterioration took place recently, or maybe hundreds or even thousands of years ago. A detailed knowledge of the changing environmental conditions of the archaeological site, a large number of objects, and a reliable measure for the state of preservation of the objects are necessary to assess the deterioration history.

In this paper an analytical method based on X-ray radiography is used to give an objective measure for the state of preservation of iron objects. It is demonstrated that the method is robust, independent of the operator, and has good precision. With this tool and applying the use of GIS, 151 lances from a water logged environment (Nydam, Denmark) were studied, to see if it was possible to correlate the state of preservation with the exact find location, the year of excavation or the method of deposition. Apparently, in this case the method of deposition was most important, so that the deterioration pattern observed today is decided during the first few years after deposition, which took place in 200–500 AD. It has not been possible to demonstrate an increased deterioration from the first excavations in 1859 until today.

The work is part of a major project in Nydam, which has also involved studying corrosion products, deterioration of modern materials, environmental parameters, and the effects of archaeological excavations.

Keywords: Iron; Deterioration; Radiography; GIS; In situ preservation; Nydam

1. Introduction

The deterioration of archaeological metal artefacts in the soil and the possible impact from pollution and modern agriculture is a matter of concern for many archaeologists [8]. With the increasing focus on in situ preservation it becomes even more important to understand and evaluate different threats to archaeological artefacts. Quantification of the actual state of preservation as well as the rate of deterioration is a necessary prerequisite to decide whether or not it is safe to leave the artefacts in situ.

Recent studies in Sweden [5] and Denmark [10] have shown that recently excavated bronze artefacts are potentially more deteriorated than similar bronze artefacts excavated in the 19th century and subsequently kept in storage. These results are deeply worrying, even if it cannot be ruled out, that there might be some problems in the representativity of the material in these studies. That is to say: if archaeologists or the public in the past only kept or reported the very best artefacts they found, the stored objects will obviously be biased and have a better average state of preservation than today, where the tendency is to keep and store all metal artefacts.

Considering iron objects, comparisons between old and recently excavated objects are only scarce. A recent project in Germany [17] investigated some of the parameters that can threaten iron objects in the soil. The study indicated, that soils in towns, forests and

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under agricultural use have become more aggressive towards metals during the 20th century, due to the effects of acid rain, fertilisers, and de-icing salt. Studies of deterioration in wetlands have mainly focused on the dramatic effect of drainage [9,11].

Certainly the current environment, and even the microenvironment, can have a major impact on the rate of deterioration. However, looking at a deteriorated iron object it can seldom be ruled out, that the deterioration might actually have taken place in the past, e.g. during a few years where the object was lying under exposed conditions before it eventually was incorporated in a more protective environment. In terms of in situ preservation, it is of course fundamental to be able to evaluate whether deterioration is ongoing, or whether it has mainly taken place in the past.

Comparing the state of preservation of different archaeological objects is not a simple task. A good method has to meet several requirements: it must be independent of the operator, it must be robust and give a single value for each artefact, and the uncertainty of the value must be low enough to allow a classification of different artefacts (i.e. the variation within an artefact must be lower than between artefacts). For bronze artefacts, visual methods have proven successful [5,10]. However, for archaeological iron the results from visual evaluation have proven to be operator dependent [13]. X-raying of iron artefacts has been used on some occasions [6,9], and even though it hasn't been thoroughly validated, it seems to be a more promising method.

In this study, we have investigated if the X-raying method actually fulfils the requirements described above. We have then tried to correlate the state of preservation of iron objects with the exact spatial distribution of the objects. Only objects from a single archaeological site (Nydam, Denmark) have been used in order to quantify the variability within a small area. The data have been used to evaluate: (1) importance of the method of deposition, (2) state of preservation today compared to the 19th century, and (3) influence from archaeological excavations in the area. Some of the problems related to the use of material from the 19th century are addressed, especially representativity problems and post-excavation corrosion.

2. Study site

Nydam is an 11-ha water meadow located in a small valley in Southern Jutland, Denmark. During the Danish Iron Age, Nydam was a shallow freshwater lake into which sacrificial offerings were deposited on at least five different occasions in the period from approximately 200–500 AD. The artefacts deposited were military and nautical paraphernalia. All kinds of weapons such as swords, arrows, spears, richly decorated shields, scabbards with precious metal fittings and personal equipment such as knives and tweezers were thrown into the lake and, in some cases, swords and lances were stabbed into the lake bed.

Archaeological excavations in Nydam began in the middle of the 19th century and later resumed in 1893, 1939, 1984 and the 1990s by the National Museum of Denmark. Due to the volume of finds and resources required for conservation, excavations were stopped in 1997 to investigate the feasibility of preserving the site in situ. Over the last five years a programme of investigation to examine the deterioration of archaeological material has been ongoing, including studies of the archaeological artefacts, of modern sacrificial materials, and of the environment in Nydam [7,11,12,18]. This paper focuses on archaeological material from three excavations (Fig. 1). For clarity, the investigated material is denominated group A, B and C, which have been excavated in 1859–1863, 1994, and 1990–1991, respectively:

Group A: Excavations in 1859–1863 were conducted by the Danish archaeologist Conrad Engelhardt [4]. He excavated in two areas (Fig. 1), where the eastern area contained two large boats. Engelhardt worked under time pressure due to an impending war between Prussia and Denmark. The war resulted in a Prussian occupation of the southern part of Denmark, including the Nydam site. The archaeological artefacts excavated in Nydam were all given to Prussia, except two boxes of artefacts that Engelhardt had "hidden" in the personal antiquity collection of the Danish king—this rather

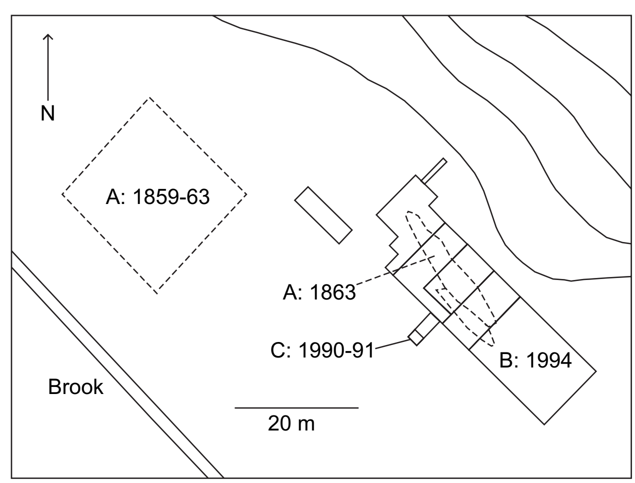

Fig. 1. Sketch of different excavations at Nydam. Dashed lines show excavations made by Conrad Engelhardt in the 19th century. The position of the boat excavations in 1863 is well known, whereas the position of the 1859–1863 excavation is only estimated. Solid lines show excavations made by the National Museum of Denmark in the 1990s, where Engelhardt's old boat excavation pit was located and re-excavated. A brook running through the centre of Nydam is indicated (lower left), as well as topographic lines of 1 m distance (upper right).

dramatic story is described in Bemmann and Bemmann [2]. Group A comes from these two boxes.

Group B: From 1989 to 1997 the old boat pits of Engelhardt were located and re-excavated, in order to find what he had left and learn more about the sacrifices [16]. During these excavations it became obvious that the state of preservation of the artefacts varied considerably throughout the area. Good preserved metal objects could be found within a few centimetres from objects that were completely converted to corrosion products [1]. On site there was no obvious single explanation for the differential state of preservation, but several theories were put forward: differences in metal composition, different methods of deposition, local differences in the soil environment, changing water levels, physical contact between different materials, effects from modern pollution, and effects from peat digging and earlier excavations.

The picture in Nydam is obscured by the fact that the finds consist of material from several sacrifices, and that the area in places has been disturbed. Changing conditions in Nydam have resulted in a layered structure of peat and gyttja, described by Christensen and Kolstrup [3]. In the excavated area (Fig. 1) 1–1.5 m of peat, overlies 0.5–1 m of iron age gyttja. Most archaeological artefacts are found in the top of the gyttja, indicating that they have been sacrificed in open water or pressed down through the peat, but a few are found up in the peat. The latter ones might have been sacrificed on the mire surface, exposed to wind and weather for some time before being finally encapsulated in the peat. The deposition process is ambiguous for many of the artefacts, because in several places the layers have been mixed up by later sacrifices, by peat digging over the centuries, or by archaeological excavations in the 19th and 20th century. Group B consists of finds from the south-eastern end of the boat pit, excavated in 1994.

Group C: The most well-defined offering in terms of mode of deposition is a weapon heap excavated in 1990–1991 (Fig. 2). The find consists of more than 1000 metal and wooden artefacts found in an area of only $1 \times 1 \times 0.3$ m [14]. The artefacts, which may have been wrapped in leather or cloth, were thrown into a prepared hole or pressed down through the peat, right through an older layer of wooden planks and other artefacts from a former sacrifice. Subsequently the weapon heap was surrounded by 30 swords stabbed into the peat. Group C consists of finds from the weapon heap, excluding artefacts from former sacrifices.

The weapon heap definitely represents a special deposition "technique" compared to the rest of the finds in Nydam. Still, it is ideal for studying which parameters decide the state of preservation because all the artefacts have been laid down on a single occasion within a very small area.

Fig. 2. Weapon heap from 450–475 AD, excavated over two excavation seasons, in 1990 and 1991. The find consisted of more than 1000 artefacts of metal and wood. The lances from this weapon heap are referred to as "group C" in the text. Photo: Per Poulsen.

The weapon heap was excavated from the top and downwards over two years: During 18 days in September 1990 the uppermost lying objects were excavated, until rain and percolating water prevented further excavations. The rest of the weapon heap—of which at least 17 lances, 24 swords and 10 shield bosses had already been exposed—was covered with a layer of sand, a layer of peat, a layer of plywood, and a top layer of peat and turf. During 21 days in May 1991 the remaining objects were excavated. As the find was lying below the ground water level in Nydam, pumping was necessary during the excavations. This pause in the excavation between 1990 and 1991 gave the chance to evaluate whether the 1990 excavation has had a measurable effect on the lower lying artefacts.

3. Methods

3.1. State of preservation

To evaluate the state of preservation of iron artefacts in Nydam on a sound statistic basis, a large number of uniform objects were required. Lances and spears were chosen because they are present in large numbers, they are spread throughout the find, and the round shape of their socket is well suited for measuring corrosion depth based on X-ray radiographs (Fig. 3). More than 1000 lances and spears have been found during the different excavation campaigns in Nydam until now. Of these, 151 lances were X-rayed in order to measure the corrosion depth. These lances came from three different excavations with 48 lances from the 1859–1863 excavations (group A), 28 from the 1994 excavation (group B), and 75 lances from the 1990–1991 excavation (group C). The lances had all been conserved and exterior corrosion products removed—for the lances from 1990–1991 and 1994 this was done mechanically in

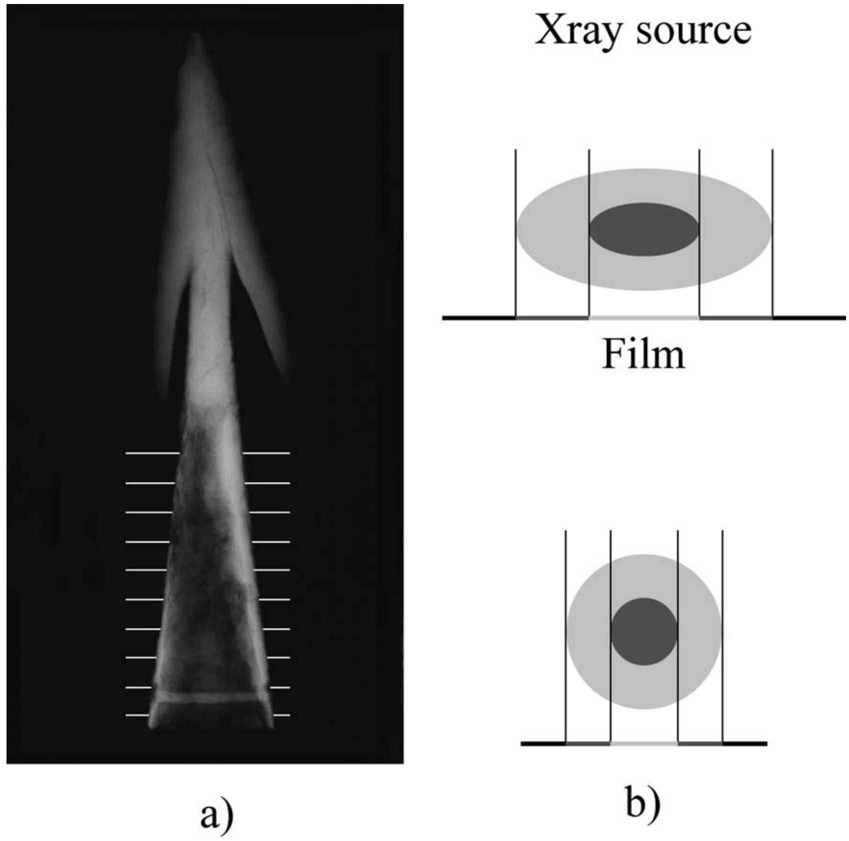

Fig. 3. (a) X-ray photo of a spear. Corrosion depth is measured in 10–15 positions on each side of the socket, indicated by white lines. Photo: Birthe Gottlieb. (b) Idealised drawing demonstrating the advantage of using round artefacts for measuring corrosion depth on X-ray photos. Dark grey indicates iron core, light grey indicates corrosion product, for simplicity the round socket is drawn without a hole in the middle. The measured corrosion depth of the socket (lower) is independent of the exact orientation of the lance or spear, whereas the measured corrosion depth of the flat head (upper) depends strongly on the orientation.

a stream of hot air, whereas the exact conservation history of the lances from 1859–1863 is not known. Consequently, the radiographs show the contours of the original surface and below that, in a lighter colour, the contours of the preserved iron core (Fig. 3). The corrosion depth was measured in 10–15 positions in 5 mm distance on each side of the picture using a digital sliding gauge, later a precision scaled magnifier. If the whole socket, or part of it, was fully converted to corrosion products a default value of 1.755 mm for "totally corroded" was used (1.755 mm corresponds to the average material thickness measured on the socket of 11 lances). All radiographs were measured by two people, to allow for an evaluation of the objectivity of this method. In addition, nine radiographs were measured using both sliding gauge and precision scaled magnifier. All radiographs were made with an Andrex type 3001 equipment, exposing 6–9 min at 105–115 kV, and using a prefilter to reduce the contrast and make the corrosion products more visible. A large distance between the X-ray source and film (170 cm) was chosen to reduce effects from parallaxes. Only very sharp radiographs could be used to measure corrosion depths.

3.2. Position of finds

The artefacts excavated in 1859–1863 (group A) cannot be located individually. Engelhardt did not measure their exact location, probably because of lack of time [2]. Even the year of excavation is only known for a few of them. During the excavations in 1990–1997 (group B and C) the find positions were measured by total station or stereo photogrammetry or documented through manual drawings. All positions and other information about the area were stored in a GIS-system (MapInfo Professional 6.5®) for this study.

4. Results

For each lance, measurements from the 20–30 measuring points and from both operators have been pooled, to give an average corrosion depth and standard deviation for each lance. Fig. 4 shows the results from all lances.

The lances have been grouped into different categories depending on their average corrosion depth, with

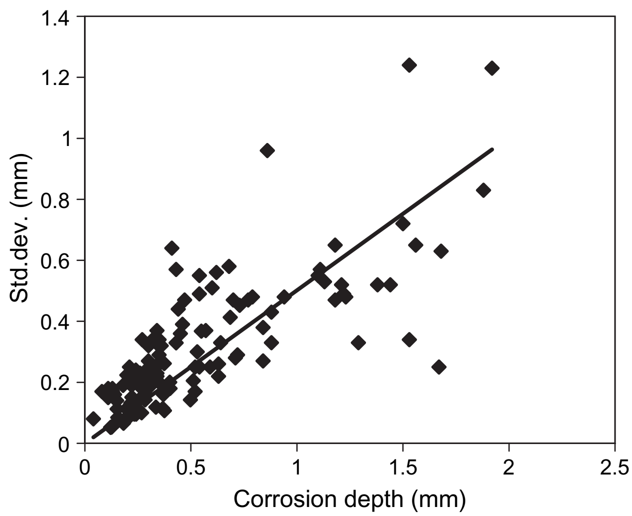

Fig. 4. Comparison between mean and standard deviation of measured corrosion depth for all 151 investigated lances. Solid line shows linear regression by least square method, slope = 0.50; $r^2 = 0.51$.

intervals of 0.25 mm. The corrosion depth is then correlated to the position of the lance, when known. Fig. 5 shows a horizontal and a vertical map of lances from the weapon heap (group C), whereas Fig. 6 shows the lances from the 1994 excavation (group B). It has not been possible to make a map of the lances from 1859–1863 (group A), as their exact find location is not known. Fig. 7 shows a comparison between the three lance populations.

5. Discussion

5.1. Evaluation of X-ray method

In this study were taken sufficient measurements to make a statistical evaluation of the method and test if it fulfils the normal requirements of a good measuring technique. We divide the requirements into three hypotheses and finally calculate the overall uncertainty for the method.

First hypothesis is, that the method is independent of the operator: Each lance has been measured at approximately 20–30 fixed points by two operators. A paired *t*-test is well suited for comparing the two operators. In this test each measuring point is treated as an individual sample and the difference between the two operators is calculated for each point. Using almost 3000 measuring points, it can be calculated, that the average difference between the operators is 0.003 mm. This difference does not allow rejection of the hypothesis (test probability 0.35 in a paired *t*-test), so we accept the method is independent of the operator.

Next hypothesis is that the method is independent of the measuring tool (digital slide or precision scaled magnifier). Nine lances, or 260 measuring points, have been measured with both tools. The results show that there is no significant difference between the two measuring tools (test probability 0.25 in a paired *t*-test).

The third hypothesis is that the method is robust and gives a well-defined corrosion depth for each lance. To test this hypothesis, nine lances have been re-evaluated by displacing the measuring points 2.5 mm, to investigate if this influences the measured corrosion depth. This time *new* points are measured, so it is not possible to make the paired *t*-test on each measuring point. Instead it is checked if the displacement gives a significantly different corrosion depth for any of the lances. This is not the case (Student *t*-test for each lance gives test probabilities of 0.14–0.79), so we accept that the method gives well-defined results.

Finally the overall uncertainty can be calculated for the method. The standard deviation for repeated measurements on a lance depends on the mean corrosion depth, however, the relative standard deviation (RSD) is fairly constant (Fig. 4). Using data from all lances, the average RSD for one measurement is calculated to 50%. As we are using typically 20 measuring points per lance, the RSD of the mean value is $50\%/\sqrt{20} = 11\%$. In other words, if a mean corrosion depth of a lance is measured to e.g. 1 mm, standard deviation of this mean is 0.11 mm, and the 95% confidence interval is [0.80 mm; 1.20 mm] when 20 measuring points are used.

We find this uncertainty acceptable, as the variation "within" a lance is smaller than the variation "between" lances in this study (below), and thus the method allows us to group the lances into several different categories. Obviously, other lance populations might show other variations, depending on the homogeneity of the corrosion depth. The necessary number of measuring points must thus be evaluated for each lance population and depends on the required precision. It must be emphasized, that the described method can only be used on populations, where most of the lances still have a preserved iron core.

5.2. Importance of method of deposition

The distribution of lances from group C excavated in 1990–1991 is shown in Fig. 5. It is remarkable, that the state of preservation differs so much within the small weapon heap, covering only 1×1×0.3 m. Still, the corrosion does not seem to be completely random. The overall tendency is, that the most corroded lances are found in the top layer and in the periphery of the weapon heap, whereas the lances in the bottom are better preserved. Statistically, the lower lying lances (2.30–2.50 m) of the heap have an average corrosion depth of 0.42 mm (std. dev. 0.32 mm, $n = 44$), whereas the higher lying lances (2.50–2.60) have an average corrosion depth of 0.83 mm (std. dev. 0.52 mm, $n = 18$).

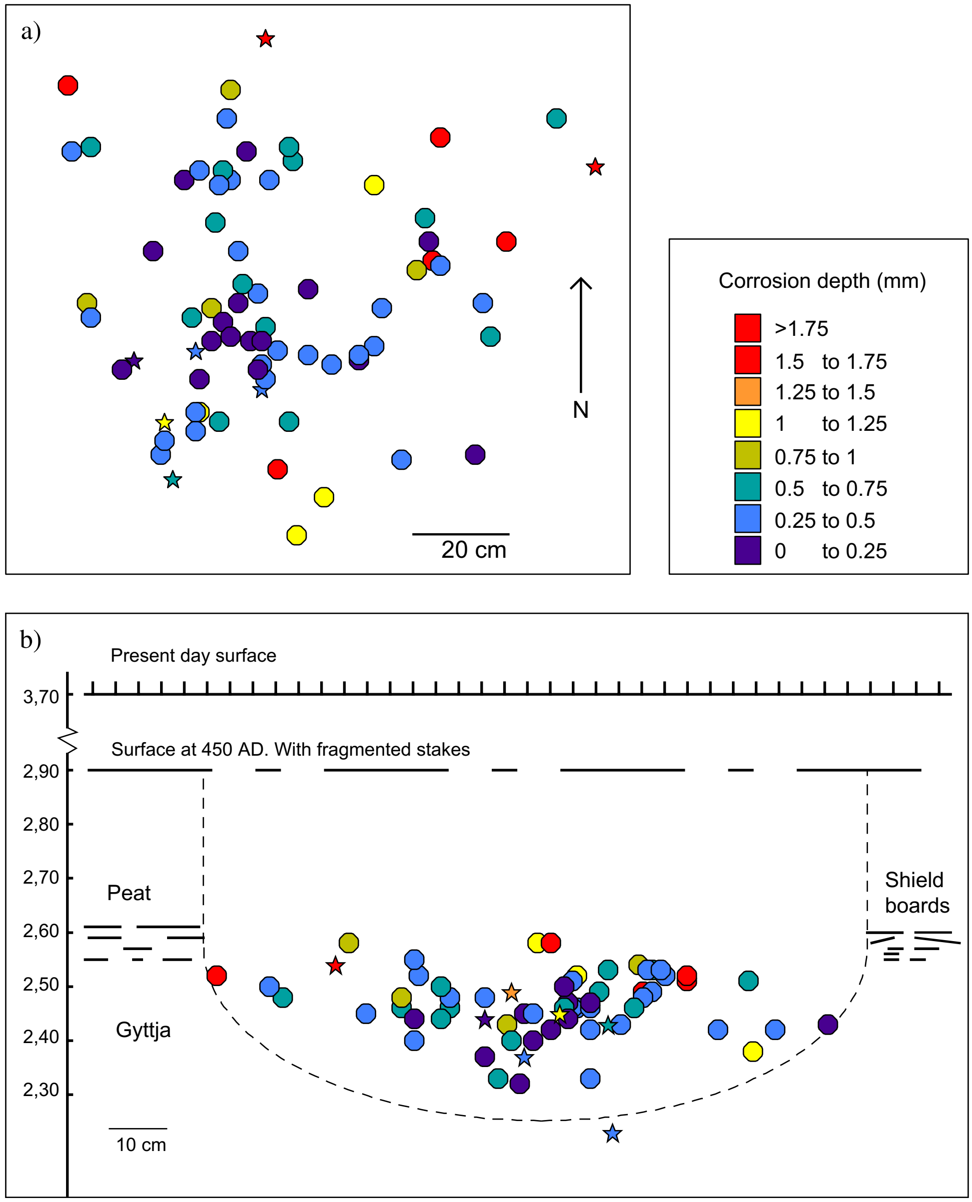

Fig. 5. Distribution and corrosion depth of lance sockets excavated in 1990–1991 (group C). Circles indicate lances belonging to the weapon heap sacrificed in 450–475 AD. Stars indicate lances from an earlier weapon sacrifice (300–350 AD), these are not included in the statistic evaluations in the text. Distinction between the two lance types was made by the excavator [15]. In between the lances are other artefacts of metal and wood, as indicated in Fig. 2. (a) Horizontal view of weapon heap. (b) Vertical profile seen from SW, demonstrating how the weapon heap has been pressed down or buried through an older layer of artefacts (shield boards and a few lances). Numbers to the left are meters above sea level.

This means, that the lower lying lances are significantly better preserved than the lances just 10 cm above (test probability = 0.006 in a Student *t*-test).

This corresponds well to the method of deposition: the weapon heap has been pressed down through the peat or thrown into a pit. This means that the lowest artefacts presumably have come under anoxic, protective conditions right away, whereas the uppermost artefacts have been more exposed. Under oxic, humid conditions in soil, unprotected iron can corrode approximately 0.1 mm per year [19], meaning that the average corrosion depth of 0.83 mm in the higher lying lances can be a matter of only a decade. It is thus realistic that the observed corrosion depth is a result of the initial deterioration. For comparison even under optimum conditions it takes 10–50 years for a plant remain (or archaeological artefact!) on the surface of a mire to become embedded in the catocelm (permanent anoxic part) of the mire [1].

On the other hand, solely from the pattern in Fig. 5 it cannot be excluded, that the observed deterioration has taken place in the recent past, or during the >1500 years since the sacrifice. The weapon heap lies right at the interface between peat and gyttja deposits.

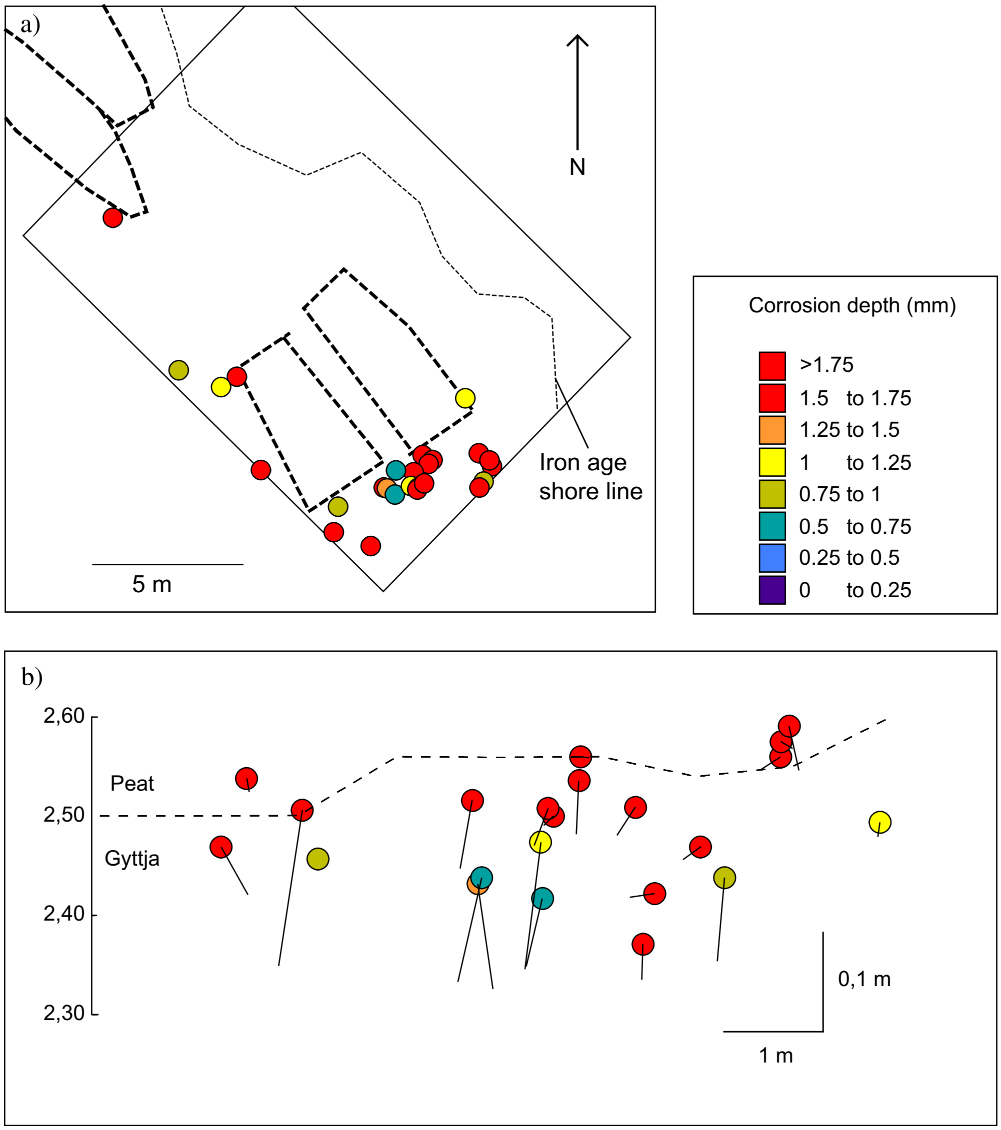

Fig. 6. Distribution and corrosion depth of lance sockets excavated in 1994 (group B). The lances probably belong to a single sacrifice around 300 AD. (a) Horizontal view. The 1994 excavation pit is shown with solid lines. Boat excavations made by Engelhardt in 1863 and other excavations made by the Prussian army in 1864 are shown with thick, dashed line. Thin dotted line shows the approximate shoreline of the iron age lake at the time of the boat sacrifice. (b) Vertical profile, seen from SE. Vertical scale is expanded 10 times, compared to horizontal scale. Dashed line indicates interface between peat and gyttja layer. Solid line at each point represents a projection of the lance on the vertical view plane, so long steep lines indicate lances deposited in a steep angle. Numbers to the left are meters above sea level.

Environmental monitoring during the latest 5 years has not indicated strong chemical gradients between the two layers (unpublished results), but with a time span of 1500 years the small differences might matter.

As regards the water level at Nydam it is currently lying approximately 1 m above the artefacts. A temporary reduction of this water level would also influence the uppermost artefacts the most. In a similar study from the drained meadow Ejsbøl, Korthauer [9] estimated that the drainage resulted in corrosion rates of approximately 0.1 mm per year for lances lying above the water table. We cannot prove that the water level at Nydam has not been lower previously, but during our 5 years of studies we have not observed any lowering of the water table down to the artefacts (except during excavations). The drainage effect from Ejsbøl is thus not a current risk at Nydam, but the water level must be monitored continuously.

Looking at the lances from group B excavated in 1994 (Fig. 6) there seems also here to be a tendency towards better preservation for the lower lying lances. Lances below 2.50 m have an average corrosion depth of 1.26 mm (std. dev. 0.43 mm, $n = 15$), and lances above 2.50 m have an average corrosion depth of 1.76 mm ($n = 11$—it is not possible to calculate a meaningful standard deviation of this population, because as many

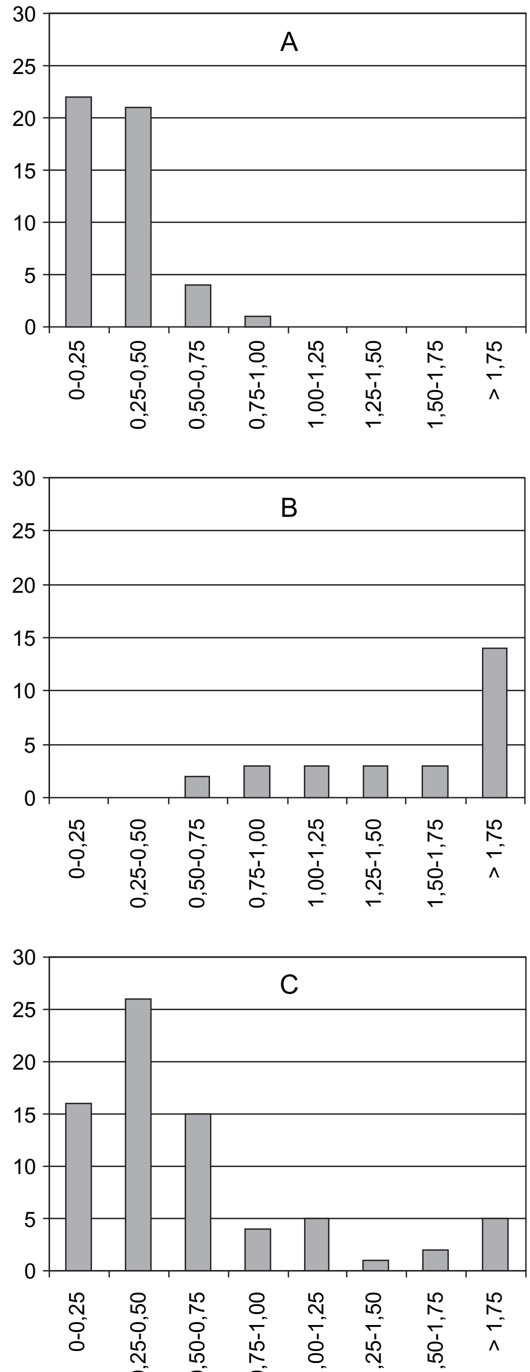

Fig. 7. Histograms showing the measured corrosion depths on lances from three different excavations. (A) Forty-eight lances excavated by Engelhardt in 1859 or 1863, average 0.30 mm, std. dev. 0.16 mm. (B) Twenty-eight lances excavated in 1994, average 1.47 mm, std. dev. 0.40 mm. (C) Sixty-six lances excavated in 1990–1991 (from the weapon heap, older lances have been excluded), average 0.54 mm, std. dev. 0.43 mm.

as seven of the lances are completely converted to corrosion products and thus given the default corrosion depth of 1.755 mm).

Apart from the depth, the angle of the lances can also be of interest: group B consists of both horizontally lying lances, and more vertical lances. From Fig. 6 it seems, that the vertical or steep lances are in a better state of preservation. It is likely, that the vertical lances have been stabbed down into the lake bottom, right down into a protective environment, whereas the horizontal lances have been lying in a more hostile environment on the lake bed or peat surface for some time. However, the data should not be over-interpreted as the area has been disturbed by peat digging and archaeological excavations over the centuries (Fig. 6).

Compared to group C, the lances from group B are generally in a much worse condition, especially the uppermost and horizontal lances. This strong deterioration is unlikely to be caused by draining: the height above sea level is the same in group B and C, meaning that drainage ought to affect the two groups in a similar way. More likely, the deterioration of group B is due the different ways of deposition: where most of the lances from group C have been actively pressed down through the peat right into a protective environment, this only applies to a few of the lances from group B.

5.3. State of preservation today compared to the 19th century

Fig. 7 shows the deterioration of lances in group A, B and C found during three different excavation campaigns: in the 19th century, in 1994, and in 1990–1991, respectively. At the first glance the picture looks very depressing, with well preserved lances in the 19th century (average corrosion 0.30 mm, std. dev. 0.16 mm), and very poorly preserved in 1994 (average corrosion 1.47 mm, std. dev. 0.40 mm). However, looking solely at the year of excavation doesn't give the whole picture. The different groups have to be considered in more detail, to be sure if they are actually representative for the general preservation conditions in Nydam at the time of excavation.

The lances from the 19th century (Fig. 7A) are from the collection at the National Museum of Denmark. They come from a special selection of artefacts, that Conrad Engelhardt sent to the Danish King to avoid them being taken by the Prussian army (out of 715 lances and spears, 92 were sent to the Danish King—[2]). The rest of the artefacts are currently at the Schloss Gottorp in Germany. We have not yet measured if these other artefacts are in the same condition, but from the drawings in Bemmann and Bemmann [2], where both collections are documented, it seems evident, that the Danish collection was selected from among the best preserved and most spectacular lances. Hopefully a future investigation of the lances in Germany can quantify this "selection effect". A further selection effect, which can probably never be proved or disproved, is the possibility, that some of the lances in the worst condition were actually never collected or kept in these early days of archaeology.

On the other hand it may be argued that lances excavated during the 19th century may be in a worse state of preservation today than at the time of excavation due to post-excavation corrosion processes. These processes are difficult to exclude as we do not know the full conservation and storage history of all the artefacts, and obviously they can result in a bias when modern radiographs are used to evaluate the preservation conditions in the 19th century. To address this question we have tried to compare the condition at the time of excavation with the condition today for some of the lances from group A. The best picture we have of their condition at the time of excavation is the description by Engelhardt along with the original archaeological line drawings made shortly after the excavation [4]—these drawings include 11 of the lances from group A. Comparing the old drawings with new archaeological line drawings of the same 11 lances made in the 1990s [2] shows no alarming differences (Fig. 8). Even if this is not formal proof, it indicates that the post-excavation corrosion has been minimal, and thus that it is possible to use modern radiographs to compare lances from different excavation campaigns.

The lances from the 1994 excavation (Fig. 7B) have caused concern about the general condition in Nydam, as they are in a very bad state of preservation compared

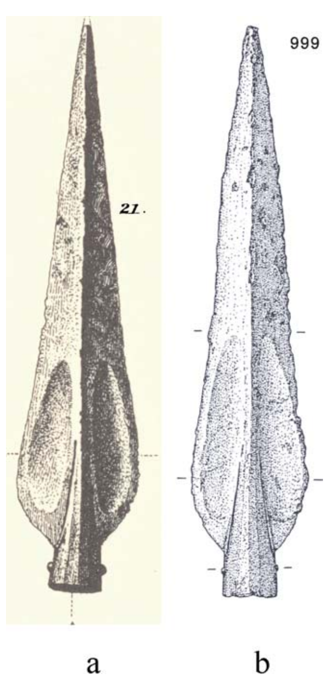

Fig. 8. Comparison between archaeological line drawings of a lance excavated by Engelhardt in 1859. (a) Drawing from Engelhardt [4] made between 1859 and 1865, (b) drawing from Bemmann and Bemmann [2] made in the 1990s. The corrosion depth measured for this lance was 0.38 mm.

to the old finds. The question has been raised whether this deterioration has occurred in modern time due to e.g. pollution or modern agricultural practise. However, Engelhardt writes himself, that most lances in this eastern excavation area, as well as the uppermost lying in the western area (Fig. 1), are strongly deteriorated already in 1863 [2]. The find location is only known for eight of the lances in Fig. 7A, and out of these only one is from the eastern excavation area marked "1863" on Fig. 1.

The lances from the weapon heap (Fig. 7C) showed a highly differentiated deterioration pattern, with deteriorated lances in the upper layer, and better preserved in the lower layer. The average corrosion depth in the lower layer of 0.42 mm (std. dev. 0.32 mm, $n = 44$) shows, that still in the 1990's it is possible to find lances comparable with the lances from the 19th century (average corrosion depth 0.30 mm, std. dev. 0.16 mm, $n = 48$), bearing in mind that the old material is handpicked from a larger population. The investigated old lances are slightly better preserved but the difference is only small. The numbers do *not* confirm that there has been a strongly increased corrosion rate from the 19th century until today.

It is very unlikely, that the much higher corrosion depth observed in 1994 (Fig. 7B) compared to the corrosion depth of the 1990–1991 excavation (Fig. 7C) is due to corrosion in the 3 years in between. That would give an annual corrosion of 0.3 mm, which is far beyond any corrosion rate we have measured on modern iron coupons [11]. It is more likely that the different corrosion depths are due to the different burial methods (above).

5.4. *Effects from excavation*

An archaeological excavation will always to some degree influence the surroundings. In Nydam it has been shown that an excavation in 1997 affected the water level up to 40 m away, and the water chemistry in the area was affected for almost 1 year. The corrosion rate of modern iron coupons near the excavation pit was 0.020–0.060 mm/y compared to <0.005 mm/y further away [11]. It is an open question whether the archaeological artefacts in the surroundings are affected as well. It has therefore been speculated if the observed deterioration patterns in Nydam are partly due to the excavations themselves.

It could be possible to check this hypothesis on the lances from group C, because after excavation of some of the artefacts there was an 8 month pause between 1990 and 1991, where the partly excavated weapon heap was lying covered with sand, plywood and peat. However, looking at the numbers, the average corrosion rate of the lances from 1990 was 0.94 mm (std. dev.

0.56 mm, $n = 23$) and for the lances from 1991 it was 0.42 mm (std. dev. 0.31 mm, $n = 51$), i.e. significantly lower in 1991 (test probability 0.0003 in Students t-test). The smaller corrosion depth in 1991 does not indicate that the lances *improve* during an excavation, but are solely an effect from the excavation strategy working from the top of the weapon heap and downwards. The 1990 population mainly consists of badly preserved lances from the top layer of the weapon heap, and it is thus not possible to confirm or disprove the hypothesis of an effect from excavation. This example illustrates the necessity of using comparable populations and the possible problems occurring when focusing solely on the year of excavation for explaining the state of preservation.

6. Conclusions/perspective

It has been demonstrated, that it is possible to obtain an objective measure of the state of preservation of conserved iron objects by measuring the distance between the original surface and the preserved iron core on X-ray radiographs. Even though the corrosion is not evenly distributed, it is possible to obtain a reliable average corrosion depth by using sufficient measuring points for each object. The method obviously requires a preserved iron core, and the geometry of the objects must be considered—round objects are preferable.

In the Nydam find, the state of preservation of similar iron objects varies considerably, even within distances of only 10–20 cm. It is estimated that this variation is mainly due to the method of deposition, and that most of the deterioration of the objects has taken place during the first few years after deposition. Based on the investigated material, it has not been possible to document an increased deterioration from the first excavations in 1859 until today.

The considerable local variation in the state of preservation found in Nydam, shows that fine scale mapping can be a useful supplement to larger scale studies, where the state of preservation is compared in different soil types in different parts of a country, e.g. Fjaestad et al. [5], Madsen et al. [10], and Scharff et al. [17].

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