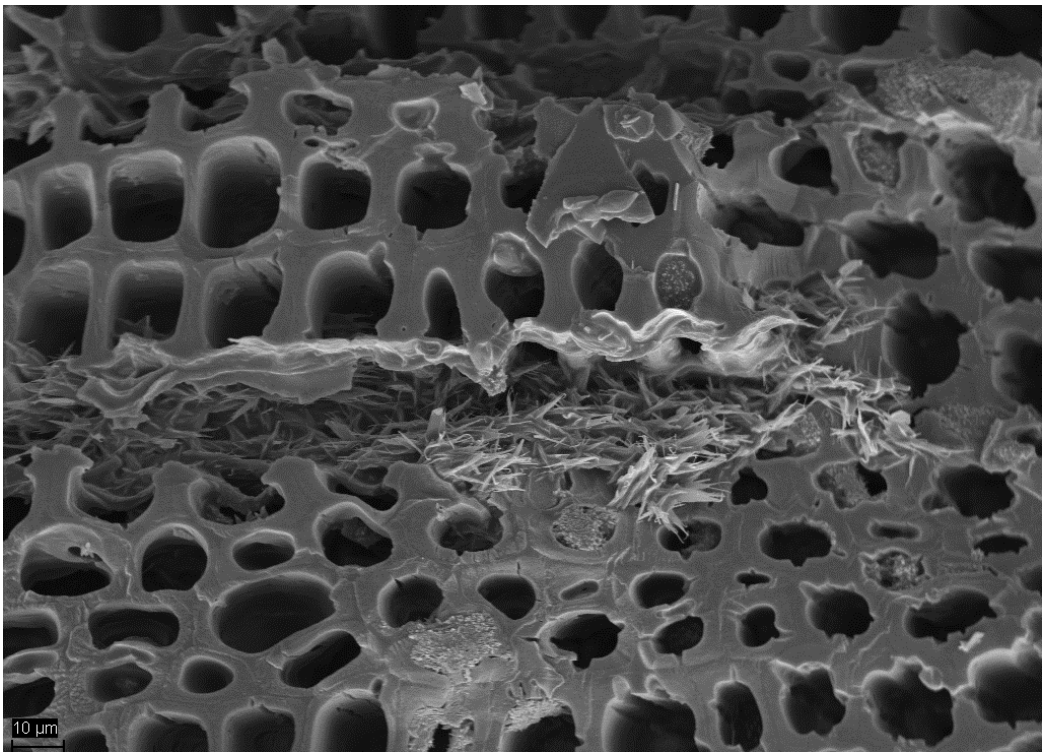
Salt damage around a bat roost at Urnes stave church

Kjersti Marie Ellewsen



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The front page image shows a salt crystal within the wooden matrix sampled from inside the bat roost at Urnes stave church (sample 7). The image is taken with an SEM at the Imaging Centre at NMBU by Hilde Raanaas Kolstad. Mag. 1500 x

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Abstract

Urnes stave church is dated to the 1130s and was inscribed on the UNESCO World Heritage List in 1979. In the south west nave corner, the bearing post and adjoining bressummer (sill beam) of original pine wood suffer from salt deterioration. The area is situated near a bat roost, and this has led to the assumption that the salts derive from bat urine. Examinations and different analytical methods were used to verify the source of the salts and examine the condition of the wood. On site investigations included test strips and portable XRF and X-ray. Samples were taken for analyses in ICP-OES, FTIR, SEM-EDX and light microscopy using lignin staining to answer the research questions. A wildlife camera, ultrasound detectors and climate loggers were part of the investigations at site to investigate present bat activity and assess the preservation climate inside the church.

Other possible sources are excluded, and the conclusion is that the salts derive from bat droppings. Salt molecules found in the samples were mainly potassium sulphates and potassium phosphates. These substrates come from the bat faeces. The wood cells at the surface of the wooden construction suffer from mechanical tear due to salt crystallization, but the speed of the degradation is low. The crystallization point is not crossed often in the climate at Urnes due to the high deliquescence relative humidity of the molecules identified. No bats use the roost at present (2016-2019). Measures to desalinate the area and prevent bats from re-using the roost are presented.

Sammendrag

Tittel: Saltskader rundt et flaggermusrede i Urnes stavkirke

Urnes stavkirke er datert til 1130-tallet og ble innskrevet på UNESCOs verdensarvliste i 1979. Den sørvestre midtromsstaven og den tilstøtende svilla lider av saltnedbrytning. Området er i nærheten av et flaggermusrede, og dette har ført til antakelsen at saltene stammer fra flaggermusurin. Undersøkelser og forskjellige analysemetoder ble brukt for å verifisere kilden til saltene og undersøke treets tilstand. Undersøkelser på stedet ble utført med test strips og bærbar XRF og røntgen. Det ble tatt prøver for analyser i ICP-OES, FTIR, SEM-EDX og lysmikroskopi ved bruk av ligninfarging for å svare på forskningsspørsmålene. Et viltkamera, ultralyddetektorer og klimaloggere var en del av undersøkelsene på stedet for å undersøke flaggermusaktivitet og vurdere bevaringsklimaet i kirken. Andre mulige kilder til saltene er vurdert. Saltmolekyler som ble funnet i prøvene var hovedsakelig kaliumsulfater og kaliumfosfater. Disse molekylene kommer fra flaggermusenes ekskrementer. Trecellene på overflaten av trekonstruksjonen lider av mekanisk nedbrytning på grunn av saltkrystallisering. Krystalliseringspunktet for disse saltene krysses ikke ofte i klimaet på Urnes, og nedbrytningshastigheten er forholdsvis lav. Det er ikke påvist noen kjemisk nedbrytning. Flaggermus har ikke brukt redet i løpet av dette prosjektet (2016-2019), men det foreslås å fjerne saltene og hindre at flaggermus bruker kirken som tilholdssted. Avbøtende tiltak for flaggermusene, i tråd med Norges forpliktelser i EUROBATS-avtalen, anbefales.

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I have had great help with all the analyses. **Susan Braovac** delivered a comprehensive report from the FTIR analyses. Thank you to **Sara Mantellato** and **Francesco Caruso** who conducted the ICP-analyses at ETH Zürich in their spare time. **Hilde Raanaas Kolstad** at NMBU imaging centre ran the SEM analyses with me and provided extra analyses over and over when I had new thoughts and ideas. Her colleague **YeonKyeong Lee** conducted the lignin analyses. **Susanne Kaun** at NIKU helped me understand the XRF peaks. Thank you all!

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I have learned what I needed to know about bats from **Tore Christian Michaelsen** and **Jeroen var der Kooij**, and the PhD of **James Hales** about bats in churches has been a great help during this project. Thank you!

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It has been fun, but I could not have done this without all of you!

Kjersti Marie Ellewsen
Kolbotn, December 2019

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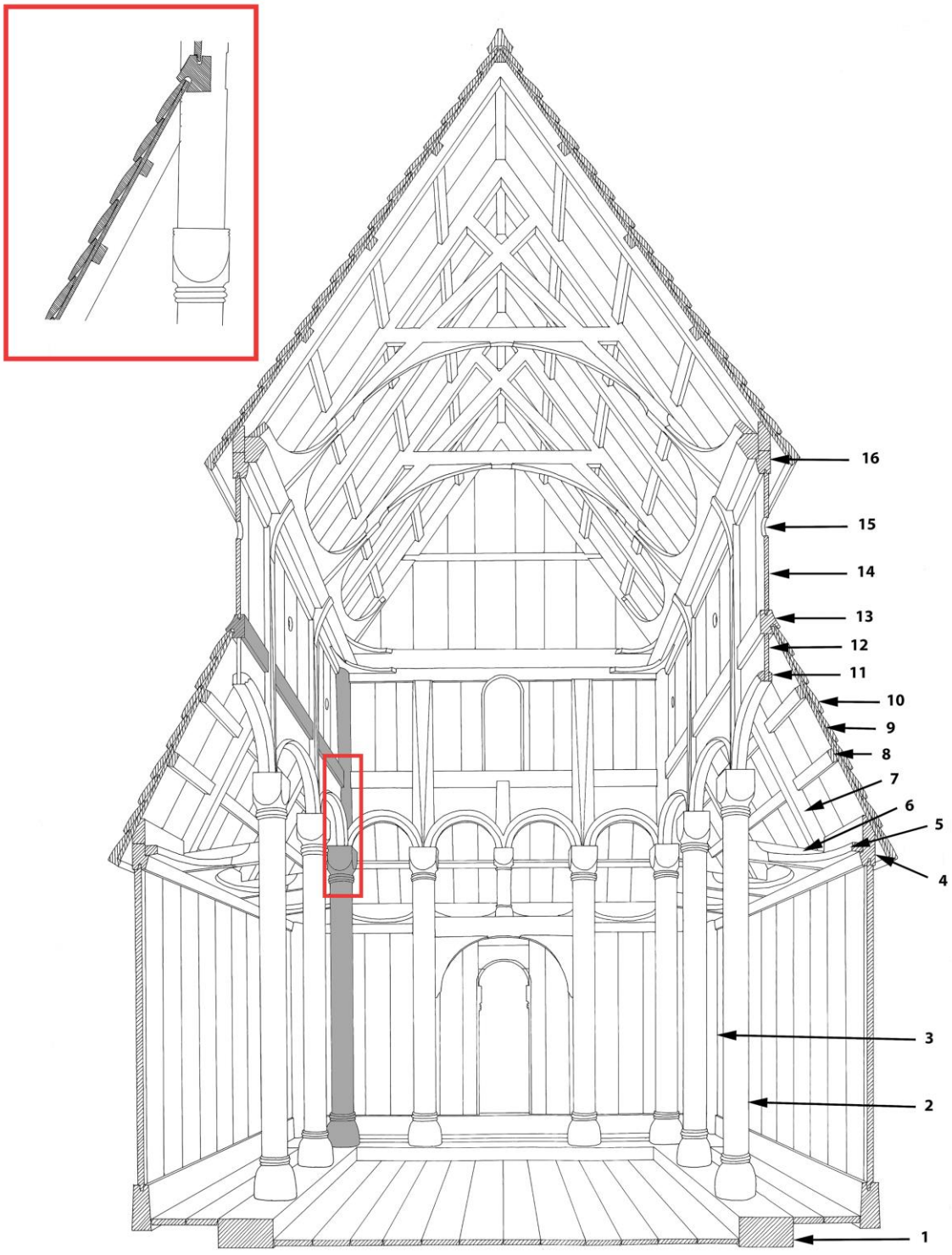

Figure 1 Two drawings of Urnes stave church, from Håkon Christie (2000). The SW nave corner post and bressummer in grey. Cross section of the aisle roof and bressummer inside the red frame.

The numbers are added to name building parts important to this dissertation:
1 Nave raft beam **2 Nave post 3** Aisle corner post **4** Lower aisle wall plate **5** Quadrant bracket **6** Aisle strut **7** Aisle rafter **8** Aisle purlin **9** Aisle roof, plank boarding **10** Aisle roof, tile cladding **11** Arcade moulding in the nave central room **12** Arcading in the nave central room **13 Nave bressummer 14** Nave wall planks **15** Port hole **16** Wall plate of the central room

INTRODUCTION

Background

Norway currently has 28 stave churches that remains from the medieval period. They are all that is left of the approximately 1000 stave churches Norway had around 1350 (Anker, 2016). These 28 churches have survived the usual threats to which most wooden constructions generally succumb: fires, biological attack and chemical degradation. Those stave churches that survived these threats may instead have been demolished due to religious and social changes at some point in history. As such, these few remaining stave churches constitute highly valuable Norwegian and international heritage.

One of the stave churches, Urnes, is a UNESCO World Heritage site. It dates to the 1130s but was built partly using materials from an older church (Krogh, 2011). Urnes church has undergone many changes during its almost 1000-year lifespan, but the main room still retains its original staves (posts) and layout. The research into the degradation of one of these posts and its adjoining structure forms the foundation for this master study. The church has been owned by Fortidsminneforeningen (National Trust of Norway) since 1882.

In 1998, degradation of an unknown character was discovered on the southwest (SW) nave corner post and the connecting bressummer (see figure 2, a and b). Since, the wooden surface has been constantly moist and there is evidence of material loss. This wooden surface is light in colour from surface deposits. Analyses have identified these deposits as salts.

The nave bressummer and corner post are connected by a joint. Together with the joints between post and ground beam and post and wall plate (see figure 1), these ensure stability in the corner of the church. Further material loss in the joint might reduce the stability of the corner if the bressummer loses connection with the corner post.

In 2012, excrement was found in the southwest corner, which confirmed a bat maternity roost inside the core of the bressummer. Historic buildings frequently represent a favourable environment for bats. Although there are no statistics specific to Norway, it is known that bat roosts in buildings are normal and the prevalence of the problem is likely much more widespread than documented at present (J. Mattsson, personal communication, 09.05.2016).

No work has previously been done in Norway on the effects of bat droppings in historic building structures.

Figures 2 a and b. An image of the contaminated area in the SW nave corner seen from the west gallery (a) and from the aisle corner (b). The surface is contaminated by salts. Chicken wire is used to prevent bats from re-entering the roost. The SW post, bressummer, arcade moulding and wall planks are seen.

The topic of this thesis

This research project has aimed to characterize the degradation of the southwest nave corner post and bressummer by identifying the salts, identifying the source of the salts and investigating the degradation factors present. The project aims to test the theory that these salts come from urine, and, in doing so, to ultimately propose measures to prevent further damage to the wood.

There is a vast number of articles about research into salt deterioration in porous materials in heritage buildings, but few address wood. Most of them deal with inorganic materials like stone and mortar. This, I think, can be explained by three factors: The majority of the world's heritage buildings are made of stone, and stone architecture has been the main focus of interest in international heritage charters. Secondly, salt is not considered a major deterioration threat to wood. On the contrary, inorganic (metal) salts are used intentionally to preserve wood, and wooden constructions in contact with salty sea water are well preserved because of the positive effect salts have against insect attacks and fungi growth (Unger, Schniewind, & Unger, 2001; Øyen, 2001). The third factor is that the effects of salts in porous inorganic building materials are dramatic, as salt can cause powdering and scaling over large areas of the building (Elena Charola, 2000). But does salt contamination in wooden constructions represent a less dramatic threat? Visual examination of floors in storage buildings used for food conservation show quite dramatic signs of deterioration, and the surface of the 900-year-old stave at Urnes looks worrying.

Research questions

The literature shows that salt deteriorates wood on a microscopic level and paves the way for ongoing corrosion of the wood cells. Several documents about the post at Urnes report salt findings (Mattsson, 2004, 2005), but it is yet unclear if the salts are the main reason for the defibrated surface and loss of material. No structured research had been undertaken prior to this master project.

Chemical analyses of the wood fibres have confirmed the presence of nitrogen compounds, which may originate from animal urine. This project will test the theory that these salt deposits come from urine and identify the true cause of the damage. It aims to propose effective and appropriate measures to prevent further damage to the wood, either by reversing or halting the deterioration of the post and its joint, for implementation.

The main research questions are:

1. **Which salt molecules contaminate the SW corner post at Urnes?**
2. **Do these salts originate from bat urine?**
3. **How do these salts affect the preservation state of the wood?**

The research questions will be answered by using the historical data available, referencing information, research carried out on similar buildings and a combination of analyses carried out for this MA study.

Urine is primarily composed of urea, as well as soluble salts (James, 2014). Urea, also known as carbamide, is an organic compound with the chemical formula $CO(NH_2)_2$. It is highly soluble in water, and it forms crystals like salts. This research will aim to examine whether urea affects the wood in the same way as soluble salts. Both mechanical and chemical deterioration processes will be discussed. The anatomy of the affected wooden cells will be examined to find proof of deterioration. The project will aim to understand whether the salts formed from urine and faeces encourage degradation of wood, rather than the preservation effect usually associated with salts.

To be able to address the problem thoroughly and suggest measures to prevent further damage, the source of the salts must be determined. During the period after the damage was first discovered at Urnes in 1998, many theories about the cause of the damage have been proposed. The findings of ammonia in samples from the contaminated wood in 2005 led to the conclusion that the surface deposits derived from a squirrel that had been observed in the church. Other potential sources of these salt deposits included the tar surface treatment of the church exterior, and previous pest treatments (Mattsson, 2005). The source of the salt remained ambiguous. Indeed, identifying the source is not straightforward, and there may be several salt sources that affect the construction over the lifespan of the building.

Bat faeces was discovered in 2012 around the southwest nave corner post. Bat droppings can be hard to find, so the incidental finding of faeces suggested that the bats had probably inhabited the post and bressummer over a long period of time (van der Kooij, 2016), possibly over centuries. These droppings have led to the assumption that the damage is due to bats. Bats are not known to make nests or cause structural damage (Bat Conservation Trust, 2015),

meaning that if the damage is caused by the presence of bats, the surface deterioration is not due to abrasion or other mechanical damage, such as scratching from bat claws. The material loss must be a result of other deterioration factors.

There are 12 known species of bats in Norway, and all of them are protected through Naturmangfoldsloven ("The Nature Diversity Act," 2009). Bats are strongly dependent on buildings, and churches have provided refuge for bats for hundreds of years. Bats look for warm roosts in the summer and maternity roosts often have a southerly or westerly exposure for maximum solar heating (Bat Conservation Trust, 2015). Temperature and humidity are important to bats (Kunz, 1982). As such, the core of the southwest bressummer at Urnes provides the perfect space for a bat roost. In Sogn og Fjordane, nine different bat species have been observed (Michaelsen & Kooij, 2006).

Dissertation structure

Chapter 2 will give the theoretical background for this project. The site at Urnes and the area of interest inside the church will be described. The literature about the different topics of this project will be reviewed; the characteristics of salts and the behavior of salts in porous materials as well as bats, the contents of bat droppings and case studies regarding deterioration on historic structures from bat droppings.

Chapter 3 will describe the methods chosen for the research. The situation of the southwest corner has been investigated using multiple methods; visual examinations, logging methods, chemical analyses and X-ray. The salt content of the wood was analysed. Analyses of contaminated wood has been compared with analyses of non-contaminated wood from the same timber post and other non-contaminated parts of the church.

Norwegian institutions have extensive expertise on wood science. The Norwegian Institute of Bioeconomy research (NIBIO) and the Saving Oseberg project at the Museum of Cultural History both have expertise in wood science and access to technical instruments for conducting the appropriate analyses. Mycoteam is an expert company in biology and deals with pest control. All institutions have contributed to the results of this project.

Chapter 4 will describe the results from the analyses and observations, whereas chapter 5 will discuss the results. Also, the implications for future research will be discussed in this chapter.

Advice for church owners struggling with urine and excrement from bats is long overdue, and this project will help Riksantikvaren to establish guidelines on how to deal with this problem. When bat colonies are first observed in a building, it is often due to the smell of the accumulated urine. The most common solution is to replace the affected construction part with fresh wood. At Urnes, with an unbroken history of the corner post for almost 900 years this is not desirable. The same applies to other historical buildings. If the bats represent a threat to our built heritage, it is important to give them alternative shelter, or to protect the sensitive materials on site from the degradation associated with bats.

This topic presents potentially conflicting interests between cultural heritage and natural environment. The stave church is a world heritage site, and automatically protected by the Norwegian Cultural Heritage Act ("The Norwegian Cultural Heritage Act," 1978). The long-eared bat found at Urnes is a listed species, and Norway has an obligation to protect all species found in Norway through *EUROBATS (1991)*. The Agreement was introduced in 1994 and ratified by Norway the same year. Through the agreement, we are obligated not to kill, injure or disturb bats living in buildings. A close collaboration with zoological experts was crucial to address the situation at Urnes and to identify the best solutions.

Theoretical background

Research object: Urnes stave church

The construction of the church

A stave church is a wooden construction where the main bearing construction is made of vertical timber posts resting on wooden ground beams. It was one of the most common ways of building during the medieval period in Norway. Urnes stave church has a bearing construction of 28 posts, made up of 18 seven-meter-tall posts in the central room and surrounded by ten lower posts in the surrounding aisle (Christie & Amlo, 2009) and chancel (see figure 3). Horizontal beams connect the posts and stabilize the building (see figure 1). The lower end of the vertical posts (staves) are tapped into wooden ground beams separated from the ground by a low stone wall. The top end of the posts is connected by a wall plate, and at the point where the aisle roof meets the main room by a bressummer. The aisle roof cladding is tapped into the bottom of the bressummer and the wall boards between the bressummer and wall plate are tapped into the top of the bressummer (see figure 1, small drawing).

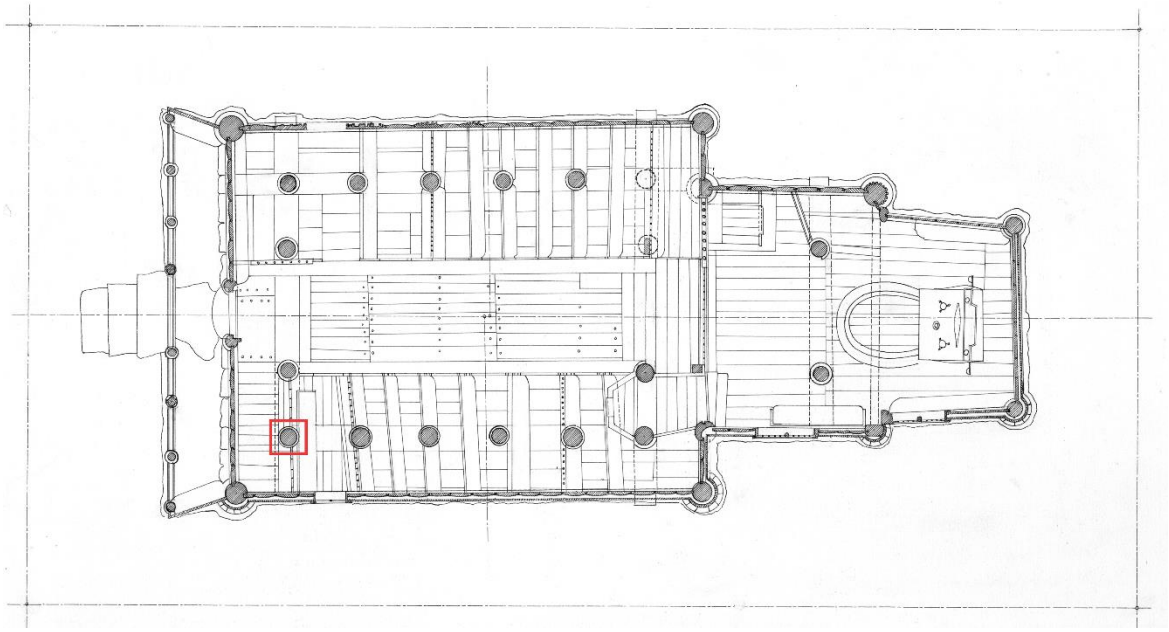

Figure 3. A plan of Urnes stave church, showing the posts. The SW nave corner post inside the red frame. Drawing by Einar Oscar Schou (1877-1966).

Conservation history SW corner

Most of the history of the church is undocumented. The archives at Riksantikvaren show very little material before 1882 when the Society for the Preservation of Ancient Norwegian Monuments (now the National Trust of Norway) took over the ownership. Prior to this time, church inventory from the 17th and 18th century can give some information. Researchers read and interpret the building itself. Håkon Christie (2009) and Knut Krogh (2011) have interpreted the early restoration history through their research. They have focused on the structural changes, the dating of the different parts and the handicraft. Erla Hohler (1976, 1999) focus on the art history, the religious use and symbols.

Most of the construction materials are still original, which is a solid proof that it has been taken care of during the whole life-span. The roof must have been repaired when leaking, and the ground wall fixed when stones fell out. The church has signs of old age but is in general in good shape. The SW corner of the church is situated towards the fjord and the rain and wind will have the most impact from the SW direction. This project has looked at the restoration history from 1970 onwards, and measures that might have affected, or is directly linked to, the SW corner of the nave will be mentioned here.

History from 1970

In 1973, a seminar about the conservation of stave churches was held in Sogn og Fjordane. Urnes stave church was visited by international experts, and proof of insect attack was found. Fortidsminneforeningen tried to raise money to treat the attack by chemicals. Whether the treatment was conducted or not is unclear from reading the archive material at Riksantikvaren. Pest treatment chemicals like “xylamon” and “basileum” were suggested, and even given to Fortidsminneforeningen for free. There is reason the believe that xylamon or similar treatments have been used over a longer period as a preventive measure in areas with signs of attack. In which areas the church was treated is not documented. Xylamon is no longer in use but it contained such biocides as lindane and/or permethrin (Unger et al., 2001) both chloride-based pesticides (Macek & et.al., 1976).

In 1984 the entire church was covered in tarpaulin and gassed with phosphine gas (PH_3). The purpose was to kill wood boring beetles. This operation was conducted on 3 stave churches in

the same area; besides Urnes also Hopperstad and Undredal. The need for such a complicated operation was controversial, as some doubted that the attack was active, and the operation was very expensive. The operation was conducted by Rentokil, a pest control company. During the same operation, the façades of the churches, and some of the most infected areas inside the churches were sprayed. The full report from the operation has not been possible to obtain, but permethrin is mentioned as the spray fluid (personal communication, Arne Nese, Rentokil, July 2017). The church warden at the time, Marit Bøen, remembers that all the silver discoloured as a result of the gassing (interview, 21.10.2019).

In 1991, a fire sprinkler was unintentionally triggered. This led to moisture in all the posts and the ground beam on the west side, and a level above 24% of moisture content was measured in the SW nave corner post. A documentation of a follow-up of these measurements has not been found.

In 1998, the salt problem in the SW corner was recognised for the first time in a letter from Knud Krogh to Riksantikvaren. The post and bressummer were moist on the surface, especially on rainy days. In the following years this was followed up by Riksantikvaren and Fortidsminneforeningen, and several measurements and examinations were undertaken. Mycoteam, a counselling company specialized on biological and climate related damages, did most of these examinations.

In 2000, the roof tiling was removed to examine possible leakages above the post. Lead fittings were mantled to ensure a tight roof. The area kept being damp and the attention was gradually drawn from water leakage to salt contamination. Samples were taken from the area and analysed for fungal growth. Grey rot was found and also proof of urine. The advice from Mycoteam and Riksantikvaren was to wash out the salts. An attempt was made in 2002, when the hollow area was cleaned with water and surface dirt inside the bressummer was removed. Over 1 litre of dirt, thought to have come from a squirrel roost, was removed. They believed at that time that one or several squirrels had lived there, as they had seen and caught several of them. Traps were set up and the squirrels caught alive and set free away from the church. The washing out measure was done by local representatives from the National Trust, but there was not much faith in the method. The water accumulated in the post and will contribute to move the salts around but not remove them.

Salts were analysed by NILU in 2005. The National Trust took the sample, and the sample was sent to Mycoteam who commissioned NILU for the analyses. Ammonium, potassium, sodium, sulphates and possibly phosphates were found. The report discusses different possible sources; residues from tar surface treatment (exterior), pesticides and urine from the squirrel. There is no documentation of where the sample was taken.

During the Stave Church Preservation Programme from 2001 to 2015, Riksantikvaren repaired all 28 stave churches. The aim of the Programme has been to raise the condition of the churches to a normal maintenance level, preserving the standing church as is. Through this work, further knowledge of the stave churches and their interior has been gleaned, both about the original state of the churches and the changes they have gone through (Mehlum, 2016). The Programme dealt with Urnes stave church in the years 2007-2011, and the work focused on the stability of the foundations and the interior art objects and decorations (Holen, 2016). The surface deterioration in the SW corner was not in focus during this work.

After the analyses in 2005, there was no mention of the SW corner until a new report from Mycoteam in 2012. Samples of animal droppings and wood fibres from the area were sent for recognition. The samples were studied under a microscope (type not documented) and recognised as bat droppings. Mycoteam (Mattsson, 2013) suggested a site visit during the winter period when the bats hibernate in a location outside the church, to find measures to keep the bats from re-entering the church in spring. This was conducted in the winter of 2015. Chicken wire was used to fill the biggest holes in the post, bressummer (see figure 2b) and wall planks. The chicken wire was removed again from the bat entrance hole in 2016. The purposes of the removal were partly because it was visually disturbing and partly to be able to document bat activity in the SW corner.

In September 2015, Leif Anker conducted a systematic testing and sampling in the SW corner, in cooperation with the author and Susan Braovac. Sulphate test strips and pH indicator paper were used and results thoroughly documented. Samples were taken and sent for analyses in FTIR at the Museum of Cultural History. This systematic work marks the start of this project.

Bats and historic buildings

Norway has 12 known species of bats ("Flaggermusarter i Norge," 2019). Bats are mammals and produce on average one offspring a year (Stephen Paine, 1993). They hibernate during the winter, and in the summer, they live in colonies in warm roosts near the insect source. Bats choose roosts with temperatures near to their thermoneutral zone (Michaelsen, Jensen, & Högstedt, 2014). In England, where a conflict between protected bats and protected buildings has drawn attention for some time, it is estimated that 6400 churches have bat presence (Hales, 2017). The change in farming and forestry management has decreased the number of natural habitats for bats, and churches in rural areas have become substitutes (Stephen Paine, 1993).

Although the nature and landscape in Norway is not comparable to England, it is reported by bat experts that man-made structures are popular roost sites (Michaelsen et al., 2014). Bats or signs of bats (insect parts, dead bats or droppings) were registered in 32 churches in Sogn og Fjordane in 2004 (Michaelsen & Kooij, 2006).

On entering and leaving a roost site, bats tend to urinate and defecate (Stephen Paine, 1993). This means that the damage is not only seen inside the roost, but also over a bigger area around the roost. Bats can squeeze through very small openings and the roost can be hard to find, but the faeces and spots of urine around the area might help to detect the roost.

A bat colony of 50 bats can produce 6-9 kg of feaces and up to 33 L of urine during the few active months between hibernation (Stephen Paine, 1993). This tremendous amount can potentially cause serious problems, especially the urine. Paine observed that “urine is chemically more aggressive than droppings and its deposition, although harder to observe, is therefore of greater conservation concern” (Stephen Paine, 1998, p. 2). The urine accumulates within the porous material, and the different ingredients in the urine affect the solid material in many ways.

The complexity of the reactions brings forward a necessity to focus on a limited part of the damaging reactions involved. This text will focus on the salts from the urine, and how they might affect the preservation state of wood. The visual examinations and a surface that is moist to the touch suggest salt contamination.

Deterioration by bat excreta

The nature of the damage from bat excreta has not been a subject for many studies. In the publication "Bats in Traditional Buildings" from 2009, Howard and Richardson reported that droppings and urine cause spotting, long-term staining and etching to porous materials.

A significant piece of work relating to deterioration mechanisms associated with bat excreta was conducted by James Hales for his PhD at the University College of London (2017). This PhD addresses the damages caused by insectivorous bats on historic surfaces. Previously some work was published on damages to wall paintings (Bakr & Abd El Hafez, 2012; Stephen Paine, 1993), but Hales was the first to deal with the effects of bats on a wide range of materials, including marble, granite, alabaster, metals and wood (pine and oak).

Stephen Paine published extensive research on damages from urine and faeces on painted plaster in "The effects of Bat excreta on wall paintings" from 1993. In his study, he used materials from 5 churches in the UK known to be residents for bats and conducted laboratory tests on new plaster blocks painted with a typical range of medieval pigments. The new samples were exposed to excreta from captive bats. Visual examinations, chemical spot tests and XRD analysis were performed on site as well as sampling for closer examinations in SEM in the laboratory. Damages like staining, flaking of paint layers and chemical changes to the pigments were documented. Fungal growth around the faeces and urine spots were also observed, and this can cause penetration of hyphae within the surface matrix. Paine concludes by saying that it is clear evidence that bat excreta, both faeces and urine, cause damage to wall paintings and other artefacts.

D'Armada (D'Armada, 2005) found that decaying faeces can lead to the formation of nitrates, phosphates and ammonia. Nitrates are particularly damaging, as the equilibrium relative humidity (RH^{eq}) at around 50% RH for the salt is crossed frequently in a normal church climate, leading to pressures from cycles between crystallization and solution. Nitrates are also a rich nutrient for micro-organisms. Phosphates are also of concern to Paine, as they can combine with calcium to form calcium phosphates and form a stable film on the surface (p. 6).

In Egypt, Bakr and Hafez completed a similar study on the effects of bat excreta on painted surfaces (2012). Bats inhabited the dome of Mohamed Ali's palace in Suez since the palace

was abandoned in 1980. The degradation caused by the excreta resulted in large areas of completely detached paint layers. Samples of detached paint were collected from the floor below the dome, and they were used for various analysis and for cultivation of the fungi and bacteria grown on it. Examination in OLM and SEM showed dark stains and "polymeric like morphology". Analysis in SEM-EDX showed the presence of many elements, where in particular the phosphates were identified as deriving from the bat guano. The main micro-organisms colonizing the painted surfaces were also identified. The results in this article and other works cited above show that bat excreta contribute significantly to the deterioration of cultural heritage.

Contents of bat droppings

To understand the damaging effects of bat droppings (urine and faeces), the composition must be understood. Analyses of urine has been conducted by James Hales (2017), but analyses of faeces were not found in the literature dealing with bats in historic buildings. Paine (1993) and Bakr/ Hafez (2012) have done extensive elemental analysis of affected materials, but the total composition of the substrate is included in their analyses without attempts to isolate the urine and faeces first.

Urine

Mammalian urine is in some literature described as 70 per cent urea, decaying to form dilute ammonia and other compounds (Paine, 1998, Howard and Richardson, 2009, Natural England, 2011). James Hales (2017) is critical to the general description of urine and the degradation of urine components and has conducted analysis in his thesis. This included pH analysis of the urine from five different bat species. He found that the major solutes in mammalian urine are urea, potassium, sodium and chloride (Hales, 2017: 120). There is little direct evidence that differences in urine chemistry between different species is a significant factor affecting deterioration (Hales, 2017: 395). However, some bat species urinate and defecate more than other species, thus causing more damage than others. Hales conducted quantitative analysis of the major solutes and compared the results from 4 different bat species. As for the pH analysis, the urine was found to be slightly acidic (between 5.3 and 6.8). Both bat urine and bat faeces are a good source of ionic compounds known to cause damage to heritage structures and materials; sodium, potassium and calcium; combined with various anions such as chlorides, sulphates, nitrates, acetates, phosphates and carbonates

(James Hales (2017), p. 383). Presence of urine and faeces is expected to give results for these elements.

Bakr and Abd El Hafez (2012)did SEM-EDX analysis of samples from the affected areas in 3 different stratigraphic layers; directly on the dark stain, the yellow surface below the stain and from a cross section of the stained sample. Sodium, potassium and chloride were all present in all layers, but also high amounts of silicon, calcium, sulphur and aluminium.

Paine (1993) used spot tests at site to look for the expected elements present on the surface of the wall paintings. The spot tests found both nitrates and phosphates on several locations. From the urine, chlorides were of most concern to Paine, as they can easily form chlorides of calcium, magnesium, sodium and potassium. Paine is also concerned with the urea, which can oxidise and form damaging nitrates. The latter statement is criticized by Hales (2017), as the decomposition of urea in nature is yet not well understood. As the results from Paine's study is not presented clearly in tables, it is hard to get an overview of his findings regarding elemental analysis.

Faeces

Faeces are dry solids and contain almost 80% of the indigestible parts of the insects in the bats' diet. Still there are constituents that have the possibility to cause damage as well, all though not as extensive as the urine. It contains nitrogen compounds and a small percentage of fats and oils (Hales, 2017: 352). The fats and oils are long-chained fatty acids, meaning they are stable and may cause very persistent stains at the porous surface. The dissolved materials from the faeces are nutrients for micro-organisms (Paine, 1993).

Bat guano (faeces) is used in the fertilizer industry as a rich phosphate source, collected from caves for centuries in Africa and USA. It has also been used to extract nitrates for the arm industry to make gun powder (Simons, 1998). Analyses of guano from African caves report high contents of nitrogen, sulphur and phosphor in all samples (in increasing amount from left to right).

As shown in the literature there are many deterioration factors involved in substrates affected by bat urine and faeces; salt weathering, fungi growth, micro-organisms, discoloration (staining) and changing acidity. The next section will focus on reviewing a selection of the

literature relevant to salt deterioration mechanisms: The characteristics of salts and the deterioration processes connected to salts in porous materials.

Characteristics of salts and urea

Different salts have different characteristics. Solubility and molecular size determine how a salt moves within a material, appears at the surface and how fast it crystallizes and hydrates. The deterioration by salts is often explained by the crystallization pressure forming when a salt goes from being dissolved in water to forming the solid crystal, and thereby increasing in size and exerting mechanical stress on the cell walls (Elena Charola, Pühringer, & Hawk Hildesheim/Holzminden/Göttingen, 2005). How much damage the crystals do depends on the size of the pores and the magnitude of the repulsive force between the salt and the pore surfaces (Scherer, 2004, p. 1613) The damage caused by urea might be similar to the damage caused by salts. Urea is not a salt, but it is soluble in water and form crystals when the relative humidity decreases to a certain level (Hales, 2017, p. 384).

The mechanisms connected to the behaviour of salts are very complex. This text does not attempt to be an exhaustive review of this complicated subject. However, the selection has been made to try to explain the most fundamental factors related to the deterioration by salts in wood.

Many salts are water active, which means that they can take up water from the air. Salts absorb moisture when the relative humidity (RH) increases above their equilibrium relative humidity (RH^{eq})(Elena Charola, 2000). A salt is at its RH^{eq} when the number of water molecules leaving the salt solution equals the number dropping back into the solution (D'Armada, 2005).

The salt molecule can exist in many phases; as ions dissolved in water, either in a saturated solution or supersaturated solution, or as a crystal (anhydrate or hydrate crystal). Change of the RH changes the thermodynamic phase of the salt. Change of thermodynamic phases represent volume change. The phase at which the salt has the largest volume, differs from salt to salt, as do the number of phases it can form. When the conditions cause a constant cycling

between wet and dry conditions, cryptocrystalline salts might form. Such aggregates can be a mixture of phases (Elena Charola et al., 2005).

Many articles discuss the effect these cycles have on historic material. Without water present, the cycle is non-existent. Through mobilization and a constant fluctuation between humid and dry phases, the salts "work" the wood. During dissolution, some salts induce a volume increase and some a volume decrease (Elena Charola et al., 2005). This has been extensively discussed in the literature, but it is hard to find any consensus (see reference Price/Brimblecrombe below).

For a crystal to grow from an ionic solution, several mechanisms might be involved. For example, during a fall in temperature, some salts decrease in solubility and a crystal will form. Such crystallization of a salt solution after temperature fall affects a much larger volume of salt per unit time than crystallization induced by evaporation, which is a more gradual process (Goudie & Viles, 1997). Another mechanism is evaporation of the moisture. A salt can crystallize only when the ambient RH is lower than the RH^{eq} of the saturated salt solution. The RH^{eq} of different salts varies considerably, and those with low values will be prone to dissolution in humid air (Goudie & Viles, 1997). This means that salts or salt mixtures with a high equilibrium moisture content are prone to exist as crystals in a normal fluctuating indoor climate. When the RH^{eq} is crossed frequently, the pressure in the pores of the substrate increase.

Some salts can produce a second solid phase, such as a hydrate. Since the damage occurs during the formation of a solid phase, the salts prone to form hydrates are more damaging than salts that form only one solid phase. However, this hypothesis needs further research (Elena Charola et al., 2005). As Menendéz has shown (2017), there are specific salts that induce volume increase due to hydration when the relative humidity increases. Previously, the formation of a hydrate was thought to appear from hydration of the crystal, representing hydration pressure. But later research done on sodium sulphate (Na_2SO_4), a salt that forms hydrates ($Na_2SO_4 \cdot 10H_2O$), shows that for a salt to create a hydrated crystal, the salt must precipitate first and then attract water molecules. In reality, this represents crystallization pressure. When salt is diluted in water, the volume of the solution can be smaller than water alone (Elena Charola et al., 2005). This can lead to the salt solution being transported further into the porous material.

According to Price and Brimblecrombe (1994), "*salts can only be regarded as acting independently of each other in exceedingly dilute solutions – solutions which are so dilute that chemists sometimes refer to them as "slightly contaminated distilled water*" (p. 91). A building is rarely contaminated by one single salt, but by many salts and other contaminants, and usually in concentrated areas of the building fabric.

The presence of a second salt results in the lowering of relative humidity required for precipitation if the salts have an ion in common. If they have no ions in common, solubility of both salts increases (Charola, 2000: 330). In the article "Preventing salt damage in porous materials", Price and Brimblecombe (1994) show that a combination of two or more salt molecules radically affects the behaviour of the single salts isolated. The computer programme PITZ93 was used to study the behaviour of salt mixtures and calculate at which relative humidity different salt combinations crystallize. The computer programme can be used to find the single point at which all systems (every single salt, liquid water and water mist) is in equilibrium. If the salts are present in a museum object where storage conditions could be controlled, the programme is a useful tool to find the perfect environment to prevent salt damage.

Whereas the article of Price and Brimblecombe (1994) showed how to calculate the critical relative humidity for salt mixtures, Menendéz (2016) took this one step further with the ECOS-RUNASALT model. This model, which Price and Brimblecombe helped develop, calculates the climate conditions at which the volume increases in a salt solution. In the computer programme, the inputs are the ionic composition and the environmental conditions (temperature and relative humidity). The calculations can be done either with a constant temperature and changing relative humidity, or vice versa. The model has been tested both with the ionic compositions normally expected in stone buildings, but also with the composition from a real building in Paris. A sample of the mortar from the building was washed out in distilled water and the solute analysed with ion chromatography. The ion data was then fed into the programme. The research showed that at each specific temperature there are several relative humidity conditions where the volume of salt changes considerably. As expected, the most important volume increases occur when the relative humidity decreases, due to precipitation processes. But there are also conditions where an increase in relative humidity produced a volume increase due to hydration processes. The calculations showed

that low temperatures are the most critical factor to volume increase in a salt mixture. At lower temperatures, the hydration processes are initiated at lower RH than at higher temperatures. This is connected to the fact that solubility increases with temperature (decreases with decreasing temperatures). Once the calculations are made, it is possible to estimate future damage in the expected climate.

Salts in wood

Wood is the main construction material in Norway due to both its widespread availability and the resilient structural traits of wood. It is extremely strong, yet flexible and has different traits in different directions of the fibres and in different parts of the tree. Its heterogeneity behaviour differentiates wood from other materials, which are more uniform. Medieval craftsmen knew how to take advantage of the different parts of the tree, demonstrated in the selection of materials at Urnes. The construction is built entirely of wood, mainly scots pine (pinus sylvestris). The SW timber post was cut down sometime between 1058 and 1130. It has a hollow core at the base due to rot, and this rot damage occurred while the post was still a living tree (personal communication, T. Bartholin, 12.18.2012). It was probably chosen carefully for the task it was given, to give structural strength in the longitudinal direction. It was long enough and thick enough to be used as a bearing post (Thun, 2016).To understand the deterioration of the southwest corner post, it is important to understand the anatomy of pine and its sensitivity to degradation factors.

Wood is a naturally occurring polymeric composite composed of cellulose, hemicellulose, lignin and extractives (Pandey, 1999, p. 1969). The crystalline cellulose gives the tree its strength, and the amorphous lignin acts as a cementing material for the wood fibres. The hemicellulose acts as a link between the two (Pandey, 1999). Pine is a softwood with regular grain structure and longitudinal tracheids (see figure 4). The tracheids are the most frequent cells and fill almost 90 % of the softwood. They function as conduits for liquids and for mechanical support (Unger et al., 2001). The two other type of cells found in softwood are the parenchyma cells and the epithelial cells. The tracheids (oriented in the longitudinal direction) and the ray tracheids (oriented in the radial direction, see figure 5) are important to the moisture transport in softwoods (Segerholm, 2007). Exchange of substances between adjacent cells occurs via openings in the cell walls, the pits (Unger et al., 2001, p. 12).

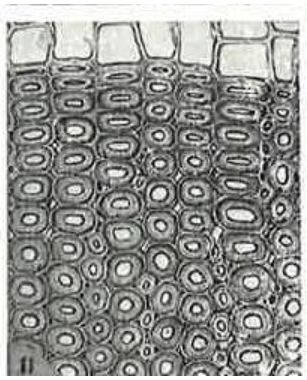

Figure 4. Cross section of a softwood, magnified 175x, showing rounded outlines of compression wood tracheids and associated intercellular spaces. (Phillips, 1948)

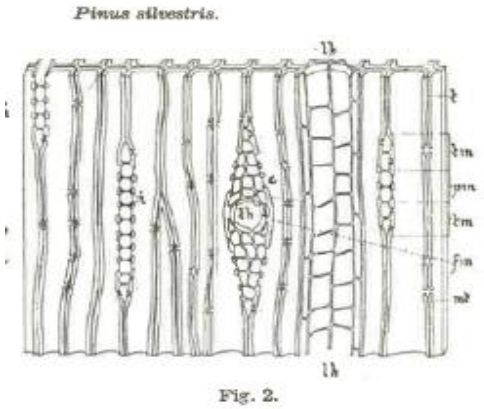

Figure 5. Transversal section of the pine tree.

(Mork, 1966)

Porosity

Wood is a hygroscopic material, as porous materials frequently are. A porous material is a material that consists of a solid matrix interspersed with voids. Where the voids interconnect to some extent, pathways can form for the transfer of liquid phases (Pender, 2004). For wood, the pathways are very important, as transport of water and nutrients from the ground are crucial factors in the life and growth of a tree. The tracheids and cells make wood hygroscopic even after felling. Timber will take up water from the air; it swells and shrinks depending on water content in the cells. When hygroscopic salts are added to the porous material, the hygroscopicity of the wood will increase.

Samples taken from Urnes for dendrochronological research have shown that the timber has a high degree of sapwood (Thun, 2016). There is a great difference in moisture uptake between heartwood and sapwood, as sapwood is more porous than the heartwood. In a report from Lund University, Maria Fredriksson (Fredriksson, 2010) reviewed the literature looking at how wood properties are affected by differences in handling, storage and drying methods after felling. She reported that the water uptake in sapwood is affected by drying method (higher in air dried wood than kiln dried), by storage method (wood that had been water stored had a higher uptake than wood stored otherwise) but felling season did not seem to matter (p. 29). Annual ring width did not seem to influence the water uptake, neither did the density, which

is surprising. In general, the moisture uptake in sapwood is higher than in heartwood. This is also reported by Rydell, Bergström and Elowson (Rydell, Bergström, & Elowson, 2005).

The damage caused by salts in wood are described in detail by Parameswaran (Parameswaran, 1981), Johnson (Johnson, Ibach, & Baker, 1992), Blanchette, Held and Farrell (Blanchette, Held, & Farrel, 2002) and Landa/ Ochanidiano (Landa & Ochanidiano, 2014) among others. They all report the same type of damage: defibrated and fuzzy surfaces, woolly appearance and detached wood fibres. The damages are seen in buildings close to the sea, where rain brings the salt from the sea, in marine pilings, and in houses used for salt storage. Common for these buildings is the deposition of salts in the wood. The damages are on the microscopic as well as the macroscopic level. None of the articles described whether this damage is due to crystallization pressure or other deterioration processes caused by the salt. Previously, this type of surface attack on wood was associated with biological deterioration processes but is now agreed to be caused by salt attack (Kirker & Glaeser, 2011).

A potash store house in Hamburg was the studied by Parameswaran (1981). Wood samples were taken to study closely the visible structural changes of the surface. Examination of the wood in SEM showed that the woolly appearance was due to separation of tracheids in the intercellular/ middle lamella region. Large crystals were deposited within the cells and on their walls, and the tracheids were partly swollen with local cracks and fissures (p. 153). The elements sulphur, chlorine and potassium were identified within the cell structure. The structural changes of the spruce from the store house were directly linked to the storage of potash in the same room.

In Tampa Bay, Florida, wooden marine pilings impregnated by CCA (chromated copper arsenate) were studied by Johnson et.al. (Johnson et al., 1992). The marine pilings had a fuzzy surface. Test blocks of CCA treated wood and untreated wood were exposed to 388 cycles of wetting and drying in the laboratory. Distilled water and synthetic seawater were used for wetting the samples. Tracheid separation became apparent after approximately 100 cycles, but the deterioration did not appear on the samples wetted with distilled water. The article concluded that the separation of the tracheids is not a result of the CCA treatment, but the seawater. The blocks were examined in SEM and showed extensive fine checking along the microfibril angle of the tracheid walls. The deterioration is explained by the growth of salt crystals within the tracheid walls. There is a separation of the lignin-rich middle lamella.

The results from Tampa Bay are similar to the observations made in SEM of wood samples from the expedition huts in the Antarctic, where the salt is carried by precipitation and winds from the sea (Blanchette et al., 2002). The chemicals in the rain and snow rapidly migrate into the porous structure of the wood. Blanchette, Held and Farrell report that these chemical reactions appear to involve a sequential degradation of hemicellulose and lignin networks. This attack causes a separation of wood cells in the middle lamella regions. Once this cementing material is altered, it results in a progressive form of degradation - *defibration*. Images of the defibration on the wooden surface of the huts in the Antarctic and the marine piling in Tampa Bay strongly resemble the surface seen on the contaminated post at Urnes.

In the Añana valley of Spain, a giant salt production area has gone through major conservation work over the last few decades (Landa & Ochanidiano, 2014). The construction is simply built, containing evaporation pans made from clay and later cement, supported by a vast number of wooden frames. The frames are exposed to brine as long as salt production is ongoing. The architects responsible for the preservation of the valley, Landa and Ochandiano, have mainly observed positive effects from the salts, as they prevent insect attacks on the wood. However, they have also observed degradation in a few wooden beams, as the degraded wood on the surface wears off due to the combined action of mechanical stress (from recrystallizing salts) and rainwater. This leaves a grey surface, similar to the degradation of wood exposed to mold fungi, UV light and rain.

Case studies on the long-term effects of application of fire retardants to historical structures show clear degradation that are consistent with damages connected to bats. Fire retardants contain salts, for example ammonia sulphates and phosphates (Kučerová, Ohlídalová, Novotná, & Michalcová, 2007). Kučerová et.al. demonstrated in research on the roof timber from Prague Castle that fire retardants not only changed the pH, but both the lignin and the cellulose in the wood were degraded, leaving a “hairy” wood surface. Breakdown in the middle lamella (lignin) was also reported here, as well as breakdown in the cell walls composed of cellulose. Salt corrosion is regarded as one of the reasons for decay, acid hydrolysis another one. The pH values differed in the corroded wood from non-corroded wood, which indicated that acid hydrolysis had taken place.

Acid hydrolysis

Apart from mechanical degradation caused by crystallization pressure, salts can cause acid hydrolysis in wood (Unger et al., 2001). The case studies mentioned above all report damage in the cell walls, mostly in the lignin rich lamellas. Lignin is the phenolic component which gives wood its rigidity, and is generally resistant to hydrolysis by acids (Unger et al., 2001). Softwoods are more resistant to acids than hardwoods. The greater resistance of softwoods is based on their higher lignin content and lower hemicellulose content compared with the hardwoods. Attack by acids generally lead to colour changes and eventually hydrolysis of the polysaccharides (cellulose and hemicellulose). Wangaard (Wangaard, 1966) tested wood resistance to acidic attack by soaking different wood species, Douglas-fir among others, in different solutions of hydrochloric acid. Research previous to Wangaard (Morath, cited by Kollman, cited by Wangaard) found that acids or alkalis in the pH range of 3 to 10 had no significant weakening effect on either softwoods nor hardwoods. The pH of the urine of bats lies between 5.3 and 6.8 and should in theory not initiate deterioration by acid hydrolysis directly.

METHODS

On site data collection

Visual examination

In June 2017, June 2018 and October 2019, the post and bressummer and all the joining building parts in the SW nave corner were thoroughly examined using a headlight and documented with a Nikon camera during the site visits. A variety of portable light and binoculars were used, and light from all angles especially along the surfaces was important to see the state of preservation, the fuzziness of the surface and the salt crystals. Examinations focused on the preservation state of the surface of the contaminated wood, but also the stability of the building parts.

This project has focused mainly on the SW corner, and all sampling has been taken from this area. It was however interesting to examine other parts of the church, both to look for similar deterioration and to compare the joints between construction parts. In October 2019 a scaffolding was mounted inside the church for buildings works. This enabled an examination of the bressummers, the posts, capitals and arcades around the entire nave of the church. The bressummers were examined using the finger knuckles to tap on the wood to find hollow areas. All the capitals were visually examined for salt deterioration, and the top of the capitals for bat droppings and insect parts. The posts were mainly examined at the base to look for soft rot and salt deterioration, and adjoining areas between the bressummer and posts were examined to look for holes where bats might hide or roost.

Situation of the church

Urnes stave church is situated by the Sognefjord, in the county of *Sogn og Fjordane*. It is connected to the nearest airport with a ferry, and not easily accessible all year round. Instruments that can collect data without operation handling were therefore chosen to document the conservation climate in the church and possible animal activity.

Logging instruments: Bats

A wildlife camera can give information about any possible animal activity inside the construction. It was mounted pointing to the SW post and the fitting between the post and bressummer (see figure 17). The camera Uovision UM 595 was used. It has infrared night imaging and a 12-megapixel resolution, and it can send pictures by SMS when the sensor is activated from movements captured by the lense.

Bat occurrence was surveyed using handheld and stationary ultrasound detectors during the evening and night between 7th and 8th of June 2017. A manual registration of possible bat activity was done using an ultrasound detector from 9 PM to 00.10 AM. The stationary detector used was a D240X, from Petterson Elektronik AB, Sweden. The detector was tuned into frequencies between 40 and 50 kHz. Simultaneously, direct observations were conducted from the north west corner of the church. The north west spot was chosen because some bats are discrete and find flying paths between trees (see figure 6). The brown long-eared bat (*Plecotus auritus*) and *Myotis* species like to fly alongside trees (Michaelsen, 2017b).

Figure 6. Urnes stave church seen from the north east. Trees grow along the north wall around the grave yard. The more discreet bat species will use this path when they enter the church building. The stationary ultrasound detector was placed high up in the tree nearest to the north east corner of the stone wall.

Logging instruments: Climate

To assess the conservation climate at Urnes, two Testo H1-175 dataloggers were set up. The loggers recorded at Urnes from the 8th of June 2017 to the 18th of June 2018, which gave one year of climate data. Data for temperature and relative humidity were stored every hour. The loggers work between minus 20 and plus 55°C, and between 0 and 100 % relative humidity. It stores up to one million measurements.

The loggers were placed in two locations; one inside the church and one outdoors (figures 7, 8 and 9). The indoor logger was placed above the bressummer close to the SW corner post. The outdoor datalogger was placed on the service building 70 metres away from the church.

Figure 7 (top left). Photo of the indoor logger on top of the bressummer in the SW corner.

Figure 8 (top right). The placement of the outdoor logger at the service building.

Figure 9 (bottom). A map showing the location of the climate loggers. Building 104 is the stave church, and building 102 is the ticket centre, and the smaller building perpendicular to this is the service building where the logger was placed under the overhanging roof on the north facade.

This site was chosen because it is not possible to hang instruments on the protected stave church, and under the overhanging roof of the service building the logger was protected from direct rain.

The aim of the outdoor logger was to compare the data from the indoor logger, to see how the indoor climate is affected by the outdoor climate. There are meteorological stations not far from Urnes (figure 10), but too far for a comparable climate. At the west coast of Norway, the landscape is varied with deep fjords and high mountains around the fjords. Precipitation can vary locally, and it affects the relative humidity and temperatures locally as well. The loggers were newly purchased and calibrated when mounted at site.

Urnes stave church is a rather open but compact building. The open construction might give an indoor climate that follows the outdoor climate closely, or one that buffers the outdoor weather changes due to the heavy wooden construction. The church is not heated, and not in use half of the year. It was interesting to see if the building shell gives enough buffering to remove the biggest peaks in abrupt changes in temperature and humidity, both during sudden changes in the weather but also between day and night when the differences in temperature and humidity can be quite severe due to the absence or presence of the sun.

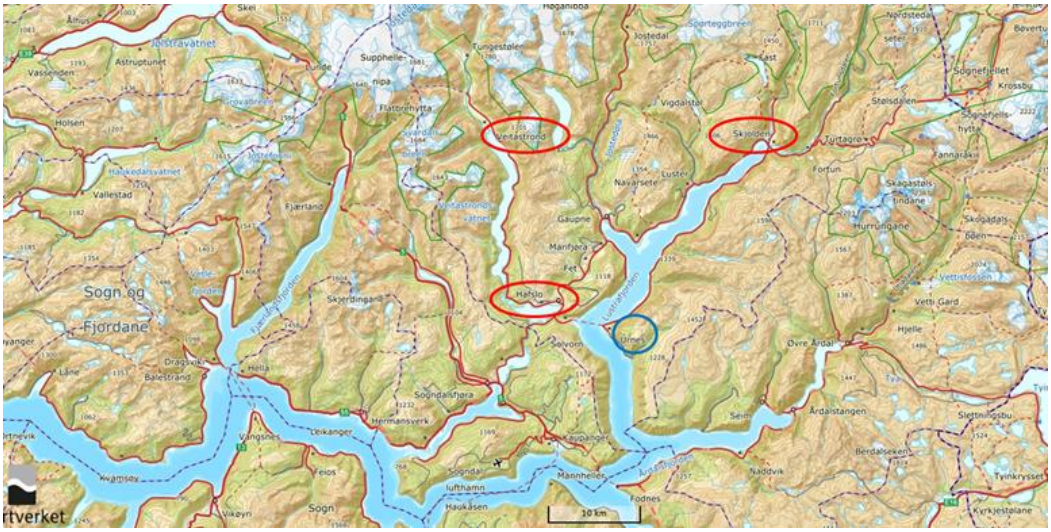

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Figure 10. The 3 nearest weather stations are situated at Hafslo, Skjolden and Veitastrond. (Source: The database "eKlima", from the Norwegian Meteorological Institute.) Urnes stave church inside the blue circle. All weather stations are either across from the fjord or as far as 30 km away.

Sampling

Samples from a cultural heritage monument should be avoided if possible, and non-destructive methods always considered first (Derrick, Stulik, & Landry, 1999). The removal of material from cultural heritage is also regulated in E.C.C.O. professional guidelines (II) – Code of Ethics, article 15 "E.C.C.O. Professional Guidelines (II) Code of Ethics" 2003). However, sampling was necessary to answer the research questions.

Sampling from the SW corner was less challenging from an ethical point of view than in most cases. The corner post has a defibrated surface, and fibres from the surface of the wood were also found on the floor near the post. The degradation made it easier to find and take samples from the post, and the sampling was invisible. The chosen analytical instruments are sensitive and can give good results with small samples. Samples of wood fibres and bat droppings were taken from the bat roost, and wooden fibres were also taken from the defibrated surface of the SW post. Samples from the floor were used to test for presence of ammonium and nitrates (figure 13).

The samples were collected using a clean tweezer or scalpel and put in clean and labelled glass containers prior to analysis. The glass containers were stored in a plastic box in an office. The size of the samples was limited to the size of lose fibres found at the surface (0,2 cm x 1 cm), but for the SEM analysis one larger samples was needed (0,4 x 1 cm).

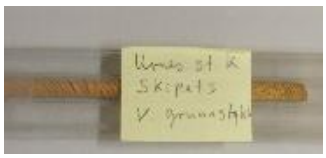


Figure 11 (left). A photographic record of the sampling was kept, and all samples numbered (see appendix xx). From the base of the SW corner post.

Figure 12 (middle). Sampling from the back of the SW post. The surface of the wood is defibrated, and sampling is not too visually invasive. The 2 holes are bore holes from dating by dendrochronology.

Figure 13 (top right). Bat faeces and wooden samples were taken from the floor below the roost.

Figure 14 (bottom right). Reference sample from the west ground beam at Urnes, taken with a drill corer for dendrochronological dating.

A photographic record was kept to document where the samples were taken from the post and bressummer (see example in figures 11 and 12). The sampling was undertaken over several periods and by different people. Thus, some sample numbers are similar. A total overview of the sampling is shown in Appendix 1.

Previously, random sampling had been made from the SW corner, but with little documentation or an overall plan of assessment and research. There was also no record of where the samples were taken. As a result, new sampling was necessary for this research project.

A total of 32 samples were collected for this research, including samples collected by Leif Anker in 2015. Some samples were used several times because only parts of the sample was used the first time (See appendix 1 for overview of the samples and their use. Samples with the same number but different letter is one sample).

Reference areas

As a reference to the analysis of the infested samples, samples from a non-infested area are needed (a blank). Urnes stave church has been dated previously through dendrochronology from several parts of the construction. These timber parts were drilled with a drill corer to extract a pencil-thick sample with as many year-rings as possible from the core to the bark, to get a match from the reference curves. To establish with precision the year the tree was cut, the year-ring closest to the bark is required. Thus, the drilled samples contain both sapwood and heartwood.

One of the drilled samples used for dendrochronological dating of Urnes stave church was available as a reference sample in this research project (figure 14). The sample was taken from the church in April 1995, from the middle of the west ground beam (below the main entrance to the church) (personal communication, T. Thun, 04.04.2017). The timber was dated to the summer of 1131 (Thun, 2016), and is approximately the same age as the timber in the SW nave corner post. The sample shows no sign of salt contamination. Bats tend to choose any gaps, voids or cavities inside a building for their roost, especially spaces between two different materials like wood and stone, lead fittings and wood, slate and wood and so on (English Heritage 2009, p. 18-19). The space between the ground beam and stone wall could

be a favourable site for a roost. There is however little chance that the reference sample from the ground beam is contaminated by salts, as it is taken from a bore hole sample inside the core of the beam.

Two other areas in the church were used as reference areas: The base of the SW nave corner post (figure 15) and the chancel north wall (figure 16). Parts of the surface of the base looks degraded. It is light in colour, and softer in the tissue than the surrounding areas. There is however no signs of salt deterioration (defibration). The chancel wall has no signs of salt deterioration neither.

Figure 15. The base of the SW nave corner post was used as a reference area. XRF was shot in two areas of the post, and samples from this area were used in SEM-EDX analyses.

Figure 16. The north chancel wall was also used as a reference area for pXRF analyses.

The chancel wall and the base of the post are both in the open area inside the church. Bats choose spaces where they fly during the night. The fly-around area may be beneath where they roost, in a neighbouring building or even some distance away (English Heritage 2009). Some species of bats tend to urinate when leaving and entering the roost (Hales, 2017, p. 398). As we do not have the full overview of potential roosts at Urnes, all surface areas inside the church could in theory be contaminated with urine. The roof construction and the attic have not been investigated. However, when choosing reference areas for the analyses, areas with no visual signs of salt contamination were chosen.

Choice of analytical methods

In condition assessments, visual examination must be complemented by different analytical techniques. To answer the research questions, several methods were chosen. Each analytical technique has its own advantages, and the use of several techniques aimed to supply complimentary information about the samples. The results seen together gave a good picture of the degradation in the SW corner at Urnes. The salt content of the wood was analyzed thoroughly, and comparative analyses aimed to verify whether the salts came from bat urine. High levels of potassium were found in samples from the wood in 2005, believed to originate from the wood itself (Mattsson, 2005). But potassium is also present in bat urine (James, 2014). Analyses of urine infested wood were compared with analyses of non-infested wood from the same timber post. The analytical instruments of portable XRF, X-ray, ICP-OES, SEM-EDX, Optical light microscopy and FTIR and have been used to answer the research questions of this thesis.

On site tests

Test strips

Sulphate strips, nitrate strips, ammonium strips and pH indicator paper were used to indicate the presence of alien ions usually found in bat guano. All test strips were purchased from Merck Millipore and were MQuant^{TM} test strips.

The test procedure at site for **ammonium** was followed thoroughly. A plastic vessel was rinsed with distilled water before every operation. For the blank test, distilled water and the reagent was filled to marked level and a test trip was dipped into the vessel. The vessel was rinsed again, and water and reagent were added. This time a sample from the back of the post was put into the vessel and left to soak for five minutes before the test strip was dipped into the vessel for three seconds. The test strip was left to soak on paper for 10 seconds, and then the colour of the strip was compared with the colour scale on the strip box.

Four samples were tested for nitrate salts in the laboratory prior to ammonium tests of the same samples. The samples were left to soak in distilled water for 30 minutes. A clean pipette was used to take some of the solute out to wet the nitrate test strips. After this the reagent fro the ammonium testing was added, and the procedure above was followed for test for ammonium.

Test strips are paper strips with a reagent matrix used for qualitative detection of a substrate. When the test strip comes into contact with a solute of the substrate or the substrate itself, the reagent will change colour if the substrate is present. They are low cost, easy to use and give immediate answers on site. The strip will also to some extent give an approximate quantitative result, as the intensity of the colour give the approximate amount of the substrate. The method is not 100% reliable but is a first step to give a pointer to whether further analyses are necessary.

The first pH indicator strips used on site were wetted in distilled water and laid directly on to the wooden surface. For this first test, conducted in 2015, pH indicator strips 0.0-14 from Sigma were used.

Later, pH indicator strips were used to measure the pH of the surplus samples (samples collected and not used). The MColorpHast^{TM} from Merck Millipore ranging from pH 0 – 6.0 was used for this test. The samples were watered out overnight in 5 ml of distilled water, and the indicator strips were immersed in the water for 3 seconds.

Portable X-ray fluorescence (XRF)

Instrumental conditions

The portable XRF instrument used for this project was a Thermo NITON Xl3 GOLDD+, and the readings were done in the Mining mode. Total measurement time was 120 seconds. The data were exported from Niton Data Transfer (NDT) to Microsoft Excel for further data interpretation. A total of 10 areas were analysed with the portable XRF, six at the post, one at the bressummer and three on the chancel wall.

The analytical technique

XRF is a method for the qualitative analysis of chemical elements, and in some instances, it can be quantitative. XRF has an X-ray source that emits an X-ray beam. When the X-rays hit the atoms in the object, the electrons are displaced and will release energy specific to this element. The energy released is read by the detector. The XRF (X-ray fluorescence) can in theory detect all elements in the periodic table except the first two. But many light elements are difficult to measure, and the practical work is often limited to the atomic numbers above 13 (Mantler & Schreiner, 2000). This means that nitrogen (with the atomic number 7), being

present in urine, cannot be detected with a handheld XRF instrument. Sodium is also present in urine (Hales, xx), and with the atomic number of 11 might be hard to detect.
Analysis with a handheld XRF on-site has the advantage of being non-invasive, but the disadvantage of being limited to the elements the instrument finds at the surface and just below surface in a small area of the object. It will also detect surface contamination. As with most analytical methods, XRF will not answer all the questions one has about the object of interest. Being a non-invasive method, XRF is useful to supplement test strip tests for the on-site investigation.

X-ray

Instrumental conditions

X-ray of the wood was conducted to get an idea of the size of the cavity within the bressummer and post. The X-ray investigation was commissioned from NIKU, and conducted by Christina Spaarshuh and Barbro Wedvik at site. A battery powered portable X-ray generator with an energy output of keV 270 was used (XRS-3). The scanner was a Dürr Image Plate Skanner CR 35 NDT, and the software where the images were read and interpreted a D-Tect 4.8.0. from Dürr. The image discs measured 35 x 43 cm.
The instrument was placed on an airlift standing on the churchyard on the south side of the church, and the shooting was controlled from the ground by a trigger button connected to a cable. In July 2000 the bressummer was protected by lead fittings from the outside, between the roof tiles and the cladding on the aisle roof. We did not know the extension of the lead fitting, but it needed to be dismantled to be able to get a good image of the wooden beams, as x-rays do not penetrate lead. The roof tiles and lead fitting were carefully dismantled by a carpenter prior to the investigation.

The analytical technique

X-ray is used to see through materials and is a non-destructive method. X-rays are electromagnetic radiation with very short wavelength and can pass through most materials. Denser materials will stop some of the X-rays and cast a shadow on the imaging film.

X-ray, being used correctly, can detect the tree rings of wood. It passes through the less dense tree rings in the summer wood easier than the denser spring wood and makes an image of the

tree ring pattern. Wooden cells are directed in the growing direction of the tree, and deteriorated areas of the wood will give a different image. As we have seen at the defibrated area of the stave and bressummer, the fibres lose their attachment from the wooden structure. In theory, this will give a different image from the X-ray analysis.

X-ray can also be done on-site with portable X-ray tubes. It requires training as the health and safety issue is important. Radiation from X-ray can cause mutation of human DNA and the exposure to X-rays are carefully recorded in a dosimeter. The radiation dose is cumulative. As with all imaging techniques, the recorded image is a two-dimensional image. Used on 3-dimensional complicated objects like buildings with several layers of building materials in different angles, the interpretation of the image can be challenging, especially from a corner of a building where the building parts are perpendicular to each other.

Lab tests

ICP-OES (Inductive Coupled Plasma – Optical Emission Spectrometry)

Instrumental conditions

The analysis was conducted by Francesco Caruso and Sara Mantellato, using a Thermo Scientific iCAP 6300 Dual View ICP-OES (from Thermo Fisher Scientific Inc., Waltham, MA, USA) with a CETAC ASX-260 autosampler (CETAC, Omaha, NE, USA). Operating conditions are reported below in table 1.

Operating condition/Instrument part	Value/Type
Effective focal length	383 nm
Spectral range	166-847 nm
Detector	CID86 chip (charge injection device)
RF generator	27.12 MHz solid state
Plasma viewing	Dual
Plasma and shear gas	Argon
Nebulizer	Burgener MiraMist High Solids Nebulizer (0.4-2.0 mL/min)
Spray chamber	Glass cyclone
Plasma torch	Enhanced matrix tolerance (EMT) semi-demountable
RF power	1150 W
Pump rate	50 rpm
Auxiliary gas flow	0.5 L/min
Nebulizing gas flow	0.5 L/min
Number of replicates per sample	3

Table 1. Operating conditions for the ICP-OES measurements with the iCAP 6300 Dual View.

Samples

Four samples were analysed at ETH Zürich in Switzerland by ICP-OES; three samples from the deteriorated area and one reference sample from the left raft beam (the pine wood here is also original material, but not infested by salts). The samples were tested for lead, arsenic, copper and sulphur. See table 2 for location from where the samples were retrieved.

There were several pest treatment operations at Urnes. The treatments have unknown chemical content. Pesticides can contain poisonous elements like copper, arsenic, mercury and lead (Mogstad, 2010). To debunk, or confirm, the possibility that the salts in the post comes from a local pest treatment, these poisonous elements were analysed using this method. These elements are not expected to be found in the reference sample, so any trace of them can most likely be connected to a conservation treatment. For the analysis of some elements in urine (nitrogen, for example), the ICP will not be able to give answers (Caruso, 2017). Complimentary methods must be used to detect nitrogen from the urine.

For the use in this analytical technique, the wood itself was not interesting, but all extracts derived from the sample. Each sample was crushed with agate mortar and pestle and the

matrix was mixed with ultrapure water and sonicated. Then the matrix was filtered and diluted in 2% nitric acid in water. Fresh 2% nitric acid in water was used as a blank.

n.	Sample name	Elements to be detected	Expected concentration (mg/L)
0	Reference sample	Hg, As, Pb, Cu S	= 0 mg/L <800 ppm
1	Gallery, south bressummer, under bat roost	Hg, As, Pb, Cu S	>0 mg/L 1600 ppm
2	Gallery, above arcade, drilled hole by SW post	Hg, As, Pb, Cu S	>0 mg/L 800 ppm
3	Aisle side, above arcade, drilled hole by SW post	Hg, As, Pb, Cu S	>0 mg/L 1200 ppm

Table 2. List of samples sent for analyses in ICP-OES in Zürich. The samples were tested for mercury (HG), Arsenic (As), Lead (Pb) and Copper (Cu), as well as Sulphur (S). The concentration of the heavy elements were unknown at the time.

The analytical technique

ICP-OES, also known as ICP-AES (atomic emission spectroscopy), is both a qualitative and quantitative method used to analyse elements. It studies the emission of energy from an atom that goes from an excited state back to the ground state (Stuart, 2007). The energy is emitted in the form of photons, or light, and the colour of the light depends on the wavelength of the energy released. Every single atom has its characteristic emission of light. The process consists of three general steps: atom formation, excitation and emission (Manning & Grow, 1997). To successfully analyse the elements, the matrix is separated into individual atoms to avoid interferences. In ICP, plasma is used to atomize the matrix, as well as being the source used to excite the atoms (Manning & Grow, 1997). ICP operate with argon as the plasma source. Over 70 elements have been successfully analysed by this method (Manning/ Grow, 1997). It has a very low limit of detection (LOD).

The ICP comes in benchtop size. It has a sample introduction system that enables the introduction of solids, liquids and gases for analysis in the instrument. All three states (Solids, liquids and gases) have been successfully introduced into the ICP (Manning & Grow, 1997). For the analysis of liquids, a nebulizer converts the liquid to an areasol prior to injection into the plasma.

Solid samples are either vaporized or introduced directly into the plasma. Several vaporization methods are available. Some samples require special preparation steps including treatment with acids, heating and microwave digestion (Manning & Grow, 1997).

A detector in the spectrometer receives the signals from the excited atoms in the plasma. The instrument has a cooling system, which cools a fluid and sends it through the spectrometer. Attached to the instrument itself is a gas tank with liquid argon, a waste tank and a computer.

TOC (Total Organic Carbon) test

The TOC content was a supplementary test during the analyses in ICP-OES. A Shimadzu TOC-V CSH total organic carbon (TOC) analyser (Shimadzu Schweiz GmbH, Reinach, Switzerland) was used.

SEM-EDX

Instrumental conditions

For the analyses in this project, a Zeiss EVO 50 Scanning Electron Microscope was used. The results were processed using the software Oxford Instruments INCA 5.05. The EDX was an INCA Energy 350. Hilde Raanaas Kolstad, Imaging Centre NIBIO, aided with these analysis. The samples were coated using gold and palladium.

Samples

A total of eight samples were analysed in the SEM-EDX (five wooden samples and three faeces), and four wooden samples were coated to study the surface morphology of the wood and contaminants. The samples were analysed “as is”, and some were also attempted to be cut in the radial direction of the wood cells to be able to study the wooden cell walls successfully.

The analytical technique

The scanning electron microscope can create highly magnified images of an object (up to 300.000x), but also, in combination with EDX (Energy Dispersive X-ray Spectroscopy) offers elemental data for the surface of the object. The SEM uses a focused beam of electrons to create images and analysis of the object. The electrons are focused by electromagnetic fields,

which allows us to study areas of interest on the sample. When the electrons hit the sample surface, several signals are produced: secondary electrons, back-scattered electrons and X-rays. The different signals are used to create highly focused images and analysis. EDS analysis is possible from the X-rays given off by the atoms when they absorb the electrons, whereas the signals from the secondary and back-scattered electrons given off from the sample are detected and used to create an image of the object.
The SEM enables a resolution up to 5 nanometres, and the window has a scale bar that shows the magnification of the area of view. The method is non-destructive, but organic samples are prepared in a way that makes them only suitable for further analysis in the SEM.

A SEM consists of an electron gun in a column, where the electrons are shot from. The electrons pass electromagnetic condenser lenses that help them being focused in the right direction, down towards the sample at the stage in a vacuum chamber. It passes a positively charged anode, and the stage is also positively charged, which aids the electrons to move in the direction of the specimen. There are two (or in the case of SEM-EDS: three) detectors for the different signals given off by the sample atoms. The electron gun is a filament (made of for example tungsten) which is applied with a current of high voltage.

SEM has a small sample chamber, which can take smaller objects like metal jewellery or glass sherds, but most objects must be sampled for the analysis.
Electrically conductive materials are better seen in the SEM, so non-metal objects must be coated to get a good image and to prevent it from burning. Organic objects and samples must be coated with carbon or gold. The advantage is the high resolution, which means very small samples are needed for good images. To study materials without the effects from topography, they might be cast in epoxy resin and polished.

Images seen in the SEM are monochromatic, which makes it harder to see contrast between different materials and details on the surface, and also sometimes hard to find the specific point of interest on a topographic surface. The EDS detects elements at the surface and deeper under the surface. The results show mixed elements from a stratigraphy. If a gilded metal object is analysed, and it shows gold, silver and tin, it is not possible to know if the silver and tin comes from the gilding material or from the alloy itself.
The technique is non-destructive, but organic samples must be coated and can therefore be hardly be used again in other instrumental techniques.

Optical microscopy with lignin staining

Instrumental conditions

The examination was carried out by YeonKyeong Lee at the Department of Plant Sciences, Faculty of Biosciences at Norwegian University of Life Sciences (NMBU) in Ås. The samples were stained with 10% (w/v) phloroglucinol in 95% ethanol for 10 min. An equal volume of concentrated HCl was added and the sections left for 2–3 min. The sections were then rinsed thoroughly with distilled water and examined using a light microscope (Leica DM6B).

The analytical technique

Microscopy aids the identification of degradation, by showing details of the surface such as surface texture, surface dirt, cracks, corrosion, delamination and other features that can help us understand the degree and character of the degradation. The scanning electron microscope examination was supplemented by examination in the light microscope. The advantage of the light microscope compared to the SEM is the possibility of seeing the sample in colours. This advantage can be used to get supplementary information about the degree of degradation. To further visualize the degradation, staining can be used. Staining can reveal details or contrasts between different cell materials and reveal the lack of certain cell materials. Differentiated staining of wood samples can be used to prove delignification. For this project the samples from Urnes were stained using Phloroglucinol, an organic reagent that colours lignin. As the literature research gave indication that salt corrosion can degrade the lignin in the secondary walls and middle lamella, the examination of the lignin content in the samples compared to a reference sample could give a direct and visual proof of the lignin degradation (Srebotnik & Messner, 1994)

FTIR

An FTIR analysis was commissioned for this project from Susan Braovac at the Museum of Cultural History to investigate the chemical preservation state of the wood.
By comparing sound and infested samples (where the salt is washed out prior to analysis) to each other, the FTIR analysis might give an indication of loss of cell material due to chemical degradation. 11 samples were delivered for analysis, originating from the post and sill beam. Samples were 2-5 mm long and 1-2 mm wide.

Instrumental conditions

For the analyses in this project, a Thermo Fisher FTIR spectrometer (Nicolet iS50) was used. The instrument was run in the ATR mode (Attentuated Total Reflectance), with a resolution of 4 cm^{-1}. The spectral range was 4000-400 cm^{-1}. Each spectrum was based on 32 scans. All samples were analysed twice. The first time the sample was analysed as received, and the second time after rinsing. The samples were rinsed three times in water before the FTIR analysis. The purpose of the rinsing was to remove salts and other (urine) residues from the wood fibres. The first rinse was used for a pH-measurement. The spectra were compared with a spectrum of a reference sample of pine heartwood milled down to a particle size of 0,5 mm.

The analytical technique

FTIR spectroscopy is an analytical technique that uses infrared light to analyse organic solids, liquids and gases. An FTIR instrument is simply built up by a light source, a beam splitter and a detector. In FTIR an interferogram is an important part.

The technique offers molecular data. The functional groups in the molecule absorb infrared light at specific wavenumbers, which in result will give very specific peaks in the spectrum. IR radiation supplies sufficient energy to produce translational, rotational and vibrational motion in molecules (Derrick et al., 1999). The light that goes through the molecules will give a high level of transmittance on the spectrum, whereas the light that is being absorbed by the functional groups will give negative peaks which can be identified as specific functional groups (hydroxylbonds, carbonylbonds and so on). It will not give us the precise structure of the molecule, but the qualitative information seen in the spectra can either be compared to reference spectra for an answer or to a reference sample analysed. An infrared spectrometer analysis in both transmittance and reflectance mode.

FTIR in the near-infrared region is used to characterize wood (Stuart, 2007). The FTIR can analyse solid samples. They can be analysed without further preparation, but a physical or chemical pre-separation will simplify the characterization of the components in the sample (Derrick et al., 1999). Samples can be prepared either as pressed sandwiches between disks of alkali halides, in a dispersion or as a thin film. To reduce interference in the analysis of salt infested wood, the salts and other contaminations should be washed out.

Hemicellulose and cellulose give overlapping bands in the IR spectra, and the extraction of chemical and structural information is often challenging (Falcker & Thygesen, 2013). Thus, purified reference samples and an empirical approach is necessary to extract information about the degradation of these polymers in the wood cells. With complimentary studies of highly magnified images in scanning electron microscope, answers to whether the salts degrade the wooden cells can be conclusive.

Microspectroscopy has been applied to several subjects within the study of wood molecular structure, among other subjects also wood cell degradation. IR spectroscopy can detect all main wood components (Falcker & Thygesen, 2013). Chemical degradation of the cellulose, hemicellulose or lignin can be studied.

RESULTS

Results are presented in four parts. Part one describes the results from investigation of bat presence at Urnes. The second part gives a description of the conservation climate at Urnes, and the third part describes the results from the methods used to characterize the contaminations in the wood (the decay mechanisms). Part four describes the results from the evaluation of the condition of the wood.

Part 1 The source of the decay mechanisms

Bat investigation

The bat investigation in June 2017 gave no sign of a bat roost at the present. No bats were seen leaving the church despite suitable weather conditions. In the same night as the bat survey, bat activity was high in other areas along the fjord (Michaelsen, 2017a). The activity with the stationary ultrasound detector recorded a total of 15 bats, which is regarded as low activity. No endangered species were recorded. Also, no bats were found inside the church during daytime on 8th of June 2017, but a few relatively fresh (probably < 1 year of age) faeces were found. This suggests that the church, at present, is not an important site for bats, but it could be occupied by few or single individuals during parts of the season (as is common in many churches).

Wildlife camera

1092 photographs were received and stored in the memory card in one year, but only images of people visiting the gallery of the church were received. The pictures are solely of people working for the church or having professional interest in the church, as it is otherwise closed (see figure 18).

The camera was set up to take 3 pictures for every movement that triggered the camera, with an instant reaction. Despite this, it is probable that this type of camera is not sensitive enough to capture the quick movements of bats.

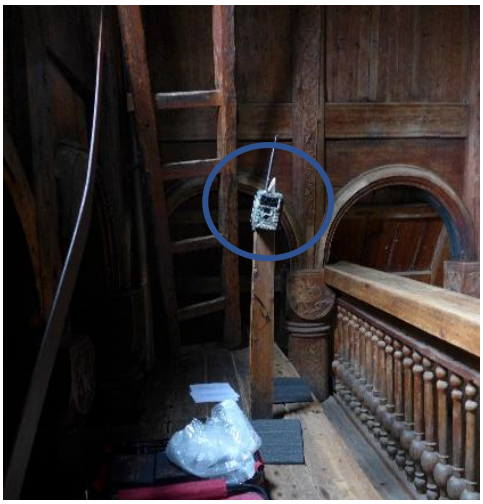


Figure 17 (left). The set-up of the wild life camera, facing the bressummer to the south.

Figure 18 (right). An example of an IR-image taken with the wild life camera. The church warden (seen behind the capital of the SW corner post) triggered the camera while climbing up the stairs to the gallery. The post and bressummer to the upper right in the image.

Part 2 The conservation climate at Urnes

Climate logging

A total of 9000 readings were recorded from each logger. Table 3 below gives a summary of the logging of temperature (T) and relative humidity (RH) through the total period. The high values for standard deviation indicate that values throughout the year vary greatly, especially for the humidity readings.

Temperature	**Outdoors**	**Indoors**	**RH**	**Outdoors**	**Indoors**
Mean value	7.4°C	7.9°C	Mean value	74.4 %	70.0 %
Median	7°C	7.9°C	Median	77.1%	73.2 %
Standard deviation	7.9	8.0	Standard deviation	18.0	15.0
Max.	30.7°C	28.4°C	Max.	99.9 %	97.1 %
Min.	-12.9°C	-11.5°C	Min.	18.5 %	25.6 %

Table 3. The mean, median, standard deviation, maximum and minimum values for temperature and relative humidity from the climate logging indoors and outdoors at Urnes stave church June 2017 – June 2018.

Urnes has a warm temperate climate. The humidity is high, but there is little precipitation. During the one year of logging, the indoor RH exceeded 90% only a few times during November, December and January. The data shows that the indoor climate follows the outdoor climate quite closely, but with a delay for both T and RH during increase and decrease of the values. The indoor values also move on a slightly smaller scale over the year of the logging. When the outdoor logger register rainfall on the 31st of January (=99,9% RH) the indoor logger register a RH of 89%. The minimum and maximum values for the outdoor logger exceed the values from the indoor logger for both temperature and relative humidity, which means that the wooden building buffers the outdoor climate somewhat as expected.

The diagram for relative humidity from January 2018 is an example of this pattern (figure 19). The red curve (indoor humidity) follows the blue curve (outdoor humidity) closely, but with a delay. This delay results in a flatter curve for the indoor environment.

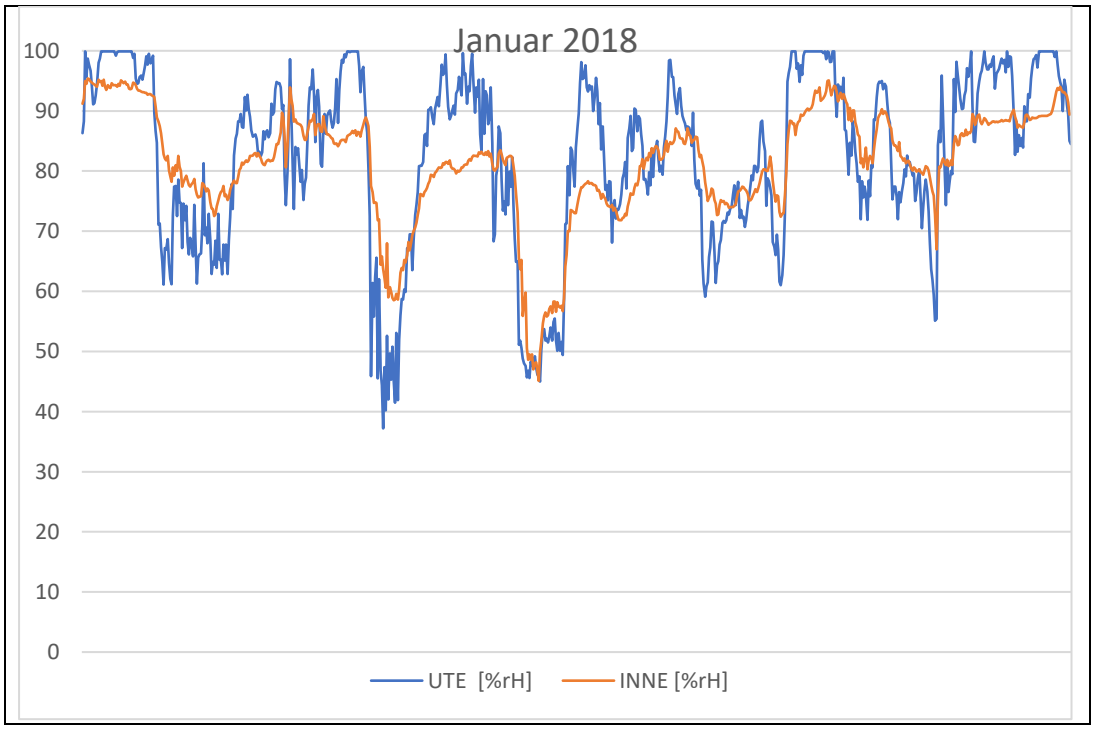


Figure 19. Humidity curves January 2018. Blue curve = outdoors, orange curve = indoors

The church is not heated, and the only factors influencing the indoor temperature and humidity are the weather and the church visitors. The church is closed during the winter months from the end of September until the beginning of May. During the summer period it is much visited by tourists, with guided tours every hour and every day. It is also used as a ceremonial church during the summer for weddings, for funerals all year and for Christmas and St. Olavs feast (29th of July) for mass.

Three monthly periods are shown in more detail; July 2017 (a warm summer month), November 2017 (a humid and cold month in transition between fall and winter) and February 2018 (a stable and cold winter month). See table 4 for values, and figures 20-22 for relative humidity curves)

	JULY 2017		**NOVEMBER 2017**		**FEBRUARY 2018**	
Temperature indoor	Mean	16,8	Mean	1,7	Mean	-1,4
	Median	16,7	Median	2,4	Median	-1,3
	Standard deviation	2,7	Standard deviation	2,7	Standard deviation	2,9
Temperature outdoor	Mean	15,9	Mean	1,5	Mean	-1,7
	Median	15,2	Median	2,2	Median	-1,7
	Standard deviation	3,5	Standard deviation	2,9	Standard deviation	3,2
Relative humidity indoor	Mean	61,6	Mean	84,1	Mean	72,3
	Median	61,5	Median	84,8	Median	74,9
	Standard deviation	11,3	Standard deviation	4,9	Standard deviation	13,4
Relative humidity outdoor	Mean	68,2	Mean	87,7	Mean	73,8
	Median	68,9	Median	89	Median	76,6
	Standard deviation	15,7	Standard deviation	9,0	Standard deviation	16,2

Table 4. The mean, median and standard deviation values for temperature and relative humidity for July, November and February at Urnes stave church.

In July the indoor temperature varied between 12 and 20 degrees, with a few hours of 25 degrees as an exception. The temperature did not drop at night to the same level as outdoor (figure 23). The relative humidity varied between 40 and 80 % indoors. It increases above 70 % five times during this month.

In November, the outdoor temperature dropped below zero during three periods, with a low point of -5,5°C. The indoor temperature was 5-7 decimals higher than the outdoor temperature. The relative humidity varied between 70 and 90 % all November 2017 Figure 21).

In February the outdoor temperature remained below freezing point most of the month. Some periods the temperature was lower inside the church than outside. When the outdoor temperature decreased slightly below zero after a warmer period, the inside temperature remained above zero. The relative humidity was mostly above 60%, but drier than in November with values down to 35% probably due to less rain (figure 22).

Humidity data

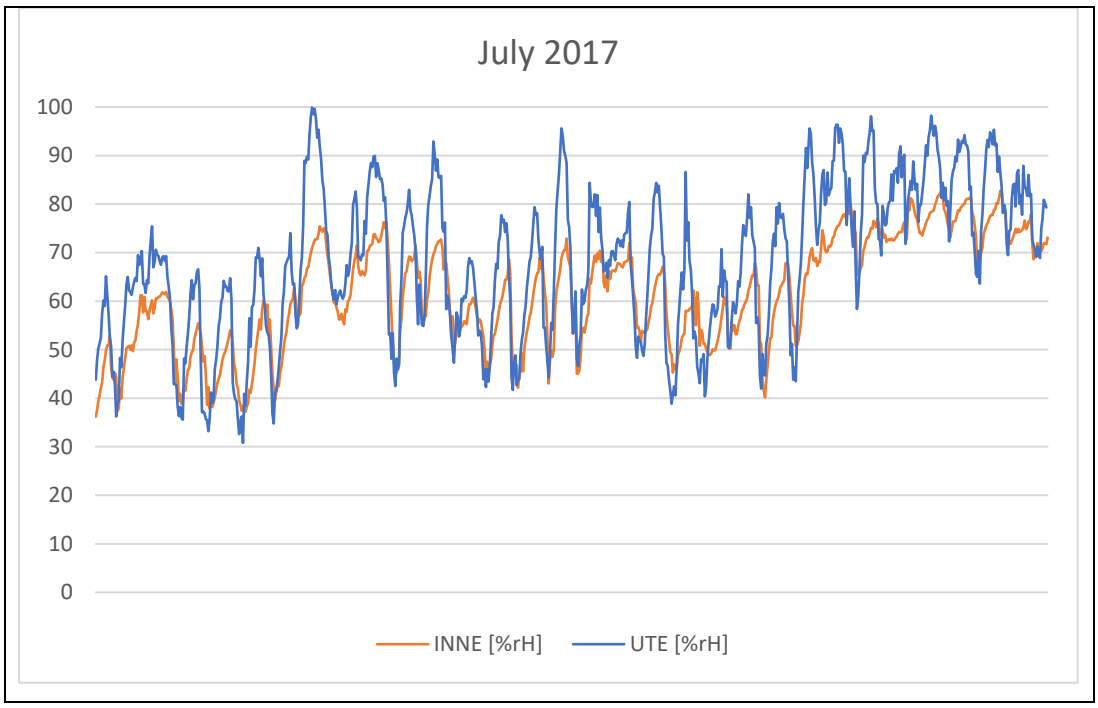


Figure 20. Humidity curves July 2017. Blue curve = outdoors, orange curve = indoors

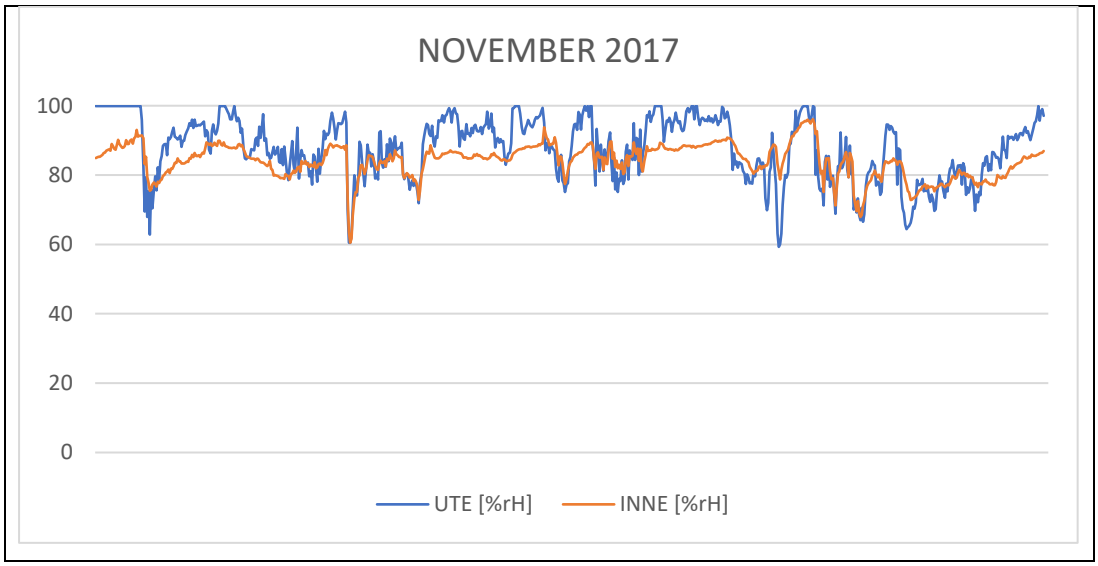


Figure 21. Humidity curves November 2017. Blue curve = outdoors, orange curve = indoors

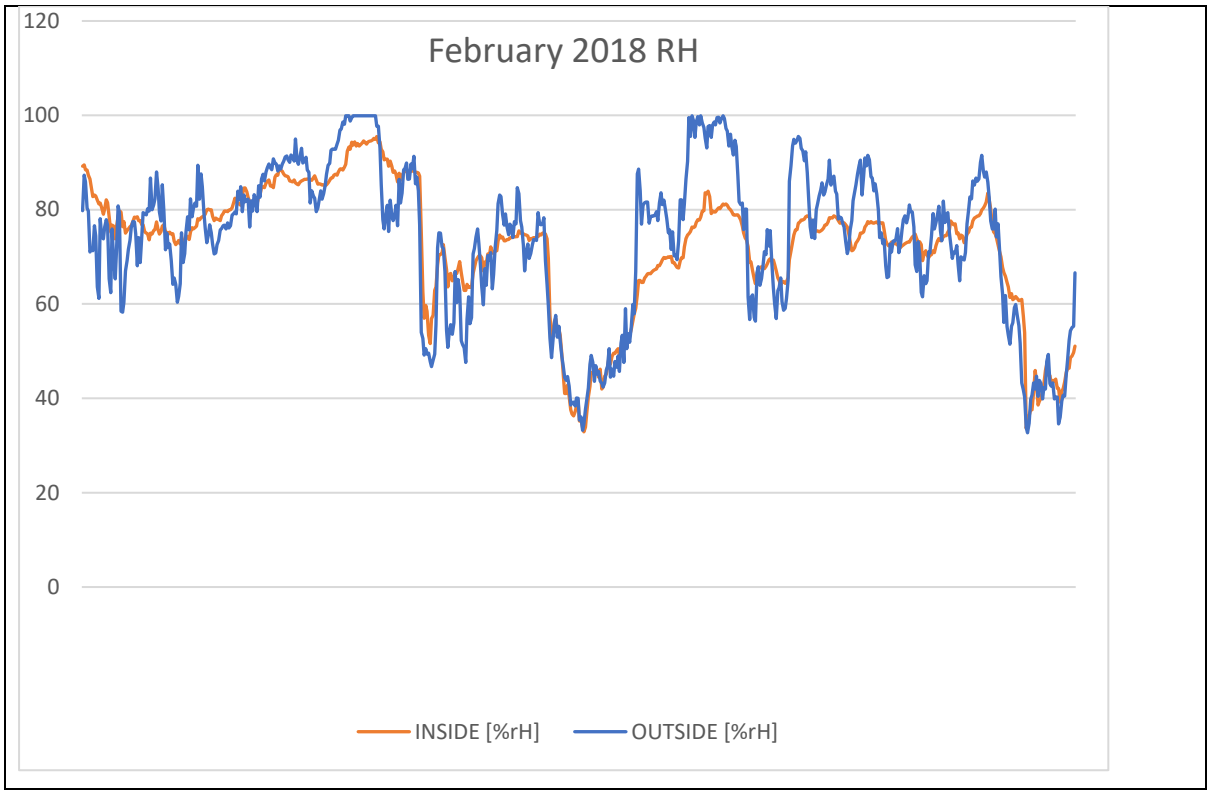


Figure 22. Humidity curves February 2018.

Looking at the humidity throughout the entire year of measurements, there are two different tendencies. Sometimes the indoor climate was affected by a sudden drop in the relative humidity outdoors, and sometimes it cannot follow but the RH remained higher indoors than outdoors for a short period of time. Exceptionally, there are some small peaks in the indoor RH, which might be a sign of visitors entering the church. In general, the indoor RH lies quite high with values between 50 and 90%. The temperature varies dependent on the outdoor climate.

Temperature data

The temperature indoors followed the outdoor temperature, but with a delay and with softer peaks. The diagrams for both July (summer) and January (winter) show this clearly (see table 23 and 24).

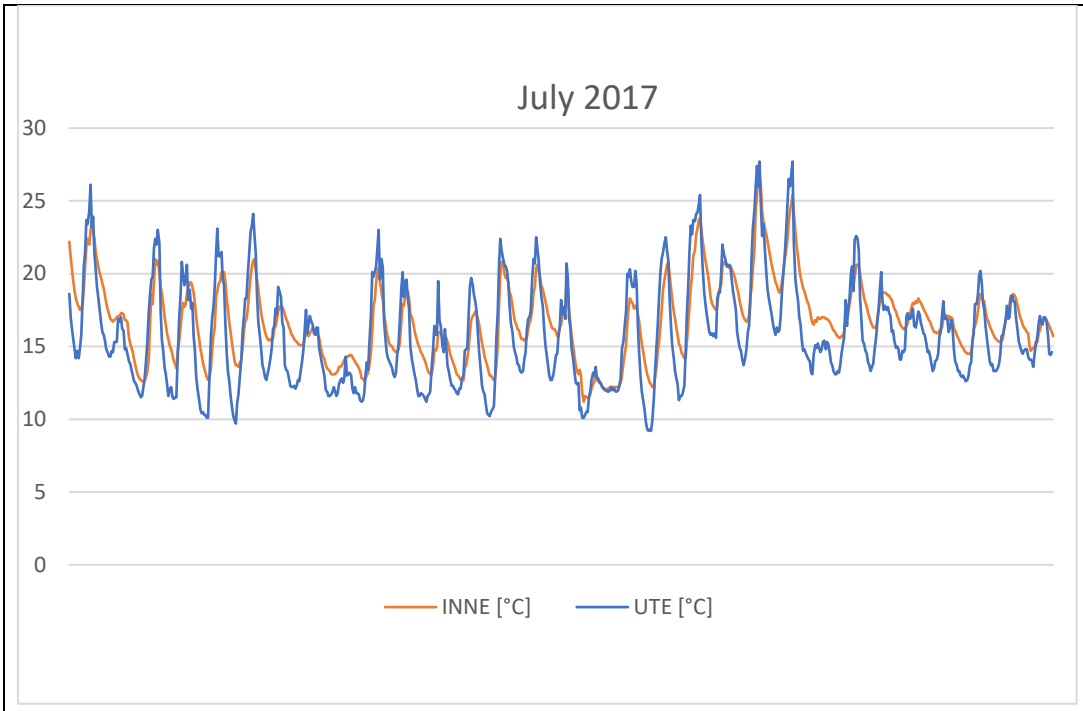


Figure 23. Temperature data July 2017. Blue curve = outdoors, orange curve = indoors

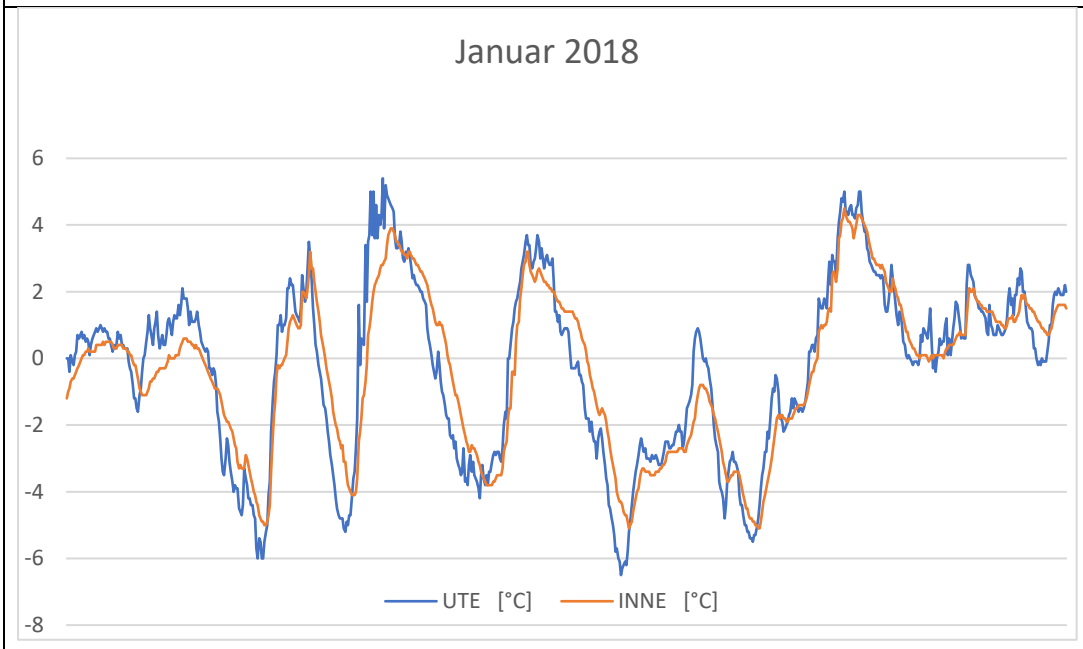


Figure 24. Temperature data January 2018. Blue curve = outdoors, orange curve = indoors

Part 3 The characteristics of contaminants

Test strips, pH measurements, ICP-OES, XRF and SEM-EDX analyses have aimed to understand the characteristics of the contamination within the wood. The results for pH measurements derive from test strips on site and from a pH-meter that measured the rinse water from the samples prior to FTIR analysis.

Test strips

Test strips were used on-site to test for ammonium and sulphates (figure 25), and test strips for ammonium and nitrates were also used in laboratory tests on samples left over from other analyses.

The test for **ammonium** on site (sample 3) showed signs of ammonium (see table 5 below). This wooden piece was sampled from the bressummer, inside the bat roost. Two of the four samples tested in the laboratory gave results for ammonium. None of the samples gave any visible reaction to the nitrate test strips.

Sample	Location	Result	Date of analysis
3	Bressummer hole, gallery side	30 mg/l NH^{4+}	June 2017
4	Bressummer, gallery side	0 mg/l NH^{4+}	August 2019
7	Bressummer hole, gallery side	10 mg/l NH^{4+}	August 2019
9	Reference: Base of SW post	0 mg/l NH^{4+}	August 2019
13	SW post, aisle side between dendro holes	30 mg/l NH^{4+}	August 2019

Table 5. Results from ammonium test strips

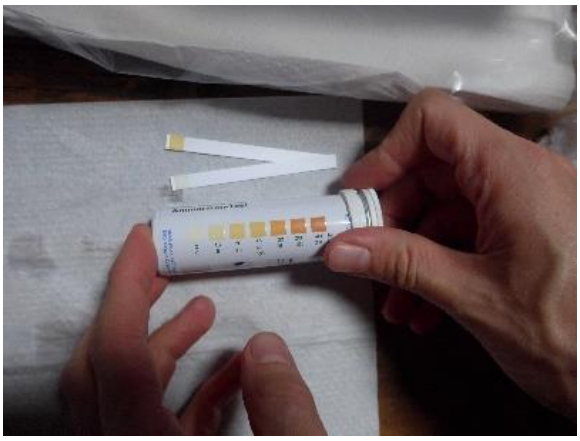


Figure 25. The picture shows the two ammonium test strips after dipping in the blank and in the vessel with the contaminated sample, from the on-site test in 2017.

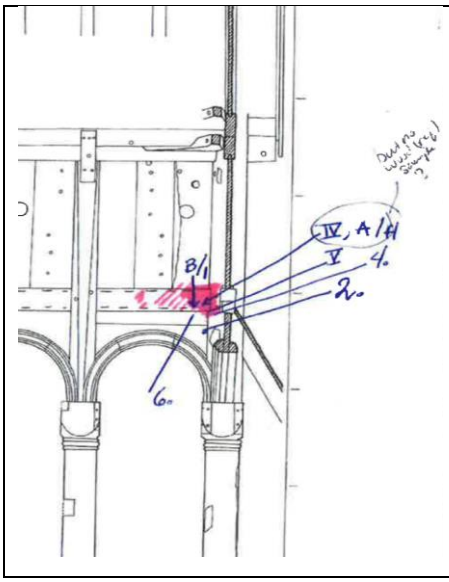


Figure 26. A drawing of the post and bressummer seen from the north, marking the location for tests and samples collected by Leif Anker in 2015. The letters A and B corresponds to pH tests, and the letters H and I corresponds to sulphate test strips. The results show a sulphate content of below 200 ppm – over 800 ppm here. The highest values of sulphates were retrieved on the aisle side, near the join between the post and bressummer where they lied between 800 and 1600 ppm.

The sulphate test strips were put on the salt contaminated surface of the post and bressummer. For location see figure 26 above, and for results see table 6 below.

Sample	Location	Results
H	Bressummer, gallery side	<200 ppm
I	Bressummer, gallery side	>800 ppm
J	Arcade, aisle side	800-1200 ppm
K	Bressummer, aisle side	>1600 ppm
L	SW post, aisle side, close to arcade	1200-1600 ppm
M	SW post, aisle side, between L and N	1200-1600 ppm
N	SW post, aisle side, beside join post/ bressummer	1200-1600 ppm

Table 6. Results from sulphate test strips.

Measurements for pH

Measurements for pH were taken both on site and in the laboratory. Test strips on site were wetted in distilled water and laid directly on the wooden surface. At the laboratory the pH was measured in connection with the FTIR analysis. Prior to the infrared spectroscopy, the samples from Urnes were rinsed with water and the pH of the water was measured. The on-site measurements gave a pH of 5 in seven of the eight spots tested. One test showed a pH between 4 and 5. The indicator paper used had a course scale, but it corresponds to the laboratory test insomuch as both are on the same side of the pH scale (slightly acidic). The laboratory tests showed slightly more acidic pH, between 3.6 and 4.3. The laboratory measurements were done for 11 different samples (Samples 1-11, see table 7). Even the

samples with no urine saturation showed a low pH (sample 8, from the base of the post, pH=4). This sample can function as a reference for comparison between urine contaminated and non-contaminated wood, and the comparison shows that the pH does not change notably when the wood is contaminated with urine.

The pH of bat urine is not very acidic. James Hales tested the pH of urine from 6 different bat species, with a total of 73 tests. The readings ranged between pH 5.3 - 6.8, with a mean value of 6.3 (Hales, 2017: 359). This corresponds to the expected value for mammalian urine. A more acidic urine would be a sign of sickness.

Sample	*Location*	*pH from water extraction*	*Urine content*
1	SW post, hole between bressummer and nave aisle roof	3.6	HIGH
2	Upper arcading, gallery side	4.3	HIGH
3	Upper arcading, aisle side	4.5	SLIGHT
4	SW post, hole below bressummer, gallery side	3.6	HIGH
5	Bressummer, aisle side, close to SW post	4.5	HIGH
6	Bressummer, gallery side, hole	3.7	HIGH
B	Bressummer, gallery side, salt contaminated area		Not analysed
7	SW post, above capital	4.7	SLIGHT
8	SW post, base	4.0	NO
9	Arcading, above capital, aisle side	4.3	HIGH
11	SW aisle strut	3.9	NO

Table 7. Tests of pH of the contaminated area using a pH meter and electrode from VWR.

Portable X-ray Fluorescence Spectroscopy (pXRF)

The analysis was conducted using a portable XRF instrument in June 2017. A total of seven readings were made on the post and sill beam (see figure 27). To rule out that the salt contamination derived from ground moisture, readings were made on several heights of the post, from the base to the infested area. The bressummer was also analysed with the pXRF instrument.

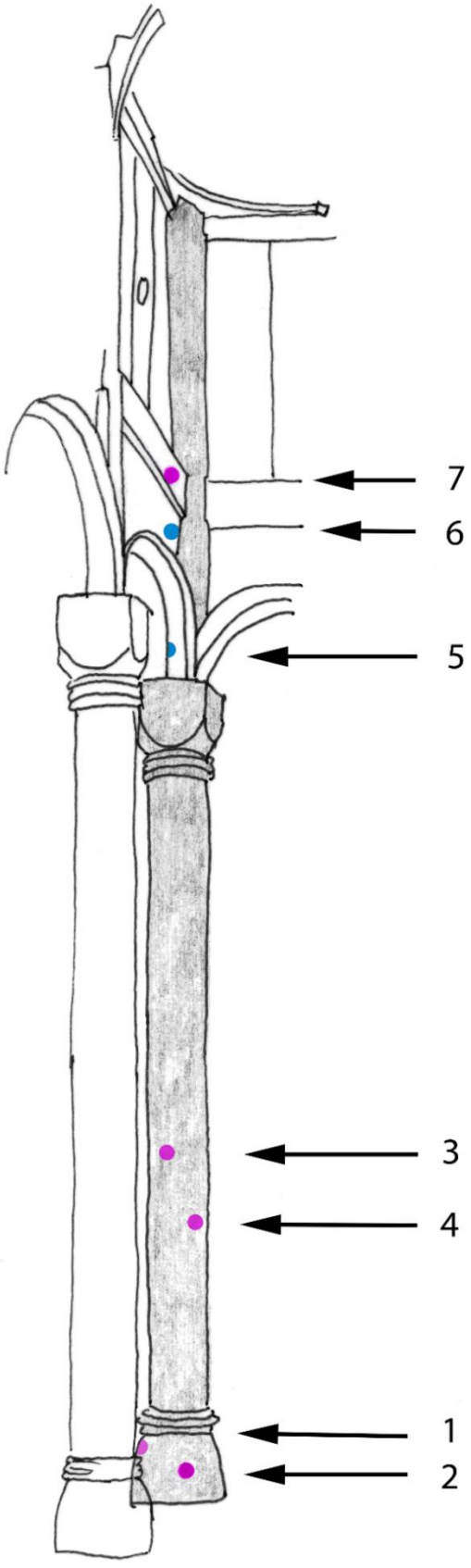


Figure 27, The location of readings of the portable XRF at the base, post and bressummer.

Reading 1 and 2 are referance areas at the base of the SW post.

Reading 3 and 4 are in standing height at the post.

Readings 5 and 6 (blue color) are from the post behind the arcading, from the aisle side of the post.

Reading 7 from the surface of the bressummer.

The grey shading shows the full length of the SW timber post.

Illustration: Anders Amlo, Riksantikvaren

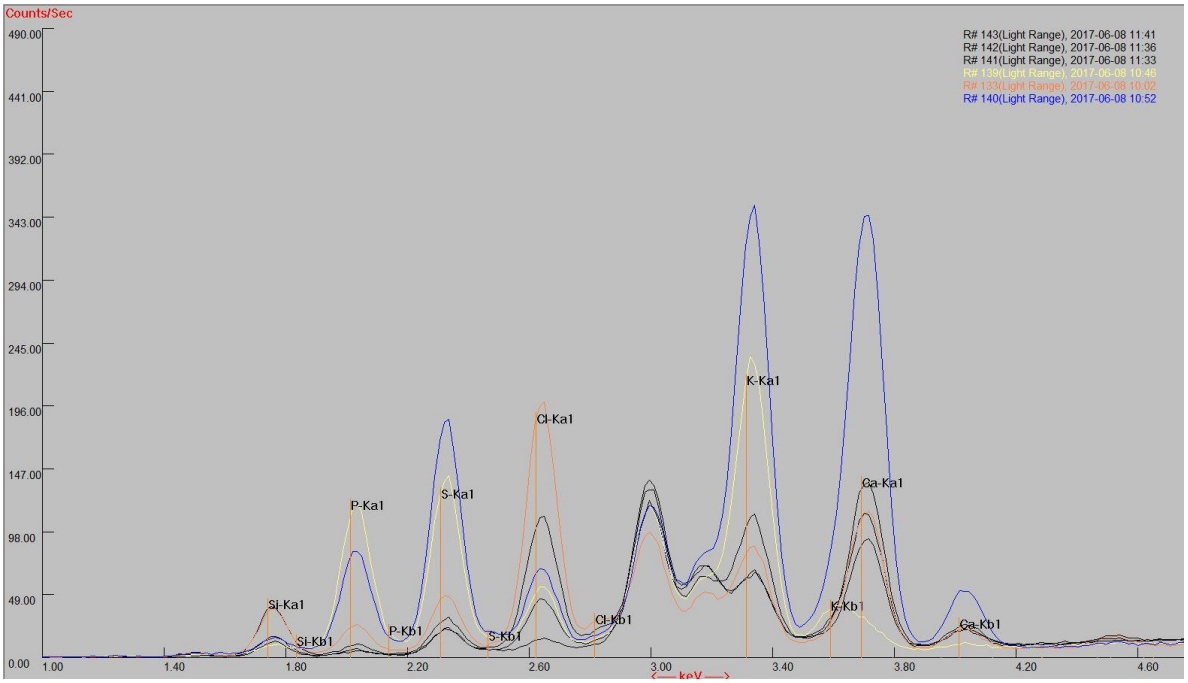


Figure 28. XRF spectra from the pXRF analyses. The three black spectra are from the chancel reference area, the orange spectrum from the base. The blue and yellow spectra are from the contaminated areas; blue from the bressummer and yellow from SW corner post.

Results from four areas will be presented here, one area from the base of the post (reading 2 = R# 133), one reading from in the contaminated area at the post (R# 139), one reading from the bressummer (R# 140) and the three readings from the chancel wall (R# 141-143). The location of all 6 readings are presented in pictures in appendix 2, and also on the drawing on the previous page (figure 27). These areas were chosen because the measurements here gave higher counts per second of elements compared to the reference areas, or they represent reference areas (base and chancel).

Table 8 shows the main elements detected. Calcium, potassium, phosphorus, chlorine, sulphate and zinc all show results above limit of detection. Comparing the results for these elements for the post and bressummer to the base and chancel (reference areas) there is a clear difference in the presence of potassium, sulphate and phosphorus. Results from a portable XRF used in Mining mode can not necessarily be interpreted quantitatively (Catelli, Bănică, & Bănică, 2016, p. 4). However, the intensity of the peaks show very clear differences between the contaminated and non-contaminated areas (figure 28). Three readings were conducted from the reference areas in the chancel, and all three readings are quite uniform. All detected elements gave similar and low amounts of counts per second for all the detected

elements. The readings from the SW post gave more intense peaks for the same elements. Reading 6 and 7 gave very clear and intense peaks for Sulphur and Potassium, whereas reading 2 gave an intense peak for Chlorine. A semiquantitative interpretation of the XRF-spectra.

Silicon is more present in the chancel and the base (table 8). Silicon can come from dirt from the shoes and clothes of visitors that accumulate, especially on areas near the floor. All areas show even results for calcium, which is present in wood itself. Zinc is not present in any significant way but is included in the table because it showed significant amounts in some of the EDX analyses (see figure 34). It can derive from the bat guano (Bakr & Abd El Hafez, 2012). The chlorine does not come from the wood itself but is naturally present in bat excrements. It can also derive from a pest treatment with permethrin in 1984.

Reading	Ca	K	P	Si	Cl	S	Zn
Base	0.905±0.02	0.633±0.02	0.749±0.03	3.740±0.09	1.697±0.02	0.927±0.02	0,007±0,01
Post	0.153±0.01	1.866±0.04	3.858±0.06	0.432±0.05	0.384±0.01	2.656±0.04	0,009±0,00
Bressummer	1.709±0.03	2.127±0.04	2.110±0.04	0.764±0.05	0.389±0.01	2.860±0.04	0,003±0,00
Chancel	0.728±0.02	0.352±0.02	< LOD	1.744±0.06	0.975±0.02	0.610±0.02	< LOD

Table 8. Results from the elemental analysis using XRF on site. The results from the salt deteriorated post and bressummer highlighted, and reference areas from the base and the chancel in the rows above and below. Potassium, phosphorus and sulphate have a higher atomic percent in the contaminated areas than the reference areas. Readings in mining mode. For spectra, see appendix 2.

SEM-EDX

Both mapping and point ID were used to find the elemental composition of the compounds. Mapping of elements in the scanning electron microscope gave interesting results. The SEM images showed clear alien and crystalline structures in the wooden cells (see figure 30). The results pointed to unexpected salt molecules, indicating that the salts must come from various sources, not only the bat urine.

The results of the main alien elements detected are shown in table 9. Some detected elements, like Carbon and Oxygen, were expected in the wood itself, so are not presented in all the tables and figures. Elements like aluminium and magnesium were detected but in such small amounts that they will not be mentioned further.

A total of one reference sample, six wooden samples and three bat droppings were analysed. For a total overview of the samples, see appendix 1.

SAMPLE	Sampled at	Major elements found in salt crystals	Salt
6	Bressummer, hole on gallery side	Potassium Phosphorus Nitrogen	Potassium phosphates No salt
7	Bressummer, hole on gallery side	Potassium Phosphorus Sulphur Nitrogen	Potassium phosphate Potassium sulphate Urea?
8	SW post, aisle side	Potassium Sulphur Zinc Phosphorus Nitrogen	Potassium sulphate Potassium phosphate Zinc Phosphate/Phosphide? Urea?
14	SW post, aisle side. Above grain	Zinc Phosphorus Potassium Sulphur	Zinc Phosphate/Phosphide? Potassium sulphate?
15	SW post, base Reference	Silicon Aluminium Sulphur Potassium	No salts
0	Ground beam Reference	Calcium Chlorine Magnesium Sodium Potassium	No salts

Table 9. A summary of the results for the salt crystals found in the EDX analyses for the wooden samples from the SW corner post and nave bressummer.

The analyses gave different results from the two sides of the SW corner post. The aisle side of the post gave signals for zinc (figure 34). Zinc was not detected in the samples from the gallery side of the post, nor from the bressummer. The image of the reference sample from the base of the post showed no salt crystals (figure 35)

The point ID function in the software was used on most samples but gave confusing information (see figure 29 and table 10). Point ID on the surface of sample 6 gave high amounts of Sulphur and Phosphorus in some points on the salt molecules, but lower amounts on other points (more similar to areas without visual salt contamination).
The mapping of the entire image gave a clearer image and result (see figure 31 for a mapping of sample 6). The mapping method of the wooden surfaces where salt crystals were found gave the molecular composition of the salt molecules within the wooden cells. The results

from the mapping showed mainly potassium sulphate (figure 31) and potassium phosphate (figures 32-33).

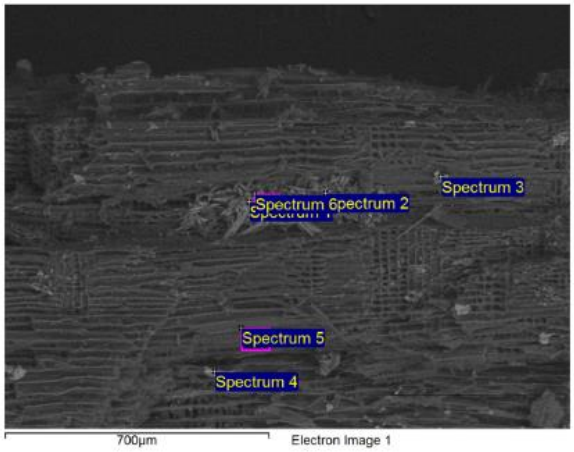


Figure 29. Radial section. Sample 6 from the sill beam hole, gallery side.

C	N	O	P	S	K
44.3	13.1	35.4	7.1	0.2	
34.0	13.8	45.3	5.5	0.1	1.3
61.8		24.7	0.2	4.6	8.7
57.5		28.6	0.2	5.2	8.5
58.2	10.2	31.3	0.2	0.1	0.1
42.4	13.2	39.1	4.1	0.1	1.1

Table 10. SEM-EDX analysis of sample 6. From top to bottom, spectrum 1-6. Spectra 1-4 taken from salt molecules, spectra 5 on wood (marked). Spectra 6 salt molecule.

Samples of wood fibres

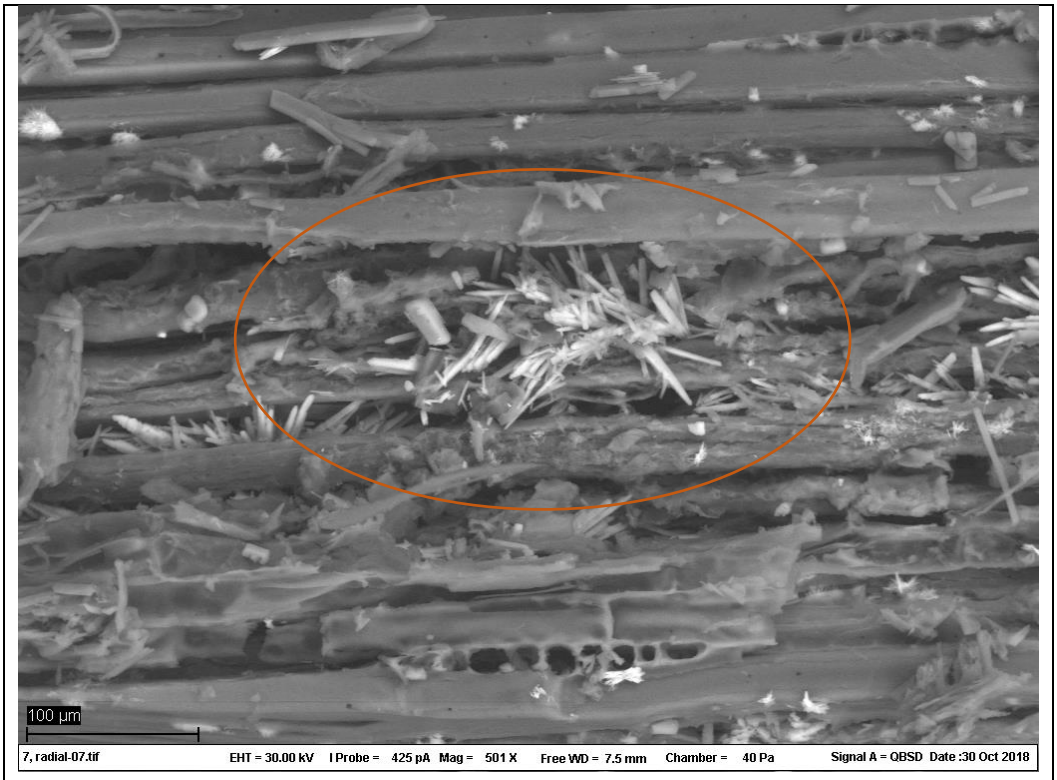


Figure 30. SEM image of sample 7, Radial section. The alien compounds are visible as white crystals with sharp tips in between the wooden matrix, seen here as darker cells with tracheids. Mag. 501x

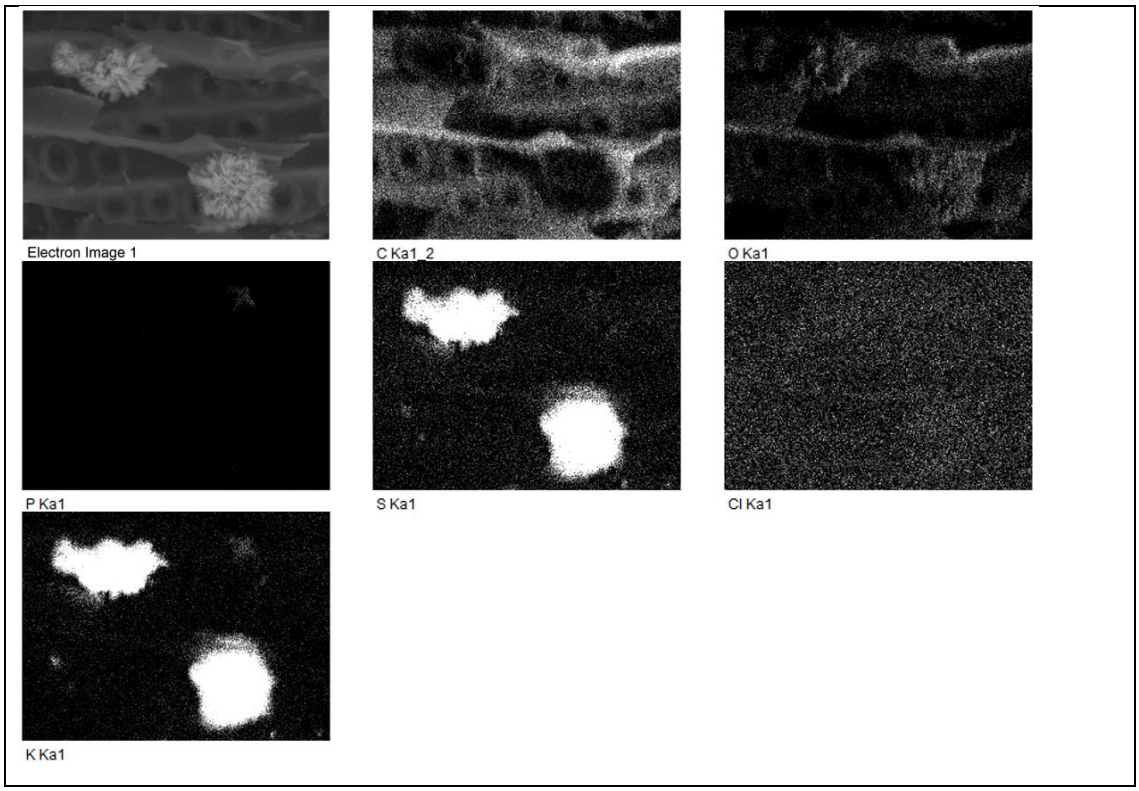


Figure 31. SEM-EDX analysis of sample 6, a wooden sample taken from the bressummer hole (bat roost). The mapping of the elements in the salt molecule show high atomic percent of Potassium (K), Sulphur (S) and some Oxygen (O), and the salt is most likely potassium sulphate (K_2SO_4).

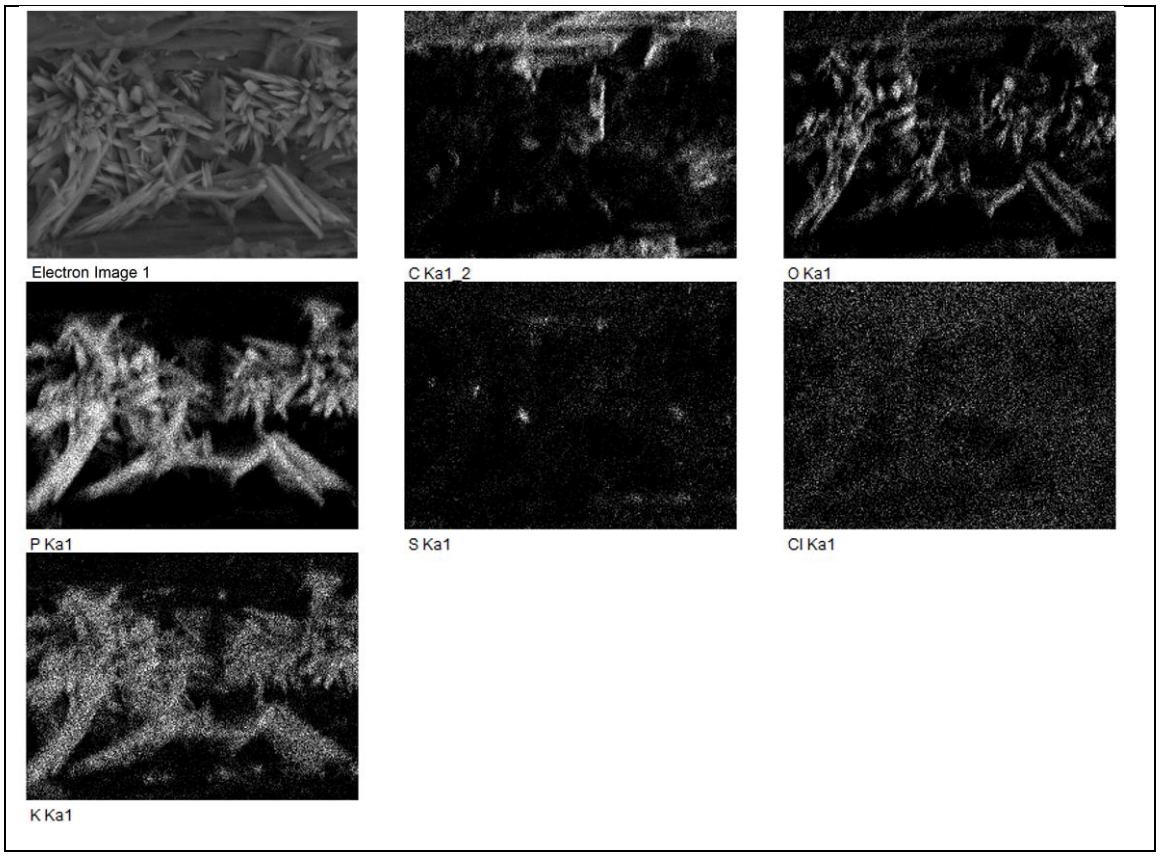


Figure 32. SEM-EDX analysis of sample 6, a wooden sample taken from the bressummer hole (bat roost). The mapping of the elements in the salt molecule show high atomic percent of Potassium (K) and Phosphorus (P) and Oxygen (O).

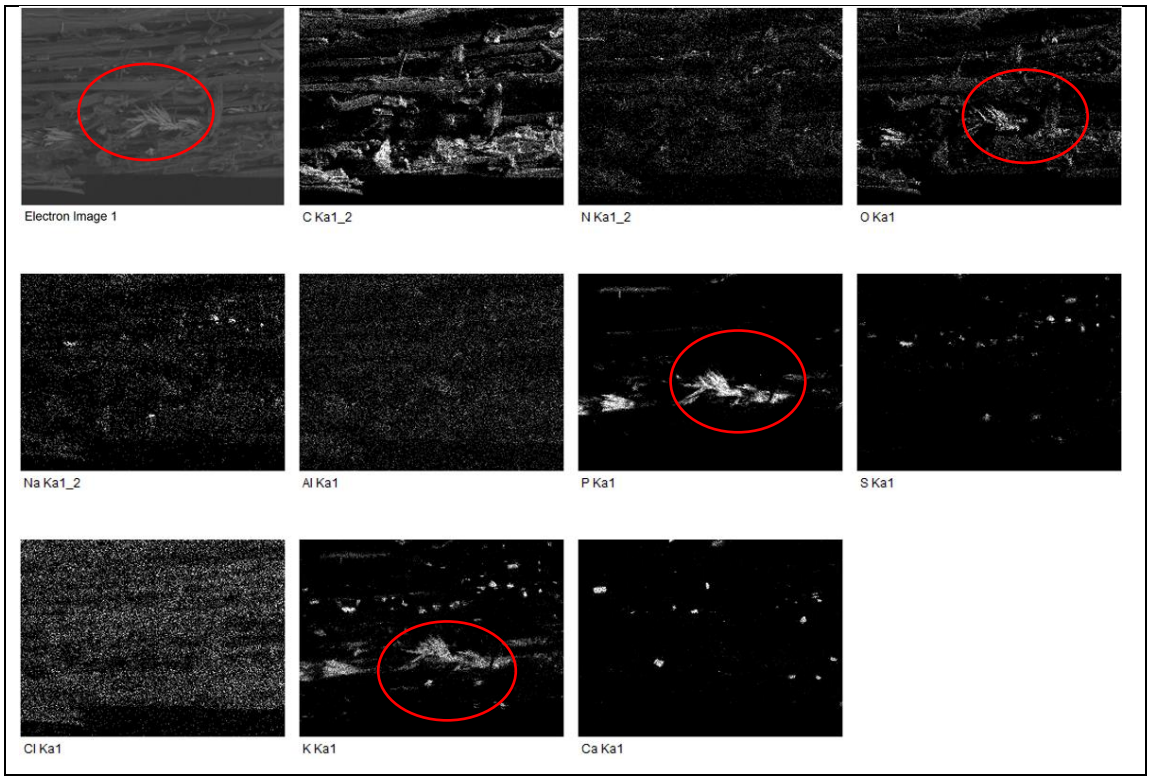


Figure 33. Sample 7, taken from the hole under the bressummer on the gallery side (bat roost). The mapping of the elements in this image show that the salt crystal contains potassium and phosphorus, and some oxygen. It is likely that the salt molecule is K_3PO_4, potassium phosphate. The image show crystals mostly at the surface but also within tracheid cells (circled).

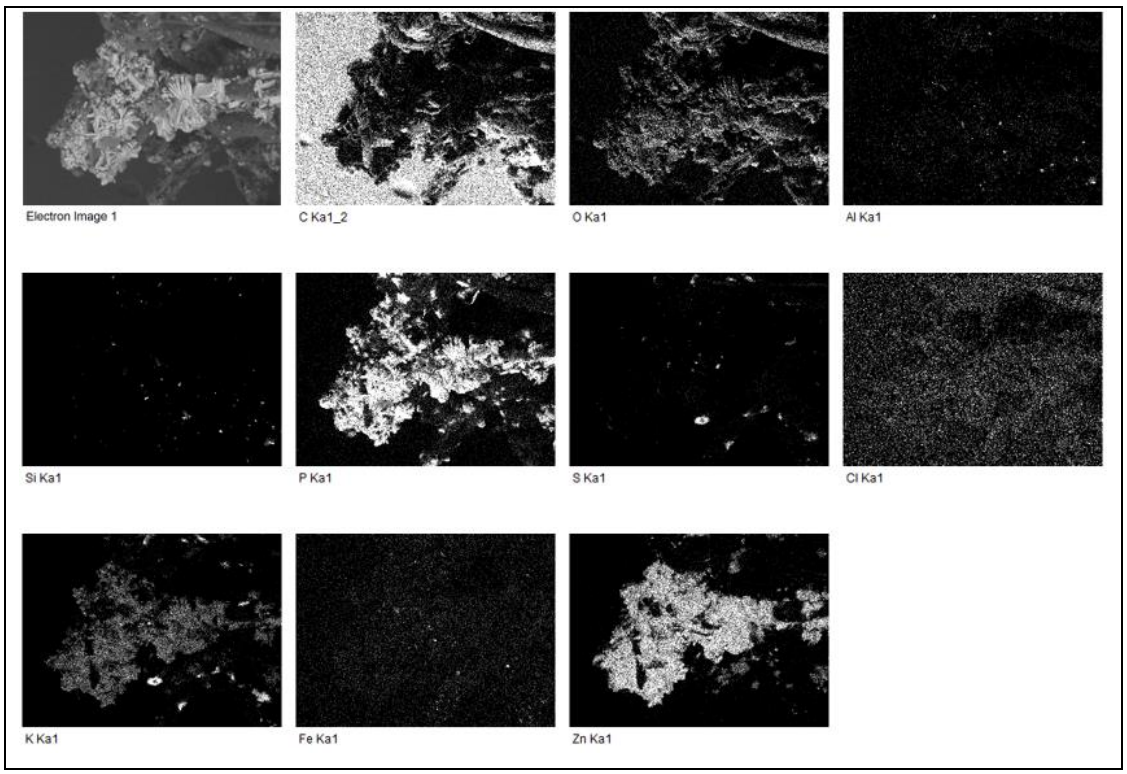


Figure 34. SEM-EDX analysis of sample 14, a wooden sample from the aisle side of the SW post. The mapping of elements shows a compound containing mainly zinc and phosphorus. It also contains some potassium and oxygen. The compound could be $Zn_3(PO_4)_2$, zinc phosphate or Zn_3P_2, zinc phosphide.

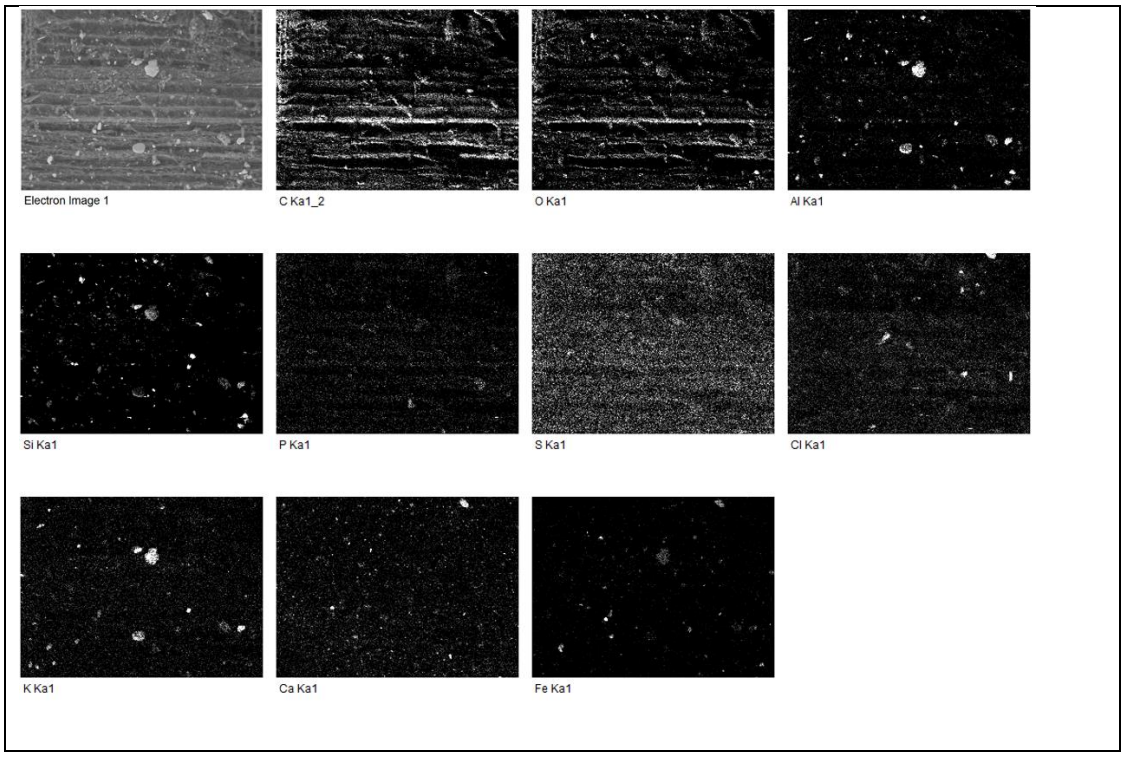


Figure 35. SEM-EDX analysis of sample 15, a wooden sample from the base of the SW post. The base is not salt degraded and is used as a reference sample to find the elements of normally degraded historic wood. The image and mapping of elements shows no salt crystals.

Samples of bat faeces

Three samples of bat faeces were analysed. It showed high amounts of Sulphur and Phosphorus (see table 11 below).

Spectrum	In stats.	C	N	O	Na	Mg	P	S	Cl	K	Ca
Spectrum 1	Yes		16.5	62.9	0.5	0.4	11.8	2.7	0.4	4.9	
Spectrum 2	Yes		14.5	73.7	0.3	0.3	7.7	1.4	0.2	1.8	
Spectrum 3	Yes		13.6	75.6	0.3	0.2	8.0	0.8	0.1	1.6	
Spectrum 4	Yes	31.3	15.2	47.8	0.1	0.1	4.1	0.3	0.0	1.2	
Spectrum 5	Yes		28.9	62.4	0.4	0.7	2.1	2.7	0.1	1.9	0.8
Max.		31.3	28.9	75.6	0.5	0.7	11.8	2.7	0.4	4.9	0.8
Min.		31.3	13.6	47.8	0.1	0.1	2.1	0.3	0.0	1.2	0.8

All results in atomic%

Table 11. Results from EDX analyses of one of the bat droppings, sampled from the bat roost. Except the elements normally found in organic matter (C, N, O) the elements sulphur and phosphorus gave the highest atomic %.

Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES)
ICP-OES analysis showed no significant presence of heavy metals in either of the three samples from Urnes. Sulphur was heavily present, and this corresponds to results from test strips, the FTIR analyses, the XRF and the EDX analyses.

The results for heavy metals are supported by the findings in XRF, where the readings in all the test areas show no detection of the heavy metals lead, arsenic and copper (below limit of detection).

Total Organic Carbon (TOC) test

The TOC results showed a significant difference in the three samples from the contaminated area compares to the reference sample. This indicate that the samples are contaminated from an external source (see appendix 5 for the full report).

Part 4 The condition of the wood

The situation of the southwest corner was investigated using visual examinations, microphotography and chemical analyses. X-ray, SEM and FTIR were used to understand the deterioration of the wood fibres. Each analytical technique has its own advantages, and the use of several techniques supplied complimentary information about the degradation process.

Visual examination

The visual examinations showed that the SW nave corner post has a heavily deteriorated surface, especially towards the south. A fuzzy, light-colored surface shows signs of salt contamination, and the area feels moist and cold to the touch. This surface has white salt efflorescence in drier weather and white spots disappear when RH is higher. The surface of the adjoining bressummer to the south shows similar signs of deterioration (see figure 36).

In the adjoining area where the bressummer meets the post, both construction parts have material loss that has resulted in thinning from the original shape, and this has enlarged the holes on both sides. The result is an easily accessible roosting area for bats. Another indication of the thinning of the original shape of the post is the protruding twig (knot) below

the joint (see figure 36). The carpenter who axed the timber to give it the shape of a post would not have left the twig protruding. At least this is not seen on other posts at Urnes (figure 37).

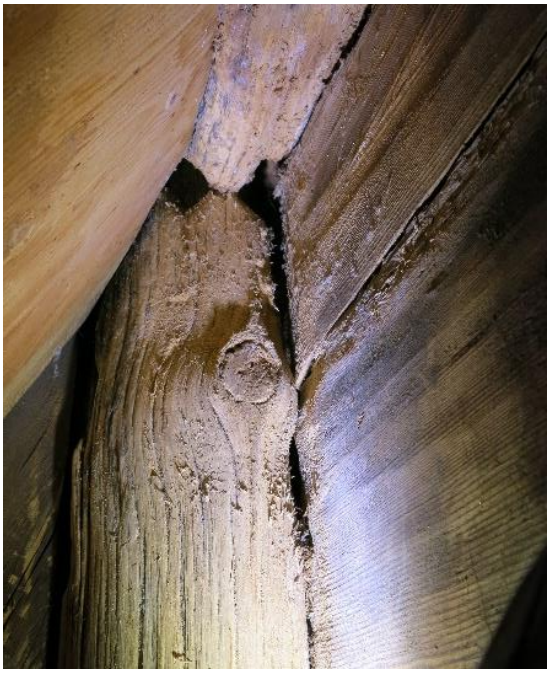


Figure 36. The vertical construction part is the SW nave corner post, the part resting on top of the post is the bressummer. The salt damage is seen as a fuzzy and light-colored surface. The joint between the post and bressummer is losing contact, and the opening enable bats to enter the hollow bressummer. The twig in the post is protruding.

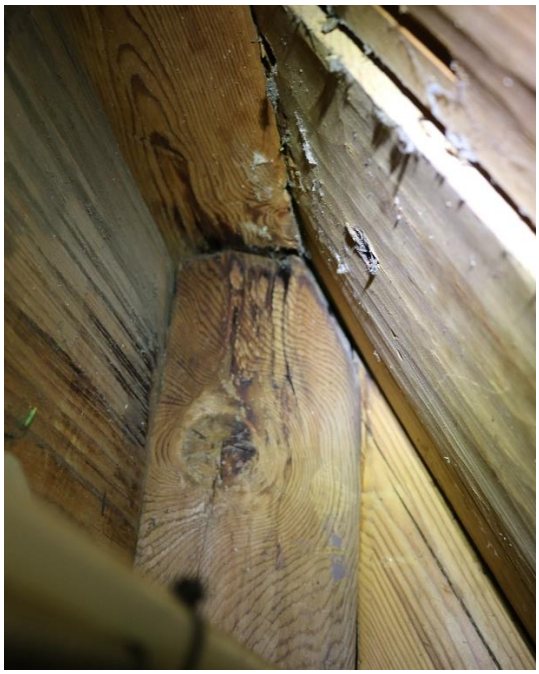


Figure 37. The northwest (NW) nave corner post in the area in the northern aisle where post, bressummer, aisle roof and aisle strut meet. The NW nave post and bressummer have a tight joint, and no bats can enter. The twig is not protruding, and the surface is healthy. This post dates to the 1130 as well.

In June 2018 the relative humidity at the time of visit was steady between 42 and 43 %. The temperature was between 19 and 20 degrees. The SW corner post was examined from the gallery. The post, adjoining nave bressummer to the south, the aisle strut, the upper arcading the south and west and the west side nave bressummer were all examined. The SW corner post had white efflorescence from the top of the bressummer (the hole on the aisle side) and down to the capital. The aisle rafter in the SW corner shows no signs of salt degradation (see figure 53) but suffers from a heavy insect attack.

In October 2019 the relative humidity was not measured, but the temperature lied between 6 and 12 degrees Celsius, with clouds and partly rain. The aisle side of the SW nave post had white salt efflorescence.

X-ray investigation of the deteriorated area

The bressummer and stave at Urnes, although fluffy on the surface, seems to be sound behind the surface. There is no sign of structural fatigue in the construction. Yet, the bats have found a room within the bressummer, meaning it must have a cavity/ a hollow space. Through the small bottom hole of the bressummer it is possible to see the lead fitting on the outside after removal of bat excreta. With a peek hole camera, the core has been photographed previously. Such a camera does not however give other than two dimensional images, and the size of the cavity was not possible to understand fully. The bressummer is hidden by roof tiles on the outside.

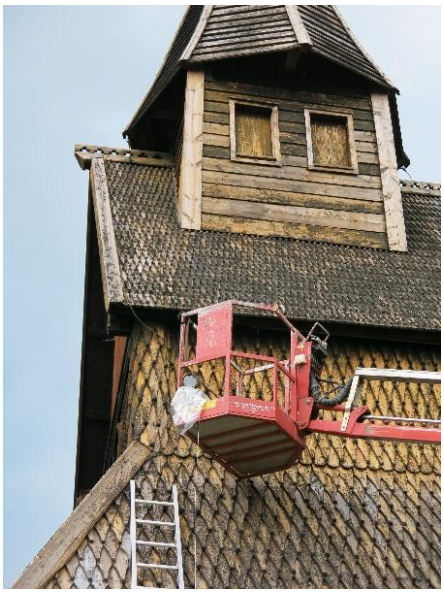


Figure 38. During X-ray examination of the SW corner. The X-ray generator was placed on an aerial lift, and the pictures were taken using a trigger button from the ground.

The shooting with X-rays was done from the outside (figure 38), and the film was placed on the inside of the church.

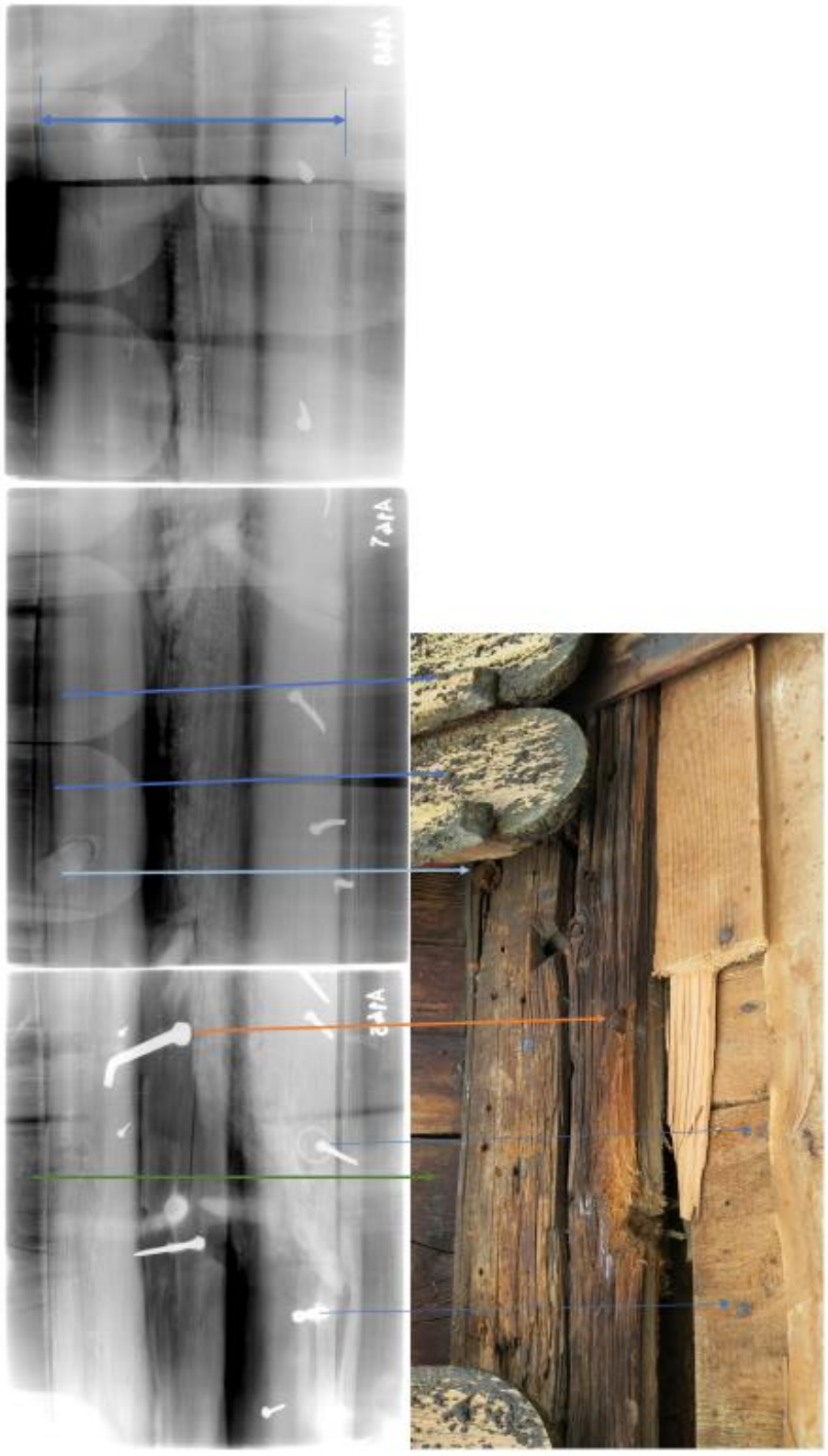
Due to high winds and rainfall the investigation was challenging, and some of the images proved to be difficult to read due to an instable instrument during the shooting. This gave double images in some areas. After a comparison of several images it was possible to interpret the results of the X-ray investigation.

The results from this investigation gave valuable results that were impossible to get using other methods. It gave a good insight into the condition of the wood construction in the SW corner. The dismantling of the cladding and fittings to prepare for the X-ray investigation gave valuable information (figure 39). The extension of the rot damage became clear, and previous repairs visible (wooden repairs and lead fittings). The bressummer has suffered from total material loss in approximately 1 meter in length.

Figure 39. Picture showing the roof area after dismantling of the roof tiles and the lead fitting. The bressummer to the upper right, two layers of cladding and a lead fitting over one of the underlying tiles on the aisle roof. A roof tile to the left.

The X-ray images of the bressummer show very clearly that the core of the timber is partly gone and partly highly deteriorated (see figure 40). The exposures show the wooden fibres clearly in the healthy areas of the beam, and a mess of fibres going in all directions in the deteriorated areas. In the deteriorated areas the iron nails are also corroded, which indicates that these areas are contaminated by salts and/ or infested by acidic material.

Knowing the size of the cavity can say something about how many individuals of bats might have used the space. X-ray established that the cavity extended all the way from the SW corner post to the intermediate post towards east. The bressummer was examined by X-ray only between these two posts.



Wall plank Nail, new and rusty Nail, big	Wooden nail Roof tiles Most nails are from the newer plank fitted to act as support for the lead fitting	The two-pointed arrow show the width of the bressummer. The core of the bressummer is deteriorated all the way from left to right in the 3 images.

Figure 40. X-ray images seen from the outside. 3 images laid side by side.
Photograph of parts of the same area, taken from the aerial lift after dismantling of the roof tiles.

Fourier Transfer Infrared Spectroscopy (FTIR)

Samples were analysed both as is and rinsed to remove the contamination. The non-rinsed samples showed band spectra that compared with band spectra of urine. The urine reference spectrum was taken from the literature (See appendix 3). The samples with a high urine content showed no sign of the molecular groups specific to wood in the fingerprint region but showed bands characteristic of urine. The pure lignin band is hidden in the samples with high urine content. In spectra where typical lignin bands were present, Braovac interpret these as samples with no urine content or slight urine content (for location of where samples were taken from the SW corner, see appendix 1, samples L1–L11).

Analyses of the rinsed samples show some evidence of chemical decay, but not dramatically so. In sample 8, taken from the base of the stave and several meters below the urine affected area, the analysis shows signs of natural aging. The holocellulose area of the spectra seems degraded, and the lignin area seems less affected. In the samples around the bat roost (samples 2,3 and 4), both lignin and holocellulose seem degraded.

Nonetheless, the report is not conclusive about the preservation state of the wood. Spectra in FTIR are hard to interpret, and the analysis is a relative technique. The general observation is that the degradation looks more dramatic visually than the results of the analysis reflect (See appendix 4, page 124), and the results show no dramatic chemical degradation in the samples analysed.

The main aim of the FTIR analysis was to investigate the possible chemical decay of the lignin, hemicellulose and cellulose. The results of this were not conclusive, but the analysis also gave answers to one of the other research questions; the source of the salts. The spectra of the non-rinsed samples gave clear spectra of urine.

Scanning Electron Microscopy (SEM)

This chapter reports the results from the SEM images conducted with SEI (secondary electron imaging). After the SEM-EDX analyses in the scanning electron microscope, some of the samples were coated to retrieve images with a higher magnification to search for deteriorated areas in the wooden cells.

The images in figures 41-44 clearly show crystallized salts within the wooden cell structure. The salt crystals grow and exert mechanical pressure on the wooden matrix and grow within its crystalline structure.

Figures 46 and 47 show salt molecules with two different typographies. The EDX analyses showed that the course crystals have more phosphate in them, whereas the finer crystals contain more sulphate and potassium.

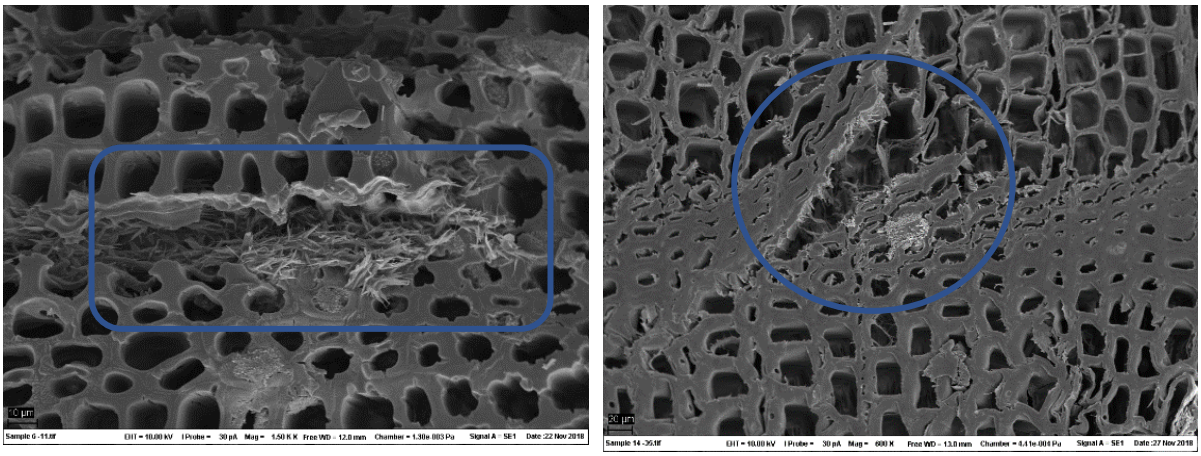


Figure 41 and Figure 42. SEM images. Images of samples 6 (Mag. 1500x) and 14 (Mag. 600x) in transverse section, showing areas where the wood cells have suffered a severe damage due to salt crystal formation.

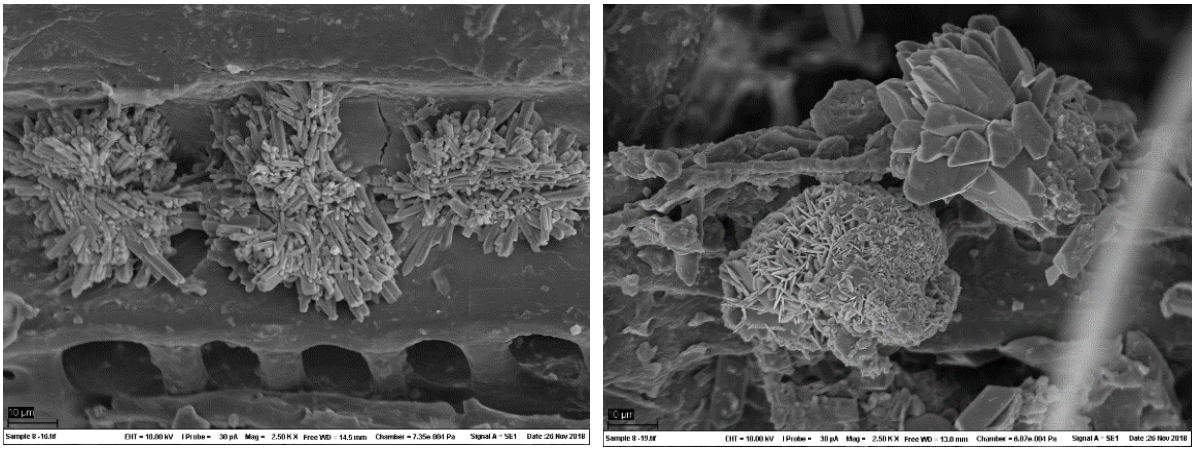


Figure 43 and Figure 44. SEM images. Images of sample 8 (Mag. 2500x), showing two different salt crystal topographies. As seen in the results from the elemental mapping, the different crystals showed different molecular composition.

Lignin staining

The lignin staining showed a clear difference in the reference sample compared to the samples from the SW corner post (figure 45). The samples tested were the reference sample, (sampled from the raft beam), sample 6, 11 and 14 (sampled from the salt infested area), and sample 15 (sampled from the base of the SW corner post).

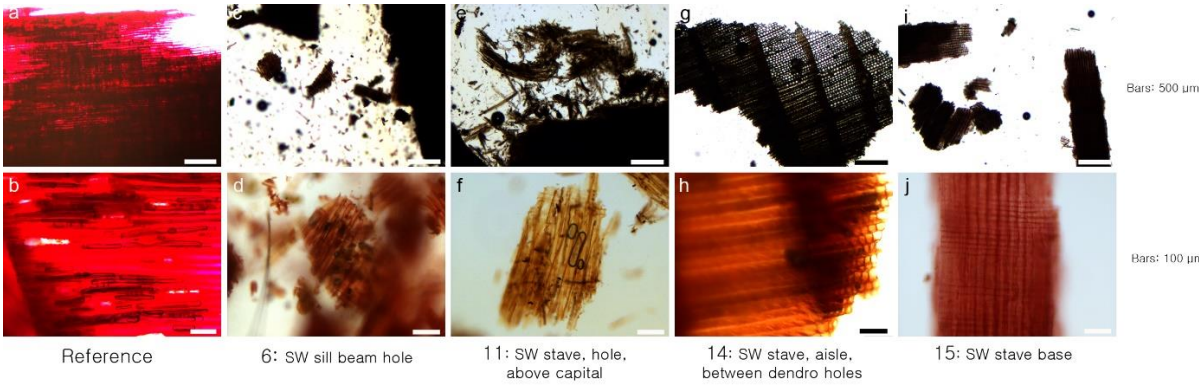


Figure 45. Results from the lignin staining. All samples are photographed in two different magnifications. Upper panel shows lower magnification and lower panel shows higher magnification. Under the low magnification, it was not easy to identify the lignin degradation, but it was distinct in the higher magnification. The sample to the left is the reference sample, and it shows a deeper red colour than the other samples. All samples were coloured using 10% phloroglucinol in ethanol.

Summary of results

The results from all chemical analyses show that there are a greater number of elements present in the contaminated samples than are generally found in wood. The elements potassium, zinc, sulphate and phosphorus were found with XRF and EDX and sulphate was also found using test strips. The results from the SEM images and FTIR show that the wooden cells in the contaminated area is affected by the salts. The images in SEM of coated samples show the force at that the crystallized salt molecules exert on the wood to break the cells. It has not been possible yet to localize where the cell deterioration takes place. From the literature, the cells were expected to break in the middle lamella, but further work is needed to state if this is the case here. FTIR spectra gave clear results for urine contamination in the wood. The presence of nitrogen is an indication of urine, but this element is hard to detect with most analytical instruments including ICP and XRF due to its small atomic mass. SEM-EDX spectra showed the presence of nitrogen for samples 6 and 7, both from the aisle side of the SW corner post. Finally, pH measurements indicate that the wood is slightly more acidic than non-contaminated wood. In conclusion the methods chosen for this project gave answers to the research questions.

DISCUSSION

The results from the investigations and the analytical studies are discussed here in relation to the research questions:

- Which salt molecules contaminate the southwest nave corner post at Urnes?
- Do these salts originate from bat urine?
- How do these salts affect the preservation state of the wood?

The results of the analyses combined with visual proof of bat droppings give clear indication as to the source of the salts. All the elements expected in the accumulated bat guano were found in the analyses of the wood samples from the SW corner post and bressummer. Microscopic images show crystallized salt molecules within the wooden matrix, and some also show-physical damage to the wooden cells due to the crystallization.

The results relating to each question will be discussed in individual sections. Also, the methods chosen to answer each specific question will be considered in relation to their relevance and feasibility to the work. Other possible sources of the elements found will be covered as they related to the restoration history of the church, and the literature. In the final section, suggestions for further research will be reviewed. Suggestions for preventing further degradation and measures to prevent new bats from entering the church will be made.

Which salt molecules contaminate the SW nave corner post at Urnes?

To identify the salt molecules, both non-invasive and invasive methods were used. Test strips and a portable XRF on-site gave a first indication of the elements present in the contaminated area of the church. Further, samples were collected to analyse the contamination in the laboratory by ICP-OES (including TOC analyser) and SEM-EDX.

SEM, ICP and partly XRF are both qualitative and quantitative methods, but they all have some drawbacks. They cannot detect lighter elements. However, the ICP can detect minute amounts of elements. This was useful for the analysis of sulphur here. All analytical instruments offer elemental data. In this section, each element identified will be discussed with regard to their natural presence in bat guano and in historic wood. Also, the elements that

can be expected from bat urine but not detected, are mentioned. In a final section in this chapter, the possible salt molecules these elements could form will be presented.

Table 12 below gives a summary of the elements detected.

Sample	Location	Analytical method	Result
Reference	SW post, base	**pXRF**	Silicon, Chlorine, Sulphur, Calcium, Phosphorus, Potassium, Iron.
Reference	Chancel	**pXRF**	Silicon, Calcium, Chlorine, Sulphur.
Contaminated area	Bressummer, gallery side	**pXRF**	Sulphur, Potassium, Phosphorus, Silicon, Calcium.
Reference	Ground beam	**ICP-OES**	No contamination by sulphur
Contaminated area	Bat roost	**ICP-OES**	Sulphur
Reference	SW post, base	**SEM-EDX**	Silicon, Aluminium, Sulphur, Potassium
Contaminated area	Bat roost	**SEM-EDX**	Sulphur, Potassium, Phosphorus, **Nitrogen**
Contaminated area	SW post, aisle side	**SEM-EDX**	**Zink**, Phosphorus, Potassium, Sulphur, **Nitrogen**
Contaminated area	Above twig near entrance hole for bats	**SEM-EDX**	**Zinc**, Phosphorus, Potassium, Sulphur

Table 12. Results from analyses by XRF, ICP-OES and EDX, showing the most detected elements in the contaminated areas and the reference areas. The elements found only in the contaminated areas are highlighted.

Elements

Sulphur

All diagnostic methods have confirmed the presence of sulphur in the contaminated and reference areas. In 2015, test strips for sulphates confirmed a high amount of sulphur near the bat roost in the SW corner (Anker, 2015).

Sulphur is present naturally in historic wood, but also is one of the elements found in analyses of the degraded wood. The ICP analyses indicated that there is a significant difference in the content of sulphur in samples from the contaminated area with respect to the reference sample from the ground beam (see table 13 below).

SAMPLE	Reference sample from ground beam	Bat roost	Above arcade, gallery side	Above arcade, aisle side
Sulphur content (mg of extracted element/kg of dry original material	**816**	**10219**	**5071**	**2851**
Standard deviation	6	101	29	13

Table 13. Results from the analysis of Sulphur in the ICP-OES.

For the XRF analyses, where the chancel wall and the base of the post were used as reference areas, there are noticeably lower intensity of peaks for Sulphur compared to the contaminated area (See figure 28). It can be assumed therefore that S must come from an external contamination.

Sulphur is not reported as a natural content of urine. It is however detected in analyses of material affected with bat droppings (Paine (1993) and Bakr et.al. (2012)). Analyses of bat excreta isolated in SEM-EDX during this project showed presence of Sulphur and Phosphorus.

Phosphorus

All samples from the SW corner analysed in SEM-EDX gave results for Phosphorus (P). In the chancel reference area, the pXRF spectra showed no signs of phosphorus (below limits of detection). The XRF detected phosphorus at the base of the post, but with a noticeable lower content than the contaminated area (see spectra, figure 28).

Phosphorus is not a natural component in wood, nor in bat urine, but is present in high concentrations in droppings (Simons, 1998). SEM-EDX analyses of droppings (from sample 5) conducted for this project report 3.76 atomic % of P, which is higher than the Sulphur, Potassium, Magnesium and Sodium also detected.

Potassium

High levels of Potassium were found in samples from the wood in 2004, believed to originate from the wood itself. Potassium is naturally present in wood (Unger et al., 2001), but it is also

one of the major solutes in bat urine (Hales, 2017). It is not surprising that all samples, and all reference areas showed the presence of this element. As expected, there is a difference in the amount of potassium in the contaminated areas compared to the reference samples and areas. The EDX results gave a high atomic percent of potassium, especially in areas with salt molecules.

Chlorine

The findings of chlorine are insignificant in the SEM-EDX analyses from the contaminated samples, although expected, as chlorine is one of the main solutes in bat urine (Hales, 2017). Chlorine is not reported in wood contents.

The pXRF detected chlorine in all areas, but a more significant result on the base of the SW corner post and the chancel wall. Besides urine, there is a possibility of other chlorine sources, which will be discussed on page 78 (Other possible sources).

If the chlorine derives from the bat urine, this means the bats urinate in many areas of the church and contaminate the walls and posts as they fly or land. It is logical that there is a lower atomic % of chlorine in the heavily salt contaminated areas in the SW corner, as the other elements like potassium, phosphorus and sulphur hide the content of chlorine. SEM-EDX spectra give comparative numbers for the content of the different detected elements.

Sodium

The analyses were not able to find sodium in the contaminated wood samples, nor in the XRF results.

Sodium is one of the major solutes in bat urine and in higher amounts than chlorine and potassium. The urine of Plecotus Auritus (long-eared bat) contains twice the amount of sodium compared to potassium and chlorine (measured in mmol/l). The same is also for the urine from other species examined by James Hales (Hales, 2017).

Sodium has the atomic number 11 and is a slightly heavier element than nitrogen, but might still have an atomic number too low to be detected by the analytical instruments used.

Nitrogen

Nitrogen is one of the main elements of urea, and the presence of nitrogen with quantities higher than in the uncontaminated wood would confirm mammal urine. Both analytical methods failed to do so. Nitrogen is naturally present in the wood itself, but with a low percentage (0,1-0,3 %) (Unger et al., 2001).

EDX found nitrogen in some of the samples. According to the EDX instrument operator (Hilde Kolstad Raanaas, Imaging Centre, NMBU), the nitrogen results cannot be confirmed as the EDX can confuse Carbon, Oxygen and Nitrogen.

In theory, both XRF and EDX should be able to detect nitrogen. In practice, elements lighter than atomic number 13 can be hard to detect using XRF (Mantler & Schreiner, 2000).

Test strips for nitrates were also used on 5 contaminated samples and a reference sample. None of the samples showed detectable nitrate contents. This is also confirmed in the mapping of the salt crystals in the EDX. None of the detected salt crystals contain nitrate ions.

Carbon and Oxygen

Urea ($CO(NH_2)_2$), the main constituent in urine besides water, is a molecule of Carbon (C), Hydrogen (H), Nitrogen (N) and Oxygen (O). C, H and O are the building blocks of all organic materials and for wood as much as 99% of the elementary composition constitute C, H and O. The analytical instruments employed for this study do not generally detect contamination from the same 3 elements in wood. Additionally, Nitrogen is hard to detect due to the low atomic number. As seen in table 10, Nitrogen was detected with SEM-EDX in the samples from the bressummer and the post near the entrance hole for the bats. The results are however not to be trusted (see section above).

FTIR spectroscopy detected urine in samples from the SW corner (see next chapter).

Iron, aluminium and silicon

XRF analyses detected iron and aluminium on the base. Silicon was found in all areas, but with decreasing numbers the further up the post the test area was. The chancel area had significant results for silicon as well. All three elements are interpreted as surface contamination like dirt from the soil entering the church with church visitors.

Zinc

Zinc was found in insignificantly small amounts using the XRF but is worth mentioning because of the EDX results. Samples from the aisle side (samples 8 and 14) found zinc, but samples from the gallery side (samples 6 and 7) of the SW corner post showed no sign of zinc in SEM-EDX analyses. Zinc is found in the same molecules as phosphate and oxygen.

Zinc is not reported to be a natural content of wood, but is reported on historic surfaces contaminated by bat guano (Bakr & Abd El Hafez, 2012).

Other possible sources will be discussed on page 78.

Salt molecules

The elements found in the contaminated areas are now known. These elements are found in a vast number of different molecular compositions in nature. To understand the characteristics of the contamination at Urnes, the molecular composition must be known here.

By mapping a specific area of the sample in EDX using the SEM image to select the area, the mapping result for every single element can be compared to each other (see figures 31-34 in Results-chapter, and figure 49). Where two or several elements are revealed in the same area and shape, the molecular composition can be found with certainty.

Examples from the EDX analyses in figures 46 and 47 show typical findings of salt molecules in the samples. Mapping of some of the salt crystals showed that the smaller crystals contain more sulphur and potassium, whereas the coarse crystals contain more phosphorus (se figures 46-47 below). It also showed unambiguous presence of potassium sulphates and potassium phosphates. While nitrate salts were not identified, this might only mean that they do not exist on the surfaces from where the samples were taken.

This interpretation method (EDX mapping) can hardly be used comprehensively to map all salt molecules present in the deteriorated area at Urnes. A comprehensive result is dependent on finding the salt crystals on the sample when the sample is magnified 300-1000 times. At high magnification, it is impossible to find all salt crystals. Thus, the results will at worst be somewhat random.

As Arnold and Zehnder has shown (Zehnder & Arnold, 1989), different ions fractionate, and the different salt crystals can be found in separate areas of a porous matrix. This sampling was taken from the surface of the construction materials, other salt molecules might have crystallized deeper into the material.

The salt crystals cannot be identified by morphology alone. The same salt may crystallize into several different shapes, depending on local conditions, structural factors like the size of pores and external factors like impurities of the solution (Zehnder, 1989, p. 47). However, the images shown below are examples of repeating morphological features for these molecules identified in SEM analyses during this project.

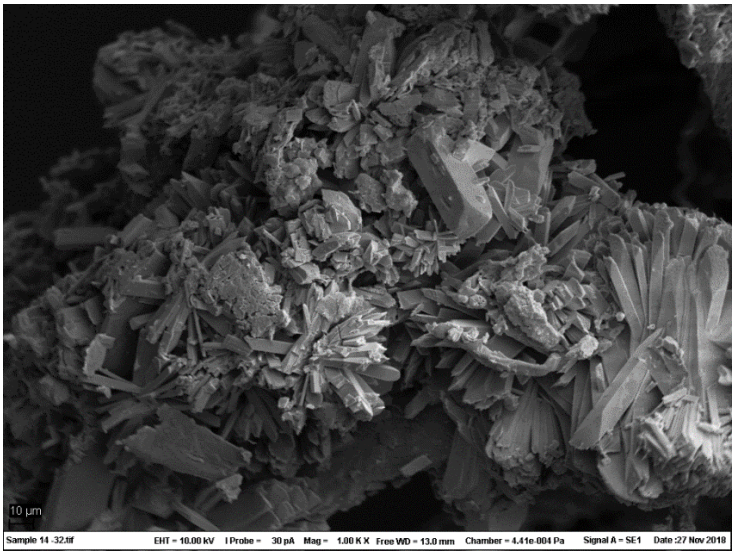


Figure 46. The coarser crystals contain more phosphorus.

Sample 14

Magnification x1000

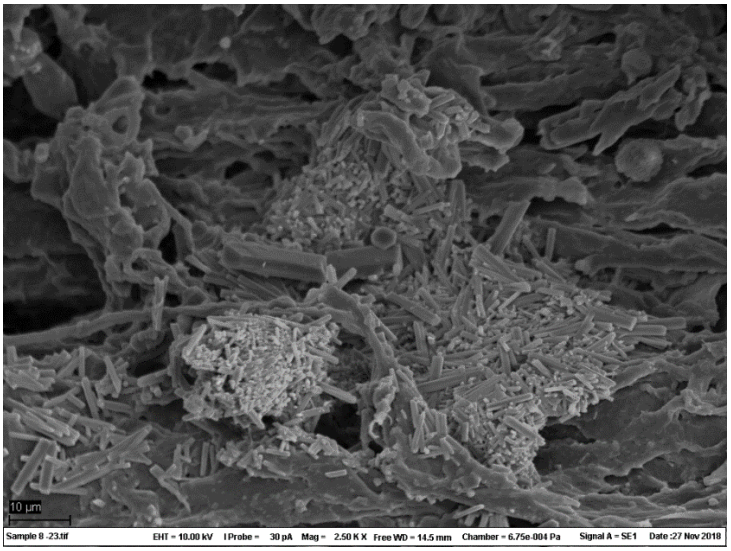


Figure 47. The finer crystals contain more sulphur and potassium.

Sample 8

Magnification

X 2500

Summary salt contamination

Mainly sulphates and phosphates are found in the samples collected from the surface of the SW nave corner post and bressummer.

Do these salts originate from bat urine?

There is clear evidence of bats in the recent past inside Urnes stave church. Bat droppings found at the floor around the SW nave corner post and inside the hollow bressummer have been identified as faeces from the *Plecotus auritus (*brown long-eared bat) (Kooij, 2016). We know from zoological reports that churches are favourable environments for bats in Sogn og Fjordane, and experts have found bat presence in 32 churches in the county (Michaelsen & Kooij, 2006).

Bats are long-lived and become well-acquainted with many suitable roosting structures over a large area. They might use them frequently or occasionally. Some buildings have records of continuous bat use over decades (*Bats in Traditional Buildings*, 2009).

The amount of bat guano inside the bressummer indicate that bats have used the space as a roost for a longer period, at least some years. The roost might have been active in the period after the roof leak was repaired with lead fittings (2000), and until recently. Potentially, it has been used for a lot longer than that. Where there is bat faeces, bat urine must also be present. A colony of 50 bats urinate 33 litres during the roosting period in summer (Paine, 1993). Over several years using the same roost, a vast amount of urine will soak into the wood.

The TOC analysis early on in this project confirmed that the contamination was of organic origin. In addition, elemental analyses and test strips have been used to look for elements known from urine composition.

The literature reports the following elements to be present in Bat urine and faeces: Nitrogen (N), Chlorine (Cl), Sodium (Na), Potassium (K). As seen in the previous chapter, only Cl and P were confirmed in the analyses conducted for this project. The presence of these elements is not enough to conclude the urine source of the salts, but other possible sources of these elements must be explored and excluded.

Previous investigations have indicated a urine source for the contamination. Ion chromatography was conducted in 2005. It confirmed the presence of nitrogen compounds, ammonium, which may originate from animal urine. 560 mg/L N of NH^4 was reported. The

sampling and the method for extraction of the sample solute was poorly documented. This raises a question of credibility for the result.

As part of this project, ammonium test strips were used. Some of the samples gave positive results of ammonia, a known "waste product" of urine (See table 5). Also, FTIR analyses gave spectra resembling urine. The extract after the washing of the samples were yellow and had a distinct smell of urine. The FTIR results together with previous analyses and ammonia presence leaves no doubt of urine contamination.

The high amounts of sulphate and phosphate salts in the wood samples cannot however be explained by urine components. Bat faeces were analysed in SEM-EDX, and it showed significant levels of Sulphur (S) and Phosphorus (P). The main salt molecules found during the mapping of elements were potassium sulphates and potassium phosphates. **This leads to the surprising result that not only the liquid urine has penetrated the wood, but also residues from the more solid faeces.**

Published literature that addresses the contents of bat excreta is limited. Most previous research concerning bat activity in historic buildings has focused on the contaminated surfaces without subtracting the contaminating urine substrate from the excreta, and without isolating the bat excreta. The high levels of sulphates and phosphates in the contaminated wood samples were confusing, as these elements are not present in urine. James Hales analysed metal samples that were exposed to urine and droppings and found that chloride-based corrosion products were present on all metal test samples, whereas phosphate and sulphate-based corrosion phases were only identified on samples that had experienced caked dropping deposits that remained on the surface for long periods (Hales, 2017, p.377). The results from the SEM-EDX analyses of faeces and the samples from the contaminated areas during this project therefore support the findings of James Hales. **There is now a clear link between bat faeces and the salt molecules within the salt contaminated wood at Urnes.**

Dissolution of bat faeces

The hollow bressummer has not been investigated because it is difficult to access, but based on the results from this study, is it possible that the dry and solid excreta, which contains exoskeleton from insects, dissolve over time or when sprayed with urine? Is this how sulphates and phosphates enter the wooden matrix, to form harmful potassium salts? The urine penetrates the guano and, in this way, harmful salts from the faeces form part of a

solution that enters the porous wood material. This would lead mainly to sulphate and phosphate salts below the roost, but they are also found at the surface of the vertical post. Salts migrate in porous materials and can “travel” in all directions and to other construction parts. Either this is the case here, or the sulphates and phosphates come from other sources.

Arnold and Zehnder (1989, p. 35) showed that with multicomponent solutions, different salt phases precipitate in sequences, according to the different solubilities or ion activities. This is called fractionation. If this is relevant in the case of urine contamination in porous wood, the different salts in the urine solution will separate and undergo spatial fractionation.

Sulphates are less soluble than chlorides and nitrates and will, in theory, migrate less than chlorides. This theory will remain unconfirmed as sampling beneath the surface has been impossible during this project.

Other possible sources of the salts

To verify the conclusion that the contamination comes from bat guano, other possible sources must be ruled out. For buildings, salts from the soil or the atmosphere, from the building materials or from conservation and restoration materials are possible sources of salt contamination.

The soil water contains salt solutions including carbonates, sulphates, chlorides, nitrates together with magnesium, potassium, calcium and ammonium ions (Arnold 1989). These are the very same salts that are found in the deteriorated area inside Urnes stave church. Furthermore, soil water penetrates porous building materials placed directly on the ground.

Urnes stave church stands on a stone wall (figure 48). Measurements from the base of the post with pXRF show lower amounts of potassium, phosphorus and sulphur compared to the contaminated area, but higher amounts of chlorine. The harmful sulphate, phosphate and potassium salts in the problematic area are several metres above ground and so cannot originate from the soil.

Figure 48. Urnes stave church seen from the south east, showing the stone wall on which the ground beams are resting. Photo: Hans Olav Stegarud, Riksantikvaren

Urnes stave church is surrounded by farm land and a fjord with salt water. This undoubtedly gives the atmosphere around the church aerosols and gases that can potentially accumulate on and in the building. The possibility of airborne contaminants is excluded as a cause of deterioration in the SW corner, as other areas would also have shown similar deterioration.

Wood naturally contains all the elements found, in small amounts (Unger et al., 2001).Quantitative methods were therefore necessary to determine whether the elements come from an external source and can be regarded as contamination or not. Also, comparison between contaminated and non-contaminated areas were necessary. Although these areas did not show visible salt deterioration, there is no certainty they are not contaminated. Bats move around the church and urinate as they land. Both the base of the post and the wall could possibly have some urine contamination.

Other mammals cannot be ruled out as a complimentary source of urine. Squirrels were seen inside the church previously. The urine of all mammals contains water and urea. The other constituents may vary dependent on the nutrient intake.

Droppings from mice, squirrels and bats are similar, and identification has been left to experts. Both Mycoteam (Mattsson, 2013) and Jeroen van der Kooij (Norsk Zoologisk forening, in conversation xx.xx.2016) have identified the faeces as coming from bats.

The chlorine was found more concentrated on the base of the SW nave corner post than in areas around the bat roost, both by the SEM and XRF analyses. It was expected higher amounts of chlorine around the bat roost than the base, since chlorine is one of the elements found in bat urine. If chlorine at the base derives from bat urine, this means the bats frequently urinate there and the chlorine is detected by the analyses because it does not penetrate below the surface. The lower detection of chlorine from the samples around the roost means that the chlorine is present in lower amounts than other elements or it fractionates inside the wood and is thus not detectable in the surface samples. The other possibility is that the chlorine found at the base derives from a different source, for example a pesticide (see page 81)

The aisle side of the SW post has a history of insect attacks and is likely to have been treated with pesticide in the past. Attack by wood boring insects initiated the treatment in 1984 with phosphine gas and permethrin liquid spray on infested surfaces. The permethrin was sprayed on to the surface and potentially could have accumulated on larger areas around the infested area.

An assessment report by Mycoteam (Mattsson, 2005) evaluated the different possible sources for the salts. The Phosphine gas treatment was not considered as a salt source, and the report does not address why it has been eliminated as a possibility. Other pesticide treatments in liquid form were also mentioned as possible sources. Mycoteam found this unlikely, as the salt accumulation would have been visible in other places inside the church.

Gas treatment against insect attack will have an instant but short-lived effect on living organisms. It kills insects, eggs and larvae, but is not a preventive measure against future attack. As it is volatile, most of it will disappear when the tent around the building is removed, thus not accumulating in the material. Mycoteam's conclusion that gas treatment is not the reason for phosphate salts in the wood seems to be sound.

The liquid treatment is however a possible source, as liquid pesticides accumulate in the material. Pesticides contain toxic elements like Copper, Lead, Arsenic and Mercury. The ICP data showed no traces of the first three elements. Pesticides can also contain Zinc, which was found in the SW area on the aisle side of the SW nave corner post (Figure 49 and 50, next page). Zinc phosphide is a highly toxic rodenticide, previously widely used in buildings. The

former church warden Marit Bøen, who was employed from 1979 until 2018, cannot recall any use of this pesticide during her time at Urnes (interview 21.10.19).

Table 14 below gives a summary of the elements detected in samples, and their possible sources from pesticides and bat guano.

Possible sources: Element:	**Wood**	**Pesticide**	**Bat urine**	**Bat faeces**	**Surface dirt**	**Comment**
Zinc		X*				*Zinc phosphide (Rat poison)
Chlorine	X	X*	X			*Permethrin
Sulphur	X	X*		X		*Copper sulphate
Phosphorus	X	X*		X		*Zinc phosphide (Rat poison)
Potassium	X		X			
Sodium	X		X			
Nitrogen	X		X			
Silicon					X	
Calcium	X				X	
	Source: Unger et al, p 15		Hales, J. 2017			

Table 14. The elements found in the analyses of the contaminated samples from the SW nave corner at Urnes stave church. The possible sources of the elements; the wood itself, a pesticide, bat urine, bat faeces and surface dirt are ticked off for every element found.

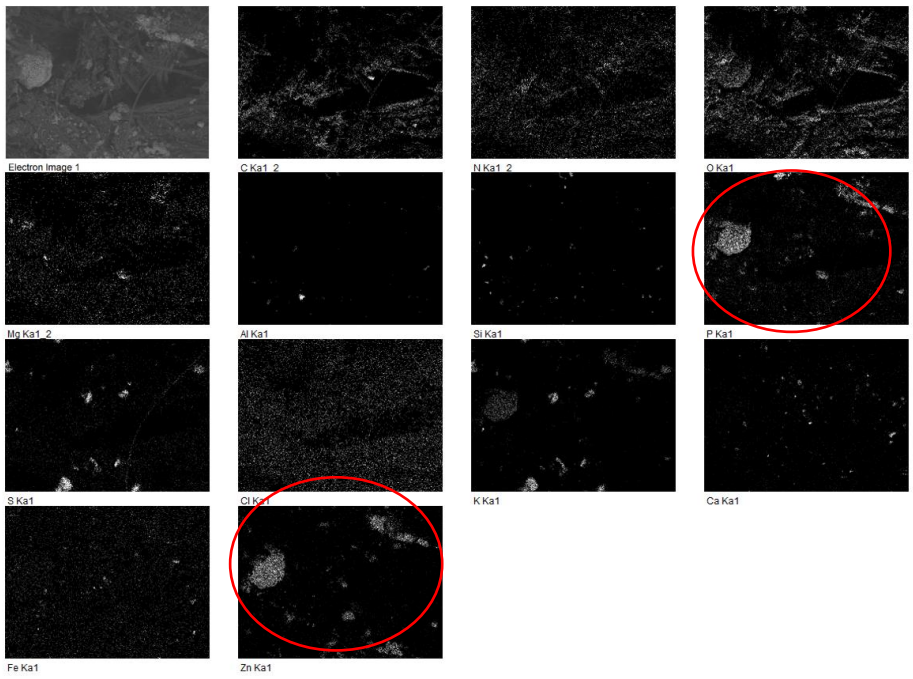


Figure 49. An image of an area in sample 8 after coating. The results of mapping of the entire area of the image from sample 8. Each image shows the results for the detected elements, where highlighted shapes reflect higher atomic % of the element. The marked images show phosphorus and zinc (Rat poison or other pesticide residues?).

Figure 50. Sample 8 was taken from the area around the bat entrance hole.

All other measures taken to prevent and kill pests (xylamon and permethrin were mentioned during the survey) would have given results of high amounts of Chlorine. These measures could be the source for the Chlorine found on the base of the SW post. Most likely, the base is an area where spray pesticide would be used, because it is close to the ground and the surface visually resembles a surface suffering from soft rot damage. The base (or several bases) could have been considered as areas exposed of insect attacks. Xylamon was used in the church at least from 1973 and onwards. It is, however, not likely that these measures are causing the salt contamination problem in the SW corner of the church.

The aisle rafter connecting the SW nave corner post and the aisle wall plate has old insect attacks (figure 51) and has probably, also, been treated with pesticides on more than one occasion. The fact that the rafter shows no signs of defibration from salts indicates that the contamination in the area of interest for this project does not come from pesticides, at least not the pesticide used in this area (Figure 53 below)

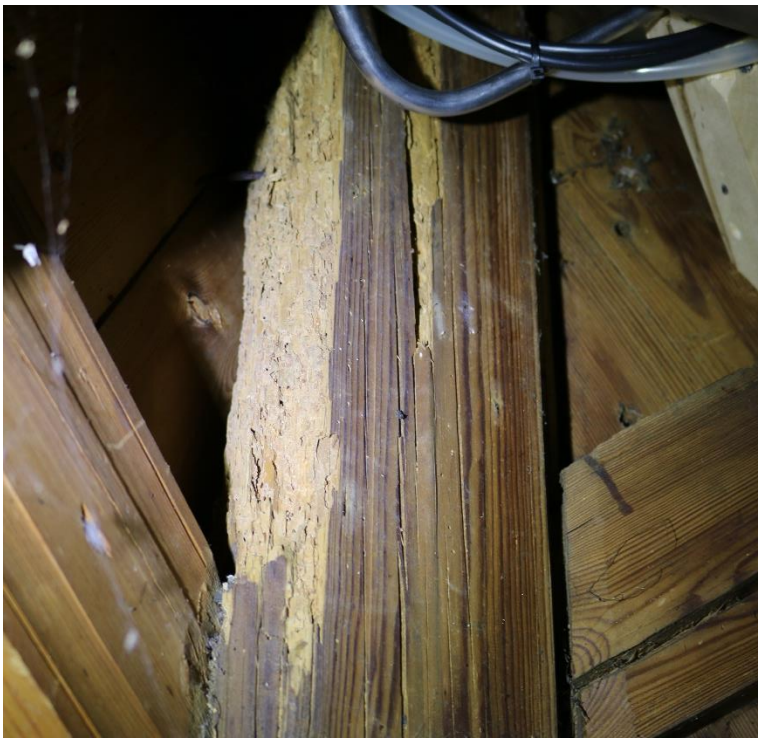


Figure 51. The aisle rafter connecting the SW nave corner post and the aisle wall plate, and carrying the aisle roof, has old insect attacks. This area will most probable have been treated with pesticides in the past but shows no sign of salt contamination.

Summary source of the salts

The elements present in bat urine and faeces potentially come from several sources. All elements present in bat droppings are present in the wood itself and in some pesticides. The lack of metal salts like Copper, Arsenic and Lead suggest that the salt defibration is not due to pesticide treatments in the area of interest. The presence of Zinc can be explained by the bat roost. Zinc might also derive from rat poison or other rodenticide treatments at some point in the church's history. Other pesticides are reported to have been used at Urnes but these pesticides have not caused crystallization damage and defibration, shown by the lack of characteristic fuzzy surface resulting from salts in the areas where wood boring beetles have attacked. The results of the analyses combined with visual proof of bat droppings give a clear indication that the bats are the source of the salts.

How do these salts affect the preservation state of the wood?

All examples from previous research demonstrate how salts cause wood deterioration on a microscopic level. Other authors have shown that degradation by salts can occur either mechanically by crystallization pressure, or chemically by altering the chemical composition of wood. Chemical decay is often explained by the decay of the middle lamella region, where the lignin and hemicellulose of the wood is degraded (Blanchette et al., 2002; Kučerová et al.,

2007). At Urnes, the deterioration is obvious through material loss and a hairy surface, but has it affected the microcrystalline structure of the wood?

The post and bressummer were examined macroscopically and microscopically and by four analytical methods: X-ray, FTIR, SEM and lignin staining. Additionally, pH of the wood gave an indication of decay and/ or contamination. On a macro level the wooden surface is degraded near the entrance of the bat roost (Figures 2b, 52 and 53). The wood is moist and fuzzy. The colour of the surface is lighter than the surrounding areas, as though it is losing surface and constantly exposing a new surface. Visual examination and material loss have shown that the affected area is constantly losing wood fibres. Because bats do not gnaw on wood, enlarge entry holes or make nests, this deterioration must solely be related to urine and faeces (Hales, 2017).

Figure 52. The SW corner post in 2005, photographed with an analogue NIKON F3. Scanned dias.

Photo: Leif Anker, Riksantikvaren

Figure 53. The joint between the SW corner post and bressummer in 2012. Photographed with NIKON D300, 12-24mm wide angle lense.

Photo: Leif Anker, Riksantikvaren

X-ray investigation showed that the bressummer is far more degraded than first assumed and has suffered extensive material loss in a large area. The causes of this degradation are extensive rot damages linked to water leakage over a longer period. Grey rot was found in samples from this area in 2004. The habitation of bats, and their urine and faeces, started the salt deterioration in an already damaged area. Mechanical and chemical degradation will be discussed.

Mechanical degradation

Mechanical degradation occurs when the salt fluctuates between hydrous and crystalline states and thereby changes the volume of the solutes. The degree of degradation and the speed of the degradation will depend on how often the salts changes between the thermodynamic phases, which again depends on many factors; the climate at Urnes, the crystallization point of the salt molecules present, and the size of the pores.

The climate over the one year (2017-18) is now known. The crystallization point for one single molecule can be found when the molecular composition is found. The crystallization point will however be affected by many factors, but this will be discussed further below.

All analyses have been elemental analysis and the molecular composition is not fully understood. The EDX analysis can to some point give an indication of the molecular composition. The SEM images clearly show salt crystal formations and these salt crystals have been mapped (see pages 58-60).

The degree of degradation also depends upon whether the salt only crystallizes at the surface of the wooden object, or whether the crystallization takes place further within the construction material, but as sampling has been done at the surface it is not possible to answer this question.

It is however logic that the salt molecules present at the surface of the post and bressummer work the wood dependent on the humidity in the air. The question is, how do these salts behave inside the wood pores? Are the salts within the wooden matrix dissolved in the urine, or will the liquid urine eventually dry out and leave residues like salts and urea crystals to destroy the wood structure through deliquescence and absorption of water from the air?

Salt crystallization related to relative humidity

Salt weathering cannot be understood without considering the interaction between microclimate and salt concentrations (Zehnder & Arnold, 1989, p. 31). Every salt has a specific relative humidity in which it precipitates/ crystallizes. The pressure in the pores of the substrate will increase when the equilibrium relative humidity (RH^{eq}) is crossed. The mechanical stress to the cell walls in the pine wood will exceed when the relative humidity frequently moves across this value.

The RH^{eq} is known for most salts, but as literature search has shown this value can change when influenced by different factors. One factor is the presence of a second salt which results in the change of relative humidity required for precipitation. A mixture of salt molecules radically affects the behaviour of the single salt isolated (Price & Brimblecombe, 1994). Additionally, low temperatures are the most critical factor to volume increase in a salt mixture. At lower temperatures, the hydration processes are initiated at lower RH than at higher temperatures. This is connected to the fact that solubility increases with temperature. So – in the winter the salts hydrate at lower RH. A third factor is that salts with an ion in common will affect the RH^{eq} of eachother, causing the salt molecules to precipitate at a lower RH (Price & Brimblecombe, 1994). Considering the factors mentioned above, the presence of many salt molecules will change the RH^{eq}.

Salt molecule EDX	**Saturation point (RH_{eq})**
Potassium sulphate (K_2SO_4)	98,2% (10°C)*
Potassium phosphate (KH_2PO_4)	95,6 % (25°C)**
Potassium nitrate	96 % (10°C)*
Zinc phosphide	Insoluble in water***
Urea	68%****
*(Greenspan, 1977) ** (Kamburova & Kirilov, 2010) ***("Zinc Phosphide. Technical Fact Sheet,") **** (Hales, 2017)	

Table 15. The equilibrium relative humidity of salts present in the Urnes SW post and bressummer.

Table 15 shows the RH^{eq} for the salt molecules found in the samples, and also urea which is a solute from urine. The salts are crystallized below the saturation point and hydrated above this point. The saturation points for the molecules identified in the samples are high, meaning that the salts stay crystallized until the RH crosses above this value. The indoor RH at Urnes crosses above 90 % only during heavy rain. This means that the thermodynamic phase for these salts are relatively constant, and the crystallization pressure low for these specific molecules.

It is important though to keep in mind that these values apply for the behaviour of the single salts. In the contaminated area, these salts exist in a mixture and the mixture of salts behave differently. The theoretical assumption for each single salt is however consistent with visual observations at Urnes, where white efflorescence is observed during rainy weather (figure 54). The contaminated area at Urnes is observed during all site visits during this project. The area feels moist and cold, and white efflorescence is visible both in sunny and rainy weather. No systematic visual observations have been made from the surface to document this efflorescence in different weather conditions, but the salt crystals at the surface indicate salts with a high saturation point.

Figure 54. White salt efflorescence on the SW post at Urnes during rainy weather. October 2019.

According to D'Armada (2005), nitrates from bat droppings are particularly damaging. Nitrogen is an indication of urine, but this element is hard to detect with most analytical instruments including ICP and XRF due to its small atomic mass. The SEM-EDX can detect Nitrogen but can confuse it with Carbon and Oxygen. Nitrates were not found here, neither by test strips nor during the EDX mapping of samples. The analyses have been conducted from the surface, and other salt contaminants can exist deeper into the wood. From the urine, the chlorides were of most concern to Paine (1993). Like nitrates, chlorides were not found as chloride salt molecules during EDX mapping. The highest amount of Chlorine was found on the base of the post where the surface shows no signs of salt deterioration.

In the initial phase of this project, urea was discussed as one of the expected contaminants. None of the analytical methods found nitrogen compounds in the wood and even test strips were not able to verify the presence of nitrates in the samples from the surface. FTIR, however, found urine and ammonia was detected by test strips. Urea, or the nitrogen

compounds they might have formed, can be present further into the material. As bat urine contains 70% urea, the molecule will be discussed.

Although not a salt in the chemical sense, urea acts like a salt. The equilibrium relative humidity is 68%. Under normal circumstances (when the urea is a solute in a porous matrix alone) the urea will be crystallised when the relative humidity is below 68% and hydrated above 68%. This specific relative humidity is a critical point, and when frequently crossed it will increase the pressure inside the wood. The climate at Urnes is warm temperate, with mild winters and high humidity most of the year. The logging showed that the median and mean relative humidity inside Urnes stave church lies around 70%. Looking at the values from month to month, the drier and warmer summer months have values just below 70% (for July the mean value is 61%). With mean and median values close to the critical relative humidity for a salt molecule, the molecule will in theory cross the critical crystallization point more frequently thus execute mechanical stress.

It should be noted that the choice of location of the two loggers affected the temperature values differently. The indoor logger was placed inside the south wall of the church, whereas the outdoor logger behind a northern wall. On sunny days the south wall of the church will be warmer than the air temperature in the shadow outside. This is seen in May 2018 for example, when the indoor temperature continued to rise for the indoor logger, whereas it reduced for the outdoor logger towards the night. The wooden wall keeps the heat, and this is also the reason why the bats have found this area of the church attractive.

EDX images showed some damages to the soft wall tissue and tracheid separation due to crystallization pressure (figure 55 and 57). It is important to keep in mind that crystal formation in laboratory does not mean the salts are harmful and causes mechanical pressure at site. The laboratory climate is warm and dry and salt molecules crystallize easily. In the church climate these salts might behave differently (stay deliquescent). The damages seen in EDX images will however show how these different salt molecules behave when they crystallize.

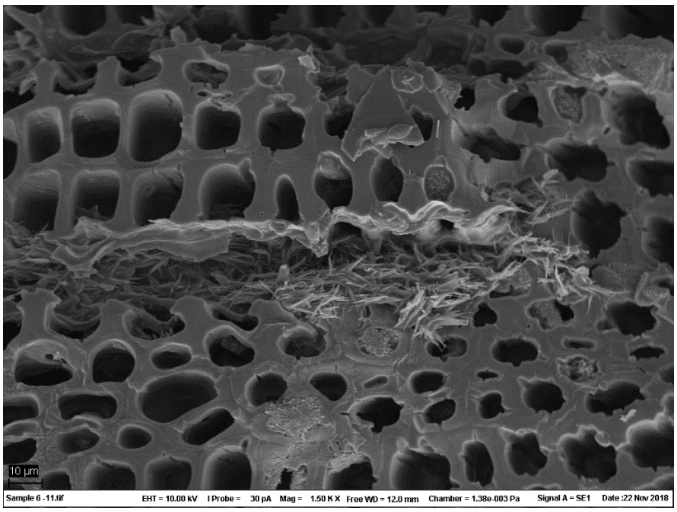


Figure 55. An image of sample 6.

The image shows tracheid separation, similar to what is reported from the research project of Tampa Bay , and others.

Magnification 1500x

An example of how the salt degradation might occur after centuries of salt contamination in wood is shown in figure 56 below. Many medieval food storage buildings in Norway suffer from salt defibration due to accumulated salt in the floor boards. Normal table salt – sodium chloride NCl – has been used to salt food, and the salt has accumulated in the floor boards. NCl has a RH^{eq} of 75,6 %.

Figure 56. The floor in this old building is heavily affected by salt degradation. The building lies in an area with dry climate, and the salts will cross their saturation point more often than in a humid climate. The photograph is taken from under the floor seen from the outside. Åsheim farm, Seljord Norway. Photo: Anders Amlo, Riksantikvaren.

Here, mechanical damage could not be ruled out. Mechanical damage cannot be proven by chemical methods. SEM images show clear indications of mechanical damagem but further work is needed.

Chemical degradation

FTIR was used to ascertain whether the wooden samples had suffered chemical degradation. Chemical analysis of degraded wood is challenging no matter the method used (Braovac,

2017, side 5). The FTIR analyses for this project were no exception. Results were not conclusive regarding the chemical degradation of the wood, at least no dramatic degradation. There was some indication of lignin and holocellulose degradation in samples from the contaminated area. The sample from the base of the SW corner post (reference sample) showed results most similar to sound pine, but with a slightly different ratio for the holocellulose.

The FTIR method is not sensitive enough to analyse samples that are slightly degraded. The report concluded that there seem to be a slight preferential decay of the lignin polymer. This conclusion is supported by the analyses in the optical microscope, where the samples had been stained by phloroglucinol. The lignin staining exercise was clear and showed a decreased lignin content compared to the reference from the drilled sample from the raft beam. However, comparison of the results from the contaminated samples to the non-contaminated samples from the base of the post was not possible. Both areas showed lignin decay.

Literature showed (Blanchette et al., 2002; Kučerová et al., 2007) that the middle lamella is affected by salt activity. Further investigation into the affected cells in the degraded post and bressummer at Urnes must be conducted to conclude if this is the case here. The samples were not rinsed prior to SEM analyses and the large salt crystals blurred the cell walls. This made it difficult to see whether the middle lamella region is deteriorated (figure 57).

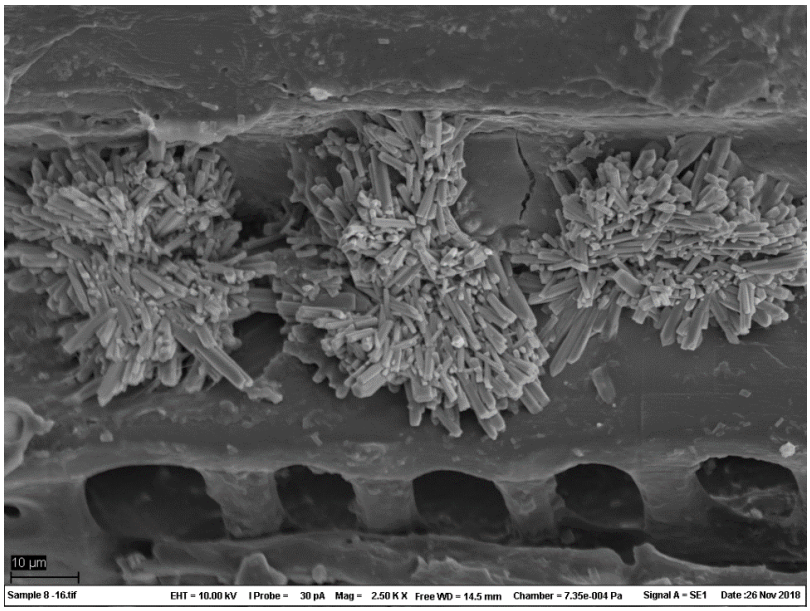


Figure 57. An SEM image of sample 8 coated with gold and palladium. The large salt crystals blur the cell walls and make it impossible to see whether the middle lamella region is deteriorated. A fracture between crystal 2 and 3 (from left) is seen.

Mag. 2500x

Acid hydrolysis

(pH – what does it say about the preservation state of the wood?)

Most wood species are weakly acidic with a pH value of approximately 5 (Unger et al., 2001, p. 98). The on-site measurements using pH indicator paper showed a pH of 5 in seven of the eight spots tested, which correlates to the normal pH of wood. The samples taken from the salt contaminated area and tested for pH in the laboratory gave a lower pH between 3,6 and 4,5. This test is more reliable than test strips. The base of the SW corner post is not affected by salt deterioration and gave a pH result as low as 4 in the laboratory. Some of the urine affected areas has a pH as low as 3,6.

There are many factors that will or can affect the pH of wood surface. Fungal growth is one example (Unger et al., 2001, p. 128). Salt decay can be confused with fungal decay (Kirker & Glaeser, 2011). The surfaces of the post and bressummer show no similarities to wood attacked by fungi. A visual comparison of the contaminated surface in the SW corner does not compare to wooden surfaces attacked by brown rot, white rot, soft rot or blue stain. The base of the SW corner post has a surface resembling that of a wooden surface attacked by soft rot (see figure 15).

Urine has a pH higher than wood. James Hales report that bat urine has a pH between 5,3 and 6,8 with a mean value of 6,3. With a "starting point" of a slightly acidic contamination of bat urine, what is the reason behind the pH decrease to below 4? Is the due to delignification of the wooden cells, or purely salt contamination?

According to the literature hydrolysis reactions by acid groups of wood components will occur when salt is present in wood (Unger et al., 2001, p. 45). Will hydrolysis of cellulose and hemicellulose (and lignin?) affect the pH of the wood? Or will the hydrolysis start because the salts make the matrix more acidic?

Acids and alkalis in the pH range of 3 to 10 have no significant weakening effect on either softwoods or hardwoods (Wangaard, 1966). This means that whatever the reason for the low pH in the degraded and contaminated wood from Urnes, the slightly acidic urine contamination will in itself not accelerate the degradation process. It seems that pH might be an indication of change, an indication of alien residues in the wood, but is not degrading to the wood.

Wangaard report that acid hydrolysis leads to loss of tenacity and embrittlement, resulting from the hydrolytic action of the acid on the carbohydrate constituents of the cell wall. The

lignin is the least affected by acid. Since there is some indication that the lignin has been affected in the samples studied here, and the visual observations at Urnes of the condition of the wooden building parts is not similar to the description given by Wangaard, the conclusion is that the degradation is not a result of acid hydrolysis.

Further work is needed to understand whether acid hydrolysis is the case here or will be the case after a longer period of contamination.

Summary preservation state of the wood

Chemical analysis of degraded wood is challenging no matter the method used (Braovac, 2017). The FTIR analyses found that there is a slight decline of the lignin and hemicellulose in the samples from the contaminated area compared to the base of the SW nave post. The analysis in optical light microscopy of the samples coloured by phloroglucinol gave a clear indication of loss of lignin. The images from the EDX of coated samples showed some sign of fractures in the wood tissue, but the salt molecules present made it difficult to explore this in detail.

The salt molecules found during EDX analyses have high equilibrium relative humidity (>90%). The complexity of salt behaviour, especially when a vast number of ions are present, makes it difficult to find the one critical relative humidity of transformation between the different thermodynamic phases of the salt mixture around the bat roost at Urnes. The characteristics of the single salts give reasons to believe that the mechanical degradation is slow. The visual observations support this hypothesis.

Measures to prevent further degradation

This topic undoubtedly presents conflicting interests between cultural heritage and natural environments. The stave church is a world heritage site, and automatically protected by Kulturminneloven ("The Norwegian Cultural Heritage Act," 1978). All bats in Norway are listed species, and Norway has an obligation to protect all species found in Norway through "EUROBATS" *(1991).* A close collaboration with zoological experts has been necessary to address the situation at Urnes and to identify the best solutions.

When bat colonies are first identified in a building, it is often due to the smell of the accumulated urine and droppings. The most common solution is to replace the affected

construction part with new materials. At Urnes, with an unbroken history of the corner post for almost 900 years, this is not desirable. Three questions arise:

- Are the salts representing a continuous and damaging threat to the construction parts?
- If so, are they possible to remove?
- How can further salt accumulation be prevented?

Further research into the damaging effects of the salt contamination must be conducted to find the speed of deterioration. Nonetheless, the salt accumulation represents a deterioration factor. Although the crystallization damage might be quite low due to a high saturation point of the identified salt molecules, the mechanical pressure is an ongoing process. Also, the salts migrate and might contaminate new construction parts. Measures to remove the salts should be tested and implemented.

Removal of salts can be challenging. An attempt of washing out the salts from the SW corner was made in 2002. Clean water was poured into the hollow roost. As there is little photographic documentation prior to this time from the deteriorated area, it is hard to tell whether the attempt reduced the surface degradation. It is however clear that this method was far from successful in washing out all the salts. Pouring water will do two things to salts; help them penetrate the porous wood and move them to other areas of the construction. This attempt might be the reason for the high findings of phosphates and sulphates originating from faeces on the vertical post away from the bat roost in the horizontal bressummer where the bat faeces have been dropped. The method was at best inefficient, at worst damaging.

In the literature, two different methods for salt removal from non-movable monuments are explored; neutralization of the surface and removal of salts by poultices. In the Chech republic, historical roof timbers were coated with ammonium phosphate and sulphate-based fire retardants. The salts degraded the surface and gradually thinning the surface creating a fibrous surface, similar to this Urnes case. Attempts were made to remove the hairy surface down to healthy surface and neutralized the surface using a solution. After a few years the degradation process started again (Kučerová et al., 2007) This method is thus not to be recommended.

Another method is the use of poultices to wash out salts. Both cellulose-based poultices and clay poultices are used. A European research project called the Desalination Project (Heritage, Heritage, & Zezza, 2013) has looked at methods for desalination of historic buildings, but like the research of salt deterioration, this research project was focused mainly on stone buildings and wall paintings. Some general knowledge might be transferable to wood. Sawdy, Lubelli, Voronina and Pel (2010) have found that for the desalination to be effective, the pore size of the poultice must be smaller than the pore size of the substrate. Desalination is a work demanding process and the result can be highly variable (Sawdy et al., 2010, p. 26), but attempts should be made in the SW corner at Urnes stave church.

Further salt accumulation is avoided by preventing the bats from re-entering the roost. The bats move out during the winter to hibernate at a site with stable temperatures close to their body temperature. It is important not to disturb the bats while roosting. During the winter measures can be taken to prevent the bats from re-entering the roosts the next roosting season (figure 59). After exclusion from the heritage building, it is important to give them alternative shelter, for instance in bat boxes (figure 60 – see also appendix 3 for advice).

Other methods to exclude bats are ultrasonic noisemakers. The effectiveness of these instruments is controversial ("How to get Bats out of a Building," 2014). At Urnes, the alarm system gives off an ultrasonic sound (Michaelsen, 2017a). This might have frightened the bat colony and prevented them from using the roost again.

The wildlife camera did not discover any activity from June 2017 to June 2018 in the SW corner of the church. There could be two reasons for this, either bats were not using the SW corner post for roosting during this period, or the settings of wild life camera are too insensitive to detect bat activity. The bats move fast. A detection using ultrasound detector in June 2017 also gave negative results. The colony could have moved out from the church permanently or temporary (Michaelsen, 2017b).

A bat was seen by the church warden inside the chancel during the period of this work (19th of August 2017). The bat was photographed (figure 58) and the image was sent to bat experts who identified it as either Whiskered Myotis (Myotis mystacinus) or a northern bat (Eptesicus nilssonii) (Personal communication, Jeroen van der Kooij, 22.11.2017). Together with the identification of the bat faeces (from long-eared bat), three possible species have been identified at Urnes. During this project, this was the only sighting of a living specimen. From

this we have reasons to believe that bats were not using the church as a roosting area during the time frame of this project.

Figure 58. This bat was found on the floor in the chancel in the middle of the day, the 8th of August 2018.

Figure 59. A method for preventing bats to re-enter the building is to seal bat entry holes.

Figure 60. Bat boxes of this kind mounted in nearby trees can offer alternative shelter for bats living in buildings.

Different bat species have different roost fidelity. Some are faithful to a roost over years, and some change roosts nearly every day (Lewis, 1995, p. 481). Of the three species identified at Urnes, the northern bat rarely switches roosts. Different disturbances can affect site fidelity, along with many other factors including microclimate and roost structure, parasitism and predation. The majority use a range of roosts, including trees, buildings and underground sites (Marnell & Presetnik, 2010). 70 % of European bat species depend on different overground roost sites, and in Norway up to 20% of all bats use churches during the roosting season (Marnell & Presetnik, 2010, p. 15).

To prevent further salt accumulation, surfaces (floors, capitals and other horizontal areas, roosts) should be cleaned on a regular basis. Measures should be implemented in the following order; 1. Remove all droppings 2. Cover sensitive surfaces when the church is closed 3. Ensure alternative shelter, and 4. Seal openings in the church and known roost sites. If these measures are not sufficient to avoid bat roosts inside Urnes stave church, bat experts should be contacted to help with relocation of the colonies.

CONCLUSIONS

The research questions posed in the first chapter of this dissertation have been answered. The salt molecules were identified, and the source of the salts determined and discussed. All elemental analyses showed presence of other elements in the samples than are generally found in wood. The results from the analyses combined with visual proof of bat droppings give a clear indication that bats are the source of the salts. Microstructural deterioration of the wood has been partly recognised, but more research is needed to address this question thoroughly.

The salt molecules do not derive from urine only, but residues from faeces play an important role in the salt deterioration at the surface of the SW post and bressummer.

Detection of the elements Potassium, Sulphur and Phosphorus were significant, both from XRF and SEM-EDX analyses. These elements are not found in urine. FTIR spectra gave results for urine contamination in the wood, but salts from urine are not identified as factors in the mechanical deterioration caused by crystallization pressure. Thus, during the course of this project, the focus shifted from urine to include the faeces also. Mainly Potassium sulphates and Potassium phosphates were found in the samples collected from the surface of the SW nave corner post and bressummer. Analyses in SEM-EDX of faeces gave significant amounts of Sulphur and Phosphorus.

Other possible sources of the contamination have been explored but excluded as the main deterioration factors. Chlorine was found on the base of the post, and the amount was higher here than around the bat roost. The Chlorine might derive from a pesticide, or from mammal urine. Zinc phosphide or phosphate was found on samples from the aisle side of the SW post, and a possible source is rat poison. Chloride based pesticides and rat poison have not caused crystallization damage and defibration, shown by the lack of characteristic fuzzy surface resulting from salts in the areas where pesticides are expected to have been used in the past (areas infested by wood boring beetles).

SEM images of samples from the contaminated area show that the wooden cells are affected by the salts. The images show the force the crystallized salt molecules exert on the wood to break the cells. There are some fractures in the wood tissue, but the crystallized salt molecules made it difficult to explore this in detail. SEM imaging was time consuming. Evidence of chemical decay in the molecular structure of the wood needs further attention. From the literature, deterioration of the middle lamella is reported, but further work is needed to state if this is the case here. FTIR analyses found that there is a slight decline of the lignin and

hemicellulose in the samples from the contaminated area compared to the base of the SW nave post. The analysis in optical light microscopy of samples stained by phloroglucinol gave signs of degraded lignin.

Potassium sulphates and phosphates have high equilibrium relative humidity (>90%). The complexity of salt behaviour, especially when a vast number of ions are present, makes it difficult to find the one critical relative humidity of transformation between the different thermodynamic phases of the salts present around the bat roost at Urnes. Thermodynamic simulations have not been conducted here. Logging instruments gave valuable information about the indoor climate and possible bat presence. The climate at Urnes is humid but will not exceed the saturation points of the single identified salt molecules very often. Thus, molecules will be stable crystals in this climate and the salt deterioration is a slow process.

Advice for church owners struggling with urine and excrements from bats is long overdue, and this project will help Riksantikvaren to establish guidelines for bats in historic buildings. At Urnes, protection of the unique stave church is important. It must be preserved for the eternity, for future generations, and deterioration factors reduced to the minimum. All preservation measures must balance the considerations between invaluable cultural heritage and vulnerable natural species. With interdisciplinary knowledge, all considerations can be met.

Further research

Salt is recognised as the most frequent and effective weathering agent in porous building materials. Most research deals with buildings made of stone and bricks. More research into the salt weathering of wooden building materials is needed to be able to address this problem thoroughly. The behaviour of salt mixtures in wood also needs further attention. Pore structure in wood is different than in stone, and the salt molecules found in wood are different. Collaboration with salt chemists to conduct thermodynamic simulation of the salt molecules found would give a more precise understanding of the behaviour of the salt mixture. Other methods than already explored here, or a development of the methods used, is necessary to answer some of the research questions.

Ion chromatography has been used successfully to find ionic compounds and is a good method to detect nitrate salts (cf. previous investigations by NILU).

FTIR gave interesting, but unclear results. The possibilities within this analytical technique can be explored some more. Also, XRD can be used to examine the degradation of cellulose.

SEM-EDX gives an understanding of microstructural degradation and the characteristics of the contamination, and the method can be exploited more into this topic. Sample treatment is important for the best results, and the examination of both rinsed and non-rinsed samples will give a more comprehensive understanding of the degradation. The contamination will behave differently in a different environment, and possibly accelerate deterioration. Thus, "freezing" the situation in the samples is important. Salt contaminated samples should be rinsed immediately after sampling to prevent further mechanical stress to take place after sampling and relocation of the samples into a different climate in the laboratory. Salt affected wooden cells from expedition huts in the Antarctic have been successfully studied in SEM. Blanchette, Held and Farrell (2002) do not report whether the samples were rinsed prior to the analyses.

Accoustic emission (AE) is a sensitive and non-destructive method that is used to monitor micro-damage in objects (Lukomski et al., 2017). It detects sound waves travelling through the material when change releases energy. It has been successfully used in cultural heritage to detect movement within wood affected by variable relative humidity. Historic wooden objects are sensitive to humidity changes, and environmental induced damage can be detected by AE (Strojecki, Lukomski, Krzemień, Sobczyk, & Bratasc, 2014). Reasearch using the AE method to monitor crystallization pressure due to salt contamination has not been found, but the potential is there. Field research should be complemented by lab research. Studies of non-contaminated areas and contaminated areas in the same climate might give an understanding of the excess pressure salt contaminated wood is exposed to compared to non-contaminated wood in the same construction. Also, the AE records can be compared to climate data to find the critical relative humidity to which the salts undergo thermodynamic change.

This project has studied samples from the surfaces of the deteriorated area. The situation deeper within the material is not known. Other salt ions, with different characteristics, might be present there. Chlorides and nitrates might have fractionated deeper into the material. Experimental laboratory work on wood contaminated with urine and faeces would help to extend the knowledge about inhabitant bats in wooden heritage buildings.

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Appendix 1 List of samples

SAMPLE	LOCATION	CONTENT	Sampled DATE	Sampled by	Analytical method	Analysis DATE	Analysed by
A	South bressummer, beside SW stave, gallery side	Test strip. Same location as H		Leif Anker	**pH strips**	21.09.2015	Leif Anker
B	Bressummer, gallery side	Same location as I		Leif Anker	**pH strips**	21.09.2015	Leif Anker
C	Arch over arcade, aisle side	Same location as J		Leif Anker	**pH strips**	21.09.2015	Leif Anker
D	Bressummer, aisle side	Same location as K		Leif Anker	**pH strips**	21.09.2015	Leif Anker
E	SW stave, above capitol	Same location as L		Leif Anker	**pH strips**	21.09.2015	Leif Anker
F	SW stave, higher than E	Same location as M		Leif Anker	**pH strips**	21.09.2015	Leif Anker
G	SW stave, higher than F	Same location as N		Leif Anker	**pH strips**	21.09.2015	Leif Anker
H	Bressummer, beside SW stave, gallery side	Same location as A		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
I	Bressummer, gallery side	Same location as B		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
J	Arch over arcade, aisle side	Same location as C		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
K	Bressummer, aisle side	Same location as D		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
L	SW stave, above capitol	Same location as E		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
M	SW stave, higher than E	Same location as F		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
N	SW stave, higher than F	Same location as G		Leif Anker	**Sulphate test strip**	21.09.2015	Leif Anker
0	Raft beam, west	Reference wood sample	19.04.1994	Terje Thun	**SEM uncoated and coated**	22.11.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
6	Sill beam hole	Wood fibres	08.06.2017	Francesco Caruso	**SEM uncoated and coated**	26.11.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen

SAMPLE	LOCATION	CONTENT	Sampled DATE	Sampled by	Analytical method	Analysis DATE	Analysed by
7	Sill beam hole	Wood fibres	08.06.2017	Francesco Caruso	**SEM uncoated**	30.10.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
8	Behind sill beam and post	Wood fibres	08.06.2017	Kjersti Ellewsen	**SEM coated**	27.11.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
9	Stave base	Wood fibres	08.06.2017	Kjersti Ellewsen	**Test strips for ammonium and nitrates**	23.08.2019	Kjersti Ellewsen
K 4	From netting under sill beam	Feces and wood fibres	08.06.2017	Kjersti Ellewsen/ Francesco Caruso	**Test strip ammonium and nitrates**	23.08.2019	Kjersti Ellewsen
K 6	Sill beam hole, gallery side	Wood fibres	08.06.2017	Francesco Caruso	**SEM-EDX**	30.10.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
K 7	Sill beam hole, gallery side	Wood fibres	08.06.2017	Francesco Caruso	**SEM-EDX**	30.10.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
K 8	Behind sill beam and post	Wood fibres	08.06.2017	Kjersti Ellewsen	**SEM-EDX**	30.10.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
K 9	Stave base	Wood fibres	08.06.2017	Kjersti Ellewsen	**Test strip ammonium and nitrates**	23.08.2019	Kjersti Ellewsen
K 14	SW post, above twig near entrance hole for bats		20.06.2018	Kjersti Ellewsen	**SEM-EDX**	30.10.2018	Hilde Raanaas Kolstad/ Kjersti Ellewsen
K 15	SW post, base		20.06.2018	Kjersti Ellewsen	**SEM-EDX**	30.10.2018	
K 16	SW bressummer, hole		10.11.2016	Kjersti Ellewsen	SEM-EDX		Kjersti Ellewsen
XRF_1	SW stave base back	Reference area			**XRF**	08.06.2017	Kjersti Ellewsen
XRF_2	SW stave base front	Reference area			**XRF**	08.06.2017	Kjersti Ellewsen
XRF_3	SW stave 2 m up front	stave exterior			**XRF**	08.06.2017	Kjersti Ellewsen
XRF_4	SW stave 1,5 m up front	stave exterior			**XRF**	08.06.2017	Francesco Caruso

SAMPLE	LOCATION	CONTENT	Sampled DATE	Sampled by	Analytical method	Analysis DATE	Analysed by
XRF_5	SW post, gallery stairs, by arcading	stave exterior			**XRF**	08.06.2017	Francesco Caruso
XRF_6	SW post, gallery stairs, top joint	stave exterior			**XRF**	08.06.2017	Kjersti Ellewsen
XRF_7	Sill beam, gallery, above hole	sill beam exterior			**XRF**	08.06.2017	Francesco Caruso
XRF_ch	Chancel N wall	Reference area			**XRF**	08.06.2017	Francesco Caruso/ Sara Mantellato
ICP_0	Left raft beam, nave	Reference sample	19.04.1995	Terje Thun	**ICP-OES**	01.04.2017	Francesco Caruso/ Sara Mantellato
ICP_1	Gallery, south sill beam, under bat area		21.09.2015	Leif Anker	**ICP-OES**	01.04.2017	Francesco Caruso/ Sara Mantellato
ICP_1	Gallery, above bow, drilled hole by SW post		21.09.2015	Leif Anker	**ICP-OES**	01.04.2017	Francesco Caruso/ Sara Mantellato
ICP_3	Aisle side, above bow, drilled hole by SW post		21.09.2015	Leif Anker	**ICP-OES**	01.04.2017	Susan Braovac
L 1	SW corner stave, hole in join between stave and bressummer	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 2	Dendro hole, gallery side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 3	Dendro hole, aisle side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 4	SW corner stave, under bressummer south side, gallery side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 5	Bressummer, by stave, aisle side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 6	Bressummer, under, 25 cm from stave, gallery side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 7	SW corner stave, above capitol to the east	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac

SAMPLE	LOCATION	CONTENT	Sampled DATE	Sampled by	Analytical method	Analysis DATE	Analysed by
L 8	SW corner stave, base	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 9	Arch over arcade, aisle side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 10	Arch over arcade, aisle side	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
L 11	Aisle rafter	Wood sample	21.09.2015	Leif Anker	**FTIR**		Susan Braovac
0	Raft beam, west	Reference wood sample	19.04.1994	Terje Thun	**Light microscopy with lignin staining**	10.12.2018	YoenKyeong Lee, NMBU Imaging Centre
K 6	Sill beam hole	Wood fibres	08.06.2017	Francesco Caruso	**Light microscopy with lignin staining**	10.12.2018	YoenKyeong Lee, NMBU Imaging Centre
K 11	SW post, loose sample inside hole above capital	Wooden piece	19.06.2018	Kjersti Ellewsen	**Light microscopy with lignin staining**	10.12.2018	YoenKyeong Lee, NMBU Imaging Centre
K 14	SW post, aisle, between dendro holes		20.06.2018	Kjersti Ellewsen	**Light microscopy with lignin staining**	10.12.2018	YoenKyeong Lee, NMBU Imaging Centre
K 15	SW post, base		20.06.2018	Kjersti Ellewsen	**Light microscopy with lignin staining**	10.12.2018	
K 17	From the floor below the roost	Wooden sample	10.11.2016	Kjersti Ellewsen	**Test strip ammonium and nitrates**	23.08.2019	

Appendix 2 XRF test areas

Test area	Picture of the shooting
Post 7 (R# 140)	
Post 6 (R# 139)	
Post 2 (R# 133)	
Chancel (R# 141)	
Chancel (R# 142)	
Chancel (R# 143)	

Appendix 3 Report from bat investigation

Flaggermus i Urnes stavkirke (Luster kommune, Sogn og Fjordane): feltundersøkelser og forslag til avbøtende tiltak

Michaelsen Biometrika, rapport 2/2017.

Michaelsen Biometrika AS

Denne rapporten tar for seg flaggermus i Urnes stavkirke (Luster, Sogn og Fjordane) og fokuserer på forekomst av flaggermus og mulige avbøtende tiltak. Kirken ble undersøkt både innendørs og utendørs med ultralyddetektorer. Det ble ikke påvist flaggermus i med tilknytning til
kirken i juni 2017, men flaggermus har tidligere hatt tilhold ved den ene staven i kirken. Fordi kirken tidligere har vært tilholdssted for flaggermus og fordi tiltak gjort i kirken trolig har hatt negative effekter for dyregruppen, anbefales det flere rimelige avbøtende tiltak som kan vurderes av Riksantikvaren. Slike avbøtende tiltak vil være særlig viktige dersom man planlegger å behandle kirken med kjemikalier som man vet er skadelige for flaggermus. Ved å gjennomføre slike tiltak, vil man, etter forfatterens oppfatning, holde seg innenfor de obligatoriske forpliktelser som Norge har i forhold til EUROBATS-avtalen.

Michaelsen Biometrika AS

Michaelsen Biometrika AS driver naturvitenskapelig forskning innen terrestrisk økologi. Firmaet leverer resultater som er på høyde med forskningsinstitusjoner og skiller seg vesentlig fra andre mindre firma som driver naturundersøkelser på grunn av svært høy kompetanse innen feltdesign og eksperimentell design, statistikk og geografiske informasjonssystemer. Michaelsen Biometrika AS fokuserer primært på studier av komplekse mønster i naturen. For mer informasjon, besøk nettsidene på www.biometrika.no

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Rapportnummer: Michaelsen Biometrika AS 2/2017

Anbefalt referanse til denne rapporten:

Michaelsen, T.C. 2017. Flaggermus i Urnes stavkirke (Luster kommune, Sogn og Fjordane): feltundersøkelser og forslag til avbøtende tiltak. Rapport 2/2017, Michaelsen Biometrika AS, Ålesund.

Forord

Dette er en nokså enkel rapport som følge av registreringer gjort ved Urnes kirke i juni 2017. Rapporten tar for seg de tema som er ønskelig å belyse nærmere basert på samtaler med Kjersti Marie Ellewsen og dels samtaler med Francesco Caruso. Selv har jeg svært beskjeden kunnskap om verneverdige bygninger og de begrensinger som naturlig nok må foreligge vedrørende hvilke inngrep man kan gjennomføre i slike bygninger. Denne rapporten vil derfor måtte være en veiledning for hva som er ønskelig med fokus på flaggermusforvaltning. Den endelige vurderingen av mulige tiltak vil til syvende og sist ligge hos Riksantikvaren. Det finnes en del retningslinjer i internasjonale avtaler og i

norsk lovgivning med hensyn til hvordan man kan oppføre seg når flaggermus bruker et sted som dagoppholdssted eller ynglekoloni. I hvilken grad man kan avvike fra slike retningslinjer når man jobber med denne typen verneverdige bygninger er ikke mulig å avgjøre for forfatteren, men Miljødirektoratet kan kanskje svare på dette. Selv er jeg alltid av den oppfatning at det må finnes gode løsninger som kan ivareta både interesser til mennesker og dyrene som lever rundt oss. Denne rapporten søker i størst mulig grad å finne slike gode løsninger som tilfredsstiller både ønsket om å bevare stavkirken (inklusive det estetiske) og samtidig ivareta flaggermusenes interesse og de internasjonale forpliktelser som Norge har valgt å være med på.

God lesning! Tore Christian Michaelsen

Summary

This report focuses on bats in Urnes stave church in Luster municipality, Sogn og Fjordane county. Urnes stave church is listed as a *World Heritage Site* by UNESCO. In this church, bats have previously used an area in connection with one of the posts («stav») and damage is likely to have occurred due to bat urine. At least brown long eared bats (*Plecotus auritus*) have been confirmed through analysis of bat droppings. Bat occurrence was surveyed using hand held and stationary ultrasound detectors during the evening and night of June 7 – June 8, 2017. No bats were seen leaving the church despite suitable weather conditions (bat activity was high in other areas along the fiord). The activity recorded with the stationary ultrasound detector was very low and no endangered species were recorded. Also, no bats were found inside the church during daytime on June 8, 2017, but a few relatively fresh (probably < 1 year of age) were found. This suggests that the church, at present, is not an important site for bats, but it could be occupied by few or single individuals during parts of the season (as is common in many churches). The church has previously been treated with chemicals dangerous to bats, and gassing was used in the 1980's. Such efforts should have had both a short time (gassing) and long-term (chemicals) negative effects on bats that would occupy the church. In addition, ultrasound (in the range 20-30 kHz) from equipment used to protect the church (surveillance/alarm systems) was strong in the area near the post with likely damage from bat urine. This too could affect the suitability of this part of some parts of the church. Several measures should be considered to reduce potential negative effects both for bats and for the church. Carrying out such measures are required as Norway is a member of the EUROBATS agreement. Sealing off damaged structures are obvious measures. Also, the use of bat boxes should be considered. Due to the World Heritage status, no measures that would be visible to visitors are recommended and the aesthetic impact is given due weight. Bat boxes can be installed in the attic (not visible from the church room) and on nearby trees outside the churchyard.

Innledning

Flaggermus utgjør omtrent 20 % av pattedyrartene i verden og er en dyregruppe som viser stor variasjon i både utseende og oppførsel. I Norge er det påvist 13 flaggermusarter pr. oktober 2015 (Flåten & Røed, 2007; Isaksen, 2007; Isaksen et al., 2009; Michaelsen, 2011a). Disse er vannflaggermus *Myotis daubentonii*, skjeggflaggermus *M. mystacinus*, skogflaggermus *M. brandtii*, børsteflaggermus *M. nattereri**, nordflaggermus *Eptesicus nilssonii*, sørflaggermus *E. serotinus**, skimmelflaggermus *Vespertilio murinus*, storflaggermus *Nyctalus noctula*, dvergflaggermus

Pipistrellus pygmaeus, trollflaggermus *P. nathusii*, tusseflaggermus *P. pipistrellus**, bredøre *Barbastella barbastellus** og brunlangøre *Plecotus auritus*. Alle disse artene er påvist i Sør-Norge, men flere av artene er sjeldne og er påvist kun på én eller svært få lokaliteter (disse er merket med * bak artsnavnet). Sørflaggermus kan ha kommet med skip eller annen transport over landegrensen og er påvist kun én gang (i Møre og Romsdal). Uten flere funn bør den ikke regnes som en norsk art.

I Sogn og Fjordane er flaggermusfaunaen nokså godt undersøkt og da særlig de nordlige områdene av fylket som har vært en del av et studieområde som har vært undersøkt med ultralydloggere over flere år. Kartleggingsarbeidet er gjort i flere omganger. Norsk Zoologisk Forening gjorde grunnarbeidet med biltransekter og en del fangst (Michaelsen & van der Kooij, 2006). Senere har nokså mange flaggermus blitt fanget inn med nett og lokkelyder (hovedsakelig av forfatteren – lagt ut på Artsobservasjoner.no) og noen biltransekter har vært gjennomført, hvor nye arter har blitt påvist (for eksempel Michaelsen, 2007). I 2016 ble et større prosjekt med ultralydloggere gjennomført om høsten og her ble igjen en ny art påvist i fylket (Michaelsen, 2016a). Kunnskap om overvintring hos flaggermus er svært mangelfull. Trolig bruker flaggermus flere ulike habitater, hvor bygninger er blant alternativene (Michaelsen et al., 2013).

Det finnes vesentlig variasjon i hvor godt de ulike kommunene i Sogn og Fjordane har vært kartlagt og detaljkunnskap mangler altså fremdeles for mange arealer. I Luster har det vært gjennomført kun en beskjeden innsats for å kartlegge flaggermusfaunaen og hoveddelen av kjent kunnskap stammer fra perioden før 2006 (se Michaelsen & van der Kooij, 2006). Her har det blant annet ikke blitt gjennomført fangst hvor man kombinerer bruk av lokkelyd og fangstnett. Heller ikke ultralydloggere har vært utplassert i området. Basert på kunnskap fra lignende fjordsystem, kan man likevel ha en viss forståelse for hva man kan forvente å finne i dette landskapet. Trolig er det slik at den sørvendte delen av fjorden har høyest tettheter og diversitet (for eksempel Michaelsen, 2011b; Michaelsen et al., 2011; Michaelsen, 2012, 2016b, c). Det er også slik at man kan forvente høyest diversitet og tettheter i de varmeste områdene i dette landskapet (Michaelsen, 2016d) og høyereliggende arealer forventes å være mindre viktige. Generelt ligger Luster i et område med nokså lite nedbør, hvilket er positivt for diversitet (Michaelsen, 2016d).

Flaggermus prefererer nokså varme steder for sine ynglekolonier (for eksempel Lourenco & Palmeirim, 2004) og svært mange arter legger kolonier til bygninger. Flaggermuskasser er også et alternativ, og på Vestlandet har slike kasser vært anvendt med stor suksess (Michaelsen, 2011c; Michaelsen et al., 2014). I mange tilfeller har det vært mulig å få flaggermus ut av bygninger ved hjelp av slike kasser. Kasser kan således være et gunstig avbøtende tiltak i de tilfeller hvor flaggermus ikke er ønsket i menneskelige konstruksjoner. I noen tilfeller vil flaggermus også være langt tryggere i slike kasser ettersom de ikke påvirkes av renovasjon, bruk av kjemikalier eller andre forhold som kan være negativt for dyregruppen. Norge har ratifisert EUROBATS-avtalen som skal sikre populasjoner av flaggermus mot negative faktorer (se www.eurobats.org). Dette inkluderer beskyttelse mot bruk av skadelige kjemikalier i bygninger (se Marnell & Presetnik, 2010). Avtaleteksten er som følger (artikkel III, paragraf 8):

«Each Party shall, wherever appropriate, consider the potential effects of pesticides on bats, when assessing pesticides for use, and shall endeavour to replace timber treatment chemicals which are highly toxic to bats with safer alternatives»

Urin fra flaggermus kan skade menneskeskapte konstruksjoner på ulike vis (se Paine, 1993) og det vil derfor være ønskelig å unngå at flaggermus kommer til slike steder. Å bruke kjemikalier rettet mot flaggermus er ikke lenger et alternativ og tiltak knyttet til utestengelse eller at man tilbyr flaggermus alternative tilholdssteder er de mest rimelige tilnærmingene til å løse problemer av denne typen. Hvordan man går frem når man skal finne gode løsninger avhenger av en rekke forhold, og tiltak som gjennomføres vil avhenge av hvilke muligheter som finnes på det aktuelle stedet. Det vil for eksempel være uaktuelt å henge opp flaggermuskasser på ytterveggene til en stavkirke på UNESCOs

verdensarvliste. Likeledes vil det være uaktuelt å bruke fyllmasse (for eksempel ulike typer byggmasse eller fug) som vil endre på sammensetningen av kirkebygningen. En annen vurdering som også må gjøres er hvilke effekt eventuelle tiltak vil ha på populasjoner av flaggermus. Her vil igjen truethetskategori hos flaggermus være en viktig faktor og mengde flaggermus som bruker en konstruksjon vil også være av betydning.

Denne rapporten oppsummerer funndata gjort i og utenfor Urnes stavkirke i juni 2017. Feltarbeidet ble gjort samtidig med at kirken ble undersøkt av personer med særlig kunnskap om verneverdiene som denne kirken utgjør. Noe av hovedformålet var å undersøke om flaggermus bruker arealer i kirken og særlig rundt den ene staven hvor flaggermus er påvist tidligere og ut fra disse resultatene gi råd om hvilke mulige tiltak som kan gjennomføres for å ta rimelig hensyn til flaggermus. Som følge av samtaler med konservator og kjemiker under feltarbeid, ble datainnsamlingen noe utvidet. Denne ekstra innsatsen gjøres uten ekstra kostnader for oppdragsgiver og fokuserer på innsamling av materiale som er sterkt påvirket av flaggermus urin og kontroll som er upåvirket. Disse kan brukes til å identifisere sammensetninger av stoffer fra flaggermus på/i trevirke.

Materiale og metoder

2.1. Registeringer utenfor kirken (07.06.-08.06.2017)

Her ble det gjennomført en kombinasjon av direkte observasjon og bruk av håndholdt ultralyddetektor (D240X, Pettersson Elektronik AB, Sverige) i tidsrommet 21.00 til 00.10 natten fra 7. juni til 8. juni 2017. Et kort avbrudd for å se på flaggermuskasser ble gjort rundt 21.30 (ca 10 minutter). Sted for observasjonene var i hovedsak det nordvestre hjørnet av kirken og ultralyddetektoren var for en stor del innstilt mellom 40 og 50 kHz. Flere av artene er gjerne godt synlig når de forlater bygninger og dette gjelder særlig de større artene og dvergflaggermus. *Myotis* arter og brunlangøre er langt mer diskret og disse vil normalt fly mot områder med vegetasjon (trær).

I tillegg til de manuelle registreringene ble en ultralydlogger (D500X, Pettersson Elektronik AB, Sverige) utplassert på en bjørk som står innenfor steinmuren til kirkegården i det nordøstre hjørnet. Denne logget data fra kl 21.00 (07.06.2017) til 04.00 (08.06.2017). Loggeren ville altså fange opp all aktivitet i den nordlige delen av kirkegården (og dermed det nærmeste området med skog i tilknytning til kirken).

2.2. Registreringer inne i kirken

Her ble alle deler av kirken som er tilgjengelig undersøkt med tanke på sportegn (ekskrementer og eventuelle rester av byttedyr med fokus på brunlangøre (Lepidoptera)). Særlig fokus var på området ved den ene staven hvor man finner skader som kan være knyttet til aktivitet fra flaggermus, men også loftet og tårnet ble godt undersøkt og arealet nedenfor stavene andre steder i kirken. Det ble også lyttet etter sosiale lyder og eventuelt andre lyder som ligger i området fra ca 20 kHz og oppover.

Resultater

3.1. Registrering av flaggermus utenfor kirken (07.06.-08.06.2017)

3.1.1. Manuelle registreringer kveld

Det ble ikke påvist flaggermus som forlot kirken mellom kl 21.00 og 00.10 og det ble heller ikke hørt flaggermus i området ved hjelp av ultralyddetektor. En ubestemt ultralyd (ikke fra flaggermus) ble

registrert når man oppholdt seg i nærheten av kirken. Denne lyden var sterkest nært inngangspartiet.

3.1.2. Ultralydlogger (D500X)

Her ble kun noen få flaggermus påvist og antallet regner jeg som svært lavt sammenlignet med det jeg ville forventet å finne på en lokalitet som er viktig for flaggermus. Totalt ble det gjort 15 opptak hvorav 8 var nordflaggermus, 1 var fra en ubestemt Myotis og 2 kunne ikke bestemmes sikkert til art eller genus (slekt). De resterende 4 opptakene var støyfiler (vind som gjør at løvverket produserer lyd). Disse opptakene er av dyr som forflytter seg i området og behøver ikke å ha tilknytning til selve kirken.

3.1.3. Aktivitet i området Urnes-Skjolden etter avsluttet økt ved Urnes kirke

I løpet av en nokså kort strekning fra Urnes i retning Skjolden ble det registrert 50 nordflaggermus og tellingen ble da avsluttet. Også ubestemte *Myotis* og dvergflaggermus ble påvist. Aktiviteten denne natten regner jeg som god.

3.2. Registreringer inne i Urnes kirke på dagtid (08.06.2017)

3.2.1. Undersøkelser med ultralyddetektor

Det ble ikke hørt sosiale lyder inne i kirken og dette inkluderer området ved den ene staven hvor flaggermus har hatt tilhold. I dette området ble det kun hørt (sterke) lyder i frekvensområdet 20 til 30 kHz (ukjent radiobølge) som forventes å komme fra utstyr montert inne i kirken (ikke knyttet til flaggermusenes ultralyder).

3.2.2. Søk etter ekskrementer og andre sportegn

Det ble påvist eldre ekskrementer ved den ene staven og ikke veldig gamle ekskrementer på kirkegulvet nedenfor staven. Dette var nokså få ekskrementer og ikke tegn på at en større koloni har tilhold på dette stedet inne i kirken - på et sted hvor ekskrementer vil finne veien til åpne områder som er tilgjengelig for mennesker. Mengden tilsvarer det et enkeltindivid kan produsere av ekskrementer i løpet av natt (basert på individer i fangenskap). Det ble ikke påvist ekskrementer på loft eller ved tårn og det ble heller ikke påvist byttedyrsrester på noe sted inne i kirken (med fokus på brunlangøre).

3.2.3. Analyse av ekskrementer påvist ved den ene staven

De tre intakte ekskrementene som ble samlet inn under den ene staven, bestod utelukkende av insektrester. Alle var godt under 1 cm lange og kan være fra en annen art enn den som tidligere er sikkert påvist i kirken (ikke mulig å sikkert avgjøre). De ble påvist svært få «skjell» fra Lepidoptera (sommerfugler) i ekskrementene, men utover det ble ingen detaljert analyse av diett gjennomført.

Diskusjon

Datagrunnlaget ansees for å være nokså godt, men man kan ikke utelukke at flaggermus skjuler seg i arealer som ikke er synlige for mennesker. Det er ikke grunnlag for å tro at rødlistede arter finnes i bygningen (se Henriksen & Hilmo, 2015 for rødlistestatus) ettersom ingen slike ble fanget opp i/ved kirken. Basert på dataene som er samlet inn og med tanke på at det ble påvist god flaggermusaktivitet andre steder i denne fjorden samme natt, finner jeg ikke grunnlag for å mistenke

at det finnes en koloni i kirken på det aktuelle tidspunktet som undersøkelsen ble gjennomført. Dette understøttes også av at kun svært få (relativt ferske) ekskrementer ble påvist ved den ene staven. Man kan likevel ikke utelukke at kirken brukes av flaggermus i perioder av året, slik som mange andre kirkebygg og andre bygninger generelt. Det er også mulig at enkeltindivider (eller svært få individer) bruker deler av kirken mye av sommeren. De få relativt ferske ekskrementene kan peke mot at dette er tilfelle, men her er det umulig å si om flaggermus også anvender arealer hvor ekskrementer ikke er synlig. Tiltak som gir flaggermusene alternative tilholdssteder vil derfor være et ønskelig (se egen omtale av avbøtende tiltak) og man tar i så måte rimelig hensyn til dyregruppen i henhold til EUROBATSavtalen.

Kirken har tidligere vært brukt av flaggermus (brunlangøre) og dette er påvist ved den ene staven hvor man mistenker at urin/ekskrementer fra flaggermus har påvirket konstruksjonen negativt. Flere tiltak har vært gjennomført som kan påvirke flaggermusenes bruk av stedet. Dette gjelder gassing og innsetting av staven med pyretroid, en syntetisk analog til pyretrinene (fra krysantemumekstrakter). Dette er informasjon basert på personlig meddelelse fra Kjersti Marie Ellewsen. Både gassing og bruk av konsentrert pyretroid kan ha ført til at alle flaggermus som var på stedet døde som følge av behandlingene. Konsentrater (pyretroid) har en langtidseffekt og den negative effekten kan ha vært gjeldene i mange år etter behandling. Området som har vært brukt av flaggermus ved den ene staven har også vært tettet ved hjelp av hønsenetting (gjennomført om vinteren av skadedyrfirma). Denne ble fjernet når denne undersøkelsen ble gjennomført. Alle disse faktorene kan ha bidratt til at flaggermus ikke ble påvist i juni 2017.

Fordi hovedkonklusjonen er at kirken ikke synes å være et viktig sted for flaggermus, og fordi ingen rødlistearter ble påvist, foreslår jeg noen avbøtende tiltak som er tilpasset denne konklusjonen. Ettersom tidligere behandling av kirken kan ha påvirket flaggermus negativt, finner jeg det ønskelig at man vurderer slike enkle avbøtende tiltak som ikke vil påvirke det estetiske i/rundt kirken. Disse vil være særlig viktige dersom man planlegger nye tiltak i kirken (for eksempel bruk av pyretroider). Flaggermus bruker noe tid på å finne alternative oppholdssteder og eventuelle avbøtende tiltak bør fortrinnsvis lenge før behandling. Jeg påpeker her at disse forslagene er tilpasset vernestatus for kirken. I andre bygninger med lavere verneverdi og med større forekomster av flaggermus, ville forslagene vært langt mer omfattende. Disse nokså enkle tiltakene må derfor på ingen måte sette presedens for hva som er akseptabelt når man finner konflikt mellom kirkebygg og flaggermus.

4.1. AVBØTENDE TILTAK

Fordi kirken har vært i bruk av flaggermus, må man forventet at én eller flere arter finner kirken attraktiv i kortere eller lengre perioder i løpet av sesongen. Det er derfor ønskelig å tilby flaggermusene alternative oppholdssteder. Dette vil være særlig viktig dersom man ønsker å behandle deler av konstruksjonen inne i kirken med kjemikalier som kan påvirke flaggermus negativt. Dersom man planlegger å behandle trevirke med et pyretroid, bør man sørge for at flaggermusene ikke får tilgang til de områdene som blir behandlet. Mulige løsninger beskrives nedenfor.

4.1.1. OPPSETTING AV FLAGGERMUSKASSER UTENDØRS

Dette er et tiltak som bør gjennomføres som et minimum av alternative avbøtende tiltak på lokaliteten. I dette tilfellet anbefaler jeg bruk av flaggermuskasser laget i trebetong. Disse kassene er godt utprøvd og brukes av flere arter også i Norge. Det finnes en rekke varianter av slike trebetongkasser. Noen av disse krever årlig oppfølging (fjerning av ekskrementer) og disse anbefales derfor ikke her. En kassetype som jeg finner gunstig for flere arter er fra Hasselfeldt (Tyskland). Kassen har et større åpent rom og er selvrensende. Denne kassen er i bruk flere steder i mitt studieområde. Link til kassen finnes på følgende nettside:

http://www.nistkasten-hasselfeldt.de/fledermauskaesten/fledermausgrossraumhoehle.html

På følgende nettside kan man se en slik kasse som er i bruk av flaggermus i Tafjorden i Møre og Romsdal (kassen nederst på treet i siste del av videoen):
https://www.youtube.com/watch?v=9dmM94N41ts

Det må påpekes at kassene må males før opphenging og at farge som må anvendes er svart (de leveres med kun grønn maling som ikke er tilfredsstillende). Området hvor flaggermusene lander for å komme inn i kassen skal ikke males. Det vil være en fordel om kassene får stå ute en tid før den tas i bruk av flaggermus og de kan med fordel henges opp i oktober slik at den får stå ubrukt gjennom vinteren. Kassen må henges opp på en slik måte at de får sollys det meste av dagen. Dette betyr at de må henges opp på et tre som har åpen stamme (ikke skygge) de nederste ca 4-5 meterne og helst med en ikke veldig tett krone. Det ble søkt etter slike lokaliteter i nærheten av kirken, men kun ett godt egnet tre ble påvist. Dette er en ask *Fraxinus excelsior* som står like ved parkeringsplassen nedenfor kirken (ved nærmeste gårdstun). Det må påpekes at kassen må henges opp slik at den ikke henger skjevt. Anbefalt kassetype er vist i vedlegg I og den mest egnede lokaliteten for opphenging av kasser (ut fra tilgjengelige trær på stedet) er vist i vedlegg II.

4.1.2. Oppsett av flaggermuskasser inne i de deler av kirken som ikke er synlig for publikum

Det er utplassert nokså mye utstyr inne i kirken som er knyttet til overvåking/alarmsystemer (inklusive sprinkleranlegg). Disse er for en stor del ikke synlig for publikum i kirkerommet og finnes i tårn og på loft. Det vil således ikke påvirke det estetiske om et par flaggermuskasser ble installert på loftet i kirken og helt opp under mønet. Slike kasser vil kunne trekke flaggermus bort fra selve kirkerommet og kanskje bort fra hulrommet som har vært brukt ved galleriet. Her kan man bruke flaggermuskasser i tre som allerede er innkjøpt for å brukes som avbøtende tiltak. Dette tiltaket vil først og fremst være av betydning dersom man planlegger ny behandling av kirken med kjemikalier som er skadelige for flaggermus.

4.1.3. Utestengelse fra konstruksjoner som man planlegger å behandle med pyretroider

Dette er tiltak som Riksantikvaren må vurderes opp mot hvilke tiltak man kan gjøre inne i denne svært verdifulle kirken. Jeg henviser her til Marnell og Presetnik (2010) som gir flere anbefalinger for mulige tiltak basert på mengde og fordeling av flaggermus inne i kirken. Fordi Norge har forpliktet seg til å finne alternative metoder til kjemikalier som vil ta livet av flaggermus gjennom EUROBATSavtalen (se obligatoriske forpliktelser, paragraf III, punkt 8, www.eurobats.org), bør det gjøres en innsats for å holde flaggermus borte fra arealer som eventuelt skal behandles med slike giftige stoffer. Her finnes det flere alternative metoder som kan gi ønsket resultat. Fordi flaggermusene i dette tilfellet har vært knyttet til et mindre hulrom ved den ene staven, vil fysisk avstenging fra det aktuelle arealet være det mest innlysende tiltaket (et forsøk med hønsenetting har vist seg å være uheldig for kirken). Her kan man for eksempel bruke hardplast eller man kan isolere hulrommet med andre stengsler som kan være mer passende. I hvilken grad dette er mulig avhenger av hvilke tiltak som kan gjøres ut fra verneforskriftene for kirken. Det har ikke undertegnede mulighet til å vurdere. Dersom man velger å tette slike hulrom slik at flaggermus holdes ute, men samtidig ønsker lufting til hulrommet, bør det ikke finnes åpning større enn ca 8-9 mm rundt staven hvor flaggermus har hatt tilhold (da ekskluderer man også de minste artene).

Et annet tiltak kan være å bruke lys inne i det aktuelle hulrommet. Flaggermusene vil ikke bruke sterkt opplyste arealer (kan oppnås med for eksempel LED-lys som avgir lite varme). Igjen er det ikke mulig for undertegnede å vurdere hvor realistisk det er å gjennomføre et slikt tiltak med tanke på verneforskrifter. Tetting av hele hulrommet (som er nokså beskjedent) med masse kan også være et alternativ, men dette kan påvirke staven som står inntil hulrommet og dette er kanskje ugunstig for selve staven. Det er igjen ikke mulig for undertegnede å vurdere om dette ligger innenfor det som er akseptabelt med tanke på verneforskrift.

Det har vært gjennomført forsøk med bruk av ultralyd for å skremme flaggermus bort fra slike tilholdssteder, men kunnskap om effektene er mangelfull. Det kan være at den kraftige lyden mellom 20 og 30 kHz som ble hørt i kirken allerede har en effekt på flaggermus. Dette er det ikke mulig å vurdere uten kunnskap om situasjonen før disse lydene ble introdusert.

ANNET

For å øke kunnskapen om trevirke med og uten urin, og dermed kanskje øke kunnskapen om effekter på stavene i kirken, ble det samlet inn materiale fra en flaggermuskasse som har vært brukt i mange år (finnes i generell omtale i Michaelsen, 2016b). Selve kassen ble hentet ned våren 2017 og video fra perioden når kassen var i bruk finnes på følgende nettside:
https://www.youtube.com/watch?v=YYAVT2AlyOA

Det er kassen til høyre i videoen som er aktuell og kassen er bygget i kryssfiner med annet trevirke som listverk. Deler av trevirket er ikke påvirket av urin/ekskrementer og det finnes derfor kontrollmateriale fra samme kasse. Resultater fra undersøkelser av materiale som videresendes vil ikke blir omtalt i denne rapporten.

I forbindelse med feltarbeid ved Urnes stavkirke, ble det også diskutert noe vedrørende litteratur som er tilgjengelig som tar for seg skader fra flaggermus (urin) på gamle bygninger. Denne rapporten henviser til slik litteratur og det finnes et sammendrag i Marnell & Presetnik (2010). Det som fremkommer av slike studier, viser at urin fra flaggermus (70 % urea) kan føre til skader og at urin har et større slikt skadepotensiale sammenlignet med ekskrementer. Marnell & Presetnik (2010) gir også forslag til avbøtende tiltak og noen slike tiltak kan være nyttig å ha kunnskap om. Jeg anbefaler derfor at både Marnell & Presetnik (2010) og Paine (1993 - og eventuelt nyere arbeid fra Paine) anskaffes dersom dette ikke allerede er gjort.

4.3. VIDERE KARTLEGGINGSARBEID

Jeg kan ikke finne grunnlag for at man skal bruke mer tid på flaggermus utover avbøtende tiltak i forbindelse med denne stavkirken. Eventuelt ny informasjon om flaggermus som måtte fremkomme ved bruk av viltkamera vil sannsynligvis ikke føre til endringer i forslag om avbøtende tiltak. Unntaket kan være dersom det viser seg at rødlistearter bruker den delen av kirken med skader og som er behandlet med kjemikalier som er svært giftige for flaggermus.

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VEDLEGG

VEDLEGG I: FLAGGERMUSKASSER TIL OPPHENGING PÅ TRÆR

Denne kassen er godt egnet for flere arter og skal være akseptabel for brunlangøre. Kassen må males svart før opphenging og de må henge solåpent med direkte sollys hoveddelen av dagen. Kassen kan bestilles hos Hasselfeldt (Tyskland) på følgende nettside;
http://www.nistkastenhasselfeldt.de/fledermauskaesten/fledermausgrossraumhoehle.html
Artikkelnummer hos Hasselfeldt er FGRH. Man kan godt spesifisere at målart for kassen er brunlangøre (Braunen Langohr på tysk). Kassen kan også brukes av andre arter i kortere eller lengre perioder om sommeren og brukes mye av året av enkeltindivider eller som harem (ikke bare ynglekoloni).

VEDLEGG II: LOKALITET FOR OPPHENGING AV FLAGGERMUSKASSE UTENDØRS

Den røde sirkelen markerer en ask som står helt inntil parkeringsplassen ved gården sørøst for kirken og dette er det mest egnede treet for opphenging av flaggermuskasser. Treet har en omkrets på 219 cm og er 18 m høy. De nedre 4-5 meterne av stammen er helt åpen og selve kronen er nokså åpen og vil slippe mye sollys inn til kassen. For at kassen skal være egnet må den henges opp ved ca 3.5- 4 m over bakken og vende mot sør. Den må plasseres slik at bakkant av kassen står helt loddrett. Hvis opphengingen gjøres feil, vil dette vesentlig redusere hvor attraktiv kassen kan være for flaggermus. Det finnes også andre trær som kan være egnet (for eksempel ved bedehuset), men disse er lenger unna kirken og derfor ikke avmerket på kart.

Appendix 4 Report from FTIR analyses

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Urnes stave church – Assessment of chemical state of preservation of wood in a salt-affected region in the South West corner of the interior using IR spectroscopy

Background

Riksantikvaren, represented by conservator Kjersti Ellewsen and historian Leif Anker requested a chemical assessment of the salt-affected area of a wooden beam involved in a structural join in September, 2015. From 2004 to 2013 several investigations of this area were undertaken [1-5]. The condition of wood was visually assessed and some earlier areas with fungal deterioration were identified, moisture content and water activity within the wood were measured in addition to the relative humidity of room. An aqueous extract from a wood sample was analyzed using ion chromatography, which identified high concentrations of sulfate, phosphate, ammonium, potassium, sodium and low molecular weight organic acids. Analyses indicated that the salt in the wood was urine likely originating from bats which had occupied the empty space near the join. It was concluded that the salt-rich area was likely not causing damage to the wood and that it was best to leave it as is.

However this region also appears to be undergoing changes in wood texture over time according to Ellewsen (personal communication). In the previous analyses, no direct assessment of the chemical state of preservation of the wood was investigated. We offered to undertake this task using infrared spectroscopy (ATR-FTIR). Additionally pH measurements of wood extract were taken.

Methods and materials

Samples

Samples were collected by Leif Anker 21-22.09.2015. Eleven wood samples were collected from at least seven different wooden elements, all of which are pine [6]. A sample overview is given in Table 1 and sampling locations are shown in Figure 1.

Reference wood: Pine heartwood (*Pinus spp.*) milled to 0.5 mm diameter particle size.

Sample treatment

All samples were analyzed in two rounds using infrared spectroscopy 'as received' and after rinsing. After analysis of 'as received' samples, the wood samples on the ATR crystal were transferred to a new Eppendorf tube and it was this portion which was rinsed. Samples 4 and 9 were rinsed in their entirety.

Rinsing

After pH measurements (see below), samples were rinsed 3 times using distilled water to remove salts, which signals interfere with those from wood (the extract used to measure pH counted as the 1st rinse). Each rinse used 1 ml water and ca 30 minutes extraction time. The sample was spun down before removing supernatant. There were varying amounts of sample in the vials (i.e. ratio of wood: water not same). Wood samples were dried at 50ºC, for about 12 hours and stored in a dessicator until analysis. Rinsed samples analyzed: 2,3,4,6,8. Unfortunately the residue of the rinse was not analyzed.

Infrared spectroscopy

Infrared spectra were collected in ATR mode (Attenuated Total Reflectance) on a Thermo Fisher FTIR spectrometer (Nicolet iS50), with a resolution of 4 cm^{-1}. The spectral range was 4000-400 cm^{-1}. The ATR-crystal was of diamond.

Each spectrum was based on 32 scans. At least least two spectra were collected for each sample to evaluate material heterogeneity. Spectra were not averaged, as heterogeneity was high within each sample. Band areas were measured for each rinsed sample spectrum at 1505 cm^{-1} (representing pure lignin) and at 1371 cm^{-1}, 1158 cm^{-1} and 895 cm^{-1} (which represent pure holocellulose signals). In all samples, the same ranges for area and for baseline were used to calculate area. To compare wood preservation states in different rinsed samples, band area ratios were calculated by dividing each holocellulose signal area with that from lignin.

The same sound pine spectrum was used to calculate 'reference' areas and ratios in the same way, repeating the calculation for each sample. Thus it was possible to compare the standard deviations of measurements to get an idea of the manual precision, in both areas and in ratios.

Band assigments are given in Table 2.

pH measurements

pH was measured using a pHenomenal pH meter and electrode (VWR). Two-point calibration was undertaken using standard buffers pH 4 and 7.

1 ml distilled of water was added to the sample vial (in the new Eppendorf tube). The ratio of wood: water was not the same in each tube as there were varying amounts of sample, but small variations should not affect pH readings greatly. The pH was measured after ca 30 min soaking. Anker used pH and sulfate indicator papers to estimate the pH and sulfate content in situ (Baker pHix and Merckoquant Sulfate Test) [6]. These values are given in Table 4 where spots matched areas from which wood was sampled.

Results and discussion

Infrared analyses

The samples were sorted into three groups, based on infrared spectra of the 'as received samples':
High urine content (samples 1, 2, 4, 5, 6, 9, 10), *Slight urine content* (samples 3, 7) or *No urine content*
(samples 8, 11). This is based on comparison with a urine spectrum from the literature [7]. Here a 'typical spectrum' for each group is shown in Figures 1 to 4. All spectra for each group are included in the Appendix. Infrared assignments are given in Table 2.

The *No urine content* sample 8 compared well with sound pine (Figure 2). Bands are typical signals from wood. Sample 8 shows signs of slight degradation due to natural aging, seen in the region of spectra containing carbonyl functional groups (C=O), at 1543 cm^{-1} and in region ca 1650-1710 cm^{-1}.

Slight urine content spectra are represented by samples 3, 7 in Figure 3. Compared to the previous figure, here different bands are visible at 3457, 3338, 3208, 1656, 1621 and 1450 cm^{-1}, which are associated with urine [7, 8]. Although there is still an overlap due to sulfates or phosphates (at 1054 cm^{-1}) and ammonium (at 1450 cm^{-1}), most other signals associated with wood in the region 1400-700 cm^{-1} are visible, such as the band for pure lignin (1509 cm^{-1}).

High urine content spectra included samples 1, 4, 5, 6, 9, and 10. Figure 4 shows a typical spectrum (sample 5) where the bands at 3447, 3339, 3208 cm^{-1} are more defined and where bands at 1654, 1618, 1448 cm^{-1} are very intense. The pure lignin band at 1505 cm^{-1} is hidden due to interference from urine compounds. The fingerprint region of sample 5 is shown in Figure 5 where it is compared against a urine spectrum found in the literature [7].
Sulfate indicator paper was used to measure the sulfate content of surfaces in situ. Measurements were obtained from similar locations from which samples 1, 5 and 9 were taken, all which were grouped in the *High urine content* group and as such should show high values. This was the case for both samples 5 (> 1600 mg/L) and 9 (>800, >1200 mg/L), but not for sample 1 (<200 mg/L), which showed unexpectedly low values. The reasons for the low value are not clear, but may involve interference of other compounds with indicator reactions.

Stereomicroscope examination of Sample 6, confirmed this sample's high salt loading. The wood has a fibrous structure (Figure 6) which indicates either lignin degradation, mechanical damage due to cycles of salt recrystallization, or both: a previous report mentions that the wood felt humid to the touch [2] indicating that the salts in the wood are hygroscopic; high sulfate levels can promote defibration of wood [9].

Effect of rinsing

In order to assess the state of preservation of the wood itself, it was necessary to remove salt interferences by rinsing samples. Removal of interference by spectral subtraction is not possible as the mixture of salts present is complex. Thus although rinsing will in fact remove some wood compounds, the resulting wood bands are clearer and can be compared more consistently with other samples. Unfortunately the extraction residues were not analyzed due to lack of time.

The extract after pH measurements is shown in Figure 7 after transfer into petri dishes. Samples 3 and 7, both sorted into the *Slight urine content* group (based on infrared spectra) had the strongest extract colour. For these samples, the spectra may have been dominated by a different salt composition relative to other spectra, but this is only a hypothesis, as their residues were not analyzed.

The effects of rinsing on infrared spectra for samples 2, 3, 4, 6, and 8 are shown in Figures 8 to 12.
Generally rinsing removed signals attributed to urine (1652, 1620, 1450 cm^{-1}) as well as sulfates /phosphates (1054 cm^{-1}) from samples 2, 3, 4 and 6. Even after rinsing, strong bands remained in 1530-1820 cm^{-1} region, slightly higher than in sample 8 (see Figure 12), indicating either a higher degree of oxidation of salt-infused wood compounds or remains of insoluble urine-derived compounds.

State of preservation of wood

As infrared spectroscopy is a relative technique (not absolute), one must somehow 'normalize' each sample spectrum before it is possible to compare it to other spectra. One way of normalizing is through the calculation of band area ratios (896/1509, 1155/1509, 1367/1509) as explained in the methods section. Figure 14 shows how the area was calculated for each band in one spectrum of sample 3. Thus by comparing such ratios (see Table 3), it is possible to compare the state of preservation of wood in different samples. This method assumes that the lignin band (1505 cm^{-1}) does not change. In many cases of wood degradation this assumption holds, as lignin is in most cases more recalcitrant than holocellulose. In cases of preferential lignin degradation, however, one observes higher ratios relative to the reference sample. In the case of equal lignin and holocellulose degradation, one will not observe differences in these ratios relative to the reference sample. This complicates comparison of infrared spectra.

After rinsing, all Urnes samples (2, 3, 4, 6, 8) had high signals in the region spanning 1550-1820 cm^{-1} compared with sound pine (Figure 13). These signals are due to functional groups containing oxygen. Sample 8 illustrates what may be expected during natural aging, as it originates away from the saltinfused region and thus may represent a 'typically' aged Urnes pine sample. Sample 8 also shows slightly reduced band area ratios relative to sound pine, indicating that the holocellulose fraction has been preferentially degraded over that of lignin.

Compared to sound pine, all ratios in sample 2 are higher, in sample 3 they are generally higher except for 1367/1509 which is the same, in sample 4 ratios are similar or lower than that for sound pine and sample 6 has higher or similar ratios. These results indicate that slightly higher lignin degradation and likely also holocellulose degradation have occurred in these samples. Samples 2, 3 and 6 generally have greater ratio differences when sample 8 is used as the reference. The ratios for sample 4 are most similar to sample 8.

Thus, we can be certain in saying that IR results do not show dramatic chemical degradation in the samples analyzed here. It should be noted, however, that replicate spectra (Appendix) show very high variability within each sample, which likely reflects a high variability in state of preservation of the wood as well. As samples originate from the surface, it is not possible to know how deep this degradation extends into the wood.

Based on the photographs of regions sampled, in regions of high urine content, samples 4, 5 and

appear fibrous while wood from which samples 2 and 8 were taken appear visually sound. Blanchette et al. discuss defibration of wood as a breakdown in the middle lamellae [9], which would be reflected as lignin degradation.

pH measurements

Table 4 shows pH values were around 3.6 to 4.5 for all samples, which is slightly lower than the 'normal' range for softwood (pH 4.1 to 4.9) according to Pedieu et al. [10]. Sample 8, which is considered an Urnes 'reference', had a pH of 4.0. The lowest pH values (3.6) were found in samples 1, 4 and 6, all of which had been taken from areas that have fibrous surfaces. Samples 3 and 7 had the highest pH values (4.5 and 4.7, respectively), and they had shown the strongest colour upon extraction (even though they had been grouped as only containing 'slight' amounts of urine based on IR spectra). Sample 3 was taken from a fibrous area (there was no photo of sample 7). The pH in samples 3 and 7 may be dominated by a potentially high salt content within the samples and not reflect wood extracts. The effect acidity has on wood is dependent several factors, such as wood anatomy, and RH, temperature, etc.

Anker's pH measurements from similar areas gave higher pH values, of 5, a decent correlation considering that the pH indicator paper scale was rather coarse (pH range 0-14) for these purposes. In the case of future measurements, higher resolution indicator paper should be used in the field (for example pH range 0-7).

Conclusion and final comments

Infrared spectra indicated the presence of urine in all samples, except for sample 8, when compared to a spectrum of urine from the literature. This may be confirmed by analyzing the salt scrapings taken [6] by XRD, IR or Raman. Sample 8 was taken from the base of a column and thus would not be expected to contain traces of urine. To be more certain about what is being rinsed out (if IR spectroscopy is to be used again), the extraction should be repeated and the residue analyzed in further work.

Extensive decay of wood was not observed in the sample set analyzed. Signs of natural aging were evident in Sample 8. In the other rinsed samples (2, 3, 4, 6) most band area ratios indicated a slight preferential decay of the lignin polymer. This may possibly be reflected in the fibrous damage visible in photographs of some of areas sampled and which may be similar to other cases found in the literature [9, 11].

The fibrous nature was more visually dramatic than reflected in the infrared spectra. The discrepancy between visual state and chemical state may be due to the insensitivity of the IR method for slight decay in samples of high heterogeneity, as in this case, and in the fact that it provides general information about wood. That said, chemical analysis of degraded wood is challenging no matter which method is used [12-14]. Nonetheless, more detailed information about wood polymers may be obtained by chemical methods giving more specific information about breakdown products and bond preservation, such as analytical pyrolysis (Py-GC/MS) coupled with NMR techniques. Microscopic examination of wood condition would complement chemical analyses.

Even though there is evidence of chemical decay, mechanical damage should not be totally ruled out. Hints that the salts are hygroscopic was given by the observation that the wood 'felt' damp even though moisture content measurements showed that it did not contain more water than unaffected wood [2].

Although mechanisms for chemical defibration are not fully understood, sulfates are thought to play a role, as their presence is known to be corrosive to all materials, including wood [9]. Regarding removal of the salt by washing, the little experience in rinsing sample 3 for analysis showed how difficult this may be if applied to the site in question: even with small amounts of sample, and relatively larger amounts of water, wash water was still rather yellow after the third rinse, indicating salt-rich regions may require copious amounts of water to remove salts in situ, a difficult task to undertake. Finding acceptable alternatives requires innovative thinking.

Visual degradation did not necessarily coincide with the presence of urine. In some cases (such as in sample 2), the photograph showed a smooth surface while infrared showed the presence of urine. Will this region eventually appear as fibrous as, for instance, sample 1? It may be interesting to follow eventual decay progression in these regions in the long term. It has been shown here that saltaffected regions are easily observed in IR spectra, and as such this method may effectively map the boundaries of the affected areas. As this requires sampling, reliability of mapping using pH- and /or sulfate-indicator paper should be further assessed/developed.

The relationship between chemical- and mechanical- states of preservation has been in focus in several recent projects dealing with archaeological or degraded wood that I am aware of [14-17] however the topic requires more research before a clear understanding of this relationship is possible. Thus, 'slight' decay in wood (as it appears to be in this case) may be most effectively assessed by mechanical tests. The problem is that standard mechanical tests are destructive. Thus, the challenge is to find other assessment methods which can measure parameters relevant to understanding structural soundness of the join over time. Ideally, non-invasive methods are preferred (both non-sampling and non-destructive) – ultrasound may be an option. Other relevant parameters may include hardness, dimensional change, colour, and wood texture (fibrillary nature of wood).

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Table 1. Sample overview

	As received	Rinsed 3x distilled water, dried 12 hours 50C	Urine category (based on IR)	Dried 50C 12 hours	Surface where sampled (Anker, 2015)
1-SV-Midtroms stav-hulromsammenføyning	x		High	x	'-very fibrous in photo
2-boret hull I svikelen-gallerisiden	x	x	High	x	-nice surface in photo? - but photo out of focus
3-boret hull i svikelen-omgangssiden	x	x	Slight	x	-slightly fibrous in photo
4-SV midtromsstav-ved underkant av sørsvill, gallerisiden	x	x	High	x	-very fibrous in photo
5-midtrommets sørsvill-omgangssiden	x		High	x	'-very fibrous in photo
6-midtrommets sørsvill-ca 25 cm fra hjørnestav, gallerisiden	x	x	High	x	'-very fibrous in one photo
7- SV-hjørnestav hulrom/sprekk o/kapitel mot øst-eldre skade	x		Slight	x	'-only shown in diagram's yellow region ('delvis oppsmuldret, eldre skade')
8-SV hørnestav-løsflis fra bruddflate I midterste vulst o/ basse???	x	x	No	x	'-from base of column, shown in diagram only (no photo).
9-Buesegment o/ kapitel SV hjørnestang omgansside	x		High	x	'-not fibrous in photo
10-samme som over: buesegment o/ kapitel SV hjørnestav omgangsside	x		High	x	-no photo, but diagram shows that it is near 9.
11-Gratsperre omgang SV	x		No	x	'-not shown on either photo or diagram - do not know location of sample
Sound pine reference (heartwood)				x	

Table 2 Infrared assignments

Band	Assignment	Reference
3400-3200	valence vibration of H-bonded OH-groups	[18]
3300-3030	ammonium ion	[19]
1750-1820	Anhydrides, acid chlorides, peroxy acids	[19]
1738-1709	C=O stretch in unconjugated ketones, carbonyls and in ester groups (hemicelluloses);	[18]
1700	conjugated aldehydes and carboxylic acids absorb around and below 1700	[18]
1675-1655	C=O stretch: in conjugated p-substituted aryl ketones; strong electronegative substituents lower the wavenumber	[18]
1668	amide II band possibly from urea and creatinine	[8]
1646	conjugated C=O groups, mainly originating from lignin	[20]
1635	adsorbed water	[18]
1605-1593	aromatic skeletal vibrations plus C=O stretch in lignin	[18]
1600	secondary ammonium salts	[19]
1587	conjugated C-O	[21]
1560-1660	N-H bending in amines, C=O in urine	[19] [7]
1550	amide II band in urinary protein	[8]
1515-1505	aromatic skeletal vibrations;	[18]
1450	ammonium salt?	[19]
1450	C-H deformation in lignin and carbohydrates; CH3, CH2, benzene ring vibration in lignin	[21]
1375-1374	CH deformation in cellulose and hemicellulose	[22]
1155	C-O-C asymmetric valence vibration in cellulose and hemicelluloses	[21]
1130-1080	inorganic sulfate	[19]
1100-1000	inorganic phosphate	[19]
1033	urine marker band, possibliy carbohydrate, RNA, etc	[8]
1024	C-O stretch in cellulose and hemicelluloses; C-O of primary alcohol	[21]
895-892	C -H deformation	[18]

1

Table 3 Band areas and ratios for reference pine samples and rinsed samples.

	Areas				Relative intensities of holocellulose bands against lignin (standard deviation in brackets)		
	896	**1155**	**1367**	**1509**	**896/1508**	**1154/1508**	**1367/1508**
COMPARING Reference spectrum pine-4							
pine powder ref from Aas-dried-4_FOR 2_AR	0.068	0.309	0.167	0.273	4.00 (0.04)	0.88 (0.03)	1.64 (0.04)
pine powder ref from Aas-dried-4-3 (for sample 3)	0.068	0.302	0.152	0.286	4.20 (0.04)	0.95 (0.03)	1.89 (0.04)
pine powder ref from Aas-dried-4-4_AR	0.073	0.317	0.162	0.280	3.83 (0.04)	0.88 (0.03)	1.73 (0.04)
pine powder ref from Aas-dried-4-6_AR	0.073	0.317	0.159	0.270	3.71 (0.04)	0.85 (0.03)	1.70 (0.04)
pine powder ref from Aas-dried-4-for 8_AR	0.068	0.309	0.159	0.276	4.06 (0.04)	0.89 (0.03)	1.74 (0.04)
pine powder ref from Aas-dried-4	0.070	0.310	0.162	0.270	3.86 (0.04)	0.87 (0.03)	1.67 (0.04)
2-boret hull i svikelen-gallerisiden-rinsed 3x_1	0.041	0.216	0.126	0.195	4.80	0.90	1.55
2-boret hull i svikelen-gallerisiden-rinsed 3x_2	0.037	0.214	0.117	0.156	4.25	0.73	1.34
2-boret hull i svikelen-gallerisiden-rinsed 3x_3	0.068	0.291	0.171	0.301	4.41	1.04	1.76
pine powder ref from Aas-dried-4_FOR 2_AR	0.068	0.309	0.167	0.273	4.00	0.88	1.64
3-boret hull i svikelen-omgangssiden-rinsed 3x_1	0.038	0.185	0.096	0.176	4.62	0.95	1.83
3-boret hull i svikelen-omgangssiden-rinsed 3x_2	0.039	0.220	0.104	0.201	5.14	0.91	1.94
3-boret hull i svikelen-omgangssiden-rinsed 3x_3	0.025	0.130	0.072	0.132	5.22	1.01	1.82
3-boret hull i svikelen-omgangssiden-rinsed 3x_4	0.048	0.228	0.127	0.210	4.37	0.92	1.65
pine powder ref from Aas-dried-4-3 (for sample 3)	0.068	0.302	0.152	0.286	4.20	0.95	1.89
4-SV-midtromsstav-undergallerisidenrinsed-dried_1	0.026	0.098	0.049	0.050	1.94	0.51	1.01
4-SV-midtromsstav-undergallerisidenrinsed-dried_2	0.037	0.148	0.084	0.130	3.55	0.88	1.55
pine powder ref from Aas-dried-4-4_AR	0.073	0.317	0.162	0.280	3.83	0.88	1.73
6-midtrommet sørsvill-25-cm hjørnestavrinsed-dried_1	0.021	0.134	0.052	0.089	4.17	0.66	1.70
6-midtrommet sørsvill-25-cm hjørnestavrinsed-dried_2	0.038	0.173	0.082	0.145	3.86	0.84	1.76
6-midtrommet sørsvill-25-cm hjørnestavrinsed-dried_3	0.035	0.218	0.106	0.183	5.22	0.84	1.73
pine powder ref from Aas-dried-4-6_AR	0.073	0.317	0.159	0.270	3.71	0.85	1.70
8-SV-hjørnestav-v-basen-rinsed-dried_1	0.041	0.206	0.110	0.106	2.56	0.52	0.97

8-SV-hjørnestav-v-basen-rinsed-dried_2	0.033	0.183	0.091	0.091	2.79	0.50	1.00
8-SV-hjørnestav-v-basen-rinsed-dried_3	0.024	0.132	0.068	0.083	3.44	0.62	1.21
pine powder ref from Aas-dried-4-for 8_AR	0.068	0.309	0.159	0.276	4.06	0.89	1.74

Table 4 pH measurements all samples with in situ measurements taken by Anker (2015).

Sample	pH	pH in situ (strips 0-14)	Sulfate indicator strips, in situ mg/L	Location of in situ measurement
1	3.6	5	<200	A, B, G (pH) H (sulfate)
2	4.3			
3	4.5	5		E, F (pH)
4	3.6	5	>1600	D (pH) K (sulfate)
5	3.9			
6	3.7			
7	4.7			
8	4.0			
9	4.3	4 to 5	>800 >1200	C (pH) J (sulfate)
10	4.0			
11	3.9			

Figures

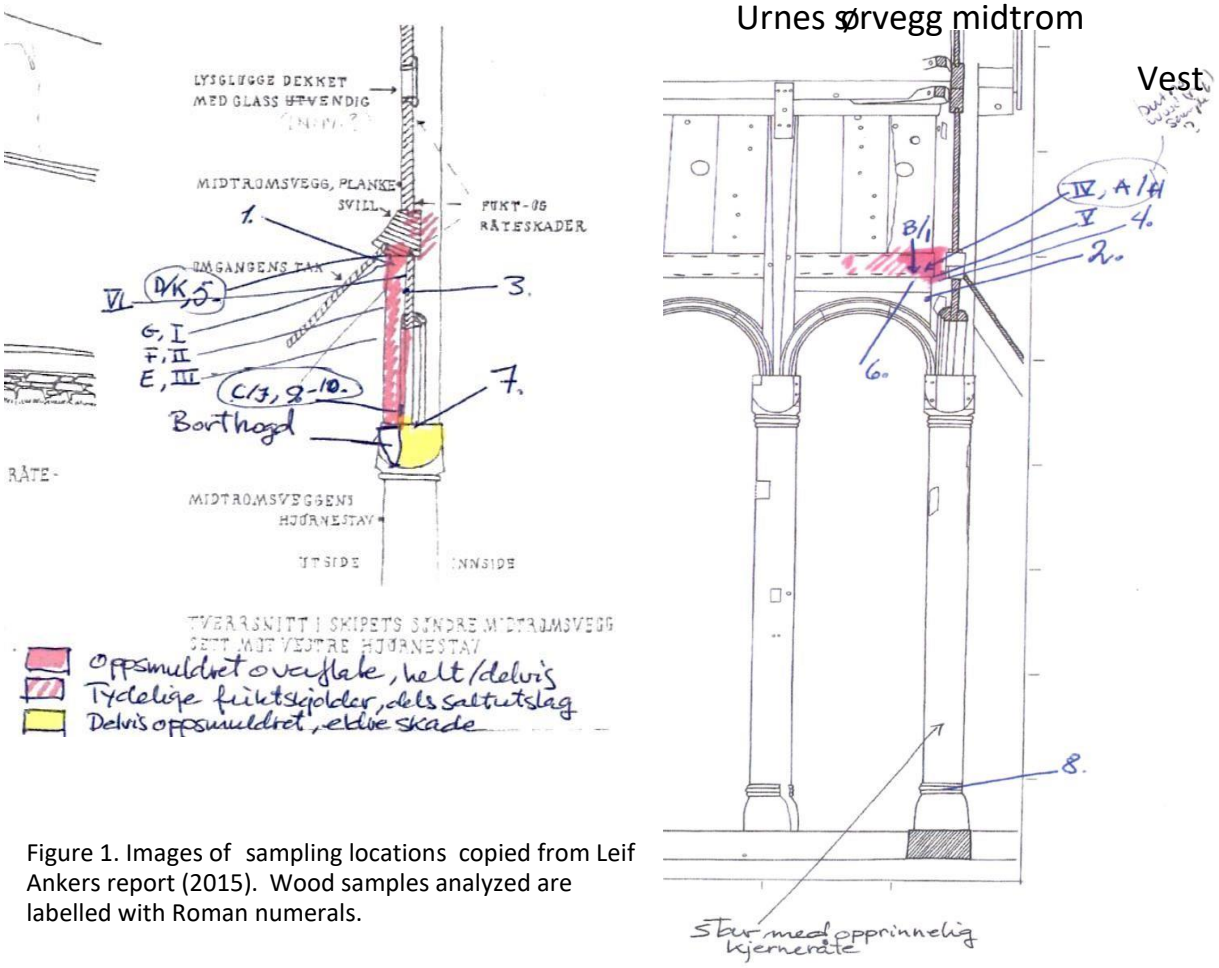


Figure 1. Images of sampling locations copied from Leif Ankers report (2015). Wood samples analyzed are labelled with Roman numerals.

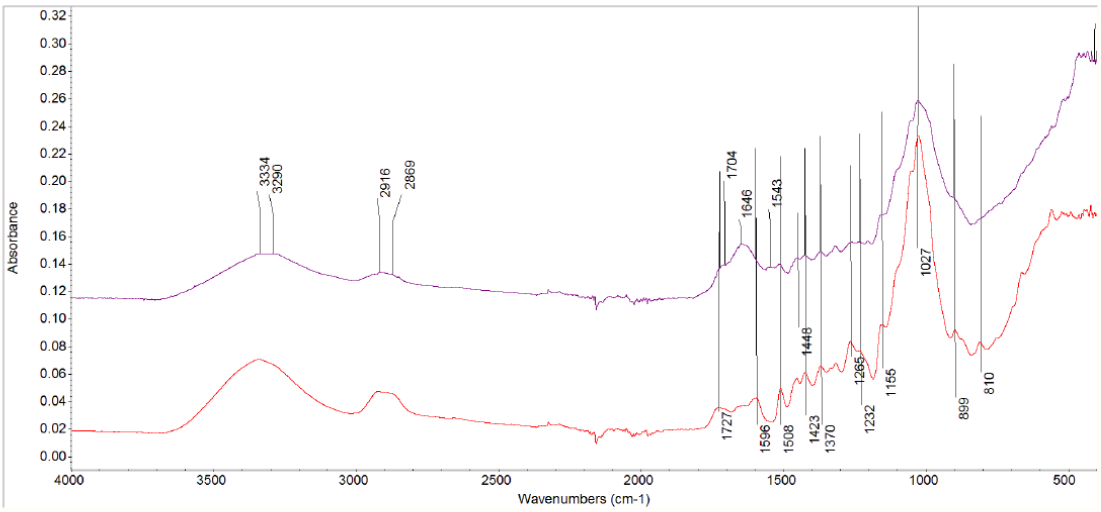


Figure 2. No urine content spectra exemplified by sample 8 (purple) and by the sound pine reference (red).

Figure 2. No urine content spectra exemplified by sample 8 (purple) and by the sound pine reference (red).

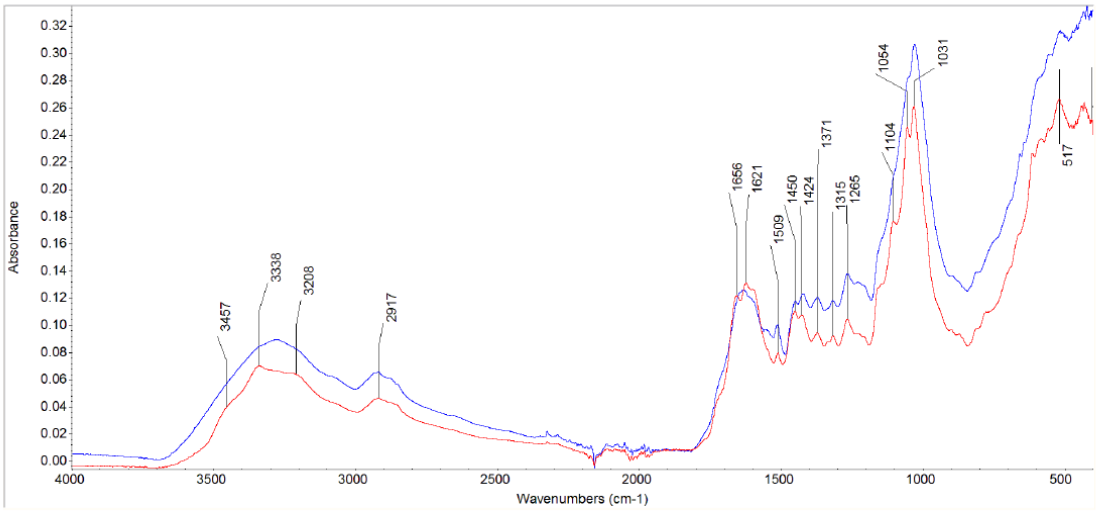


Figure 3. Slight urine content spectra, illustrated by sample 3 (red) and sample 7 (blue).

Figure 3. Slight urine content spectra, illustrated by sample 3 (red) and sample 7 (blue).

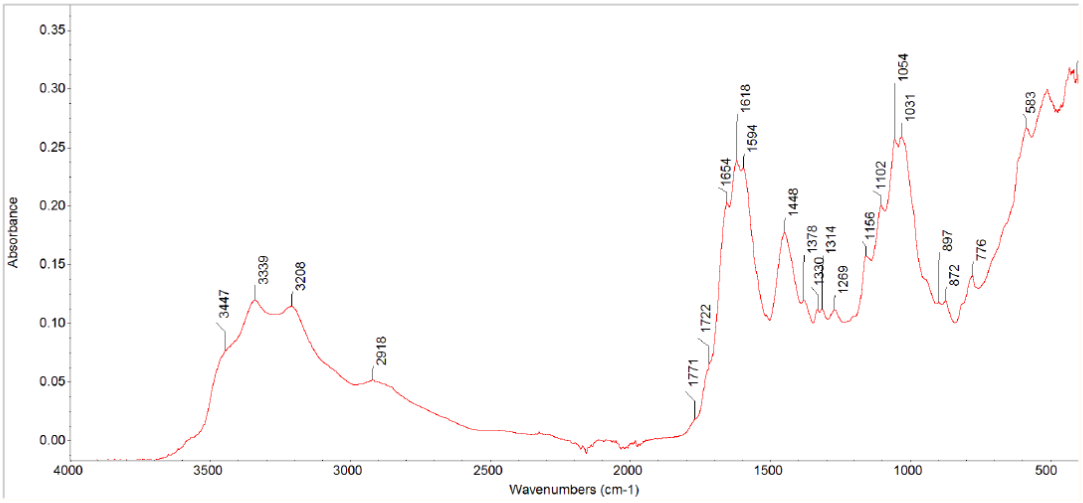


Figure 4. High urine content spectrum illustrated by sample 5.

Figure 4. High urine content spectrum illustrated by sample 5.

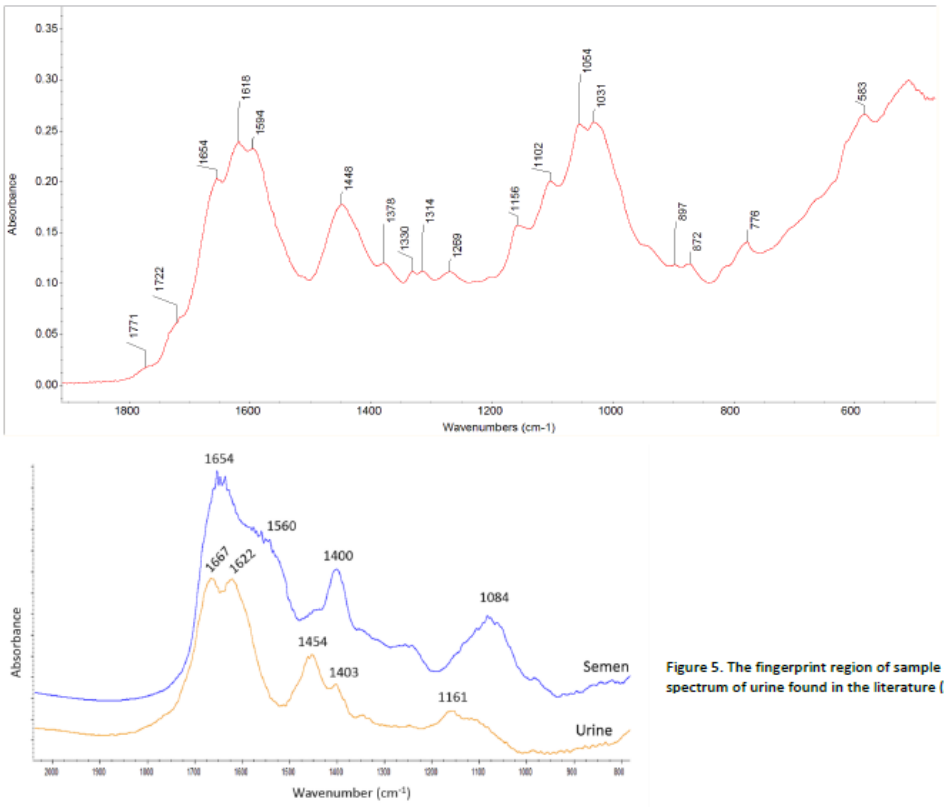


Figure 5. The fingerprint region of sample 5 compared with a spectrum of urine found in the literature (Zapata et al. 2016).

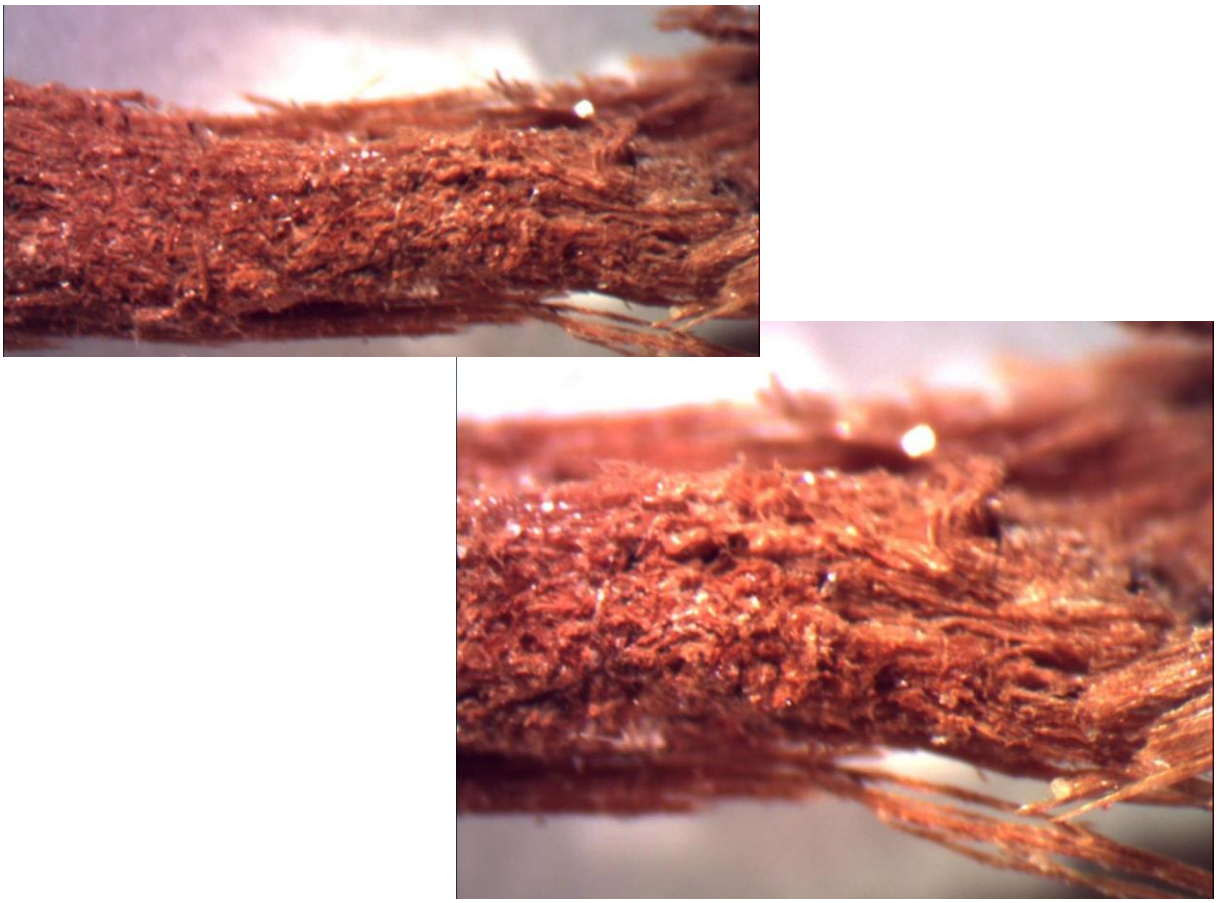


Figure 6. Stereomicrograph image of Sample 6 (ca
magnification). The wood fibers fall easily apart and salt crystals are visible

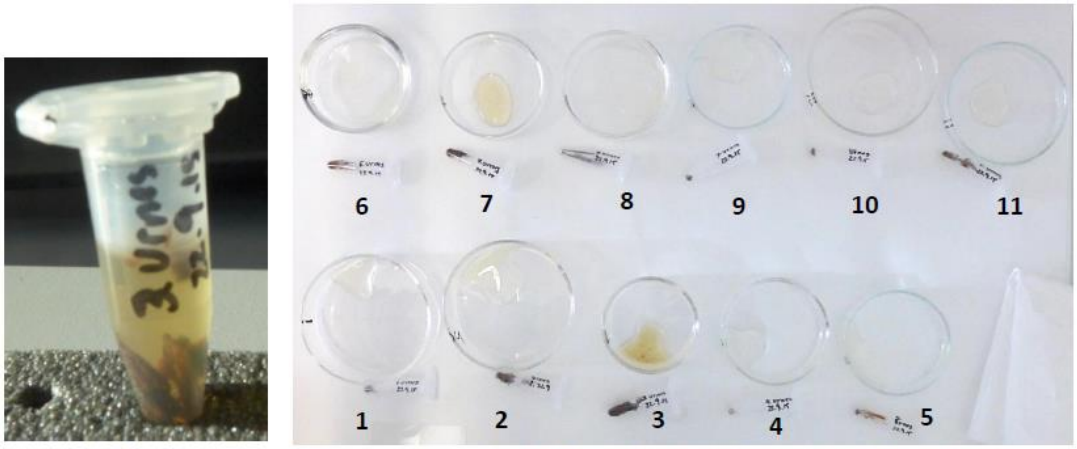


Figure 7. After pH measurements, the supernatant was transferred to petri dishes. Note the strong yellow colouring of the extract in samples 3 and 7, both of which had only 'Slight' urine content according to interpretation of infrared spectra.

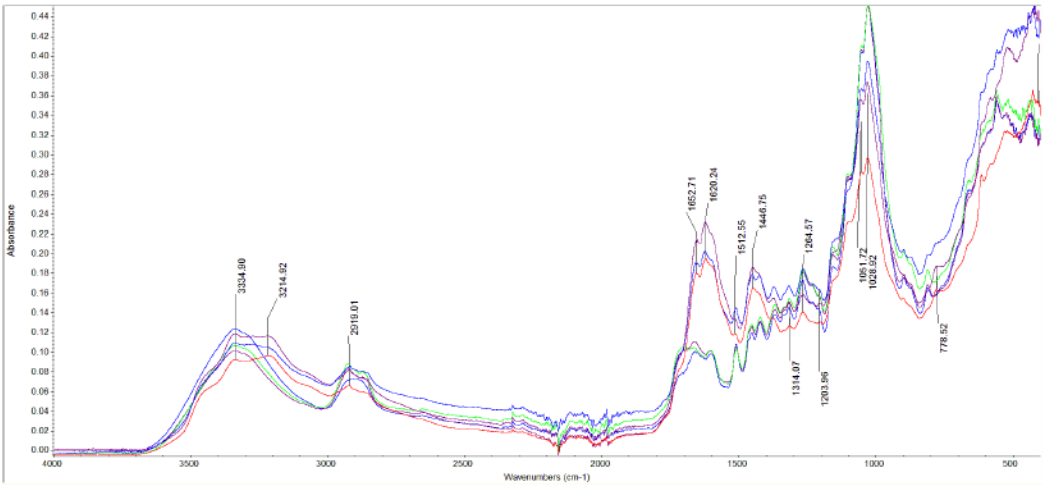


Figure 8. Effect of rinsing sample 2 Rinsed spectra have lower intensities in the 1500-2000 cm^{-1} region.

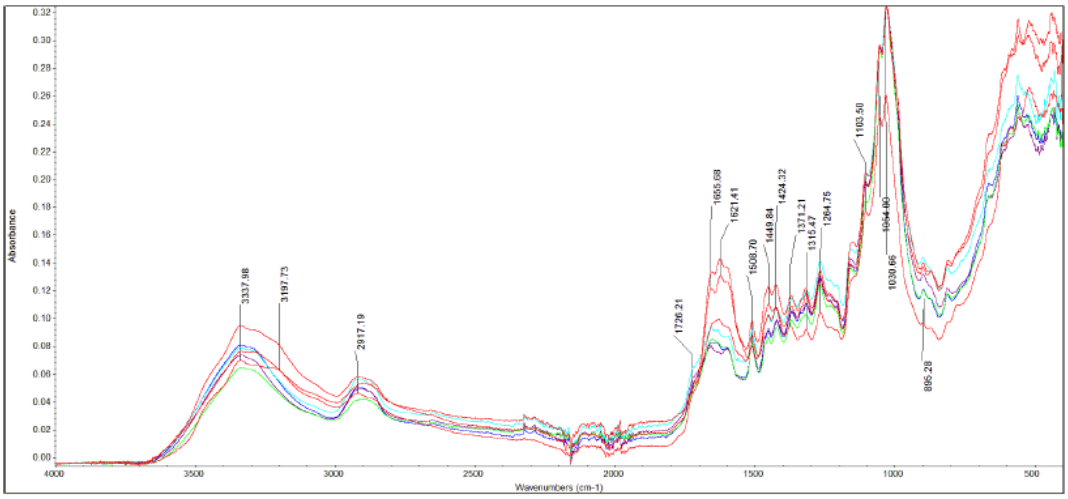


Figure 9. Effect of rinsing sample 3 (red spectra are before rinsing).

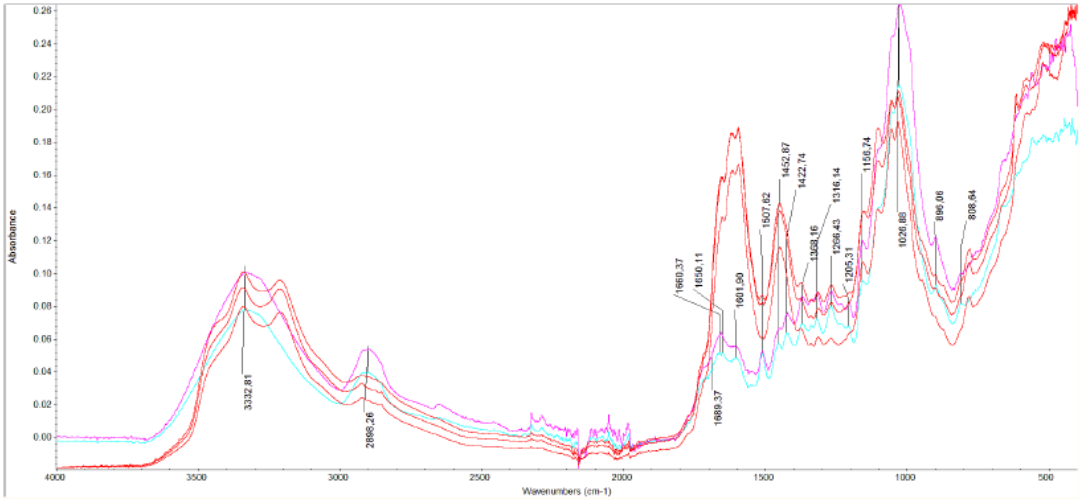


Figure 10. Effect of rinsing sample 4 (red spectra are before

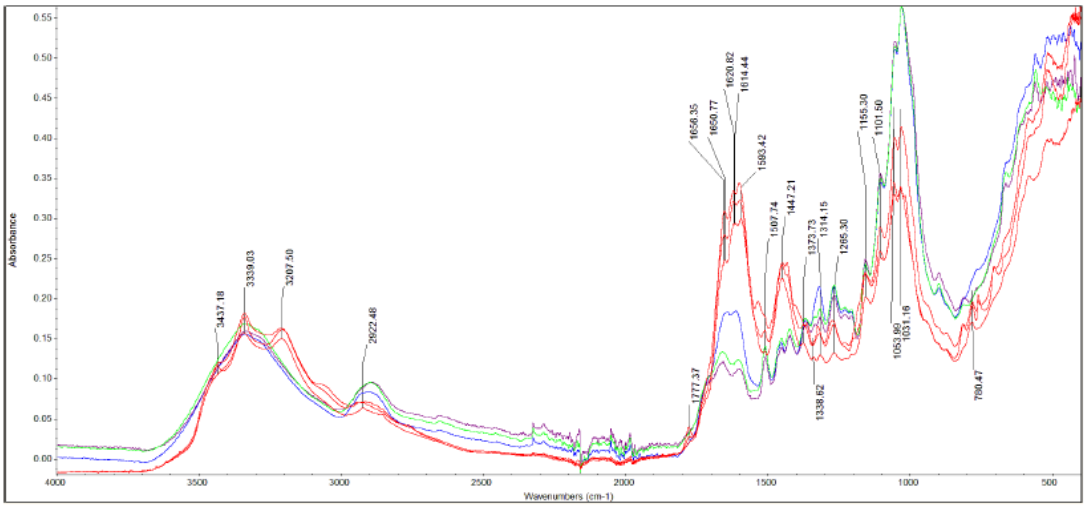


Figure 11. Effect of rinsing sample 6 (red spectra are before rinsing).

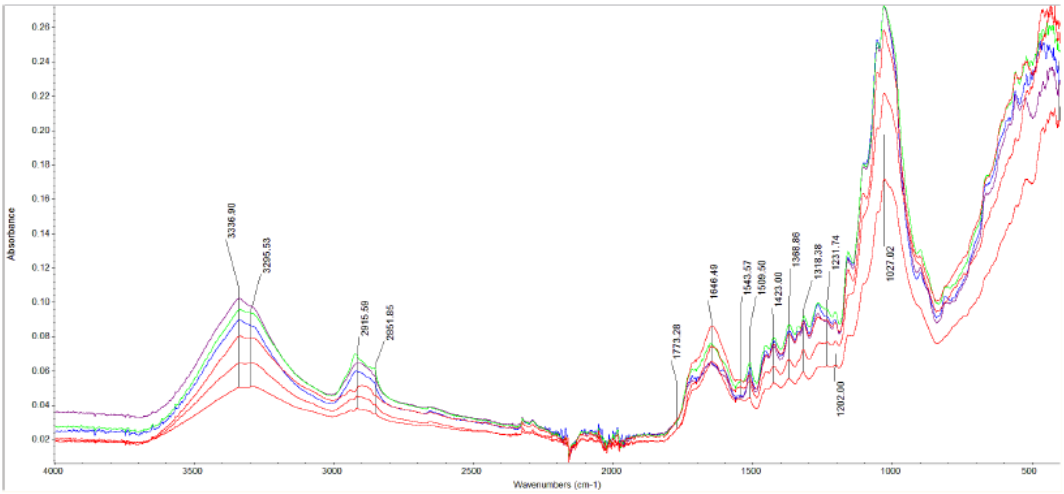


Figure 12. Effect of rinsing sample 8 (red spectra are before rinsing).

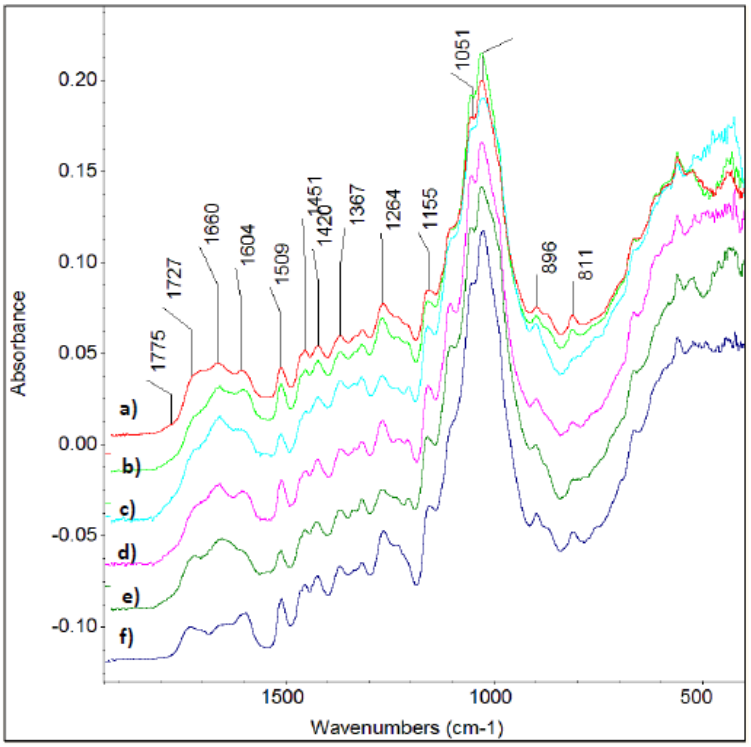


Figure 13. Rinsed samples together (1 spectrum from each sample was chosen) showing fingerprint region only. a) sample 2, b) sample 3, c) sample 4, d) sample 6, e) sample 8, f) Sound pine reference.

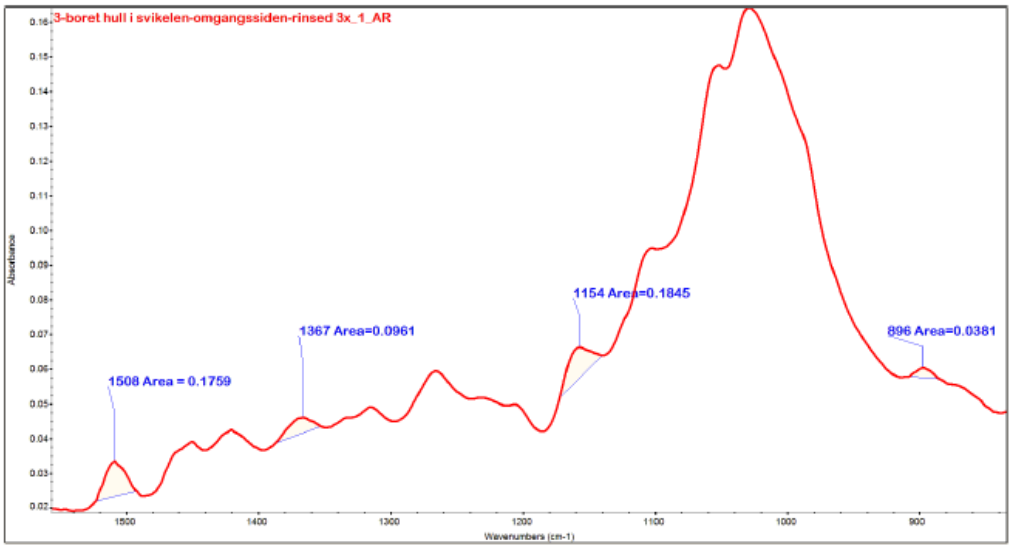
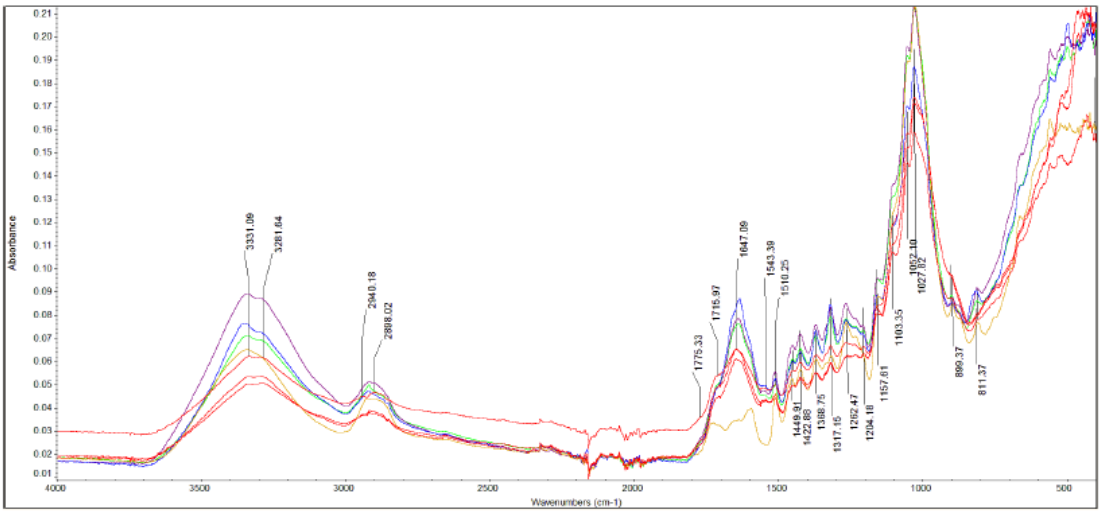
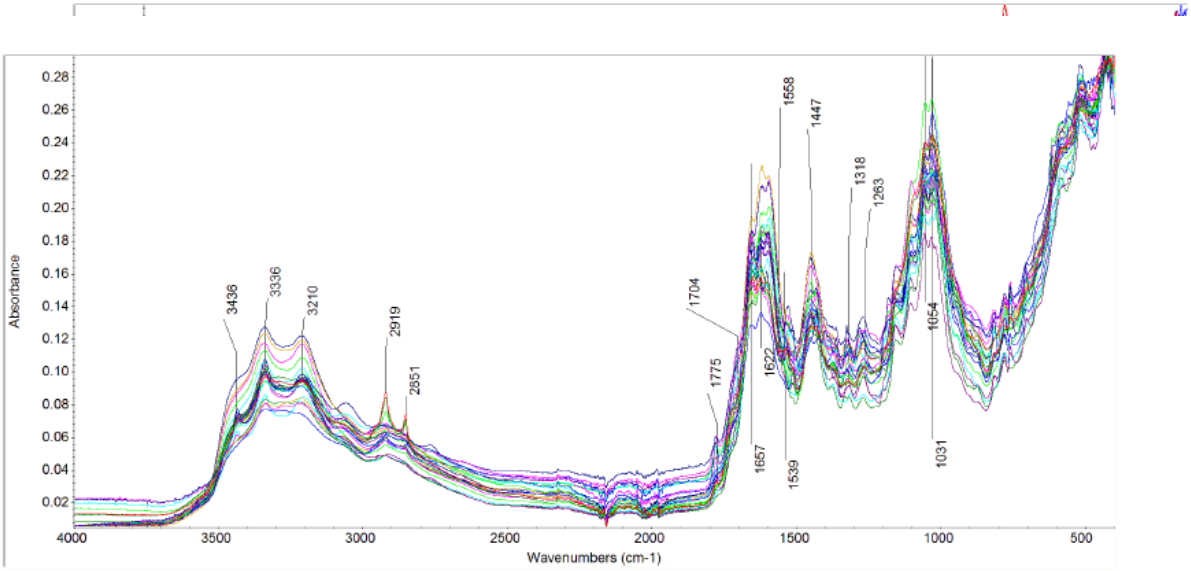


Figure 14. Example of area calculation in sample 3.

APPENDIX



Appendix 1. No urine content: samples 8 (red) and 11 with sound pine at bottom (in ochre).



Appendix 3. High urine content, samples 1, 2, 4, 5, 6, 9, 10.

Appendix 5 Report from ICP-OES and TOC analysis

Experimental method

We adopted the following protocol for the extraction of the samples:

- We crushed the samples with agate mortar and pestle;
- We weighed the crushed samples, in clean, new PP screwed cap containers;
- We treated the samples with a known quantity of ultrapure water (UPW) (average m_{UPW}/m_{sample} ratio $\approx$ 500). The used UPW (ρ = 18.2 MW·cm, TOC around 1-2 ppb) was dispensed by a Milli-Q A+ water purification system from MilliPore (Merck & Cie, Schaffhausen, Switzerland);
- We sonicated the dispersions of wood and UPW for 1 h;
- We left the dispersions of wood samples and UPW to extract overnight;
- We filtered all the dispersions with a vacuum membrane filtration system (Classic Glass Filter Holder by MilliPore) previously mounted with nylon 0.45 µm membrane filters (no. 25006) by Sartorius (Sartorius Stedim Biotech GmbH, Göttingen, Germany);
- We also saved the filters and the solid part of the dispersions (the remaining wood) in clean PP containers;
- For the ICP-OES analyses, we diluted a portion of the filtered solution (around 1:10) with 2% (w/w) HNO_3 in UPW. Fresh 2% (w/w) HNO_3 in UPW was the blank used for the analyses. The used ICP-grade nitric (TraceSELECT, $\geq$ 69%) was purchased from Fluka (Sigma-Aldrich Chemie GmbH, Buchs, Switzerland);
- For the TOC analyses, we diluted a portion of the filtered solution (around 1:3) with 0.05 M HCl in UPW. However, fresh UPW was the blank used for the analyses. The used HCl (TraceSELECT, fuming, $\geq$ 37%) was purchased from Sigma-Aldrich.

Instrumental conditions for ICP-OES

We used a Thermo Scientific iCAP 6300 Dual View ICP-OES (Thermo Fisher Scientific Inc., Waltham, MA, USA) with a CETAC ASX-260 autosampler (CETAC, Omaha, NE, USA) for the analyses. Its operating conditions are reported in the following table:

Operating condition/Instrument part Effective	**Value/Type** 383
focal length	nm
Spectral range	166-847 nm
Detector	CID86 chip (charge injection device)
RF generator	27.12 MHz solid state
Plasma viewing	Dual
Plasma and shear gas	Argon
Nebulizer	Burgener MiraMist High Solids Nebulizer (0.4-2.0 mL/min)
Spray chamber	Glass cyclone
Plasma torch	Enhanced matrix tolerance (EMT) semi-demountable
RF power	1150 W

Pump rate	50 rpm
Auxiliary gas flow	0.5 L/min
Nebulizing gas flow	0.5 L/min
Number of replicates per sample	3
Maximum integration time for low WL range	15 s (both axial and radial)
Maximum integration time for high WL range	10 s (axial) and 5 s (radial)
Flush time	45 s

Standard and reference solutions

According to the expected concentrations, we prepared the following multi-elemental standard and reference solutions by suitably diluting the Multielement standard solution 4 (c_{As}: 40 mg/L; c_{Cu}: 20 mg/L; c_{Pb}: 40 mg/L) and 1000 mg/L sulfur standard solution for ICP (both TraceCERT, Fluka) in 2% (w/w) HNO_3 in UPW:

Element	Standard (mg/L)	Reference (mg/L)
As	2	1
Cu	1	0.5
Pb	2	1
S	100	50

Analytical figures of merit

Then, we optimized the method. In the following table, we report the selected spectral lines, their view mode, the percentage deviation (note that this is a measurement of the trueness of the method) between the measured and the expected concentrations of the above-mentioned reference solution (two samples from the same reference solution were spilled), and the obtained Limit of Detections (LODs) and Limit of Quantifications (LOQs) (n_{blanks} = 3):

Element	Spectral line (nm)	View Mode	Closeness of agreement	LOD (µg/L)	LOQ (µg/L)
As	189.042	Axial	1.0%	1	3
Cu	324.754	Axial	2.4%	na	na
Pb	220.353	Axial	1.5%	na	na
S	182.624	Axial	1.2%	21	70

Results

In the following table, we report the values of the content of the elements, expressed in mg of the extracted element/kg of dry original material (along with their standard deviations, reported as sc) in the samples:

Sample	RA_0	RA_1	RA_2	RA_3
cAs (mg/kg)	1.398	10.117	7.350	0.000
scAs (mg/kg)	0.000			0.000
cCu (mg/kg)	4.193			6.715
scCu (mg/kg)	0.000			0.000
cPb (mg/kg)	1		0.000	0
			14.700	
			0.000	
			7.350	
			0.000	
			5071	
scPb (mg/kg)	1			3
cS (mg/kg)	816			2851
scS (mg/ kg)	6	101	29	13

Discussion of the ICP-OES results

The obtained results on the content of sulfur show a significant difference in samples RA_1, RA_2 and RA_3 with respect to the reference sample RA_0. This probably indicates an external contamination of these samples. The results of the content of the heavy metals do not show any significant presence.

Instrumental conditions for TOC

A Shimadzu TOC-V CSH total organic carbon (TOC) analyser (Shimadzu Schweiz GmbH, Reinach, Switzerland) was used to quantify the organic substances that could be extracted from the given samples.

Standard and reference solutions

The instrument was calibrated by suitably diluting a 1000 mg/L TOC standard (according to ISO/CEN EN1484, by Sigma-Aldrich) in UPW to have a calibration curve ranging 0-100 ppm. The reference material had a concentration of 50 ppm of TOC, also prepared by diluting the above-mentioned TOC standard solution.

Analytical figures of merit

We report here the percentage deviation (note that this is a measurement of the trueness of the TOC method) between the measured and the expected concentrations of the above-mentioned reference material (four samples from the same reference solution were spilled), and the obtained Limit of Detections (LODs) and Limit of Quantifications (LOQs) (n_{blanks} = 3):

	Closeness of agreement	**LOD (mg/L)**	**LOQ (mg/L)**
TOC	1.7%	0.10	0.35

Results

In the following table, we report the values of the extracted organic content, expressed in mg of extracted organic substance/kg of dry original material (along with their standard deviations, reported as sTOC) in the samples:

Sample	**TOC (mg/kg)**	**sTOC (mg/kg)**
RA_0	8528	136
RA_1	142041	497
RA_2	57611	661
RA_3	43531	208

Discussion of the TOC results

The obtained results on the content of TOC show a significant difference in samples RA_1, RA_2 and RA_3 with respect to the reference sample RA_0. This probably indicates an external contamination of these samples.

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cicciofuori

http://www.hf.uio.no/iakh/english/people/aca/franccar/index.html
https://scholar.google.com/citations?user=V1OsmBQAAAAJ&hl=en

NIKU OPPDRAGSRAPPORT 64/2018

Appendix 6 Report from X-ray analysis

RØNTGENUNDERSØKELSE AV TREKONSTRUKSJONER

A 284 Urnes stavkyrkje, Luster

Wedvik, Barbro

NORSK INSTITUTT FOR KULTURMINNEFORSKNING

Norsk institutt for kulturminneforskning (NIKU)
Storgata 2, Postboks 736 Sentrum, 0105 Oslo
Telefon: 23 35 50 00

www.niku.no

Tittel Røntgenundersøkelse av trekonstruksjoner A 284 Urnes stavkyrkje, Luster	Rapporttype/nummer NIKU Oppdragsrapport 64/2018	Publiseringsdato 30.08.2018
	Prosjektnummer 1021305	Oppdragstidspunkt 18.06. – 20.06.2018
	Forsidebilde Røntgenrør på lift. Foto: NIKU	
Forfatter(e) Wedvik, Barbro	Sider 23	Tilgjengelighet Åpen
	Avdeling Konservering	

Prosjektleder Barbro Wedvik
Prosjektmedarbeider(e) Christina Spaarschuh
Kvalitetssikrer Ellen Hole

Oppdragsgiver(e) Riksantikvaren v/Kjersti Ellewsen

Sammendrag

Røntgenfotografering kan brukes til undersøkelse av trekonstruksjoner i bygninger der det er ønskelig med lite inngrep. Urnes stavkyrkje er en stavkirke fra middelalderen og automatisk fredet. Målet for røntgenundersøkelsen var å undersøke søndre midtromssvill og sørvestre hjørnestav. Midtromssvilla har vært bosted for flaggermus. Oppdragsgiver ønsket å se på utstrekning av nedbrutt område i midtromssvill og å undersøke staven for nedbrytning, hulrom og mulig innflygningshull for flaggermus. Metode: XRS pulsapparat ble plassert på utsiden av veggen og røntgenfilmen på innsiden. Til vurdering av tilstanden ble det benyttet NIKUs tidligere opparbeidet referansemateriale fra røntgenbilder av biologisk nedbrutte trekonstruksjoner. Røntgenundersøkelsen visualiserte og lokaliserte skadde områder i midtromssvill. Områder med biologisk og/eller kjemisk nedbrytning er omfattende og strekker seg i hele det undersøkte områdets lengde, ca. 100 cm. Det ser også ut til å være noe skade i plank i buefelt nedenfor midtromssvill. Ingen skade ble observert i staven med røntgenundersøkelsen, men dette utelukker ikke at det kan være nedbrutte områder også her.

Emneord
X-ray, radiografi, tre, furu, stavkirke, kirke, trekonstruksjon, fuktskade, flaggermus, salt, nedbrytning

Avdelingsleder

Ellen Hole

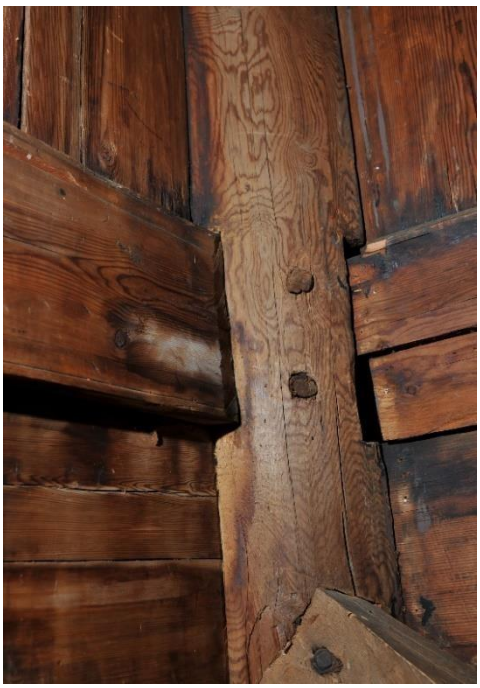
Innholdsfortegnelse

Objekt

Objekt:	A 284 Urnes stavkyrkje, Luster. Stavkirke. Automatisk fredet, og på UNESCOs verdensarvliste.
Datering:	Middelalder, datert til 1130-årene (Christie, 2009)
Materialer:	Bygningskonstruksjoner av tre, de undersøkte bygningsdelene er av furu.
Bygningselement:	Søndre del av midtromssvill på sørside samt sørvestre stav der denne møter midtromssvill.

Mål

Målet var å undersøke tidligere tilholdssted/rede for flaggermus i/ved hjørnekonstruksjon mot sørvest i Urnes stavkyrkje, se figur 1 og 2. Vestre del av søndre midtromssvill og dens innfelling i sørvestre hjørnestav var fokus for undersøkelsen. Oppdragsgiver antar at tilgangen for flaggermus har vært fra innsiden av kirken, og at flaggermusene har likt seg i staven, særlig etter at det ble lagt et blybeslag i overgangen mellom vegg og svalgangstak på utsiden, fordi beslaget har skapt et svært varmt og beskyttet rom.



Figur 1. ***Sørvestre hjørnestav ses midt i bildet, søndre midtromssvill ses til venstre i bildet. Foto: Riksantikvaren.***

Figur 2. ***Detalj fra figur 1 som viser områder med indikasjoner på biologisk/kjemisk skade: lyse/hvite områder i treet med mørkere skjolder rundt. Foto: Riksantikvaren.***

Oppdragsgivers bestilling:

- Undersøke hulrom i sørvestre hjørnestav og søndre midtromssvill som er festet til denne
- Undersøke i hvor stor grad de ulike bygningselementene har berøringspunkt til hverandre etter nedbrytningen
- Undersøke hvor blybeslag er

Metode

Til røntgenundersøkelsen ble det brukt et batteridrevet røntgenpulsapparat og digitale billedplater. Røntgenplatene ble skannet ved kirken slik at bildene kunne vurderes umiddelbart og sammen med oppdragsgiver. Et område rundt kirken ble sperret av og holdt under oppsyn for å sikre publikum ved røntgeneksponering. Røntgeneksponeringene ble utført slik at røntgenstrålene gikk fra utsiden av bygningen og inn, dvs. at billedplatene ble plassert inne i bygningen. På innsiden av kirken var det enkel tilkomst for plassering av film fra galleriet i vest. Røntgenapparatet var plassert på en personlift på utsiden, ca. 7 meter over bakkeplan, se figur 3. En del av taksponet ble demontert for å bedre lesbarhet på røntgenopptakene, se figur 6. Justering av apparatets plassering og opptaksvinkel ble gjort fra stige, se figur 4. Eksponeringene ble aktivert med fjernutløser.

Figur 3, a-b. ***Røntgenoppsett. 3a: Røntgenapparatet var plassert på lift på utsiden av kirken. 3b: Røntgenfilmen var plassert på veggen på innsiden av kirken Foto: NIKU.***

Figur 4, a-d. ***Røntgenrigging og -eksponering. 4 a og b: røntgenoperatør C. Spaarschuh, NIKU; 4 c: oppdragsgiver K. Ellewsen, Riksantikvaren; 4d: røntgenoperatør B. Wedvik, NIKU og tømrer E. Gjelsvik, Jølster Bilelag. Foto: NIKU.***

Røntgenutstyr

Røntgenapparat:	XRS-3, keV 270
Skanner:	Dürr Image Plate Skanner CR 35 NDT
Programvare:	D-Tect 4.8.0. (Dürr)
Billedplater:	Dürr, normaloppløsning (35 x 43) cm og (18 x 24) cm
Skanning:	Billedplatene ble skannet med oppløsningen 50 og 100 µm

Eksponeringer

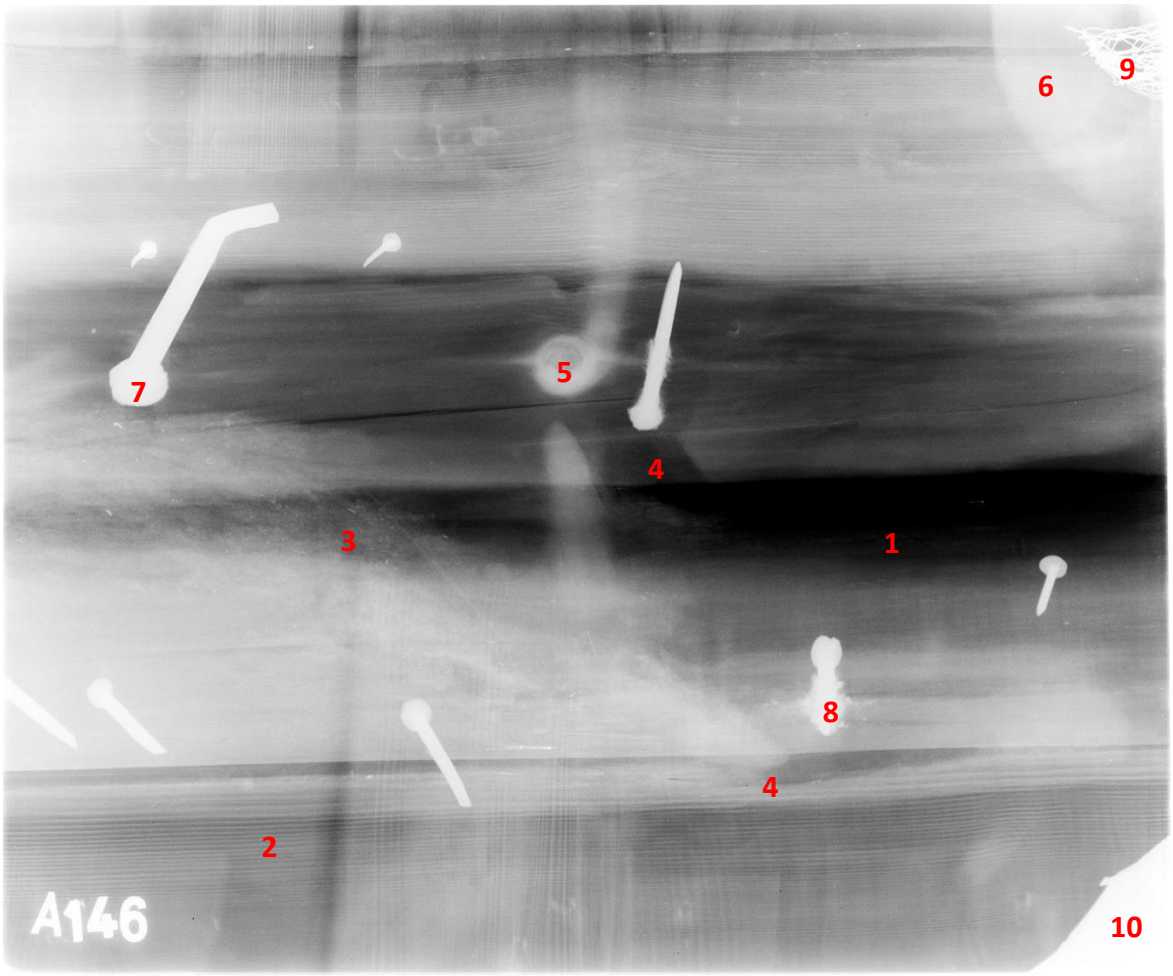
Dato	ID	Objekt	FFD Avstand	Antall puls
19.06.2018	A145	Urnes stavkirke midtromssvill S mot stav SV	ca 100	198
19.06.2018	A146	Urnes stavkirke midtromssvill S mot stav SV	ca 100	99
20.06.2018	A147	Urnes stavkirke midtromssvill S mellom stav SV og stav S2 fra V	ca 100	198
20.06.2018	A148	Urnes stavkirke midtromssvill S, V for stav S2 fra V	ca 100	198
20.06.2018	A149	Urnes stavkirke stav SV	ca 100	297
20.06.2018	A150	Urnes stavkirke stav SV	ca 100	396
20.06.2018	A151	Urnes stavkirke stav SV	ca 100	495
20.06.2018	A152	Urnes stavkirke stav SV (utelatt i rapport)	ca 100	594 (under-eksponert)

Røntgenbildene

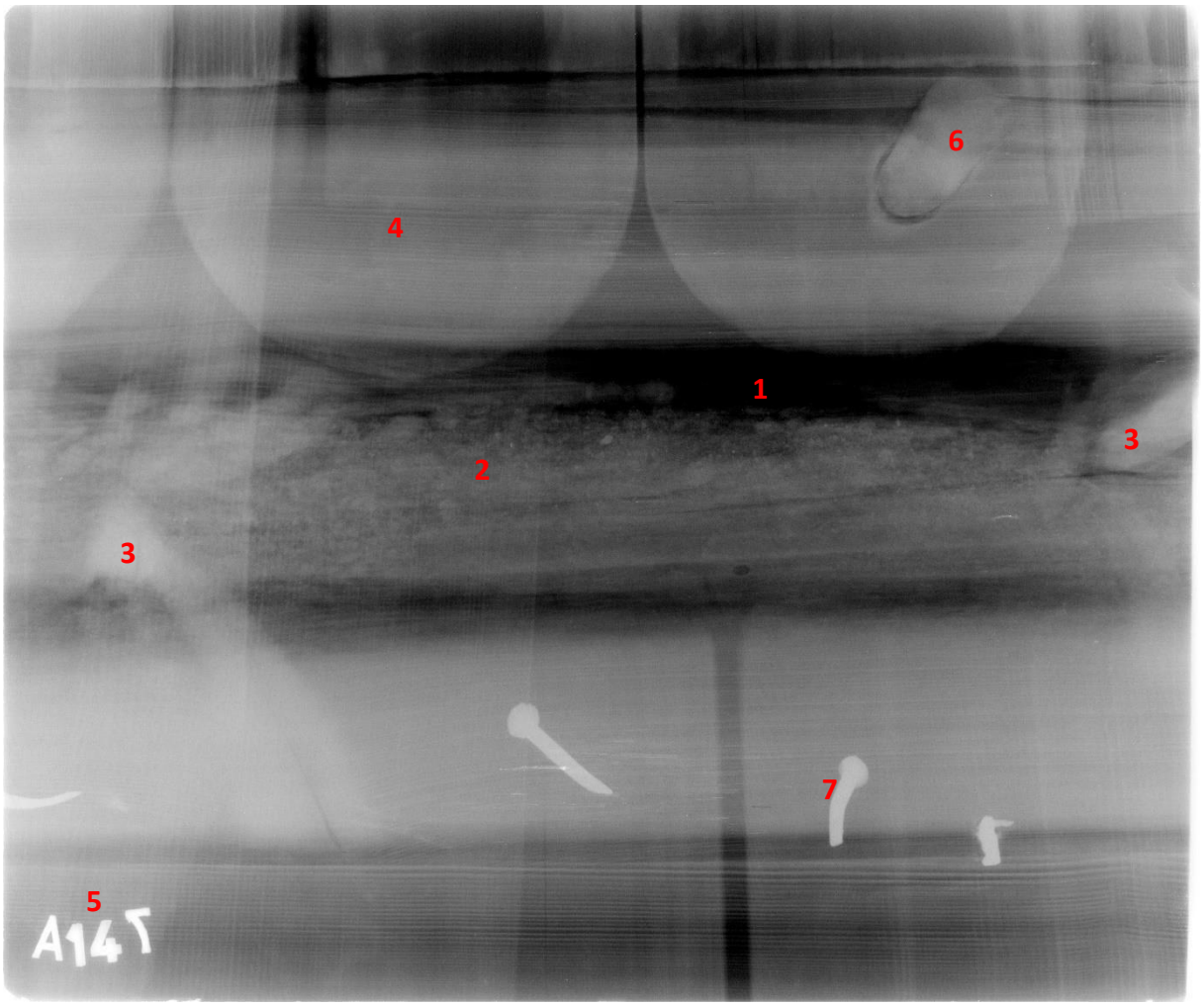
Søndre midtromssvill

Figur 5. ***Firkantene markerer røntgenfilmenes plassering på midtromssvilla inne i kirken. Hjørnestav mot sørvest på høyre kant i bildet; en av fire mellomstaver på sørsiden ses på venstre kant i bildet. Foto: NIKU***

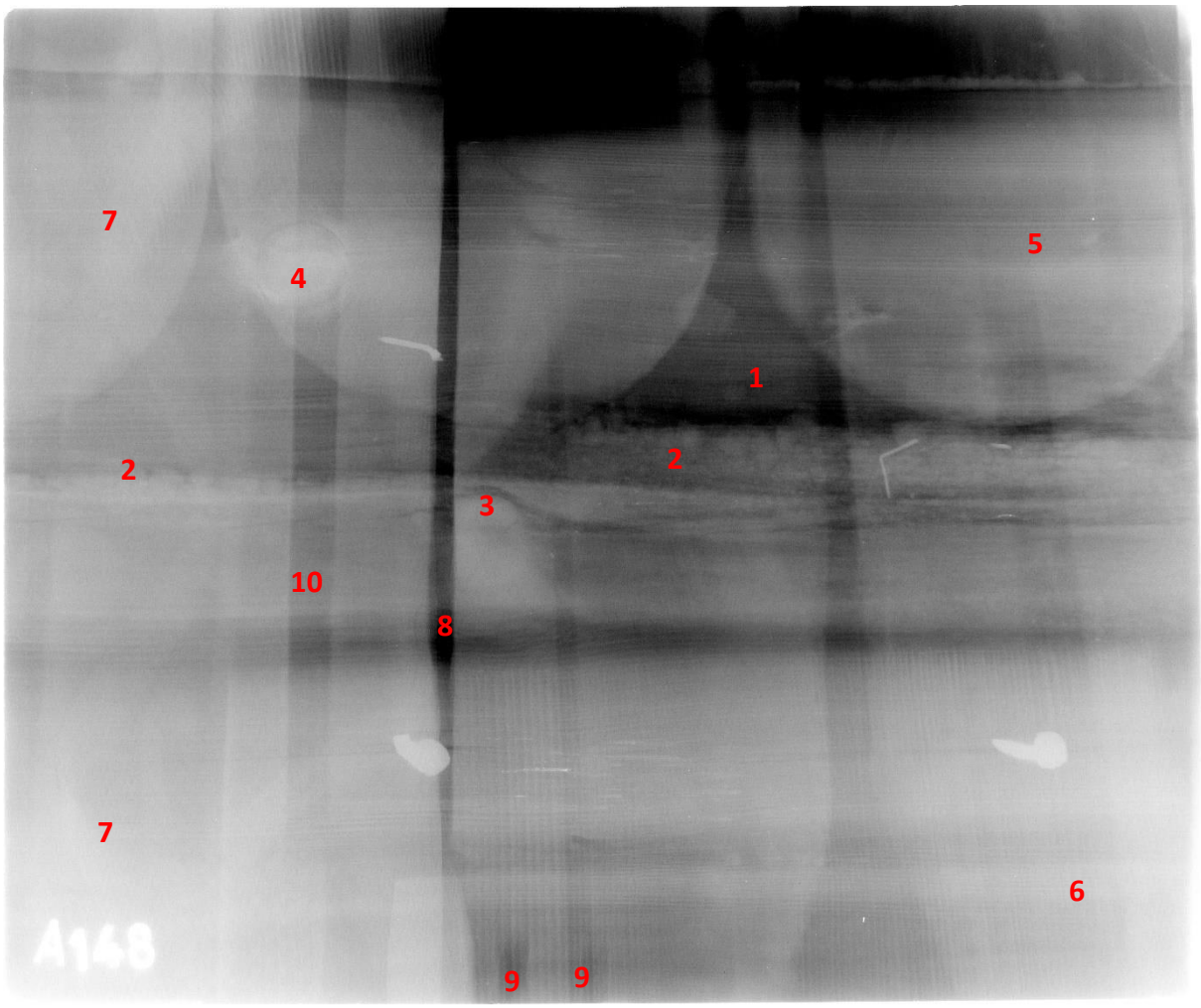
Figur 6. ***Firkantene markerer omtrentlig opptakenes fokusområde på utsiden. Foto: NIKU***



Figur 7. ***Røntgenopptak av søndre midtromssvill, opptak inntil sørvestre stav. Tilsvarer rød firkant i figur 5 og 6. Høyre kant av bildet viser området inntil staven. 1) I det mørke området er mye treverk borte/svært nedbrutt. 2) Friskt treverk, liggende fiberretning. 3) Nedbrutt treverk; årringer og fiberretning er gått i oppløsning og kan ikke leses i bildet. Irregulære klumper, opp til ca. 1 cm diameter. Noen lange fibre ligger diagonalt på fiberretningen. 4) Definerte hulrom på langs og tvers av årringene, muligens forårsaket av insektsangrep. 5) Kvist. 6) Takspon, tungeformet. 7) Spiker. 8) Rusten spiker. 9)Hønsenetting. 10) Blytekking. Foto: NIKU***



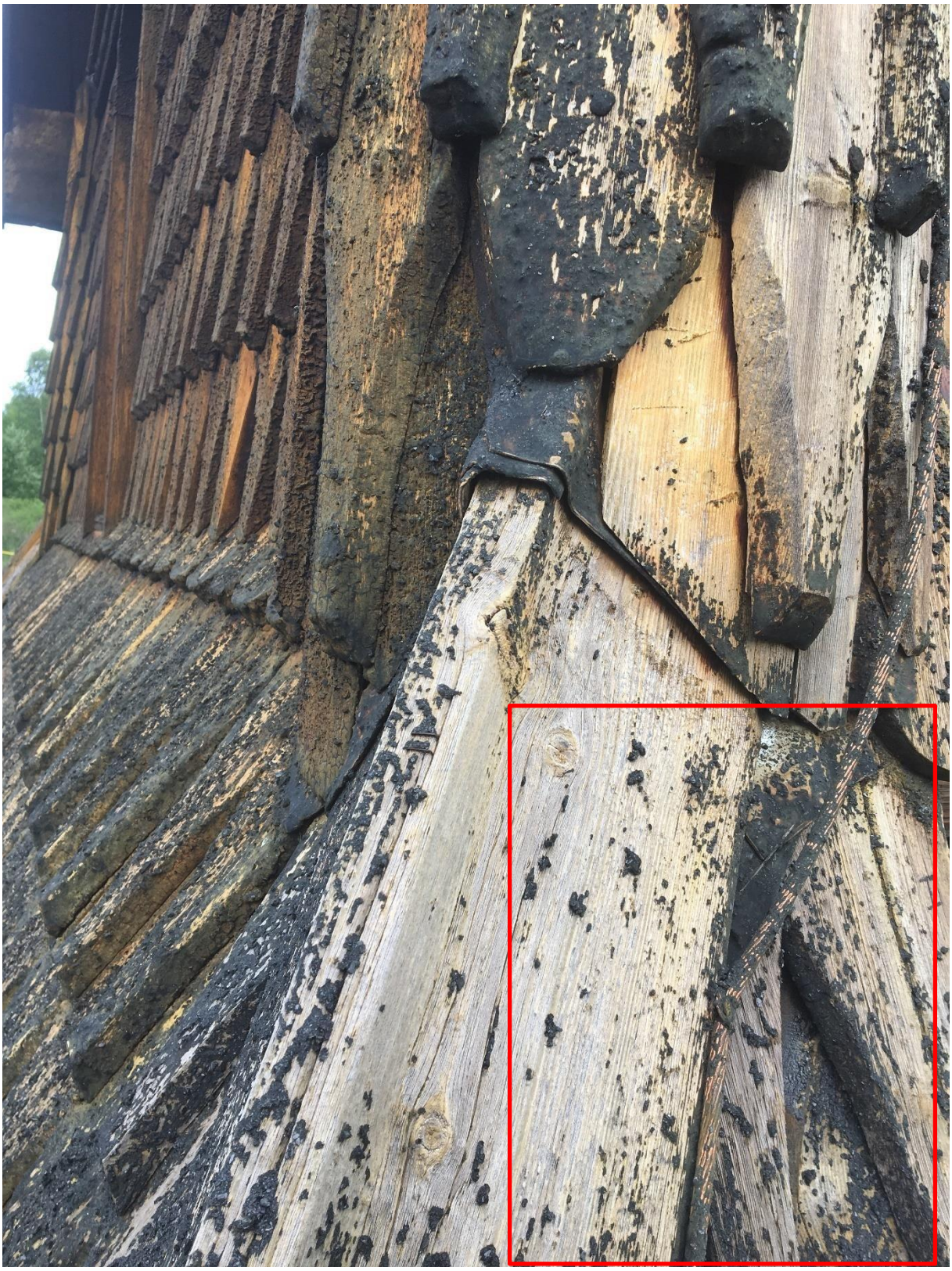
Figur 8. ***Røntgenopptak av midtromssvill, midtre opptak. Tilsvarer gul firkant i Figur 5 og 6. 1) I det mørke området er mye treverk borte/svært nedbrutt. 2) Nedbrutt treverk; årringer og fiberretning synes ikke. Irregulære klumper, opp til ca. 1 cm diameter. 3) Kvist. 4) Takspon, tungeformet. 5) Takspon, spisset. 6) Treplugg. 7) Spiker. Foto: NIKU***



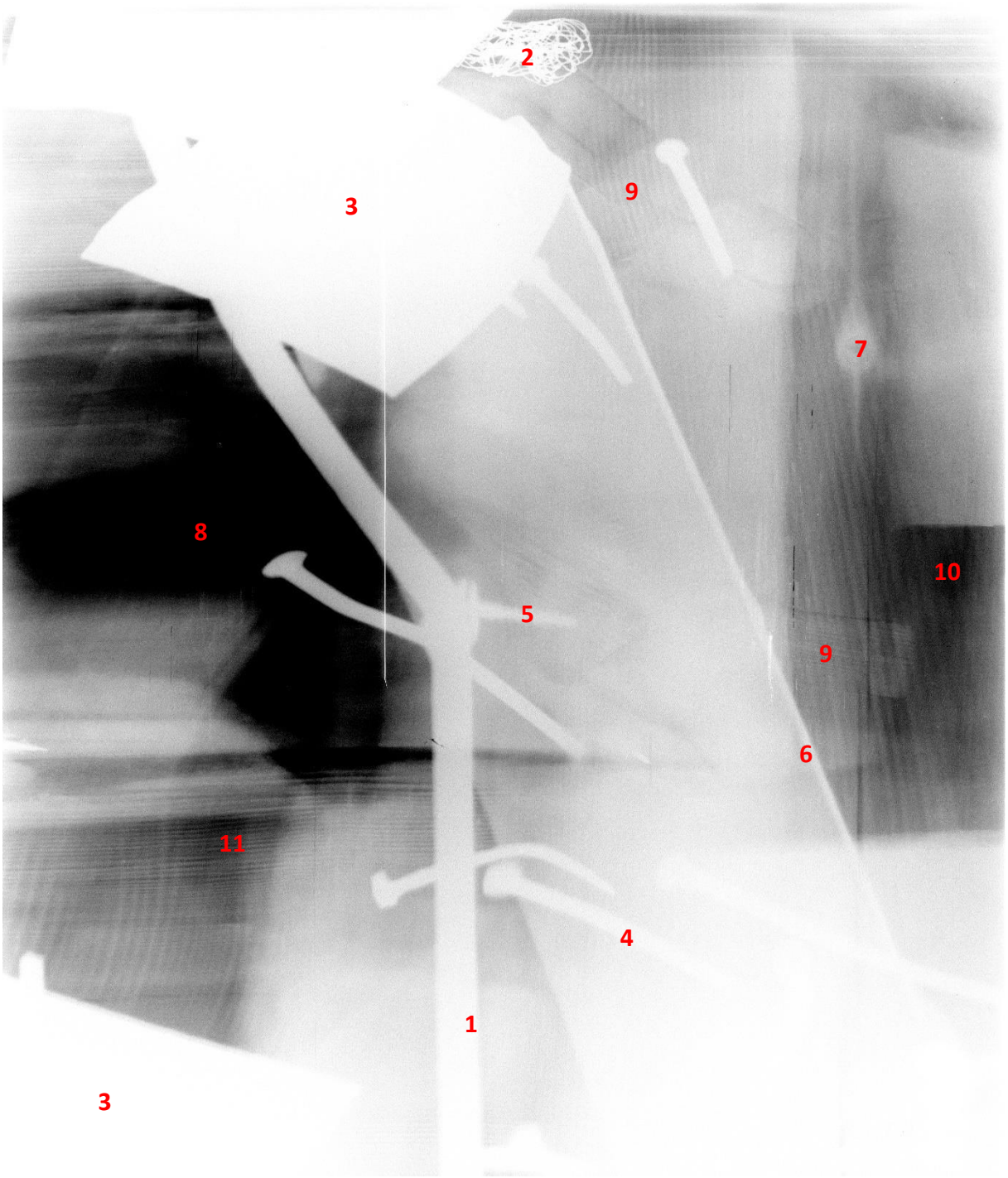
Figur 9. ***Røntgenopptak av midtromssvill, østre opptak. Tilsvarer grønn firkant i figur 5 og 6. 1) I det mørke området er mye treverk borte/svært nedbrutt. 2) Irregulære klumper, opp til ca. 1 cm diameter. 3) Kvist og sprekk. 4) Trenagl som sikrer sammenføyningen mellom midtromssvill og mellomstav. 5) Takspon, tungeformet. 6) Takspon, spisset. 7) Treskurd 8) Kant uttak av midtromssvill for innfelling i mellomstav. 9) Dendroprøveuttak. 10) Glippe ved svillas innfelling i mellomstav? Foto: NIKU***

Sørvestre hjørnestav

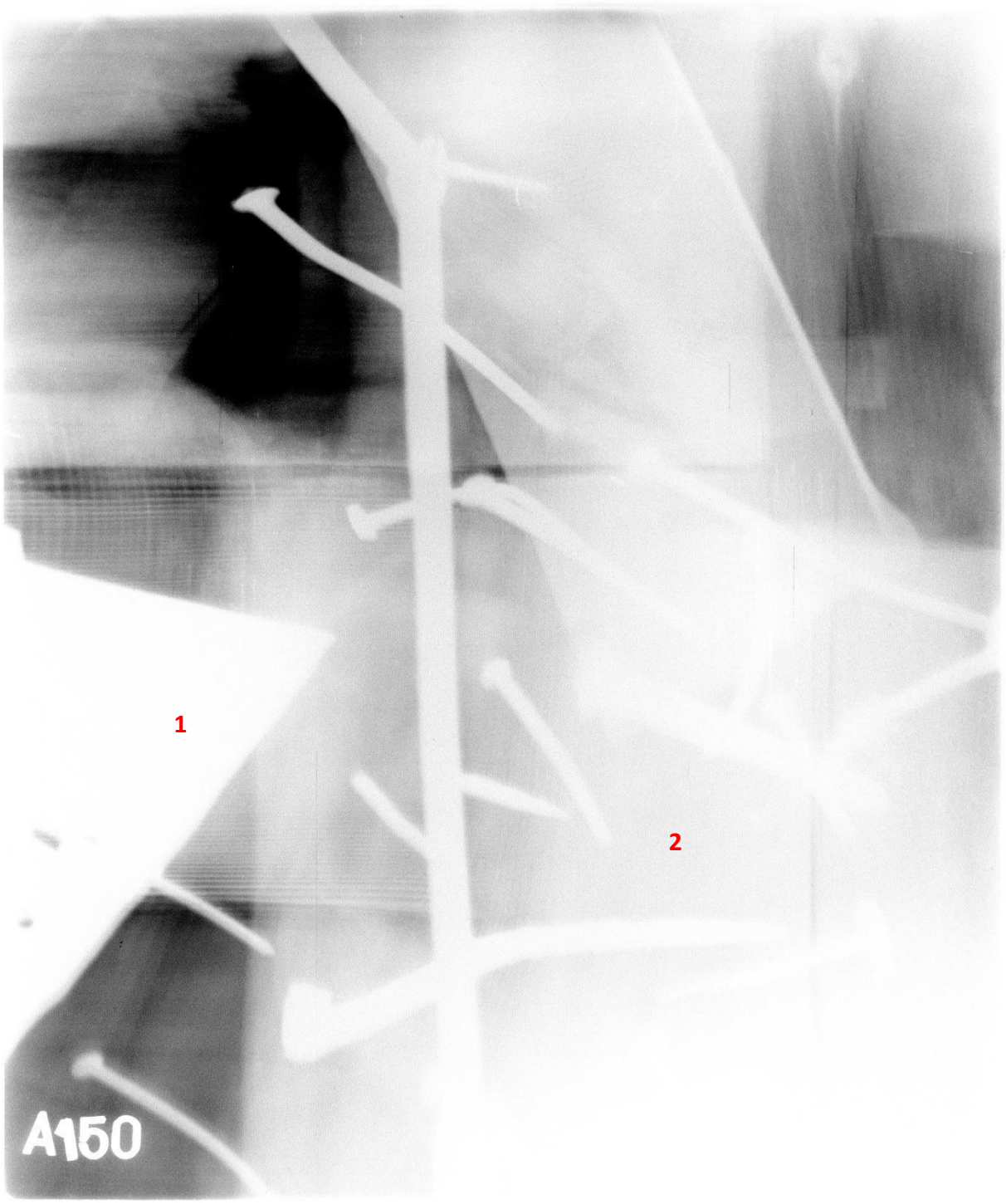
Figur 10. ***SV stav med inntappede midtromssviller. Firkantene markerer røntgenfilmenes plassering på staven, rød svarer til figur 12, grønn til figur 13 (de gule prikkene er NIKUs tegnestifter, brukt til å feste røntgenfilmen til veggen.) Foto: NIKU***



Figur 11. ***Firkanter i rødt markerer omtrentlig opptakenes fokusområde på utsiden, på V-siden av omgangstakets SV-re møne. Foto: NIKU***



Figur 12. ***Røntgenopptak SV stav, se rød firkant i figur 10. 1) Lynavleder 2) Hønsenetting. 3) Blyplate. 4) Spiker. 5) Skrue. 6) Møne på omgangens tak. 7) Kvist 8) I det mørke området er mye treverk borte/svært nedbrutt. 9) Treplugger som sikrer S- og V-midtromssvill til stav. 10) Hulrom i konstruksjonen ved inntapping i staven fordi nedre del av Vmidtromssvillen mangler. 11) Område med hulrom/nedbrytning i øvre plank i buefelt. Foto: NIKU***



Figur 13. ***Røntgenopptak SV stav, se grønn firkant i figur 10. Røntgenopptak SV stav. 1) Man kan se mer av blydekket enn i Figur 9. 2) Årringene i staven fremtrer ikke tydelig, men dette kan skyldes opptakssituasjon. Foto: NIKU***

Tolkning

Søndre midtromssvill

Ved visuell undersøkelse på svillas utside er det tydelig at treverket er sterkt nedbrutt, trolig på grunn innsig av vann. Det er tidligere gjort tettings-tiltak med plankebord og blytekking, se figur 6. Ved opptakstidspunktet kjentes treverket fuktig.

Selv om midtromssvilla er +/- 22 cm tykk absorberer den relativt lite røntgenstråling over det hele om man sammenligner med de andre tynnere, friske tre-elementene i opptakene, se figur 7, 8 og 9. Dette kan tyde på at treet i hele den røntgenundersøkte delen av midtromssvilla er nedbrutt, men i ulik grad. Områder med kvist nedbrytes i mindre grad og fremstår som lysere, se figur 7 pkt. 5, 8 pkt. 3 og 9 pkt 3.

På røntgenbilder av uskadd trematerialе av jevn tykkelse vil røntgenopptaket ha relativt lik svertning i hele emnet. At noen områder er mørkere enn det omkringliggende treverket tilhørende samme bygningsdel og med samme tykkelse tyder på manglende materiale eller nedbrutt materiale med en lavere tetthet. På friskt treverk kan man skille porøs vårved (lav tetthet) fra hard vinterved (høy tetthet), se f.eks. området over pkt. 9 på figur 9. Når årringene ikke kan ses kan det være fordi treet er så nedbrutt at røntgenopptaket ikke lenger kan registrere noen forskjell i tetthet mellom vårved og vinterved. På røntgenopptakene av midtromssvilla viser treverket seg noen steder som sterkt nedbrutt. Årringene synes i liten grad, og i de mørkere områdene synes de ikke i det hele tatt, se figur 7, pkt. 1, figur 8, pkt. 1 og figur 9, pkt. 1.

På midtromssvilla, nærme hjørnestaven, ser man med det blotte øyet områder med hvitt belegg. I et av røntgenopptakene, se figur 7, pkt. 3, ses formasjoner som kan være lange, flussede trefibre. I alle røntgenopptakene ses mange kantete klumper, opp til ca. 1 cm diameter, se figur 8, pkt. 2, figur 9, pkt. 2 og figur 15 b. De lange fibrene kan skyldes kjemisk nedbrytning av treet, at limet mellom trefibrene brytes ned og fibrene løsner fra hverandre. En slik nedbrytning kan skje ved påvirkning fra sterke syrer. På røntgenopptak av råteskadet tre kan man noen ganger observere råteklosser

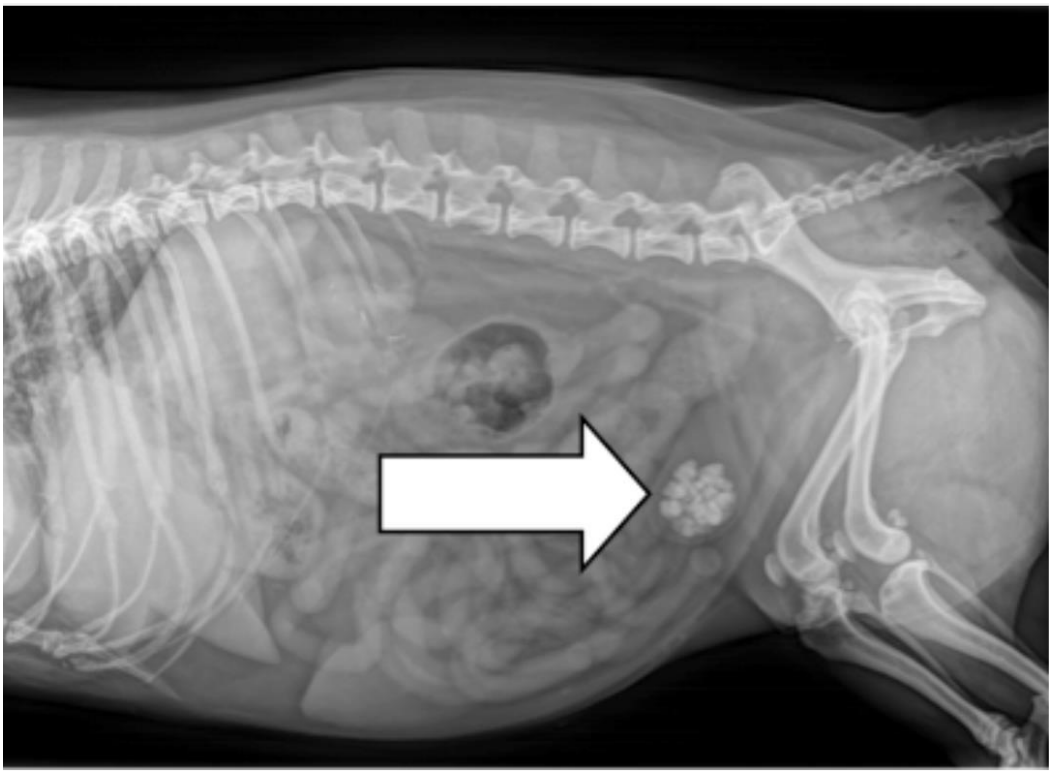
(brunråte), med sprekker på lang og tvers av fiberretningen. Klumpene som synes i røntgenopptakene av svilla følger ikke treets struktur. Kanskje kan krystalliserte salter i nedbrutt treverk danner slike irregulære former? Western Bat Specialists[1] beskriver et typisk skadebilde forårsaket av flaggermus slik:

> *Guano and urine have a chemical effect on building materials. Both substances contain high levels of uric and other acids. […] Guano contains high levels of phosphates, ammonium, potassium, chlorides, and other materials. These and the salts resulting from acid corrosion can result in severe problems of efflorescence and breaking. Similarly, the effect of the acids and salts on the porosity of masonry and other materials can result in accelerated moisture and frost damage. The acid can also serve as a catalyst in the process of oxidation on nails, screws, and metal flashing's around the structure. […] Bat urine readily crystallizes at room temperature. In warm conditions under roofs exposed to sun and on chimney walls, the urine evaporates so quickly that it crystallizes in great accumulations. Boards and beams saturated with urine acquire a whitish powder-like coating. With large numbers of bats, thick and hard stalactites and stalagmites of crystallized bat urine are occasionally formed. […] As already mentioned, bat guano and urine have a high concentration of uric and other acids, meaning that the guano and urine are extremely corrosive. This is especially true when there is repeated contact with surfaces such as metals and wood. Over a long period of time urine may cause wood deterioration. As the urine saturates the surfaces of dry wood beams and*

[1] http://batproblems.net/bat-guano/bat-guano-urine-damages/

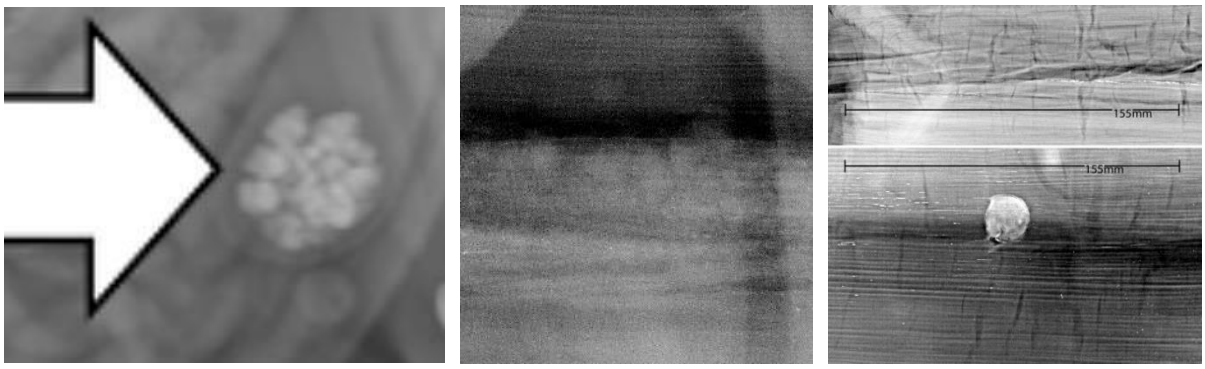
crystallizes, the wood fibers expand and separate. This can be quite severe, ultimately resulting in the need to replace such materials.

NIKU har ikke referansebilder av treverk nedbrutt av flaggermus-urin eller -avføring, men nettsider som diskuterer problematikken omkring avføring og urin fra flaggermus i trekonstruksjoner viser bilder av avsetninger og fibrete treoverflater som kan stemme overens med tilstanden som viser seg på røntgenopptakene av midtromssvilla, se eksempel i figur 16. Studier av blant annet brannhemmende impregnering av treverk viser også at treoverflater som blir utsatt for syre- og saltpåvirkning kan bli flussete (Kučerová et al. 2008). Fra tidligere røntgenundersøkelser vet man at saltkrystaller vises på røntgenopptak. For eksempel vises salt fra alum-impregnering av arkeologisk tre på røntgenbilder seg som røntgenabsorberende.[2] Saltkrystaller viser seg også på røntgenbilder av «stein» i urinblæra på mennesker og dyr, se eksempel i røntgenopptak av urinblæra til en hund, figur 14 og 15.



Figur 14. ***Røntgenbilde av hund med blærestein. Blærestein er en forsteining av ulike mineraler/salter. Hentet fra nettside:*** **https://d8zzf9mjbijrc.cloudfront.net/wp-content/uploads/2015/08/Bladder-stones-X-ray-stones.png**

[2] https://www.statsbygg.no/Files/samfunnsansvar/fou/nanokatedral/susanBraovac.pdf



Figur 15, a-c. ***For sammenligning. 15 a: detaljfoto av figur 14, røntgenopptak av hund med blærestein; 15 b: detalj fra figur 9, uregelmessige klumper/kantete former i treet; 15 c: eksempel på to røntgenopptak av råteklosser i fuktskadet treverk, trolig brunråte (Stein, 2013). Råteskadet tre vil normalt sprekke opp på tvers av fibrene, mens formene/nedbrytningen vi ser på detaljen fra røntgenopptaket av midtromssvillen (figur 15 b) er uavhengige av fiberretning og kan ha blitt dannet av tilført materiale i treverket, eksempelvis urin og/eller ekskrementer fra flaggermus.***

En av spikerne viser seg som sterkt korrodert på røntgenopptaket (figur 9, pkt. 8). Dette kan skyldes særlig surt miljø i dette området (James 2014), og kan være forårsaket av flaggermus-urin. Noen hulrom på langs og tvers av årringene i opptaket nærmest hjørnestaven kan være insekts-ganger, muligens stokkmaur. Se figur 7, pkt. 4. (Stein and Wedvik 2013) (Wedvik et al. 2015)

Figur 16. ***Foto av flaggermus i trekonstruksjon. I nedre del av bildet vises klumpete forsteininger som dannes av urin og avføring fra flaggermus. Øverst til venstre i bildet: svært flusset treoverflate. Viser dette nedbrytning av treverk som kan skyldes flaggermus-urin? Hentet fra nettside https://www.mass.gov/news/study-on-little-brown-bats-continues.***

Sørvestre hjørnestav og øvre plank i buefelt

Ut fra røntgenbildene av staven, se figur 12 og 13, kan det ikke påvises nedbrutt treverk eller hulrom som skyldes nedbrytning. På røntgenbildet av staven synes årringene på stavens vestre side og her er også tre-elementenes kuttflater klart definerte. På stavens østre side er både årringer og kuttkanter mindre tydelig gjengitt, men dette kan skyldes andre forhold enn nedbrytning, som bevegelse i røntgenapparat under eksponering (plassert på utvendig lift i sterk vind) eller sterk fortegning, som det blir ved opptak av hjørnekonstruksjoner.

På opptakene av staven er det imidlertid også informasjon om den delen av øvre planke i buefeltet som ligger nærmest staven, se figur 12, pkt. 11. Det ser ut til å være et hulrom eller område med nedbrutt treverk rett under midtromssvilla, i forlengelsen av et svært nedbrutt område i denne.

Konklusjon

Søndre midtromssvill

Midtromssvillas treverk er nedbrutt i hele det røntgenfotograferte området, stedvis sterkt nedbrutt. Trolig har svilla vært utsatt for fuktpåvirkning med påfølgende råte før flaggermusene flyttet inn i den, siden disse ikke kan rydde seg plass i friskt treverk. Ut fra innhentet informasjon om typer nedbrytning som skyldes flaggermus-urin og -ekskrementer virker det sannsynlig at en del av skadebildet som vises på røntgenbildene - de flussete trefibrene og de kantete klumpene i treverket - kan være sekundærskader som kan ses i sammenheng med at svilla har vært bosted for flaggermus.

Midtromssvillas bæreevne og festeevnen i hjørnestaven bør vurderes og den svekkede delen overvåkes, sikres eller byttes.

Dersom det besluttes at den undersøkte delen av midtromssvillen må erstattes vil NIKU svært gjerne motta den som materialprøve for å få bekreftet, nyansert eller avkreftet vår tolkning av skadebildet, og for eventuell bruk som referansemateriale for nedbrytning av treverk forårsaket av flaggermus.

Sørvestre hjørnestav og øvre plank i buefelt

Røntgenbildene kunne ikke bekrefte noen skader i hjørnestaven, men området mot midtromssvilla er utydelig på bildene, så det kan ikke utelukkes at det kan være nedbrutt treverk også her. Området bør undersøkes også med andre metoder.

Det ser ut til å være et nedbrutt område eller hulrom i øvre plank i buefeltet nedenfor svilla. Området ligger rett under et svært nedbrutt område i svilla, og nedbrytningen i disse områdene kan trolig ses i sammenheng med hverandre. Buefeltet har ifølge Håkon Christie (Christie, Amlo, and Riksantikvaren 2009) ingen bærende funksjon.

Christie, Håkon, Anders Amlo, and Riksantikvaren. 2009. *Urnes stavkirke : den nåværende kirken på Urnes*. Oslo: Pax.

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Kučerová, Irena, Martina Ohlídalová, Jiři Frankl, Michal Kloiber, and Alena Michalcová. 2008. "Debrifing of historical rood beams caused by ammonium sulphate and ammonium phosphates based fire retardants." Wood Science for Conservation of Cultural Heritage, Braga.

Stein, M. , and B. Wedvik. 2013. "Historische Holzbauwerke röntgen. Identifikation und Aufzeichnung der biologischen Zerstörung von Holz mittels tragbarer Röntgenröhren und digitalem Röntgen. ." *Restauro. Forum für Restauratoren, Konservatoren und Denkmalpfleger* 2013 (5) 48-57.

Wedvik, Barbro, Mille Stein, Jan Michael Stornes, and Johan Mattsson. 2015. "On-site Radioscopic Qualitative Assessment of Historic Timber Structures: Identification and Mapping of Biological Deterioration of Wood." *International Journal of Architectural Heritage*. doi: 10.1080/15583058.2015.1077905.

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