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SUCCESSFUL AMS ^{14}C DATING OF NON-HYDRAULIC LIME MORTARS FROM THE MEDIEVAL CHURCHES OF THE ÅLAND ISLANDS, FINLAND

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ABSTRACT. Fifteen years of research on accelerator mass spectrometry (AMS) radiocarbon dating of non-hydraulic mortar has now led to the establishment of a chronology for the medieval stone churches of the Åland Islands (Finland), where no contemporary written records could shed light on the first building phases. In contrast to other material for dating, well-preserved mortar is abundantly available from every building stage.

We have gathered experience from AMS dating of 150 Åland mortar samples. Approximately half of them have age control from dendrochronology or from ^{14}C analysis of wooden fragments in direct contact with the mortar. Of the samples with age control, 95% of the results agree with the age of the wood. The age control from dendrochronology, petrologic microscopy, chemical testing of the mortars, and mathematical modeling of their behavior during dissolution in acid have helped us to define criteria of reliability to interpret the ^{14}C results when mortar dating is the only possibility to constrain the buildings in time. With these criteria, 80% of all samples reached conclusive results, and we have thus far been able to establish the chronology of 12 out of the 14 churches and chapels, while 2 still require complementary analyses.

INTRODUCTION

For decades, the chronology of the medieval churches of the Åland Islands, Finland, has been the subject of a heated debate. With the aim to solve this problem and create an objective chronology for the 12 medieval stone churches and 2 chapels, the project "The Churches of the Åland Islands" was initiated in 1990. Different scientific methods were applied, initially with focusing on dendrochronology and conventional radiocarbon dating of mortar. In 1994, the introduction of AMS ^{14}C analysis presented a new opening, resulting in the interdisciplinary *International Mortar Dating Project*. Our methodological and theoretical development efforts have been the subject of a dissertation (Lindroos 2005) and have also been published in different scientific and archaeological journals and monographs as well as proceedings of international conferences (e.g. Ringbom and Remmer 1995, 2000, 2005; Heinemeier et al. 1997; Hale et al. 2003; Ringbom et al. 2006, 2009; Lindroos et al. 2007). We have also extended the application of mortar dating to mortars of Roman ruins in Portugal (Langley et al. 2010) and Rome (Hodgins et al. 2010; Lindroos et al. 2010; Ringbom et al. 2010), where the hydraulic nature (Borrelli 1999) of the pozzolana mortar makes the interpretation more complex than in the case of the Åland churches. In the present paper, we focus on the results and lessons of the non-hydraulic mortars of Åland.

The incentive to develop and use the costly ^{14}C mortar dating technique to resolve the chronology of the Åland churches has been the general lack of alternatives:

- There are no preserved historical sources to shed light on the chronology of the Åland churches;
- Coins and archaeological artifacts do not date mortared structures;
- Only few datable materials are available;
- Dendrochronology was performed on all the churches in 1991–1992. However, due to the early timber constructions having been consumed by fires or rot, the result was disappointing since it did not date the original structures, only secondary building stages (towers) and later repairs;
- There are essentially no brick constructions and thus thermoluminescence dating has not been an option.

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In contrast to all other datable materials, there is always plenty of original mortar from every stage of the building construction, which naturally makes successful mortar dating techniques very rewarding, offering a potential key to classical and medieval archaeology. Throughout, we have supplemented this with dating of alternative materials, such as inclusions in the mortar of charcoal for control purposes, but we have generally seen confirmation of the findings of others (e.g. Tubbs and Kinder 1990) that charcoal inclusions often are far older than the mortar. By contrast, carefully selected samples of wood fragments from the surface of scaffolding or from timber embedded in the mortar during construction have turned out to be useful. Here, we present the full series of dating measurements from the Åland Islands, the inferred dates of each building unit compared to independent, science-based chronological evidence, mainly dendrochronology and ^{14}C analysis of wood, where available. Finally, we give an overview of the resulting chronology of the 12 churches and chapels dealt with so far out of the 14 existing in the Åland Islands.

BACKGROUND

The principle of the method of dating lime mortars using standard ^{14}C carbonate procedures has been known since the 1960s (Labeyrie and Delibrias 1964; Stuiver and Smith 1965; see Figure 1).

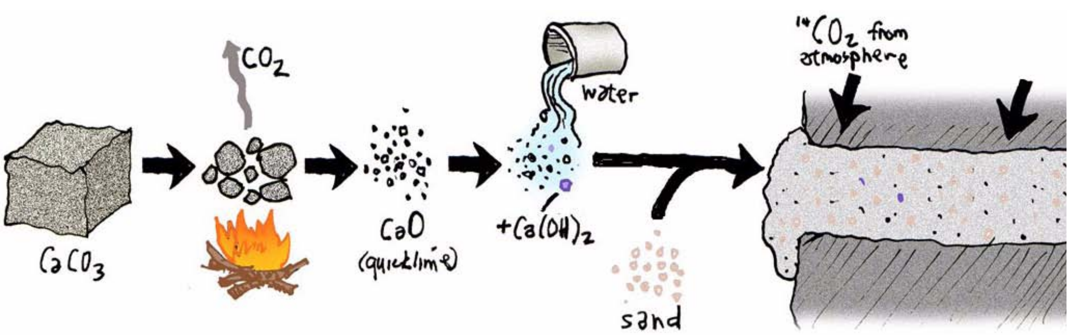

Figure 1 Mortar absorbs carbon dioxide from the atmosphere when it hardens, which makes it potentially suitable for ^{14}C dating (from Hale et al. 2003, with modifications).

Atmospheric carbon dioxide is fixed in the carbonate formed during the hardening of lime mortar at the time of construction, which in principle makes it ideally suited for ^{14}C dating. To produce building lime, limestone is heated to at least 900 °C to liberate carbon dioxide and produce quicklime (calcium oxide, CaO). The quicklime is then slaked with water to form calcium hydroxide ($Ca(OH)_2$) or building lime, which is mixed with aggregates or filler (sand) and water to form mortar. Calcium hydroxide in mortar reacts with atmospheric carbon dioxide forming calcium carbonate ($CaCO_3$), as the binder in the hardened mortar. The ^{14}C content of a mortar sample can thus in principle give a measure of the time elapsed since the time of hardening.

There are, however, well-known risks associated with the method as it is sensitive to contamination effects that have been poorly understood and it has therefore been used with precaution and with varying success in archaeometry (e.g. Baxter and Walton 1970; Folk and Valastro 1976; Van Strydonck et al. 1983; Willaime et al. 1983). The mortar may contain old limestone, either as remains from incomplete conversion into calcium oxide in the burning process or from sedimentary carbonate in the aggregate, yielding apparent ages that are too old due to this form of contamination. Conversely, delayed hardening in thick walls or later recrystallization of the carbonate incorporating younger carbon dioxide can lead to dates that are too young. Some systematic studies of mortar hardening and dissolution versus chemical activity of stable isotopes have been published (Pachiaudi et al. 1986; Van Strydonck et al. 1986, 1989; Ambers 1987; Van Strydonck and Dupas 1991; Sonninen and Jungner 2001), but the link to carbonate mineralogy and stable isotope geochemistry has been dealt with in more detail (Létolle et al. 1990; Lindroos 2005; Lindroos et al. 2007).

Concerning sampling strategy, it is important to avoid secondary repairs. In the Åland churches, most sampling has taken place under roofs in sheltered places. The sample is taken carefully with a chisel from the surface, where the mortar has hardened quickly. First, the outermost layer is gently cleaned with the chisel. The risk of delayed hardening has to be considered; therefore, drilling into the mortar is avoided. Generally, one handful of mortar is sufficient for each sample. Of this, only a small percentage is analyzed; the rest is kept for mineralogical and chemical analyses, for archival use, and for any possible need to repeat the analysis. Details of the theoretical background for mortar hardening and dissolution, sample preparation techniques, and prescreening of samples to evaluate suitability for dating have been given previously (Lindroos et al. 2007).

For the ^{14}C measurements, accelerator mass spectrometry (AMS) is needed. The major advantage of AMS analysis over conventional ^{14}C measurement is that much smaller samples are required. Whereas a conventional measurement typically requires several grams of prepared carbon, AMS demands only a milligram or less. This allows higher selectivity in many small fractions and uniform acid dissolution reaction in small volumes. Our initial attempts of mortar dating with the conventional ^{14}C method (e.g. Ringbom and Remmer 1995; Ringbom et al. 1996) were sensitive to contamination, resulting in large scatter and too high ages. Thus, we now only rely on age determinations based on AMS.

METHODS

We have focused our AMS measurements on well-defined concentrates of binder carbonates. Via mechanical separation we try to produce some hundreds of milligrams of powder that is homogenous with respect to both grain size and composition for AMS dating. The mortar sample is gently crushed—a process that preferentially breaks up the porous, soft mortar carbonate while leaving the harder limestone particles intact—and then sieved using increasingly fine mesh widths ranging between 20–500 µm. The grain-size fractions <100 µm that may be used for dating are subsequently wet sieved. The small grains of mortar carbonate fragments pass through the coarser sieves and are thus separated from the large aggregate grains, including the calcite crystals of the unburned limestone. By wet sieving, the mortar carbonate is enriched to 60–80% in the fine grain-size windows extracted for dating (usually 39–75, 39–62, or 63–74 µm depending on sample size and available sieves). Recently, we have mostly used 46–75 µm, whereas the content of limestone is typically reduced to less than 3%.

Following the mechanical separation, the mineral composition is analyzed by petrographic microscopy supplemented with cathodoluminescence, which helps to identify the contamination from aggregate limestone and marble (Lindroos et al. 2007 and references therein). Calcite of geological origin is usually, but not always, revealed as brilliant orange or red spots against the mortar binder carbonate, which forms a dull gray or brown background (Figure 2). Incompletely calcinated limestone residues are best identified microscopically in thin sections of mortar pieces where they show up as rusty lumps.

We have usually disqualified samples displaying abundant luminescent calcite or analyzed them only in order to get information about the nature of the contamination. In some cases, however, the contaminants are not luminescent, or they have lost their luminescence due to weathering, fire dam-

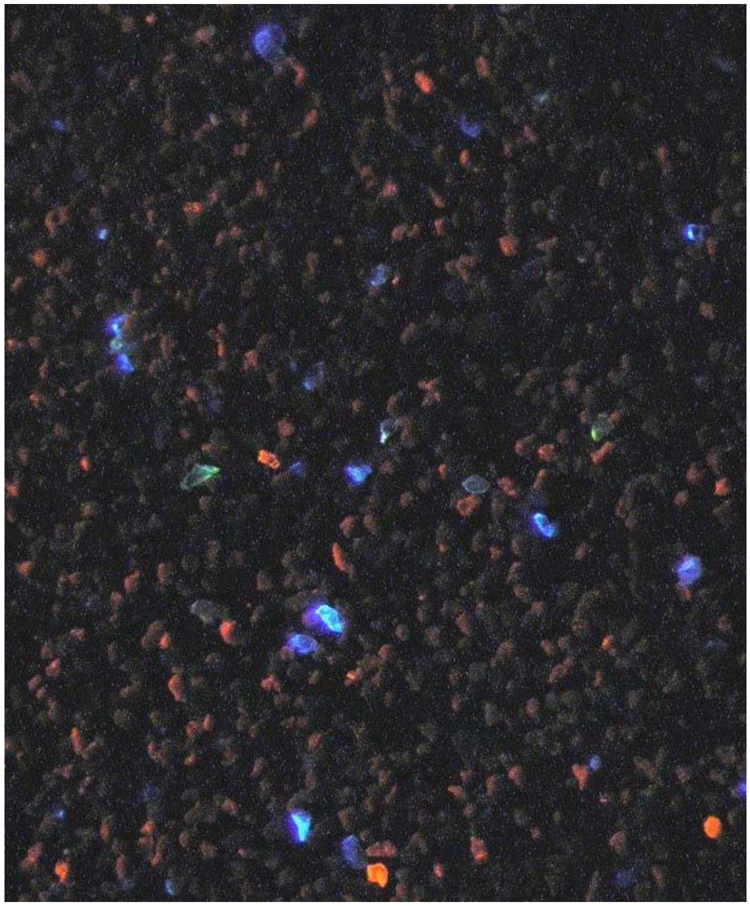

Figure 2 Cathodoluminescence microscopy. The orange-red spots show contaminating filler limestone, whereas the blue spots are quartz crystals without any significance for the dating analysis. Sample 146 from the church of Saltvik; 63–74µm grain-size fraction.

age, etc. The ^{14}C profiles (see below) themselves are therefore the most reliable and sensitive indicators of contamination.

In the chemical separation, 85% phosphoric acid is poured over the mortar powder under vacuum. In theory, mortar binder carbonate dissolves much easier than limestone. Thus, the process starts out with a violent reaction, liberating CO_2 from the fast dissolution of the pure binder carbonate, and then the reaction gradually slows down, reflecting the slow dissolution of the remaining binder carbonate and the slowly dissolving sedimentary filler carbonates and unburned limestone from the quarry. Until about 2002, the emitted CO_2 gas was collected cryogenically in 2 successive fractions, the first representing the gas evolved in less than 10 s and the second fraction the gas produced the following 20–40 min, respectively. Only these 2 fractions were dated while the remaining CO_2 was not collected (nor measured). The age of the first CO_2 fraction is assumed to be closer to the true date than that of the second fraction (Folk and Valastro 1976).

To gain more information on the dissolution process and the content and nature of contaminants, we started collecting typically 5 successive fractions to create age profiles of the samples. When the acid is admitted to the sample, the reaction releases 10–20% of the total carbon dioxide in a matter of seconds. The evolved gas is quickly collected cryogenically in a glass vial as a first CO_2 fraction. The reaction gradually slows down, and the second fraction comprising the next 10–20% is collected in a matter of minutes, while the subsequent fractions are reacted and collected sequentially in the order of hours (Figure 3). Since there is abundant mortar binder carbonate that is more readily soluble than limestone, the binder will be strongly represented in the carbon dioxide of the first CO_2 fraction, which is assumed to be less affected by contamination from the slowly dissolving unburned limestone than subsequent fractions. Only in rare cases is the first fraction affected by too-young CO_2 due to recrystallization or the building having been exposed to fire. This is revealed either in the chemical prescreening with phenolphthalein showing an alkaline reaction or by the age profile itself as discussed below. This method of chemical separation based on reaction rates works well for the Åland mortars, but elsewhere other methods like titration with diluted hydrochloric acid (HCl) have been tried, e.g. on Roman pozzolana mortars (Hodgins et al. 2010).

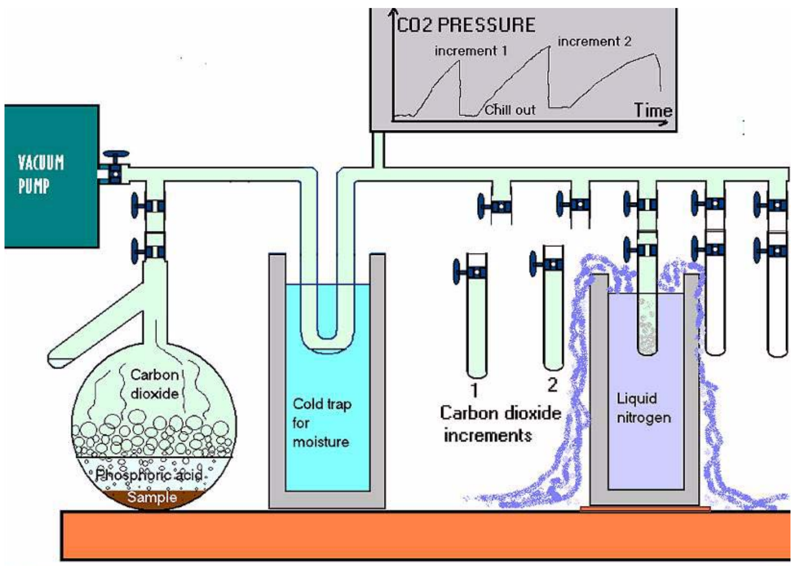

Figure 3 Chemical separation in 5 CO_2 fractions. The reaction has continued for some minutes and 2 CO_2 fractions have already been isolated. The third fraction is being chilled out cryogenically using liquid nitrogen.

AMS and Stable Isotope Measurements

Part of the resulting CO_2 gas was used for $\delta^{13}C$ and $\delta^{18}O$ analysis on a GV Instruments Isoprime stable isotope mass spectrometer to a precision of 0.15‰, while the rest was converted to graphite for AMS ^{14}C measurements via reduction with H_2 using cobalt as a catalyst (Vogel et al. 1984). Prior to laboratory number AAR-10100, stable isotope measurements were performed on the mass spectrometer at the Science Institute, Reykjavík. All AMS ^{14}C measurements were carried out using the EN tandem accelerator at Aarhus University (Denmark). The dating results are reported according to international convention (Stuiver and Polach 1977) as conventional ^{14}C dates in ^{14}C yr BP (before AD 1950) based on the measured $^{14}C/^{13}C$ ratio corrected for the natural isotopic fractionation by normalizing the result to the standard $\delta^{13}C$ value of –25‰ PDB (Andersen et al. 1989). The conventional ^{14}C dates were calibrated using the OxCal v 3.10 program (Bronk Ramsey 1995, 2001).

The Åland Limestone and Mortar

The Åland Islands are a central part of the Scandinavian, Precambrian basement in northern Europe. The main island is composed of granites and the smaller islands to the west and south (Kumlinge, Föglö, and Kökar; Figure 13) of granites, gneisses, and schists. There are no marble quarries in the basement rocks in Åland, but they are common in the archipelago to the east, closer to the Finnish mainland. North of the islands, the bottom of the Baltic Sea is, however, covered with Ordovician limestone (Winterhalter et al. 1981) and the limestone has probably also covered the Åland Islands, but it has been eroded away during the glaciations. It can only be found at the bottom of Lumparn Bay, and as a major component in the loose overburden (the glacial till). It also occurs as abundant glacial blocks all over the area except for Kökar. It has different colors, reddish, yellowish, and different shades of gray and a benthic (organisms living on the sea floor) fauna with macrofossils. The mortar in the churches has been made by collecting and burning limestone blocks lying around in the terrain.

Interpretation of Age Profiles

The well-preserved medieval mortars from the churches of the Åland Islands have had a central role in developing an AMS ^{14}C-based method for dating non-hydraulic mortars. The theoretical principles and several examples from the churches have been presented in Lindroos et al. (2007). That article is, however, addressed to the scientific community and it only discusses the interpretation of age profiles in several fractions, or the results obtained after 2002. This time, we present the entire corpus of the Åland results beginning from 1994 when we changed from conventional ^{14}C dating to ^{14}C AMS analysis, thus also including results analyzed in only 2 fractions between 1994 and 2002. The feedback we received from archaeologists is that our complex method should be presented in a more readable way so that those other than specialized scientists can also interpret the results and evaluate if a dating is reliable or not. We have therefore defined different reliability criteria based on our experience from Åland, Portugal, and Rome (Langley et al. 2010; Ringbom et al. 2010).

We have modeled the dissolution of limestone-based mortar as follows:

1. The binder is composed of 2 types of crystals: A, rapidly dissolving (sharp corners and edges of grains; lime-lump dust; well-developed, pure crystals). B, the remaining, impure cryptocrystalline to microcrystalline binder dissolving slowly.
2. Very slowly dissolving contaminants of improperly burned limestone forming rusty lumps together with iron and manganese hydroxides. This component is responsible for the generally occurring increase in age at the end of the profile.
3. Sedimentary limestone grains originating from the filler. They dissolve slower than 1A but faster than 1B. This intermediate behavior creates a bump in the profiles. Figure 4 shows theoretical, modeled profiles including components 1–3.

When we consider these components and give numerical values to the dissolution rates, a typical mortar sample from Åland would yield profiles like the ones in Figure 4.

The distinction between aggregate limestone and improperly burned limestone residues is based on measured limestone dissolution rates (Lindroos 2005) and the stable isotope signatures (δ^{13}C values in the Appendix). In dissolution tests, the Åland limestone dissolves relatively rapidly and as an Ordovician marine limestone; its δ^{13}C value is near zero or slightly negative (according to a general Ordovician trend by Veizer et al. 1999; no measured values are available). The mortar binders tend to have δ^{13}C values more negative than –7 (see Appendix). We interpret the commonly occurring, increased ^{14}C ages and δ^{13}C values for the second and third fractions as being due to aggregate lime-

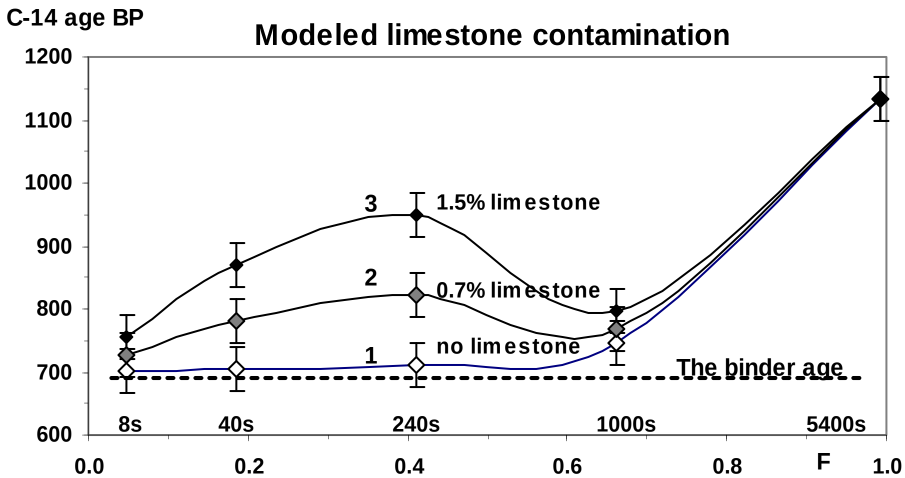

Figure 4 Modeled ^{14}C profiles showing the effect of typical limestone contamination. The sample age is set at 700 BP and 3 profiles were generated by modeling with 0%, 0.7%, and 1.5% filler limestone contamination, respectively. The dissolution progress F (from 0–1 or 0–100%) is shown as abscissa together with the dissolution time in seconds. The other parameters (30% rapidly dissolving binder, 68% slowly dissolving binder, and 1% unburned limestone residues) are kept constant. The increasing ages at the end of the profiles are due to the slowly dissolving limestone residues after incomplete calcination. The calculations are presented in Lindroos et al. (2007).

stone contamination. The fifth fractions have commonly increased ^{14}C ages, but no clear correlation with the $\delta^{13}C$ values. In some cases, the last fractions are the most negative ones and clearly not caused by limestone. We have reasoned that the last fractions are affected by unburned limestone residues. They dissolve slowly because they contain iron and magnesium hydroxides after thermal break-down of the iron and magnesium carbonate component of the limestone. The rather negative $\delta^{13}C$ values may be due to several days of interaction with carbon dioxide and water vapor from wood during lime burning.

The shift in $\delta^{13}C$ values has been used to estimate the amount of limestone contamination present in mortars (e.g. Van Strydonck et al. 1986; Ambers 1987). The Åland material is unsuitable for this kind of calculation (Lindroos et al. 2007). The main reasons are the broad spectrum of $\delta^{13}C$ values for the binder carbonate within a sample, commonly occurring lime lumps with deviating values, and the lack of data for the limestone.

Practically all the Åland samples have turned out to yield curves resembling those of Figure 4, and the first fraction usually dates the time of hardening of the mortar (exceptions are fire-damaged mortars, where the first fraction is generally too young as discussed below). In Åland, where we know the dissolution behavior of the mortars, we would consider a profile resembling profile 1 in Figure 4 a successful dating giving a conclusive result. We define this type of result as Criterion I (CI):

Criterion I
The ^{14}C ages of the first 2 CO_2 fractions are the same (1 sample per building unit is in principle sufficient for a conclusive result).

The rationale behind this criterion is that if there is no age gradient (i.e. no increase in limestone contamination) from fraction 1 to fraction 2, then both fractions are most likely free of contamination and therefore date the time of hardening of the mortar. The quoted date of the mortar sample is based on fraction 1 only in order not to exaggerate the precision of the result.

Most profiles resemble profiles 2 and 3 (initial positive age gradient) in Figure 4. If the first fractions consistently yield the same age, we consider it a successful dating according to Criterion II (CII):

Criterion II
Mutual agreement between the dates of the first CO_2 fractions in a series of 3 or more samples from 1 single building unit.

The rationale behind this criterion is the following: Although the age gradient indicates a degree of contamination in fraction 2—and therefore possibly also in fraction 1—it is more likely that all first fractions have insignificant limestone contamination than all of them having the same amount of significant contamination, leading to the same age excess for all samples.

Many samples yield valuable data that are not sufficient for conclusive dating, but when put into a context it may help to clarify the chronology:

Criterion III
Mutual agreement between the dates of the first CO_2 fractions in 2 samples from 1 single building unit.

Criterion IV
Where the first CO_2 fraction from 1 sample in a building unit yields a date that fits into a relative chronology.

Below, we give some examples of the use of the criteria as well as a comparison with dendrochronology:

CI. The church of Geta provides an example of CI mortar dates, and attempts of dendrochronological dating have been published earlier (Ringbom et al. 2009). This church, originally a satellite chapel under the church of Finström, is also an example of how confusing the results of dendrochronology can be. Every second roof truss pointed towards the 1590s; the other half belonged to the 1820s—clearly a case of stepwise renewal of timber, possibly with none of the original remaining. Only 1 timber log, a wall plate integrated in the wall, appeared to be part of the original, medieval construction. It was felled some time shortly after 1450. In this case, mortar dating was the only possible way to resolve the chronology.

In this case, 3 age profiles of mortars from the nave provided reliable CI dates (Figure 5) and one of them is especially reliable because it shows no limestone contamination at all. The combined calibration of the first CO_2 fractions suggests the age AD 1435–1455, in excellent agreement with the dendrochronological date of the wall plate (Figure 5, top right). This result is further supported by the ^{14}C age of a wooden fragment encapsulated in the mortar giving a minimum age. Mortar dating solved the riddle of the dendrochronology results: the medieval wall plate does indeed reflect the age of the nave of the church in Geta.

CII. The 4 mortar age profiles from the nave of the church of Finström represent a CII case (Figure 6). This church is one of the best preserved medieval buildings in Finland. This is true of both the exterior and the interior and the decorative program. Many different indications suggest that it must have been one of the most important—and therefore early—churches in the Åland Islands, with close connections to the Diocese in Turku (mainland Finland). Yet, this church has an incredibly confusing building history. Remains of a wooden predecessor on the site have been excavated archaeologically. It probably dates from the end of the 12th century, whereas dendrochronology on the present church points towards a substantial rebuilding of the stone church in the mid-15th century, cf. other interpretations (Sárkány 1973; Dreijer 1983:307–16; Hiekkanen 2007:366–71).

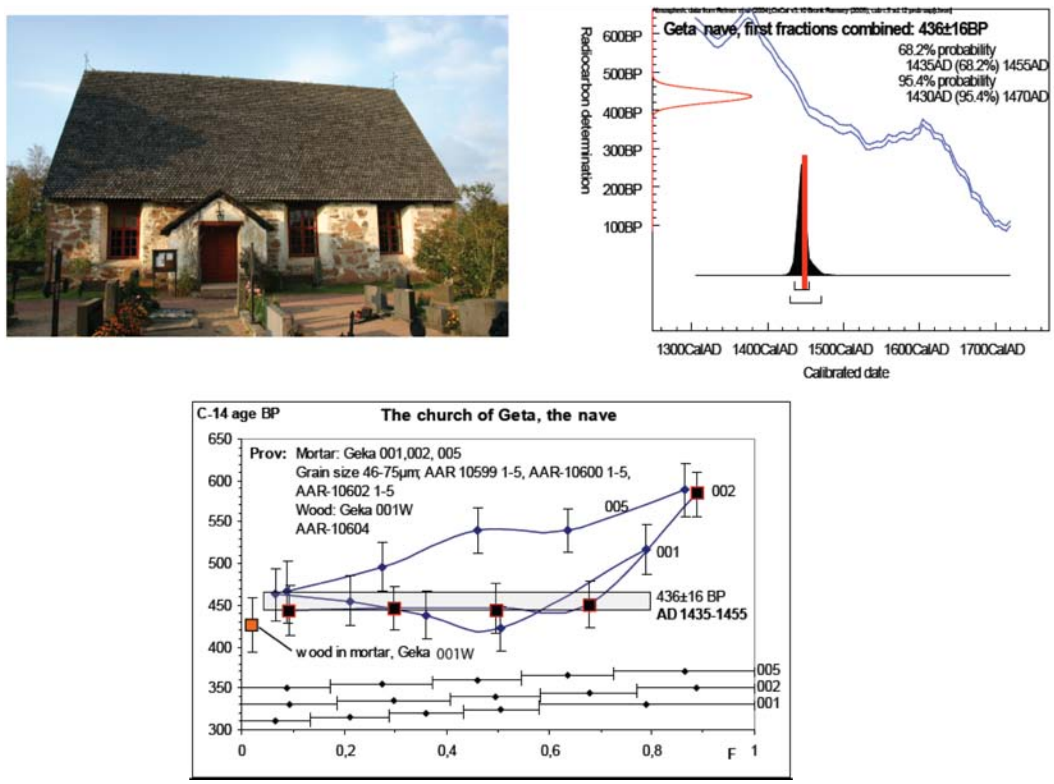

Figure 5 The church of Geta with 3 age profiles from mortar analysis and 1 dating of a wooden chip within one of the mortar samples. The size of respective CO_2 fraction is marked at the bottom of the plot. The combined calibration of the first CO_2 fractions yield AD 1435–1455 (top right panel), in excellent agreement with the dendro date (vertical line) of roof timber integrated in the wall. The age profile for Geka 002 (marked with large, square symbols) is very similar to profile 1 in Figure 4, making it especially reliable and a clear CI case. The 2 other samples also belong to CI because the first and the second fraction have overlapping ages. The mortar dating is further supported by the ^{14}C age of a wooden chip enclosed in the mortar 001.

Dendrochronological analysis of the timber provides clear results for the different building units. Oldest is the sacristy from the AD 1440s, followed by the nave ~1450, the porch in the 1450s, and the tower in 1467. This late medieval age for the entire building was most surprising, and therefore, a number of mortar samples from the nave were taken to test whether the dendrochronological results really represent the age of the stone structures.

From a technical point of view, the lime of the mortar was well burned and has only little limestone contamination. The scarcity of unburned limestone residues is indicated by moderate or insignificant increase in ages for the fifth fractions. On the other hand, the significant bump in the mid-section of the age profile for sample Fika 058 indicates a non-negligible amount of limestone contamination in the filler. One of the age profiles, Fika 060, is almost horizontal, and completely devoid of contamination. The timber wood sample (Fika 060W) fits into the picture, with the highest probability AD 1440–1520. This is an example where 3 of the age profiles classify as CI, whereas they all 4 together represent CII. The first fractions thus provide a highly conclusive mortar date of AD 1440–1465, in perfect agreement with dendrochronology (~AD 1450) for the nave (Figure 6, top right, and Figure 12a).

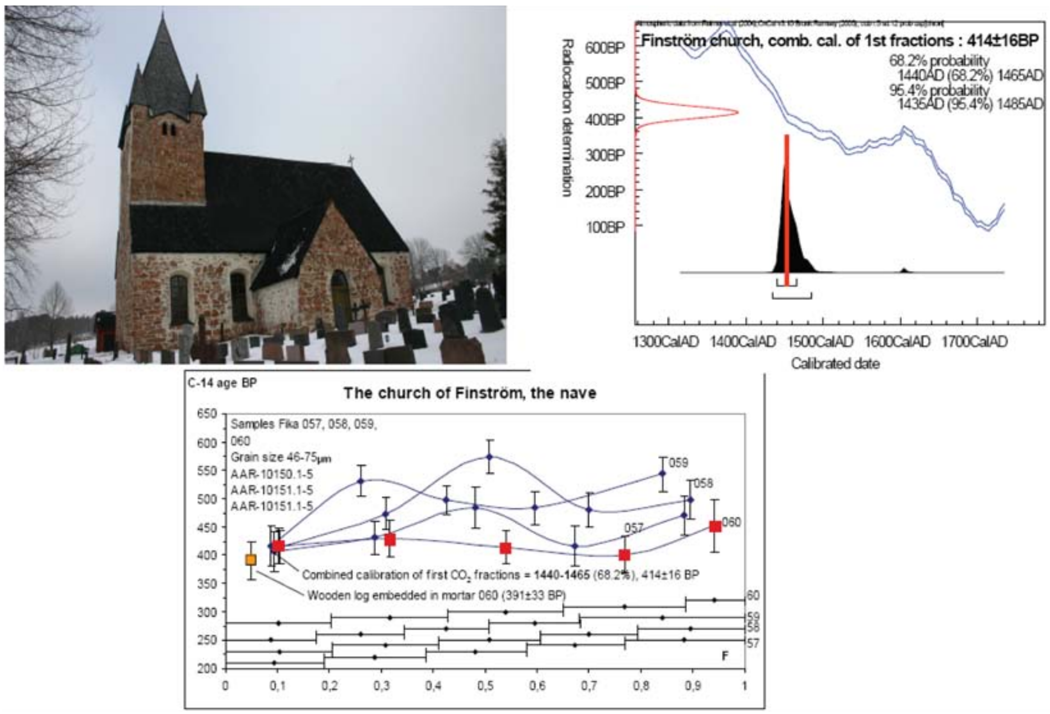

Figure 6 The church of Finström. In the plot of 4 age profiles from the nave, all first CO_2 fractions coincide giving the weighted average age of 414 ± 16 BP. The calibrated combined age probability distribution, AD 1440–1465 (top right panel) is completely consistent with the date suggested by dendrochronology of the nave, i.e. AD 1450 (vertical line; see also Figure 12a).

Atypical profiles: fire damage. The church of Sund is the largest among the Åland churches. There are, unfortunately, no results from dendrochronology available for this church. All datable wood from the nave has been consumed by several severe fires. The only surviving wooden samples were a couple of charred fragments of scaffolding and from a cast form in the staircase of the tower. They were also ^{14}C analyzed (cf. Figure 12c).

Thus, to determine the age of the nave, ^{14}C AMS analysis of scorched mortar was the only option. From the nave, including the vault, there are 5 age profiles, all of them behaving radically different from all other Åland samples. Two of the age profiles (Figure 7) have been presented in Lindroos et al. (2007). They may be considered special cases of fire-damaged mortars where a horizontal plateau in the middle of the profile corresponds to the archaeological age. The combined calibration of the plateaus yields AD 1255–1280, indicating that the nave of the church of Sund may be coeval with the early stages of all the other churches of the main island of Åland.

Naturally, these atypical age profiles have to be interpreted critically and with care, especially in the absence of age control. Yet, our recent research from other fire-damaged constructions, where there is age control, support our theory that burned mortars reach the correct age in later fractions of the age profile, whereas the early fractions from fast-reacting mortar carbonate appear young, reflecting recrystallization or conversion to active lime due to fire. Our experience from Sund has given important insights into identifying, interpreting, and dating buildings that have been devastated by fire. We have noted that age profiles from fire-damaged mortars that form clear plateaus seem to be

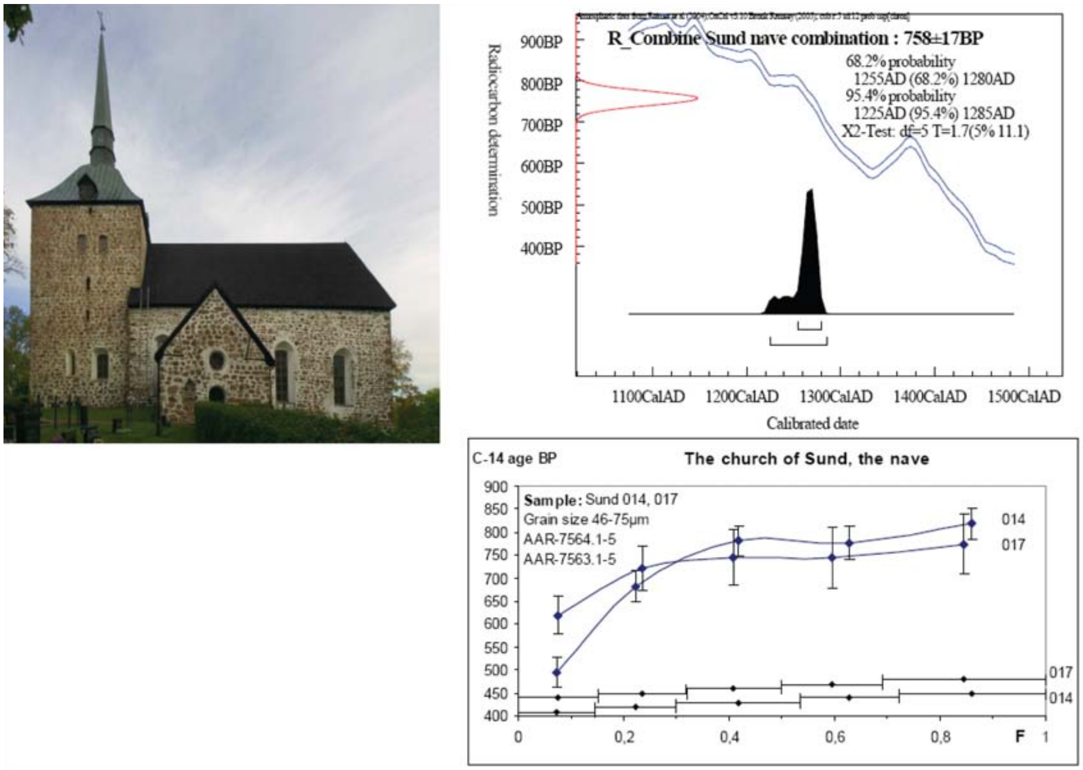

Figure 7 The church of Sund. Two age profiles of fire damaged mortar from the nave, both with mutually agreeing horizontal plateaus in the middle of the profiles. The plateaus are well-defined because they represent more than 50% of the CO_2 from each sample. A combined calibration of the fractions defining the plateaus yields a date of AD 1255–1280.

conclusive and reliable. These samples are therefore included as conclusive in the statistics. However, we still need further confirmation before we can state it as a fact.

RESULTS

All the results for mortar samples dated in age profiles of 2–5 CO_2 fractions are given for each building unit in the Appendix along with ^{14}C dates on wood and charcoal samples as well as summary dendrochronological dates. To begin with, in 1991–1992, dendrochronological analysis was applied wherever possible. Of the 283 total samples, 159 were conclusive. Some 107 were of medieval origin. The rest were inconclusive, either because the timber used was spruce, which cannot be dated satisfactorily, or because the annual rings were too few to establish a date matching to the master curve.

Dendrochronological dates have been published (Ringbom and Remmer 1995, 2000, 2005; Ringbom et al. 2009). Even though dendrochronology could not resolve the chronology of the earliest building stages, it generally provided firm datings for later building stages, and has thus been an important key to validation of mortar dating.

The strategy from the beginning of the project has been to test mortar dating on as many samples as possible against the dendrochronological age of the structure. There are altogether 38 mortar results that can be compared to dendrochronology. Where the calibrated ^{14}C dates are imprecise, for instance in the 14th century where one can only identify the right century, dendrochronology often provides the much needed precision. Thus, the 2 methods are complementary. Dendrochronology gives the precise age and mortar dating confirms that it is relevant for the building phase we want to date. In Figure 8, we present calibrated ^{14}C age probability distributions of the mortar dates compared with the dendrochronological dates.

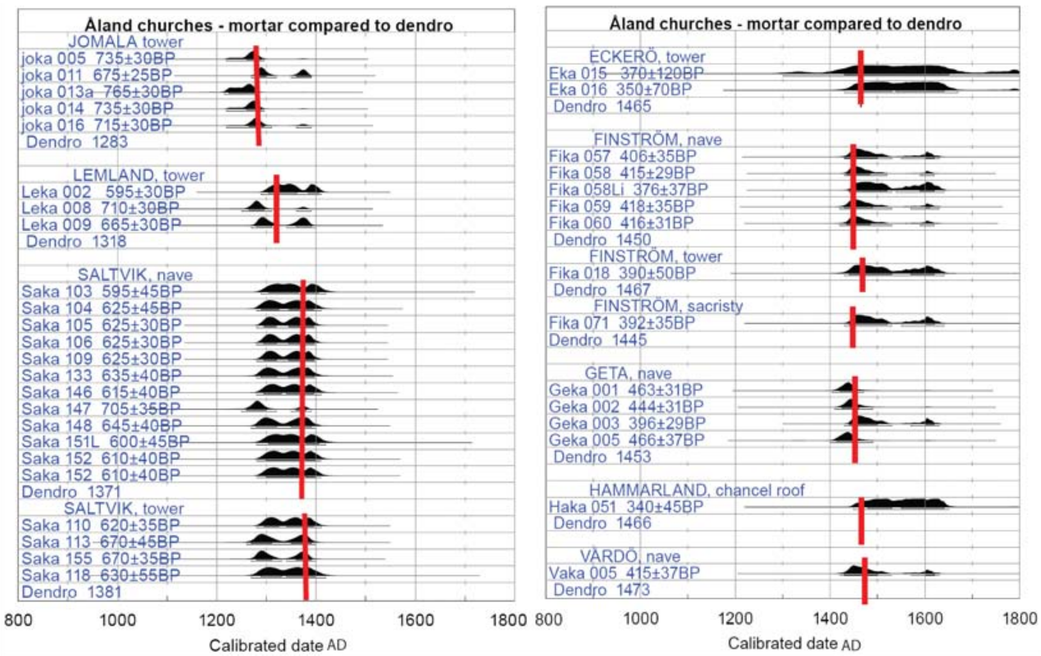

Figure 8 CI and CII Åland mortars (calibrated dates of the first CO_2 fractions in black, presented horizontally) from a number of structures compared with the dendrochronologically determined age of the structures (vertical lines). Samples denoted Saka 151L and Fika 058Li are lime lumps from mortar samples with the same number.

Although many of the distributions are bimodal and do not point to an unambiguous date, the agreement is excellent. Thus, among 38 mortar samples dated by their first fractions according to CI and CII, 36 were found consistent at the 68.2% probability level with age control from dendrochronology.

However, it is possible to provide a more direct, unambiguous test of the reliability of the method of mortar dating, i.e. the assumption that it is possible to isolate and date a homogenous binder concentrate of the mortar sample, the ^{14}C content of which reflects the atmospheric content at the time of the mortar hardening. Figure 9 shows all the conventional ^{14}C dates plotted against their known calendar ages obtained from dendrochronology. The agreement of the ^{14}C dates with the atmospheric calibration curve shown for reference is impressive, as more than 68% of the ^{14}C results deviate less than 1 σ from the atmospheric value.

We have analyzed a total of 150 mortar samples (Figure 10). In many cases, the mortars were in contact with wood that could not be dendrochronologically dated but ^{14}C dating was possible. When we include these in our database, we have 79 dated mortar samples with age control. For reasons not understood, 4 of them failed, yielding a deviating (older) age even if their age profiles look like CI samples. Some 75 mortar samples with age control proved to be conclusive and accurate within the measuring precision. The corresponding failure rate is thus ~5%. The remaining 71 samples had unknown ages, i.e. no independent age control. The reliability criteria were applied to these samples.

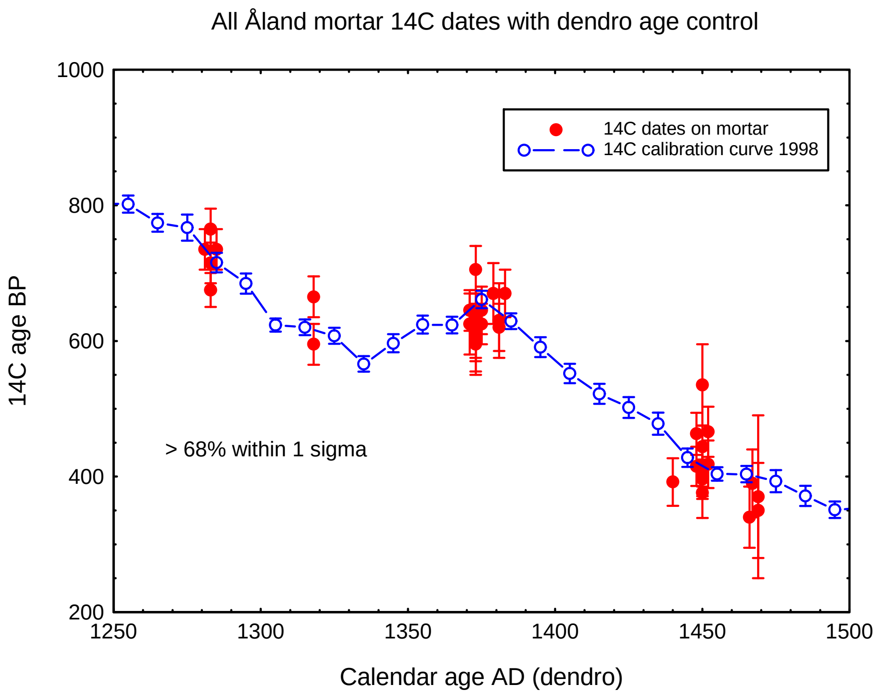

Figure 9 All Åland mortar samples with calendar ages known from dendrochronology. The conventional, uncalibrated mortar ^{14}C dates are plotted against the corresponding dendro age. Data points of the same calendar age are shown with slight x-offsets to allow distinction between points. The atmospheric calibration curve is shown for reference.

A majority (45) meet the requirements of CI and/or CII and we therefore regard these as successfully and firmly dated samples. These are our most important results, since they show the real potential of the mortar dating method. Here, mortar dating was the only option, and yet the results are conclusive. Based on our results for samples with age control, we expect the failure rate to be only about 5% for samples satisfying CI and/or CII and not exhibiting atypical age profiles. The 26 samples to the very right in Figure 10 are inconclusive, but for reasons well known. They have therefore been helpful in the development of the method. Some of them yield ages for the first CO_2 fractions that fit into the context provided by the other samples, but there are too few samples per unit (<3) to qualify for CII. That is, at least 3 samples should be dated from each building unit. In some cases, there are abnormal age profiles that we have not tried to interpret. Among them are several samples from the burned Sund church with inconsistent first CO_2 fractions and no clear age plateau in the mid-section of the profile.

The Chronology of the Åland Churches

In Figure 11a–d, we present all the conclusive datings including dendrochronology and ^{14}C results from wood (see Appendix). Those in black denote calibrated ages of mortar dates. In all cases, except for the church of Sund and the east gable of Kumlinge, we have used the dates of the first CO_2 fractions. In yellow are the calibrated results of ^{14}C analysis of wood embedded in the mortar, or from fragments of wood, not well enough preserved for dendrochronology. Dendrochronological results are indicated by vertical lines in red.

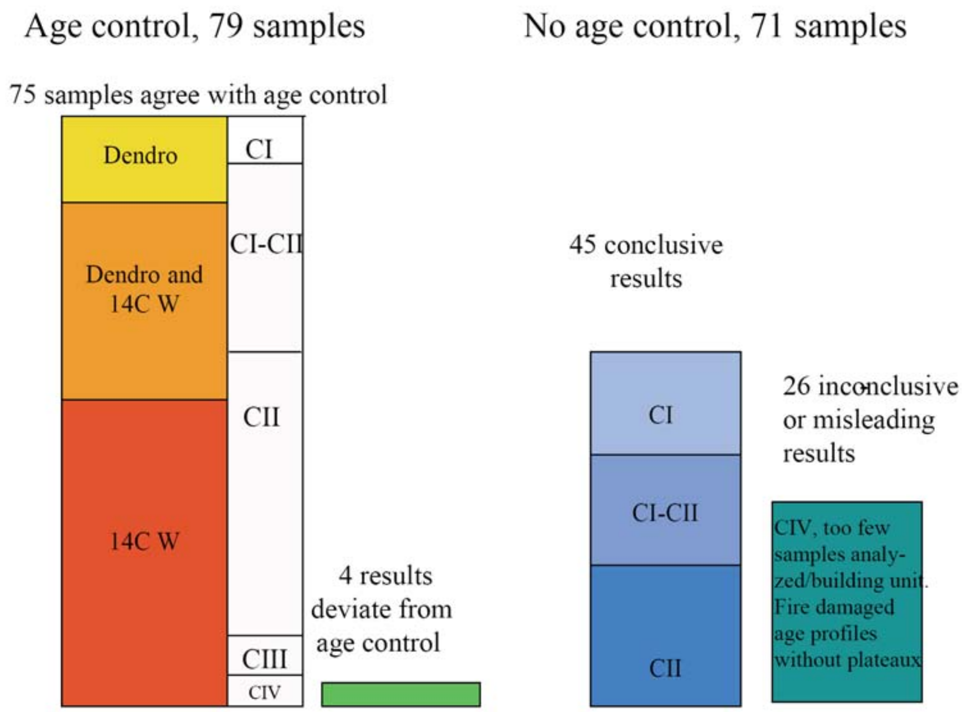

Figure 10 Classification of non-hydraulic samples from Åland. The stacks to the left in different colors (shades of gray), yellow (top), orange and red (bottom) include samples with an age control based on dendrochronology and/or ^{14}C-dated wooden structures. Some 75 samples out of a total of 79 agree with the known age. Four samples (second stack, in green) yielded deviating ages. The 2 stacks to the right show the datings without age control. The third stack in different shades of blue represents samples that yield results corresponding to CI and CII. They are our most important samples, providing successful and conclusive results where mortar was the only datable material available. The remaining 26 samples of unknown age remain inconclusive (far right), for reasons well understood.

Wherever there is age control, one can note a good agreement between wood and mortar. In rare cases, the wooden samples give a different age. They can be significantly older (Eka 007W, Haka 024W), or only a little older (Fika 018W, Fika 21W and Fika 063W). In case the odd wooden sample among otherwise homogenous results is younger (Eka 18W), one can suspect secondary replacements. In 2 cases, the mortar has yielded significantly older results (Haka 047 and Haka 045). Together with Leka 009 and Leka 008, they belong to those 4 that disagree with age control. Note further that dendrochronology, whenever it is available for a respective building unit, coincides with both the mortar and ^{14}C analysis of wood. In Hammarland, dendrochronology of the nave dates the rebuilding in the AD 1440s, after a fire, and is therefore not included in the diagram.

This comparison does not include ^{14}C analysis of charcoal embedded in the mortar, because it is generally too old. It yields uneven results, thus reflecting the "old wood effect." This is due to the fact that countless annual rings have burnt away in the fire, and the inner core often represents the only remains of the timber in questions. Charcoal has been systematically tested and analyzed for reference. By chance, the charcoal can yield an age identical to the mortar, but obviously it should not be younger than the mortar (charcoal dates are included in the Appendix).

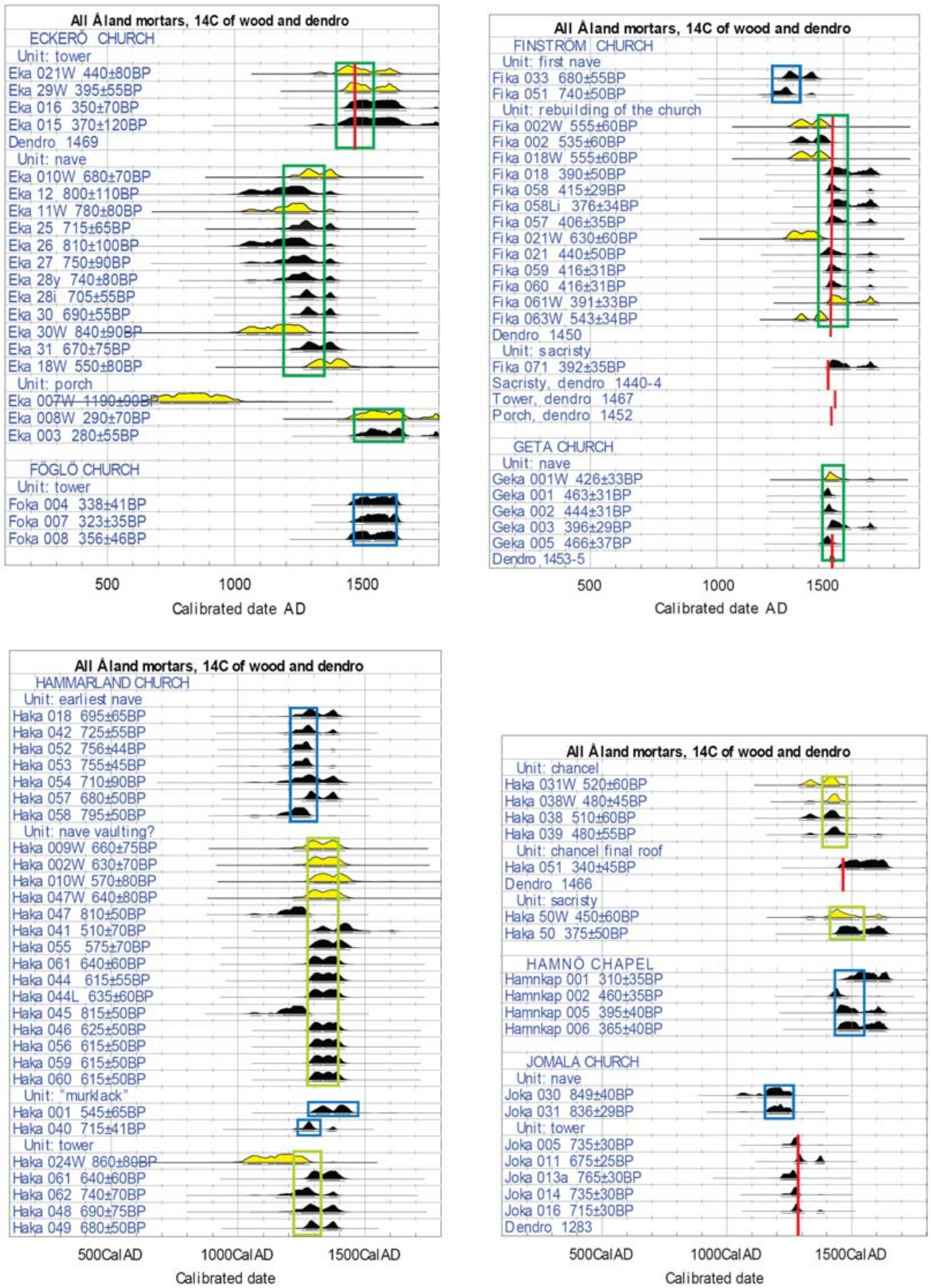

Figure 11a–d The chronology of the Åland churches based on CI and CII mortar samples and ^{14}C analysis and dendrochronology of preserved wood. Calibrated results of wood (W after ID number) are marked in yellow, mortar in black, and results of dendrochronology are indicated by a red vertical line. Framing rectangles in green mark the ages for different building units where the age is determined by mortar and ^{14}C of wood. Rectangles in blue present the age for building units where mortar has been the only dateable material.

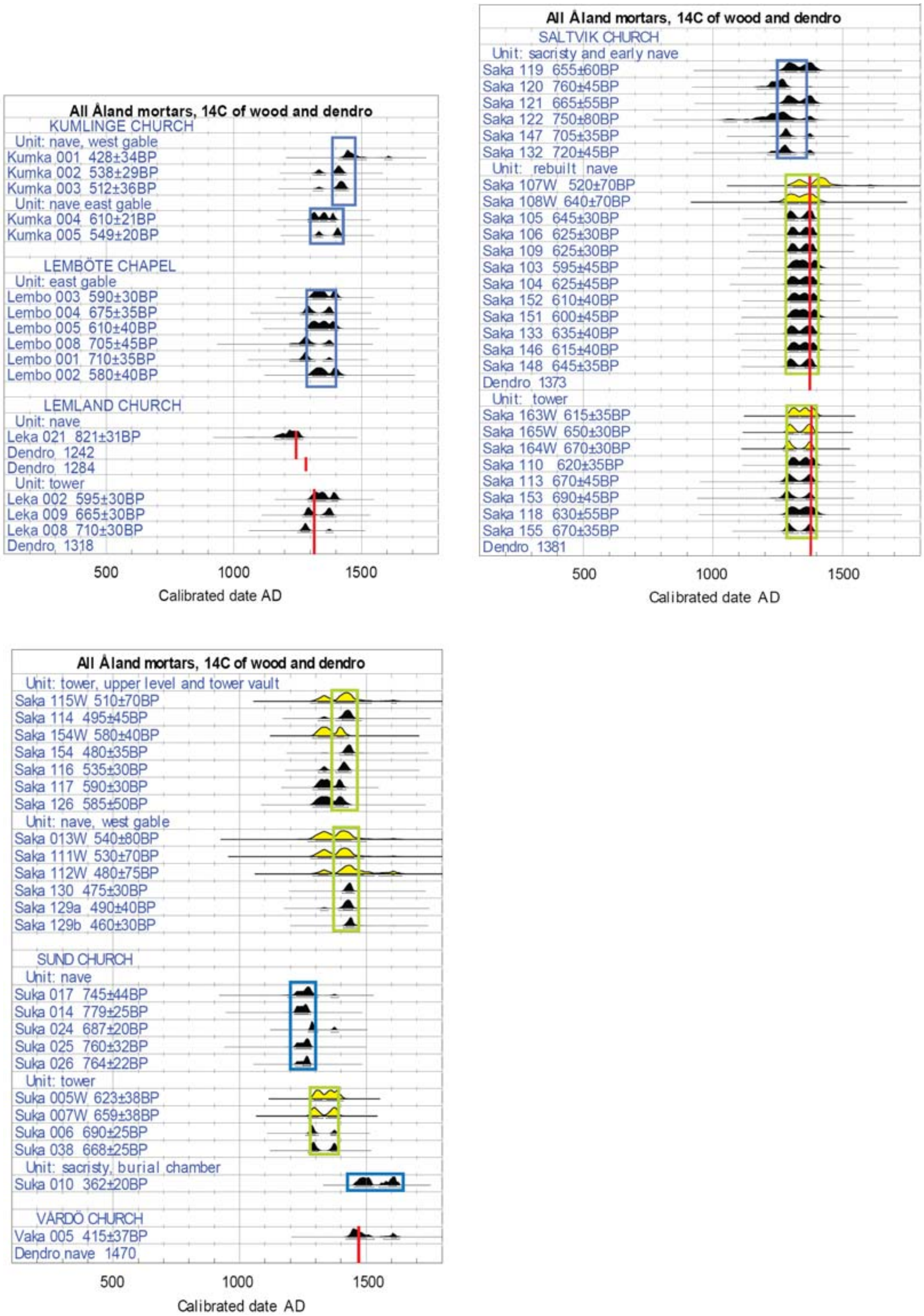

Figure 11a–d *(Continued)*

The green rectangles surrounding the samples of separate building units show the date suggested by mortar dating and age control from ^{14}C analysis of wood and dendrochronology. And, most importantly, the rectangles in blue show the result of building units where mortar has been the only option for scientific dating.

Considering the large amount of data and the fact that the mortar samples from Åland behave in a predictable way, we dare claim that the chronology of the Åland churches is taking shape (Figure 12a–b, cf. Figures 11a–d and Figure 13). It is noteworthy that the chronology basically remains the same, whether it is based on mortar dating or on scientific dating of wood. But once more it has to be stressed that mortar dating often is the only way to confine the time of the earliest building stages. We can see that the building activity is spreading rather uniformly from the end of the 13th century to the end of the Middle Ages.

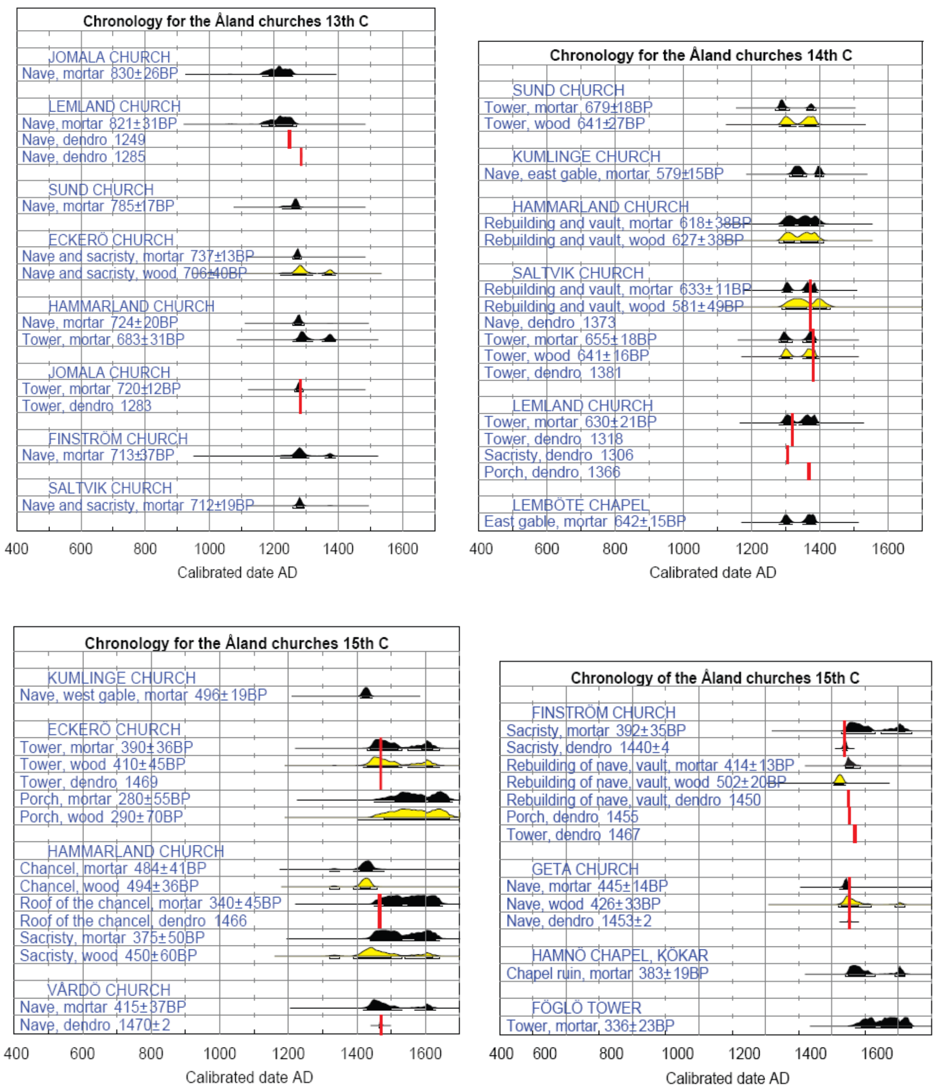

Figure 12a–b The compiled chronology for the medieval stone churches in Åland, presented century by century from the 13th to the 15th century. It is based on different science-based dating methods: ^{14}C AMS analysis of samples of mortar and wood (conclusive dates combined in each category), as well as results from dendrochronology.

The main churches, or the mother churches, on the main island in Sund, Jomala, Eckerö, Hammarland, Saltvik, and Lemland (Figure 13), were all erected during the 13th century. The same age is indicated also at Finström, from a couple of preliminary mortar sample analyses from the foundation level of the nave (Figure 11a). It is therefore conceivable that an early stone church did exist in Finström, but both the plan and exterior so far remain unknown. These early dates often rely on mortar dating alone, on results that fulfill the demands of CI or CII, often a combination of both. Still, for the early naves in Jomala, Lemland, and Finström, it is our intention to have more samples analyzed. Lemland has the only 13th century nave dated by dendrochronology, and Jomala has the only church tower from that century.

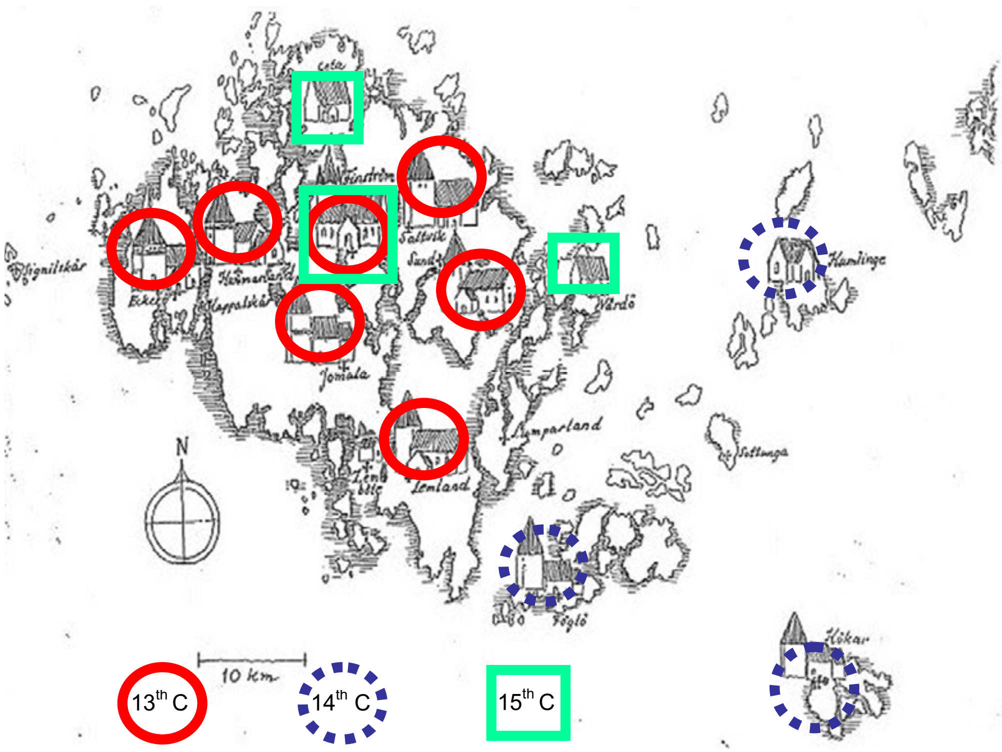

Figure 13 Chronology of the Åland churches

The chronology of the 14th century is not yet complete. As is well known, it is a century that is not easily defined by ^{14}C dating. Due to the irregular calibration curve, the timing so far remains unresolved. The century is remarkable for its many church towers and other secondary building units as sacristies and porches. Radical rebuilding and vaulting takes place in Saltvik at the end of the century, and these events are firmly dated by mortar dating and dendrochronology. The chapel of Lemböte, by the old sailing route from Denmark to Estonia, was either built at the end of the 13th century or in the 14th century. We have the age of the nave in Kumlinge fairly well established despite the fire-damaged mortars. The church on the remote island of Kökar will require additional consideration because the mortar is not necessarily made of the Åland limestone. Several different indications (archaeological artifacts, preliminary results, etc.) suggest that this church also may belong to the 14th century, as may also the church in Föglö.

The 15th century is a third dynamic building period in the Åland Islands. We have established evidence of a more or less total rebuilding of the stone church in Finström. Here, the dendrochronology suggested new roofs in the nave and sacristy. It also marked the erection of a porch and an impressive new tower. The mortar, sampled from a wide area around the roof construction, confirms that the dendrochronology actually marks a wider rebuilding of the entire church. It also involved the vaulting and the heightening of the nave. Three more towers were erected this late, in Eckerö, Föglö, and Kumlinge. Completely new constructions were the satellite churches, or the chapels of Geta and Vårdö, administered by Finström and Sund, respectively. Surprisingly enough, it seems that the little wooden chapel "Kappalskatan" in Hamnö, Kökar, belongs to the very end of this building period. No wood remained for analysis, but mortar from the foundation level indicates that this may be the most recent medieval ecclesiastic building in Åland, from the very beginning of the 16th century.

However, to get the full picture of the chronology of the Åland churches, it may be useful to compare Figure 12 with the map of the Åland churches, where the different ages of the naves are marked in different colors (Figure 13). It is obvious that the 13th century is the most dynamic period in the islands, with 7 mother churches (marked in red) erected close together on the main island. The 14th century meant new churches in the archipelago (marked in dotted blue circles). On the main island, it was only a matter of adding secondary building units to existing naves.

The 15th century appears strongly represented in Figure 12b. However, it looks different when it comes to the bigger building projects (Figure 13). Apart from the remarkable rebuilding of Finström, it really only involves the erection of 2 new satellite chapels, Geta and Vårdö, plus innumerable secondary building units added to earlier naves.

Our work on ^{14}C mortar dating has been consistently criticized since 1994 by one author, who specializes in medieval stone churches in Finland (Hiekkanen 1994, 1998, 2004, 2007, 2008, 2009). This author believes that the mortar-dating approach cannot be used for dating these materials.

CONCLUSIONS

In conclusion, Åland mortars have turned out to be exceptionally "well behaved" and well suited for ^{14}C dating compared to samples from our later studies of mortars from ancient Rome. Analyzed in 2 or more CO_2 fractions, the results of the first CO_2 fractions are simple to interpret and yield unambiguous dates:

- It was fortunate that our systematic development of mortar dating was initiated in the Åland Islands, where the non-hydraulic lime mortar is well-preserved and behaves in a predictable way in phosphoric acid hydrolysis and where there is plenty of feedback available from age control of dendrochronology and AMS ^{14}C analysis of wood.
- Mortar dating is often the only way to determine the age of the first building stage of the churches. Without mortar dating, the chronology of the Åland churches could not have been established.
- Wherever age control has been available, 95% of all mortar sample dates are correct.
- Of all the 150 samples analyzed, 80% are conclusive (that is, they either agree with age control or satisfy CI and/or CII).
- Churches devastated by fire have mortars that yield atypical ^{14}C profiles.
- While petrographic microscopy and cathodoluminescence are useful for a crude screening against mortar samples that are unsuited for ^{14}C dating, the ^{14}C profiles are the most reliable and sensitive indicators of possible dating errors due to contamination.

For the future, it is our aim to map areas where mortar dating is feasible. From our vast experience of dating 444 mortar samples from all over Europe, from classical antiquity to Post-Reformation times, from different parts of the Roman Empire to different parts of Scandinavia, we can already now say that non-hydraulic lime mortars seem to be easier to analyze than hydraulic mortars. Our reliability criteria work also outside the Åland Islands, but we still have to find out how universally they can be applied. In cases when they may not work, we will have to find out why. We will have to compare results from parallel testing of hydrochloric acid and phosphoric acid in the chemical separation, and find out if they behave differently in different geological terrains.

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APPENDIX

Dated mortar samples and fractions along with comparative dates on wood and charcoal as well as dendro dates. Those CO_2 fractions that date the samples according to criteria discussed in the text are emphasized in **boldface**, while wood and charcoal samples that are clearly not associated with the time of hardening of the mortar are given in *italics*. Misleading or inconclusive mortar samples are also given in italics. Laboratory numbers are Aarhus AAR numbers unless otherwise indicated (Hel-# are Helsinki conventional Radiocarbon Laboratory). Where only estimates are available, $\delta^{13}C$ values are given in square brackets. Grain-size fractions that have not been recorded are marked NR.

Appendix Dated mortal samples and fractions.

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (μm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
ECKERÖ CHURCH										
Unit: tower *(conclusive)*										
Eka 021	1474	plant			440	80	–28.5			
EKA 029W	2001	wood			395	55	–23.4			
Eka 015	**1471.1**	**mortar**	**3.8; NR**	**45**	**370**	**120**	**–11.7**	**–17.3**	**CI**	
Eka 015	1471.2	mortar		55	390	90	–11.5	–18.6		
Eka 016	**1472.1**	**mortar**	**5.2; NR**	**48**	**350**	**70**	**–10.4**	**–19.9**	**CIII**	
Eka 016	1472.2	mortar		52	570	70	–8.6	–20.9		
Dendro: AD 1469										
Unit: nave *(conclusive)*										
Eka 010W	Hel-2999	wood			680	70				
Eka 012	**1470.1**	**mortar**	**6.2; NR**	**40**	**800**	**110**	**–15.7**	**–22.4**	**CI, CII**	
Eka 012	1470.2	mortar		60	855	65	–8.9	–21.4		
Eka 011W	Hel-3000	wood			780	80				
EKA 025.1	**2062.1**	**mortar**	**8.6; 63–74**	**29**	**715**	**65**	**–13.3**	**–13.3**	**CI, CII**	
EKA 025.2	2062.2	mortar		71	790	75	–11.1	–11.1		
EKA 026.1	**2063.1**	**mortar**	**5.8; 63–74**	**43**	**810**	**100**	**–16.1**	**–22.7**	**CI, CII**	
EKA 026.2	2063.2	mortar		57	850	55	–14.6	–22.5		
EKA 027.1	**2064.1**	**mortar**	**5.4; 63–74**	**46**	**750**	**90**	**–11.5**	**–19.2**	**CII**	
EKA 027.2	2064.2	mortar		54	1040	150	–10.9	–19.2		
Eka 027-2.1	**2064-2.1**	**mortar**	**4.8; 76–125**	**19.2**	**855**	**50**	**–12.64**	**–19.57**	**CII**	
Eka 027-2.2	2064-2.2	mortar		18.4	965	48	[–9]			
Eka 027-2.3	2064-2.3	mortar		19.0	1076	47	–11.29	–19.82		
Eka 027-2.4	2064-2.4	mortar		17.7	1149	49	–11.37	–19.87		
Eka 027-2.5	2064-2.5	mortar		24.4	1801	44	–10.96	–19.82		
EKA 028 C	*2000*	*charcoal*			*640*	*60*	*–24.2*			
EKA 028i.1	**2065.1**	**mortar**	**8.1; 63–74**	**32**	**740**	**80**	**–13.6**	**–19.6**	**CII**	
EKA 028i.2	2065.2	mortar		68	1010	55	–9.4	–17.8		
EKA 028y.1	**2066.1**	**mortar**	**6.7; 63–74**	**34**	**705**	**55**	**–13.3**	**–20.4**	**CII**	
EKA 028y.2	2066.2	mortar		66	1260	55	–10	–19.9		
EKA 030 W	2049	wood			840	90	–24.2			
EKA 030.1	**2067.1**	**mortar**	**7.3; 63–74**	**33**	**690**	**55**	**–18.5**	**–19.9**	**CI, CII**	
EKA 030.2	2067.2	mortar		67	690	60	–13.3	–17.3		
Eka 030-2.1	**2067-2.2.1**	**mortar**	**7.7; 63–74**	**22.1**	**[705]**	**55**	**–19.64**	**–19.94**	**CI, CII**	
Eka 030-2.2	2067-2.2.2	mortar		17.3	889		–7.73	–14.94		
Eka 030-2.3	2067-2.2.3	mortar		23.9	955	44	–14.62	–17.89		
Eka 030-2.4	2067-2.2.4	mortar		19.3	895	55	–15.42	–17.39		
Eka 030-2.5	2067-2.2.5	mortar		38.2	1200	50	[–15]			
EKA 031.1	**2068.1**	**mortar**	**6.0; 63–74**	**40**	**670**	**75**	**–11.4**	**–20.1**	**CI, CII**	
EKA 031.2	2068.2	mortar		60	670	60	–12	–22.1		
Eka 018W	*Hel-3002*	*wood*			*550*	*80*				
Unit: porch *(conclusive)*										
Eka 007W	*Hel-2997*	*wood*			*1190*	*90*				

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (μm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Eka 008W	Hel-2998	wood			290	70				
Eka 003.1	**1469.1**	**mortar**	**7.4; NR**	**35**	**280**	**55**	**–13**		**CI**	
Eka 003.2	1469.2	mortar		65	210	70	–10.4	–18.9		
FINSTRÖM CHURCH										
Unit: first nave *(conclusive?)*										
Fika 033.1	**1877.1**	**mortar**	**4.8, <250 panned**	**32**	**680**	**55**	**–13.4**	**–15.1**	**CI, CIII**	
FIKA-033.2	1877.2	mortar		68	760	60	–8.7	–13.1		
Fika 050.1	***8952.1***	***mortar***	***4.7; 76–150***	***19.9***	***505***	***47***	***–20.64***	***–16.56***	***test sample***	from deep within wall, i.e. delayed hardening, and very negative $\delta^{13}C$
Fika 050.2	8952.2	mortar		19.6	660	60	–19.87	–21.66		
Fika 050.3	8952.3	mortar		19.4	667	45	–22.02	–24.41		
Fika 050.4	8952.4	mortar		18.4	592	47	–21.81	–23.88		
Fika 050.5	8952.5	mortar		22.3	740	90	–21.7	–24.83		
Fika 051-2.1	**8953-2.1**	**mortar**	**6.4; 76–150**	**15.7**	**740**	**50**	**–19.82**	**–20.08**	**CI, CIII**	
Fika 051-2.2	8953-2.2	mortar		17.3	687	48	–17.34	–20.4		
Fika 051-2.3	8953-2.3	mortar		15.3	712	47	–18.66	–21.02		
Fika 051-2.4	8953-2.4	mortar		14.9	675	70	–19.4	–22.58		
Fika 051-2.5	8953-2.5	mortar		37.3	738	47	–19.26	–23.48		
Unit: rebuilding of church *(conclusive)*										
Fika 052.1	**8954.1**	**mortar**	**4.0; 76–150**	**19.7**	**496**	**43**	**–11.49**	**–13.16**		
Fika 052.2	8954.2	mortar		21.6	450	65	–12.67	–15.08		
Fika 052.3	8954.3	mortar		20.3	515	75	–13.31	–16.12		
Fika 052.4	8954.4	mortar		12.2	500	50	–13.37	–16.67		
Fika 052.5	8954.5	mortar		26.8	553	50	–13.2	–17.28		
Fika 002.1	**1862.1**	**mortar**	**8.8; <250 panned**	**25**	**535**	**60**	**–13.7**	**–18.4**	**CI, CII**	
Fika 002.2	1862.2	mortar		75	375	45	–9.6	–16.8		
Fika 002W	1863	wood			555	60	–24.2			
Fika 018.1	**1864.1**	**mortar**	**8.5; <250 panned**	**33**	**390**	**50**	**–11.8**	**–20.2**	**CI, CII**	
Fika 018.2	1864.2	mortar		67	470	60	–9.2	–19		
Fika 018W	1865	wood			555	65	–20.3			
Fika 058.1	**10151.1**	**mortar**	**7.1; 46–75**	**20.7**	**415**	**29**	**–10.51**	**–19.01**	**CI, CII**	
Fika 058.2	10151.2	mortar		20.4	473	28	–10.01	–18.74		
Fika 058.3	10151.3	mortar		19.5	574	29	–10.86	–20.67		
Fika 058.4	10151.4	mortar		18.8	480	30	–10.74	–21.09		
Fika 058.5	10151.5	mortar		20.7	499	35	–11.88	–21.41		
Fika 058Li.1	**10155.1**	**lime**	**5.3; 21–150**	**75**	**376**	**34**	**–7.04**	**–19.31**	**CI, CII**	
Fika 058Li.2	10155.2	lime		25	439	39	–8.14	–21.29		
Fika 057.1	**10150.1**	**mortar**	**6.7; 46–75**	**18.9**	**406**	**35**	**–10.5**	**–18.68**	**CI, CII**	
Fika 057.2	10150.2	mortar		19.6	431	30	–10.4	–18.85		
Fika 057.3	10150.3	mortar		19.4	485	37	–11.21	–20.52		
Fika 057.4	10150.4	mortar		18.9	417	35	–11.68	–21.08		
Fika 057.5	10150.5	mortar		23.2	470	34	–11.23	–21.85		
Fika 021.1	**1866.1**	**mortar**	**6.3; <250 panned**	**50**	**440**	**50**	**–12.1**	**–19.1**	**CI, CII**	
Fika 021.2	1866.2	mortar		50	470	50	–11.3	–18.3		
Fika 021	**1867**	**lime**	**NR; NR**		**400**	**55**	**–7.4**		**CII**	
Fika 021W	*1878*	*wood*			*630*	*60*	*–24.1*			
Fika 022W	1868	wood			405	55	–24.3			
Fika 059.1	**10152.1**	**mortar**	**6.7; 46–75**	**17.6**	**416**	**35**	**–17.59**	**–20.37**	**CII**	
Fika 059.2	10152.2	mortar		16.7	531	28	–9.46	–16.57		
Fika 059.3	10152.3	mortar		16.6	498	26	–13.02	–18.76		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Fika 059.4	10152.4	mortar		17.4	484	30	–13.86	–19.54		
Fika 059.5	10152.5	mortar		31.8	544	31	–13.47	–19.59		
Fika 060.1	**10153.1**	**mortar**	**6.7; 46–75**	**20.5**	**416**	**31**	**–11.97**	**–19.21**	**CI, CII**	
Fika 060.2	10153.2	mortar		22.5	430	33	–6.2	–16.9		
Fika 060.3	10153.3	mortar		22.1	414	29	–9.25	–18.87		
Fika 060.4	10153.4	mortar		23.4	401	32	–10.07	–19.06		
Fika 060.5	10153.5	mortar		11.5	453	46	–10.88	–19.29		
Fika 061W	10156	wood			391	33	–25.5			
Fika 063W	10157	wood			543	34	–24.73			
Unit: sacristy										
Fika 071.1	**10154.1**	**mortar**	**7.8; 46–75**	**23**	**392**	**35**	**–16.27**	**–18.62**	**CI**	
Fika 071.2	10154.2	mortar		21	432	38	–9.4	–15.99		
Fika 071.3	10154.3	mortar		20.2	398	43	–12.8	–17.32		
Fika 071.4	10154.4	mortar		19.8	350	36	–13.96	–17.83		
Fika 071.5	10154.5	mortar		16	589	32	–13.85	–17.51		
Dendro: AD 1440–1440										
Unit: tower										
Dendro: AD 1467										
Unit: porch										
Dendro: AD 1452										
FÖGLÖ CHURCH										
Unit: nave *(inconclusive)*										
Foka 001.1	*11855.1*	*mortar*	*8.4; 46–75*	*12.7*	*393*	*34*	*–21.95*	*–20.48*	*inconclusive*	too recent, secondary repair?
Foka 001.2	11855.2	mortar		20.4	571	32	–11.01	–17.89		
Foka 001.3	11855.3	mortar		22.6	760	39	–12.26	–19.15		
Foka 003.1	***11857.1***	***mortar***	***8.8; 46–75***	***10.8***	***610***	***31***	***–20.67***	***–20.72***	***CIV***	too few samples analyzed
Foka 003.2	11857.2	mortar		23	714	28	–8.84	–18.6		
Foka 003.3	11857.3	mortar		21.3	1085	46	–9.88	–19.29		
Unit: tower *(conclusive)*										
Foka 004.1	**12323.1**	**mortar**	**8.3; 46–75**	**9.1**	**338**	**41**	**–26.36**	**–14.86**	**CII**	
Foka 004.2	12323.2	mortar		19.7	446	30	–13.49	–15.42		
Foka 004.3	12323.3	mortar		18.0	636	33	–13.71	–15.6		
Foka 006.1	*12324.1*	*mortar*	*8.0; 46–75*	*9.1*	*475*	*35*	*–26.05*	*–19.26*	*inconclusive*	
Foka 006.2	12324.2	mortar		20.0	589	35	–11.44	–17.47		
Foka 006.3	12324.3	mortar		18.1	694	44	–10.67	–17.57		
Foka 007.1	**12325.1**	**mortar**	**7.6; 46–75**	**9.3**	**323**	**35**	**–20.43**	**–19.89**	**CII**	
Foka 007.2	12325.2	mortar		20.2	493	36	–6.93	–17.58		
Foka 007.3	12325.3	mortar		19.3	481	34	–9.19	–18.71		
Foka 008.1	**12326.1**	**mortar**	**6.7; 46–75**	**9.7**	**356**	**47**	**–22.7**	**–18.16**	**CII**	
Foka 008.2	12326.2	mortar		21.9	495	31	–14.9	–16.6		
Foka 008.3	12326.3	mortar		15.0	605	22	–15.79	–17.89		
GETA CHURCH										
Unit: nave *(conclusive)*										
Geka 001-2.1	**10599-2.1**	**mortar**	**8.0; 46–75**	**13.3**	**463**	**31**	**–20.15**	**–22.46**	**CI, CII**	
Geka 001-2.2	10599-2.2	mortar		15.4	455	30	–5.58	–18.09		
Geka 001-2.3	10599-2.3	mortar		14.5	438	28	–9.81	–18.7		
Geka 001-2.4	10599-2.4	mortar		14.8	422	27	–12.25	–18.75		
Geka 001-2.5	10599-2.5	mortar		41.9	517	31	–12.89	–20.67		
Geka 001W	10604	wood			426	33	–23.32			
Geka 002.1	**10600.1**	**mortar**	**7.0; 46–75**	**18.6**	**444**	**31**	**–20.25**	**–23.74**	**CI, CII**	
Geka 002.2	10600.2	mortar		22.0	447	26	–4.01	–18.47		
Geka 002.3	10600.3	mortar		17.7	446	30	–10.19	–20.07		
Geka 002.4	10600.4	mortar		18.9	451	28	–11.72	–21.3		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (μm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	δ^{13}C ‰ VPDB	δ^{18}O ‰ VPDB	Criteria	Comments
Geka 002.5	10600.5	mortar		22.8	584	27	–13.03	–20.87		
Geka 003.1	**10601.1**	**mortar**	**6.5; 46–75**	**16.3**	**396**	**29**	**–18.44**	**–21.02**	**CII**	
Geka 003.2	10601.2	mortar		17.9	463	27	–5.59	–16.11		
Geka 003.3	10601.3	mortar		16.7	443	31	–11.36	–18.55		
Geka 003.4	10601.4	mortar		16.5	372	36	–12.48	–19.39		
Geka 003.5	10601.5	mortar		32.5	484	28	–13.49	–19.98		
Geka 005.1	**10602.1**	**mortar**	**7.2; 46–75**	**17.4**	**466**	**37**	**–20.1**	**–22.78**	**CI, CII**	
Geka 005.2	10602.2	mortar		19.9	496	30	–2.94	–16.97		
Geka 005.3	10602.3	mortar		17.2	540	28	–9.57	–19.44		
Geka 005.4	10602.4	mortar		18.2	540	26	–11.22	–21.01		
Geka 005.5	10602.5	mortar		27.3	589	32	–12.84	–21.22		
Geka 006C	10605	charcoal			492	28	–24.8			
Dendro: AD 1470–1475										
HAMMARLAND CHURCH										
Unit: early nave (conclusive)										
Haka 018.1	**1465.1**	**mortar**	**5.3; NR**	**45**	**695**	**65**	**–12.9**	**–22.1**	**CI, CII**	
Haka 018.2	1465.2	mortar		55	750	60	–8	–21.4		
Haka 018 C	*1466*	*charcoal*			*820*	*60*	*–26.7*			
Haka 042.1	**2521.1**	**mortar**	**6.9; 39–75**	**30**	**725**	**55**	**–19.4**	**–20.4**	**CI, CII**	
Haka 042.2	2521.2	mortar		70	815	50	–11.3	–17.5		
Haka 052.1	**2168.1**	**mortar**	**7.2; 63–74**	**40**	**690**	**65**	**–13.9**	**–20.3**	**CII**	
Haka 052.2	2168.2	mortar		60	875	70	–8.4	–18.6		
Haka 052-2.1	**2168-2.2.1**	**mortar**	**2.9; 76–125**	**19.5**	**756**	**44**	**[–17.04]**	**[–13.53]**	**CII**	
Haka 052-2.2	2168-2.2.2	mortar		17.1	841	43	–3.98	–16.19		
Haka 052-2.3	2168-2.2.3	mortar		18.1	882	44	–9.19	–18.52		
Haka 052-2.4	2168-2.2.4	mortar		16.9	729	33	–9.72	–19.12		
Haka 052-2.5	2168-2.2.5	mortar		28.1	1010	55	–11.04	–19.07		
Haka 52 C	*2169*	*charcoal*			*970*	*70*	*–23.1*			
Haka 53.1	**2522.1**	**mortar**	**6.8; 39–75**	**29**	**755**	**45**	**–16.5**	**–21.4**	**CI, CII**	
Haka 53.2	2522.2	mortar		71	790	40	–9.6	–19		
Haka 54.1	**2171.1**	**mortar**	**5.2; 63–74**	**40**	**710**	**90**	**–12**	**–19.2**	**CI, CII**	
Haka 54.2	2171.2	mortar		60	730	60	–10.9	–19.4		
Haka 57.1	**2174.1**	**mortar**	**5.8; 63–74**	**40**	**680**	**50**	**–12.5**	**–18.1**	**CI, CII**	
Haka 57.2	2174.2	mortar		60	755	45	–10.7	–19		
Haka 58.1	**2176.1**	**mortar**	**5.3; 63–74**	**40**	**795**	**50**	**–11.5**	**–17.7**	**CI, CII**	
Haka 58.2	2176.2	mortar		60	845	60	–10.4	–19.3		
Haka 58 C	*2177*	*charcoal*			*950*	*55*	*–24.1*			
Unit: tower *(conclusive)*										
Haka 024W	*Hel-2996*	*wood*			*860*	*70*				
Haka 061 C	*2182*	*charcoal*			*1015*	*45*	*–24.5*			
Haka 062.1	**2184.1**	**mortar**	**6.1; 63–74**	**39**	**740**	**70**	**–14.2**	**–17.8**	**CI, CII**	
Haka 062.2	2184.2	mortar		61	700	55	–11.6	–18.1		
Haka 048.1	**2080.1**	**mortar**	**4.0; 63–74**	**73**	**690**	**75**	**–12.3**	**–17.6**	**CII**	
Haka 048.2	2080.2	mortar		27	910	45	–8.2	–17		
Haka 048 C	2048	charcoal			745	65	–26.2			
Haka 049.1	**2081.1**	**mortar**	**8.7; 63–74**	**31**	**680**	**50**	**–13.9**	**–20.5**	**CI, CII**	
Haka 049.2	2081.2	mortar		69	660	50	–9.2	–19.5		
Unit: vaulting and rebuilding of nave *(conclusive)*										
Haka 009W	Hel-2995	wood			660	75				
Haka 002W	Hel-2994	wood			630	70				
Haka 010W	Hel-3313	wood			570	80				
Haka 047W	2046	wood			640	80	–28.9			
Haka 047.1	***2079.1***	***mortar***	***3.8; 63–74***	***58***	***810***	***50***	***–12.4***	***–19.9***	***CI***	probably wrong, older than attached wood
Haka 047.2	2079.2	mortar		42	800	75	–10.7	–19.1		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	δ^{13}C ‰ VPDB	δ^{18}O ‰ VPDB	Criteria	Comments
Haka 047 C	*2047*	*charcoal*			*910*	*75*	*–24.8*			
Haka 045.1	***2077.1***	***mortar***	***5.7; 63–74***	***47***	***815***	***45***	***–11.7***	***–19.4***	***CI***	probably wrong, too old
Haka 045.2	2077.2	mortar		53	730	50	–9.2	–19.1		
Haka 041.1	**2072.1**	**mortar**	**5.7; 63–74**	**44**	**510**	**70**	**–13**	**–21.9**	**CII**	
Haka 041.2	2072.2	mortar		56	800	80	–7.6	–19.6		
Haka 055.1	**2172.1**	**mortar**	**NR; 63–74**	**39**	**575**	**70**	**–11.9**	**–19.4**	**CII**	
Haka 055.2	2172.2	mortar		61	845	55	–10.3	–19.5		
Haka 055-2.1	***2172-2.2.1***	***mortar***	***3.0; 76–125***	***16.8***	***739***	***32***	***–13.85***	***–18.83***	***CI***	profile younger than result from profile in 2 fractions, possibly due to different grain-size fractions
Haka 055-2.2	2172-2.2.2	mortar		17.0	768	30	[–8]			
Haka 055-2.3	2172-2.2.3	mortar		16.4	807	33	–10.25	–18.6		
Haka 055-2.4	2172-2.2.4	mortar		17.1	740	33	[–8.68]	[–14.32]		
Haka 055-2.5	2172-2.2.5	mortar		32.0	825	50	–10.32	–19.28		
Haka 061.1	**2181.1**	**mortar**	**6.0; 63–74**	**43**	**640**	**60**	**–13.3**	**–18.6**	**CI, CII**	
Haka 061.2	2181.2	mortar		57	690	90	–10.4	–18.3		
Haka 044.1	**2075.1**	**mortar**	**5.3; 63–74**	**56**	**615**	**55**	**–12.5**	**–19.6**	**CII**	
Haka 044.2	2075.2	mortar		44	760	55	–10.2	–18.8		
Haka 044L.1	**2076.1**	**lime**	**5.8; not sieved**	**47**	**635**	**60**	**–10.3**	**–19.3**	**CI, CII**	
Haka 044L.2	2076.2	lime		53	660	115	–6.7	–19.9		
Haka 046.1	**2078.1**	**mortar**	**5.6; 63–74**	**46**	**625**	**50**	**–13.9**	**–20.9**	**CII**	
Haka 046.2	2078.2	mortar		54	880	55	–8.1	–19.6		
Haka 056.1	**2173.1**	**mortar**	**6.0; 63–74**	**37**	**615**	**50**	**–11.9**	**–18.9**	**CI, CII**	
Haka 056.2	2173.2	mortar		63	675	60	–11	–19.9		
Haka 059.1	**2178.1**	**mortar**	**7.2; 63–74**	**33**	**615**	**55**	**–13**	**–19**	**CII**	
Haka 059.2	2178.2	mortar		67	730	60	–11.1	–18.8		
Haka 059C	*2179*	*charcoal*			*1270*	*60*	*–26*			
Haka 060.1	**2180.1**	**mortar**	**6.0; 63–74**	**38**	**615**	**50**	**–11.9**	**–19.3**	**CII**	
Haka 060.2	2180.2	mortar		62	715	50	–10.5	–19.8		
Unit: "murklack" *(composite building unit - conclusive?)*										
Haka 001.1	**1463.1**	**mortar**	**4; NR**	**50**	**545**	**65**	**–10.1**	**–16.7**	**CI**	
Haka 001.2	1463.2	mortar		50	630	70	–9.8	–16.4		
Haka 001 C	1464	charcoal			430	60	–26.5			
Haka 040.1	**2071.1**	**mortar**	**5.7; 63–74**	**47**	**715**	**45**	**–12.8**	**–18.9**	**CI**	
Haka 040.2	2071.2	mortar		53	760	75	–11.6	–18.6		
Haka 043.1	**2074.1**	**mortar**	**6.3; 63–74**	**35**	**490**	**80**	**–15**	**–19.8**	**CII**	
Haka 043.2	2074.2	mortar		65	690	80	–14.4	–20.6		
Unit: chancel *(conclusive)*										
Haka 031W	Hel-3260	wood			520	60				
Haka 038.1	**2069.1**	**mortar**	**7.5; 63–74**	**36**	**510**	**60**	**–15.2**	**–21.5**	**CI, CII**	
Haka 038.2	2069.2	mortar		64	600	65	–10.4	–19.8		
Haka 038C	2089	charcoal			570	45	–25			
Haka 038W	2088	wood			480	50	–25.3			
Haka 039.1	**2070.1**	**mortar**	**7.2; 63–74**	**43**	**480**	**55**	**–15.8**	**–20.9**	**CIII**	
Haka 039.2	2070.2	mortar		57	695	65	–10.7	–17.8		
Unit: chancel roof construction *(conclusive)*										
Haka 051.1	**2083.1**	**mortar**	**4.6; 63–74**	**57**	**340**	**45**	**–16.2**	**–19.3**	**CIV**	
Haka 051.2	2083.2	mortar		43	730	45	–15.4	–17.6		
Dendro: AD 1466										
Unit: sacristy *(conclusive)*										
Haka 050.1	**2082.1**	**mortar**	**7.6; 63–74**	**43**	**375**	**50**	**–14.3**	**–20.7**	**CIV**	
Haka 050.2	2082.2	mortar		57	795	50	–11.2	–18.5		
Haka 050 W	2090	wood			450	60	–25.6			

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (μm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
HAMNÖ CHAPEL, KÖKAR ***(conclusive)***										
Hamnkap. 001.1	**4236.1**	**mortar**	**8.4; 39–75**	**20**	**310**	**35**	**–18.1**	**–21.2**	**CI**	
Hamnkap. 001.2	4236.2	mortar		80	315	45	–12.7	–21		
Hamnkap. 002.1	**4237.1**	**mortar**	**7.7; 39–75**	**30**	**460**	**35**	**–12.8**	**–19.7**	**CI**	
Hamnkap. 002.2	4237.2	mortar		70	440	40	–12.1	–20.2		
Hamnkap. 005.1	**4238.1-1**	**mortar**	**8.0; 39–75**	**28**	**395**	**40**	**–16.9**	**–21.5**	**CII**	
Hamnkap. 005.2	4238.2-1	mortar		72	540	65	–13.2	–20.3		
Hamnkap. 005.2.1	**4238.2-1**	**mortar**	**8.1; 39–75**	**22**	**390**	**45**	**–18.2**	**–21.2**	**CII**	
Hamnkap. 005.2.2	4238.2-2	mortar		78	520	50	–13.3	–20.4		
Hamnkap. 006.1	**4239.1**	**mortar**	**8.9; 39–75**	**25**	**365**	**40**	**–14.3**	**–21.2**	**CII**	
Hamnkap. 006.2	4239.2	mortar		75	515	50	–12.7	–22		
JOMALA CHURCH										
Unit: nave (conclusive)										
Joka 030.1	**13006.1**	**mortar**	**7.4; 46–75**	**17.0**	**849**	**40**	**–11.08**	**–11.13**	**CI, CII**	
Joka 030.2	13006.2	mortar		18.1	886	44	–10.55	–10.03		
Joka 031.1	**13144.1**	**mortar**	**6.1; 46–75**	**12.2**	**817**	**34**	**–11.75**	**–12.01**	**CI, CII**	
Joka 031.2	13144.2	mortar		18.3	787	29	–11.81	–11.3		
Joka 031.4	13144.4	mortar		14.7	885	28	–11.72	–11.04		
Joka 031.5	13144.5	mortar		17.4	936	29	–11.6	–10.76		
Joka 033W	Oxford	wood			780	15				
Unit: tower (conclusive)										
Joka 005.1	**4839.1**	**mortar**	**8.3; 39–75**	**27**	**735**	**30**	**–17.7**	**–22.4**	**CII**	
Joka 005.2	4839.2	mortar		72	865	50	–9.5	–19.5		
Joka 011.1	**4836.1**	**mortar**	**9.5; 39–75**	**17**	**675**	**25**	**–19.5**	**–22.6**	**CI, CII**	
Joka 011.2	4836.2	mortar		83	740	40	–8.3	–19.5		
Joka 013a.1	**4835.1**	**mortar**	**5.7; 39–75**	**28**	**765**	**30**	**–22.8**	**–25**	**CII**	
Joka 013a.2	4835.2	mortar		72	900	45	–9.8	–22		
Joka 013a.2.1	**4835.2.1**	**mortar**	**3.6; 39–75**	**10.3**	**810**	**35**	**–23.35**	**–22.72**	**CI, CII**	age profile within 2 σ of result from profile in 2 fractions
Joka 013a.2.2	4835.2.2	mortar		42.8	865	30	–11.61	–19.42		
Joka 013a.2.3	4835.2.3	mortar		24.1	850	35	–10.01	–19.53		
Joka 013a.2.4	4835.2.4	mortar		22.5	840	30	–11.13	–20.16		
Joka 013a.3.1	**4835.3.1**	**mortar**	**4.6; 39–75**	**3.5**	**825**	**35**	**–30.22**	**–23.97**	**CII**	age profile within 2 σ of result from profile in 2 fractions
Joka 013a.3.2	4835.3.2	mortar		28.2	907	28	–10.82	–19.48		
Joka 013a.3.3	4835.3.3	mortar		15.0			–12.03	–19.42		
Joka 013a.3.4	4835.3.4	mortar		12.2	890	30	–10.05	–19.17		
Joka 013a.3.5	4835.3.5	mortar		15.0			–10.87	–20.01		
Joka 013a.3.6	4835.3.6	mortar		12.4	886	29	–11.06	–19.89		
Joka 013a.3.7	4835.3.7	mortar		8.0			–11.16	–19.59		
Joka 013a.3.8	4835.3.8	mortar		2.6	1135	50	–11.71	–18.82		
Joka 013a.3.9	4835.3.9	mortar		3.0			–11.24	–16.76		
Joka 014.1	**4838.1**	**mortar**	**8.9; 39–75**	**22**	**735**	**30**	**–15**	**–17.9**	**CII**	
Joka 014.2	4838.2	mortar		78	815	45	–8.1	–16.4		
Joka 014-2.1	***4838-2.2.1***	***mortar***	***6.3; 46–75***	***17.9***	***879***	***47***	***–14.64***	***–16.29***	***CI***	age profile older than result from profile in 2 fractions, reason unknown
Joka 014-2.2	4838-2.2.2	mortar		19.2	900	80	–3.1	–12.55		
Joka 014-2.3	4838-2.2.3	mortar		18.5	893	50	–9.27	–15.04		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Joka 014-2.4	4838-2.2.4	mortar		18.9	930	42	–9.96	–15.36		
Joka 014-2.5	4838-2.2.5	mortar		24.6	1055	47	–10.08	–15.13		
Joka 016.1	**4837.1**	**mortar**	**8.8; 39–75**	**20**	**715**	**30**	**–20.9**	**–21.5**	**CII**	
Joka 016.2	4837.2	mortar		80	925	40	–10.9	–18.2		
Dendro: AD 1283										
KUMLINGE CHURCH										
Unit: nave, west gable *(conclusive)*										
Kumka 001.1	**11852.1**	**mortar**	**2.8; 46–75**	**17.4**	**428**	**34**	**–15.07**	**–17.23**	**CI**	
Kumka 001.2	11852.2	mortar		18.8	495	27	–4.21	–13.21		
Kumka 001.3	11852.3	mortar		25.0	528	28	–9.4	–16.1		
Kumka 002.1	**11853.1**	**mortar**	**7.4; 46–75**	**18.5**	**535**	**29**	**–15.18**	**–18.1**	**CI, CII**	
Kumka 002.2	11853.2	mortar		24.9	516	29	–6.64	–17.31		
Kumka 002.3	11853.3	mortar		25.1	489	26	–10.78	–17.31		
Kumka 003.1	**12319.1**	**mortar**	**7.4; 46–75**	**18.5**	**512**	**36**	**–16.88**	**–15.77**	**CI, CII**	
Kumka 003.2	12319.2	mortar		24.9	491	42	–5.56	–11.99		
Kumka 003.3	12319.3	mortar		25.1	583	40	–9.59	–13.6		
Unit: nave east gable *(conclusive)*										
Kumka 004.1	11854.1	mortar	7.5; 46–75	14.6	250	27	–11.36	–15.98		
Kumka 004.2	**11854.2**	**mortar**		**23.6**	**632**	**49**	**–8.24**	**–15.19**	**plateau**	fire damage
Kumka 004.3	**11854.3**	**mortar**		**24.3**	**607**	**34**	**–11.72**	**–18.05**		
Kumka 004.4	**11854.4**	**mortar**		**24.1**	**603**	**31**	**–11.93**	**–18.3**		
Kumka 004.5	11854.5	mortar		13.4	806	27	–12.29	–18.15		
Kumka 005.1	12320.1	mortar	6.0; 46–75	10.8	294	48	–15.54	–18.19		
Kumka 005.2	12320.2	mortar		23.8	420	34	–4.87	–16.02		
Kumka 005.3	**12320.3**	**mortar**		**23.7**	**550**	**35**	**–9.21**	**–17.89**	**plateau**	fire damage
Kumka 005.4	**12320.4**	**mortar**		**21.2**	**549**	**25**	**–10.63**	**–19.32**		
Kumka 005.5	**12320.5**	**mortar**		**20.4**	**678**	**25**	**–11.29**	**–18.98**		
Kumka 006.1	12321.1	mortar	5.6; 46–75	9.0	107	33	–16.18	–17.22		
Kumka 006.2	***12321.2***	***mortar***		***21.2***	***401***	***34***	***–8.11***	***–15.65***	***plateau***	probably later repair
Kumka 006.3	***12321.3***	***mortar***		***20.7***	***420***	***34***	***–10.86***	***–15.61***		
Kumka 006.4	***12321.4***	***mortar***		***21.5***	***464***	***27***	***–11.62***	***–18.61***		
Kumka 006.5	12321.5	mortar		27.5	616	29	–11.69	–18.82		
Unit: tower staircase *(inconclusive)*										
Kumka 007.1	***13005.1***	***mortar***	***5.7; 46–75***	***9.9***	***440***	***39***	***–15.63***	***–19.36***	***CIV***	too few samples analyzed
Kumka 007.2	13005.2	mortar		22.7	573	26	–6.1	–16.11		
Kumka 007.3	13005.3	mortar		18.9	543	36	–10.16	–18.44		
KÖKAR CHURCH										
Unit: chancel *(inconclusive)*										
Kökar 010.1	*13147.1*	*mortar*	*8.6; 46–75*	*9.3*	*775*	*48*	*–16.13*	*–11.91*	*test sample*	atypical profile, test using HCl hydrolysis
Kökar 010.2	13147.2	mortar		11.4	751	31	–15.64	–10.88		
Kökar 010.3	13147.3	mortar		11.8	734	34	–16.22	–11.13		
Kökar 010.4	13147.4	mortar		16.8	634	30	–15.65	–9.96		
Kökar 010.5	13147.5	mortar		50.4	637	34	–15.04	–11.09		
LEMBÖTE CHAPEL										
Unit: east gable *(conclusive)*										
Lembo 3.1	**4232.1**	**mortar**	**5.4; 39–62**	**41**	**590**	**30**	**–15.9**	**–18.2**	**CII**	
Lembo 3.2	4232.2	mortar		59	775	55	–17.3	–19.7		
Lembo 4.1	**4233.1**	**mortar**	**4.4; 39–62**	**50**	**675**	**35**	**–19.4**	**–20.8**	**CII**	
Lembo 4.2	4233.2	mortar		50	785	50	–20.2	–23.1		
Lembo 5.1	**4234.1**	**mortar**	**5.6; 39–62**	**32**	**610**	**40**	**–16.9**	**–19.7**	**CII**	
Lembo 5.2	4234.2	mortar		68	755	55	–18.5	–21		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (μm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Lembo 8.1	**4235.1**	**mortar**	**5.6; 39–62**	**32**	**705**	**45**	**–12.8**	**–20.6**	**CI, CII**	
Lembo 8.2	4235.2	mortar		68	770	50	–10.9	–22		
Lembo-1.1	**3186.1**	**mortar**	**8.5; 39–62**	**65**	**710**	**35**	**–18.9**	**–19.4**	**CII**	
Lembo-1.2	3186.2	mortar		35	815	40	–19	–20.3		
Lembo-2.1	**3187.1**	**mortar**	**5.8; 39–62**	**34**	**580**	**40**	**–12**	**–18.8**	**CII**	
Lembo-2.2	3187.2	mortar		66	795	35	[–12]			
LEMLAND CHURCH										
Unit: nave *(conclusive)*										
Leka 021.1	**13145.1**	**mortar**	**2.3; 46–75**	**34.2**	**821**	**31**	**–6.29**	**–4.97**	**CI**	
Leka 021.2	13145.2	mortar		26.5	836	29	–6.81	–4.72		
Leka 021.3	13145.3	mortar		27.7	875	29	–7.12	–5.09		
Dendro: AD 1239–44										
Dendro: AD 1285–88										
Dendro: AD 1292–1295										
Unit: tower *(conclusive)*										
Leka 002.1	**4808.1**	**mortar**	**5.4; 39–75**	**28**	**595**	**30**	**–10.3**	**–13**	**CIII**	
Leka 002.2	4808.2	mortar		72	760	45	–7.2	–14.6		
Leka 003c	*4809*	*charcoal*			*725*	*25*	*–22.5*			
Leka 004c	*4810*	*charcoal*			*710*	*25*	*–21.7*			
Leka 006c	*4811*	*charcoal*			*945*	*20*	*–23.8*			
Leka 007.1	***4812.1***	***mortar***	***4.4; 39–75***	***32***	***475***	***30***	***–10.1***	***–18***		alkaline sample
Leka 007.2	4812.2	mortar		68	715	40	–8.5	–18.1		
Leka 008.1	***4814.1***	***mortar***	***5.8; <39***	***26***	***710***	***30***	***–18.2***	***–20.4***	***CI***	
Leka 008.2	4814.2	mortar		74	650	40	–8.8	–17.7		
Leka 008c	*4813*	*charcoal*			*870*	*25*	*–24.3*			
Leka 009.1	**4815.1**	**mortar**	**7.5; 39–75**	**21**	**665**	**30**	**–18.5**	**–20.9**	**CIII**	
Leka 009.2	4815.2	mortar		79	785	40	–9.4	–24		
Dendro: AD 1318										
SALTVIK CHURCH										
Unit: sacristy and early nave *(conclusive)*										
Saka 119.1	**2534.1**	**mortar**	**7.8; 63–74**	**29**	**655**	**60**	**–5.1**	**–11**	**CI, CII**	
Saka 119.2	2534.2	mortar		71	780	110	–3	–9.8		
Saka 120.1	**2535.1**	**mortar**	**6.9; 63–74**	**33**	**[760]**	**45**	**[–15]**		**CI, CII**	
Saka 120.2	2535.2	mortar		77	740	90	–7.6	–14.2		
Saka 121.1	**2536.1**	**mortar**	**6.8; 63–74**	**34**	**665**	**55**	**–11.6**	**–17.3**	**CII**	
Saka 121.2	2536.2	mortar		66	770	55	–7.9	–16.2		
Saka 121-2.1	*2536-2.2.1*	*mortar*	*5.0; 76–125*	*20.0*	*448*	*43*	*–10.8*	*–10.8*		profile younger than result from profile in 2 fractions, possibly due to different grain-size fractions
Saka 121-2.2	2536-2.2.2	mortar		14.4	559	49	–5.89	–5.89		
Saka 121-2.3	2536-2.2.3	mortar		14.6	580	55	–9.26	–9.26		
Saka 121-2.4	2536-2.2.4	mortar		13.7	499	44	–9.04	–9.04		
Saka 121-2.5	2536-2.2.5	mortar		37.3	642	38	–9.44	–9.44		
Saka 122.1	**2537.1**	**mortar**	**7.9; 63–74**	**30**	**750**	**80**	**–16.7**	**–19.6**	**CI, CII**	
Saka 122.2	2537.2	mortar		70	865	45	–11.7	–17.5		
Saka 122-2.1	**2537-2.1**	**mortar**	**6.8; 76–125**	**13.3**	**763**	**42**	**–16.55**	**–17.45**	**CI, CII**	
Saka 122-2.2	2537-2.2	mortar		16.2	751	50	–10.02	–15.95		
Saka 122-2.3	2537-2.3	mortar		15.9	825	55	–12.98	–17.48		
Saka 122-2.4	2537-2.4	mortar		18.5	740	55	–13.36	–17.26		
Saka 122-2.5	2537-2.5	mortar		36.5	840	55	–13.53	–16.52		
Saka 132.1	**3013.1**	**mortar**	**7.0; 39–62**	**39**	**720**	**45**	**–7.3**	**–13.8**	**CI, CII**	

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Saka 132.2	3013.2	mortar		61	790	35	–7.7	–13.9		
Saka 147.1	**4563.1**	**mortar**	**5.8; 63–74**	**34**	**705**	**35**	**–9.8**	**–14.9**	**CI, CII**	
Saka 147.2	4563.2	mortar		66	695	50	–9.6	–14.8		
Unit: rebuilding of nave *(conclusive)*										
Saka 107W	Hel-3561	wood			520	70				
Saka 108W	Hel-3562	wood			640	70				
Saka 103.1	**2524.1**	**mortar**	**6.8; 63–74**	**29**	**595**	**45**	**–22.4**	**–22.9**	**CII**	
Saka 103.2	2524.2	mortar		71	865	60	–10.6	–18.4		
Saka 104.1	**2525.1**	**mortar**	**7.7; 63–74**	**29**	**625**	**45**	**–12.1**	**–17**	**CII**	
Saka 104.2	2525.2	mortar		71	1385	50	–6.8	–14.6		
Saka 105.1	**2995.1**	**mortar**	**7.7; <62**	**35**	**645**	**30**	**–11.7**	**–16.3**	**CI, CII**	
Saka 105.2	2995.2	mortar		65	690	25	–10.4	–16		
Saka 106.1	**2996.1**	**mortar**	**8.1; <62**	**43**	**625**	**30**	**–7.8**	**–11.9**	**CII**	
Saka 106.2	2996.2	mortar		57	700	40	–9.2	–12.8		
Saka 109.1	**2997.1**	**mortar**	**7.8; <62**	**50**	**625**	**30**	**–8.6**	**–14.1**	**CII**	
Saka 109.2	2997.2	mortar		50	705	30	–9.4	–14.9		
Saka 133.1	**3014.1**	**mortar**	**6.5; 39–62**	**43**	**635**	**40**	**–10**	**–16**	**CII**	
Saka 133.2	3014.2	mortar		57	765	35	–10.5	–16.5		
Saka 146.1	**4562.1**	**mortar**	**7.0; 39–62**	**27**	**615**	**40**	**–9.6**	**–15.5**	**CII**	
Saka 146.2	4562.2	mortar		73	900	55	–8.4	–15.9		
Saka 146-2.1	**4562-2.1**	**mortar**	**6.1; 63–74**	**16.5**	**632**	**44**	**–9.69**	**–14.36**	**CII**	
Saka 146-2.2	4562-2.2	mortar		19.0	810	65	–7.46	–13.38		
Saka 146-2.3	4562-2.3	mortar		18.7	895	55	–9.15	–15.08		
Saka 146-2.4	4562-2.4	mortar		20.8	894	46	–9.46	–15.09		
Saka 146-2.5	4562-2.5	mortar		24.2	948	48	–9.2	–14.71		
Saka 148.1	**4241.1**	**mortar**	**7.2; 39–75**	**34**	**645**	**35**	**–9.6**	**–13.8**	**CII**	
Saka 148.2	4241.2	mortar		66	735	35	–8.9	–14		
Saka 148-2.1	**4241-2.1**	**mortar**	**6.6; 39–62**	**17.3**	**613**	**43**	**–11.87**	**–14.05**	**CI, CII**	
Saka 148-2.2	4241-2.2	mortar		18.1	615	48	–6.13	–6.13		
Saka 148-2.3	4241-2.3	mortar		18.2	730	60	–9	–13.14		
Saka 148-2.4	4241-2.4	mortar		18.5	665	55	–9.41	–12.52		
Saka 148-2.5	4241-2.5	mortar		28.2	758	41	–9.86	–14.04		
Saka 151.1	**4564.1**	**mortar**	**7.1; 39–75**	**28**	**600**	**45**	**–10.3**	**–14.8**	**CII**	
Saka 151.2	4564.2	mortar		72	705	50	–9.1	–15.3		
Saka 152.1	**4242.1**	**mortar**	**7.6; NR**	**29**	**610**	**40**	**–10.6**	**–13.6**	**CI, CII**	
Saka 152.2	4242.2	mortar		71	645	45	–8.5	–14.8		
Dendro: AD 1373										
Unit: tower *(conclusive)*										
Saka 163W	5421	wood			615	35	–26.4			
Saka 164W	5422	wood			670	30	–23.1			
Saka 165W	5423	wood			650	30	–23			
Saka 110.1	**2998.1**	**mortar**	**6.3; <62**	**44**	**620**	**35**	**–10.6**	**–19.7**	**CII**	
Saka 110.2	2998.2	mortar		56	790	40	–9.5	–20.1		
Saka 113.1	**2529.1**	**mortar**	**8.2; 63–74**	**32**	**670**	**45**	**–15.3**	**–19.5**	**CII**	
Saka 113.2	2529.2	mortar		68	840	50	–7	–16.4		
Saka 153W	4243	wood			690	45	–24			
Saka 118.1	**2533.1**	**mortar**	**6.9; 63–74**	**35**	**630**	**55**	**–13.3**	**–20.5**	**CII**	
Saka 118.2	2533.2	mortar		65	815	60	–9.7	–19.2		
Saka 155.1	**4246.1**	**mortar**	**6.2; 39–62**	**35**	**670**	**35**	**–22.3**	**–20.9**	**CI, CII**	
Saka 155.2	4246.2	mortar		65	675	35	–20.5	–21		
Dendro: AD 1381										
Unit: tower upper level *(conclusive)*										
Saka 115W	Hel-3565	wood			495	45				
Saka 114.1	**2530.1**	**mortar**	**7.8; 63–74**	**31**	**495**	**45**	**–15.8**	**–20**	**CII**	
Saka 114.2	2530.2	mortar		69	590	55	–7.8	–17.6		
Saka 116.1	**3000.1**	**mortar**	**6.2; <62**	**35**	**535**	**30**	**–16.7**	**–20.4**	**CII**	
Saka 116.2	3000.2	mortar		65	630	35	–12.3	–19.1		
Saka 117.1	**3001.1**	**mortar**	**6.4; <62**	**36**	**590**	**35**	**–15.1**	**–19**	**CII**	

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Saka 117.2	3001.2	mortar		64	780	30	–11.5	–17.6		
Saka 125.1	3006.1	mortar	7.7; 39–62	34	715	35	–11.1	–19.2		
Saka 125.2	3006.2	mortar		66	830	35	–6.5	–18.1		
Saka 126b.1	**3007.1**	**mortar**	**6.6; 39–62**	**36**	**585**	**50**	**–13**	**–22.5**	**CII**	
Saka 126b.2	3007.2	mortar		64	710	30	–8.8	–22		
Saka 154-2.1	**4244.1**	**mortar**	**7.6; NR**		**480**	**35**	**–10.6**	**–13.6**	**CII**	
Saka 154-2.2	4244.2	mortar			625	40	–8.2	–14.8		
Saka 154W	4245	wood			580	40	–23.6			
Unit: nave west gable *(conclusive)*										
Saka 013W	Hel-3332	wood			540	80				
Saka 111W	Hel-3563	wood			530	70				
Saka 112W	Hel-3564	wood			480	75				
Saka 129a.1	**3009.1**	**mortar**	**7.1; 39–62**	**31**	**490**	**40**	**–21.3**	**–20.9**	**CII**	
Saka 129a.2	3009.2	mortar		69	655	30	–19	–20.4		
Saka 129b.1	**3010.1**	**mortar**	**6.7; 39–62**	**30**	**460**	**30**	**–18.1**	**–18.9**	**CII**	
Saka 129b.2	3010.2	mortar		70	600	35	–16.9	–18.2		
Saka 130.1	**3011.1**	**mortar**	**7.1; 39–62**	**30**	**475**	**30**	**–18.3**	**–19.9**	**CII**	
Saka 130.2	3011.2	mortar		70	605	35	–17.3	–19.4		
SUND CHURCH										
Unit: nave *(fire damage, conclusive?)*										
Suka 014.1	7563.1	mortar	5.9; 46–75	14.4	496	32	–22.26	–21.96		
Suka 014.2	7563.2	mortar		15.7	683	33	–11.69	–19.74		
Suka 014.3	**7563.3**	**mortar**		**23.3**	**781**	**33**	**–10.81**	**–17.76**	**plateau**	
Suka 014.4	**7563.4**	**mortar**		**18.8**	**777**	**36**	**–13.09**	**–19.78**		
Suka 014.5	7563.5	mortar		27.8	819	33	–13.87	–19.47		
Suka 017.1	7564.1	mortar	5.9; 46–75	15.2	619	42	–24.69	–22.49		
Suka 017.2	**7564.2**	**mortar**		**16.6**	**723**	**49**	**–15.13**	**–18.43**		
Suka 017.3	**7564.3**	**mortar**		**18.1**	**745**	**60**	**–18.84**	**–20.22**	**plateau**	
Suka 017.4	**7564.4**	**mortar**		**19.1**	**745**	**65**	**–20.22**	**–20.94**		
Suka 017.5	7564.5	mortar		31.1	[775]	65	–22.47	–20.64		
Suka 024.2.1	7567.2.1	mortar	6.9; 46–75	14.6	503	38	–18.01	–18.41		
Suka 024.2.2	**7567.2.2**	**mortar**		**19.8**	**675**	**35**	**–11.74**	**–17.81**		
Suka 024.2.3	**7567.2.3**	**mortar**		**21.9**	**735**	**38**	**–13.6**	**–19.87**	**plateau**	
Suka 024.2.4	**7567.2.4**	**mortar**		**20.4**	**669**	**28**	**–14.01**	**–19.57**		
Suka 024.2.5	7567.2.5	mortar		23.4	805	37	–14.25	–19.17		
Suka 025.1	7568.1	mortar	4.2; 46–75	17.1	242	47	–19.93	–17.29		
Suka 025.2	7568.2	mortar		22.4	450	50	–8.4	–16.42		
Suka 025.3	**7568.3**	**mortar**		**19.5**	**742**	**41**	**–10.63**	**–19.03**	**plateau**	
Suka 025.4	**7568.4**	**mortar**		**14.2**	**790**	**50**	**–11.81**	**–18.19**		
Suka 025.5	7568.5	mortar		26.7	[545]	75	–12.96	–19.98		
Suka 026-2.1	7569-2.1	mortar	5.3; 46–75	18.0	315	29	–16.01	–17.97		
Suka 026-2.2	**7569-2.2**	**mortar**		**20.1**	**732**	**33**	**–7.26**	**–16.2**	**plateau**	
Suka 026-2.3	**7569-2.3**	**mortar**		**20.6**	**790**	**30**	**–9.74**	**–17.79**		
Suka 026-2.4	7569-2.4	mortar		21.3	546	36	–11.4	–18.18		
Suka 026-2.5	7569-2.5	mortar		20.0	541	36	–12.25	–17.47		
Suka 002.1	*7559.1*	*mortar*	*4.0; 46–75*	*16.0*	*936*	*36*	*–24.95*	*–22.66*	*incon-clusive*	Results too old? Sample from founda-tion level
Suka 002.2	7559.2	mortar		13.6	938	38	–18.66	–20.1		
Suka 002.3	7559.3	mortar		70.4	916	35	–22.3	–23.51		
Suka 002.2.1	*7559.2.1*	*mortar*	*3.2; 46–75*	*15.4*	*992*	*34*	*–24.55*	*–22.71*	*incon-clusive*	Results too old? Sample from founda-tion level
Suka 002.2.2	7559.2.2	mortar		23.8	905	36	–20.22	–21.65		
Suka 002.2.3	7559.2.3	mortar		24.3	952	37	–22.13	–22.68		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Suka 002.2.4	7559.2.4	mortar		21.9	988	36	–22.43	–22.86		
Suka 002.2.5	7559.2.5	mortar		10.8	979	37	–22.42	–22.68		
Suka 002C	*7598*	*charcoal*			*1555*	*38*	*–25.07*			
Suka 028.1	*8721.1*	*mortar*	*3.0; 46–75*	*24.6*	*246*	*43*	*[–12]*	*–15.84*	*incon-clusive*	atypical age profile
Suka 028.2	8721.2	mortar		26.2	697	34	–4.8	–17.12		
Suka 028.3	8721.3	mortar		24.2	1182	38	–8.81	–18.77		
Suka 028.4	8721.4	mortar		23.4	768	41	–10.79			
Suka 028.5	8721.5	mortar		1.7	lost					
Suka 028Li.1	**8722-2.1**	**mortar**	**9.6, 76–150**	**57.8**	**192**	**35**	**–10.61**	**–20.01**	**CI**	probably dates documented re-pairs after fire
Suka 028Li.2	8722-2.2	mortar		28.3	219	40	–10.34	–19.95		
Suka 028Li.3	8722-2.3	mortar		14.1	253	43	–9.28	–19.61		
Suka 028Li.5	8722-2.5	mortar		65.9	279	40	–10.26	–21.26		
Unit: west gable of nave *(fire damage, inconclusive)*										
Suka 019.1	7565.1	mortar	8.9; 46–75	0.26	497	36	–12.38	–17.98		age profile in-sufficient
Suka 019.2	7565.2	mortar		0.36	602	36	–9.15	–17.97		
Suka 019.3	7565.3	mortar		0.38	660	31	–11.42	–18.72		
Suka 020.1	7566.1	mortar	8.7; 46–75	0.24	695	36	–15.29	–18.47		atypical age profile
Suka 020.2	7566.2	mortar		0.34	625	35	–10.92	–18.15		
Suka 020.3	7566.3	mortar		0.41	610	37	–12.86	–19.05		
Unit: tower *(fire damage, conclusive)*										
Suka 001W	1475	wood			510	45	–24.8			
Suka 005W	7599	wood			623	38	–23.62			
Suka 007W	7600	wood			659	38	–24.61			
Suka 006.1	7560.1	mortar	6.2; 46–75	10.2	435	70	–16.34	–15.38		
Suka 006.2	**7560.2**	**mortar**		**14.3**	**509**	**40**	**–7.18**	**–12.61**	**plateau**	
Suka 006.3	**7560.3**	**mortar**		**13.4**	**679**	**33**	**–6.72**	**–12.21**		
Suka 006.4	7560.4	mortar		13.9	706	39	–10.58	–14.37		
Suka 006.5	7560.5	mortar		48.3	499	37	–11.2	–14.21		
Suka 027.1	*8720.1*	*mortar*	*3.4; 46–75*	*27.6*	*325*	*37*	*–15.4*	*–17.83*	*incon-clusive*	atypical age profile
Suka 027.2	8720.2	mortar		22.5	1024	41	–8.4	–17.16		
Suka 027.3	8720.3	mortar		20.3	924	38	–10.7	–18.52		
Suka 027.4	8720.4	mortar		19.6	594	46	–11.97	–18.83		
Suka 027.5	8720.5	mortar		9.3	990	70	–12.29	–18.27		
Suka 038.1	7572.1	mortar	5.4; 46–75	17.5	580	150	–13.31	–16.88		
Suka 038.2	**7572.2**	**mortar**		**21.7**	**690**	**80**	**–7.81**	**–14.64**		
Suka 038.3	**7572.3**	**mortar**		**18.0**	**668**	**37**	**–11.05**	**–17.44**	**plateau**	
Suka 038.4	**7572.4**	**mortar**		**16.9**	**664**	**37**	**–11.37**	**–16.08**		
Suka 038.5	7572.5	mortar		26.0	744	41	–10.93	–16.76		
Suka 035.1	*7571.1*	*mortar*	*6.2; 46–75*	*25.4*	*572*	*37*	*–14.45*	*–19.14*	*incon-clusive*	uncertain inter-pretation
Suka 035.2	7571.2	mortar		37.9	776	34	–8.14	–17.04		of age profile
Suka 035.3	7571.3	mortar		36.7	857	35	–10.71	–17.58		
Suka 040.1	*7573.1*	*mortar*	*7.7; 46–75*	*25.4*	*630*	*37*	*–14.38*	*–15.32*	*incon-clusive*	uncertain inter-pretation of age profile
Suka 040.2	7573.2	mortar		39.5	904	36	–8.92	–13.19		
Suka 040.3	7573.3	mortar		35.0	1147	38	–10.73	–13.83		
Suka 044.1	*7574.1*	*mortar*	*6.2; 46–75*	*24.6*	*290*	*33*	*–15.72*	*–15.11*	*incon-clusive*	uncertain inter-pretation of age profile
Suka 044.2	7574.2	mortar		35.7	605	39	–7.3	–15.27		
Suka 044.3	7574.3	mortar		39.7	585	31	–9.85	–14.59		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Unit: sacristy, burial chamber *(conclusive)*										
Suka 010.1	**7561.1**	**mortar**	**3.0; 46–75**	**21.3**	**354**	**36**	**–20.03**	**–23.3**	**CI**	
Suka 010.2	7561.2	mortar		25.0	420	55	–13.07	–15.69		
Suka 010.3	7561.3	mortar		27.3	318	39	–16.04	–19.11		
Suka 010.4	7561.4	mortar		22.6	385	37	–16.17	–17.83		
Suka 010.5	7561.5	mortar		3.8	548	45	[–17]			
Unit: sacristy *(inconclusive)*										
Suka 013.2.1	*7562.2.1*	*mortar*	*6.1; 46–75*	*16.0*	*189*	*34*	*–13.28*	*–15.28*	*incon-clusive*	secondary repair in sacristy?
Suka 013.2.2	7562.2.2	mortar		19.6	399	39	–10.64	–14.6		
Suka 013.2.3	7562.2.3	mortar		17.6	459	36	–11.93	–15.84		
Suka 013.2.4	7562.2.4	mortar		17.1	492	31	–12.17	–16.64		
Suka 013.2.5	7562.2.5	mortar		29.7	603	37	–12.05	–17.12		
Suka 015.1	*9058.1*	*mortar*	*3.9; 46–75*	*18.1*	*627*	*37*	*–19.3*	*–20.6*	*incon-clusive*	uncertain interpretation of age profile
Suka 015.2	9058.2	mortar		17.2	794	38	–9.89	–15.29		
Suka 015.3	9058.3	mortar		17.4	888	37	–13.09	–16.06		
Suka 015.4	9058.4	mortar		17.1	886	29	–15.25	–18.86		
Suka 015.5	9058.5	mortar		30.8	987	46	–15.74	–18.72		
Suka 016.1	*9059.1*	*mortar*	*3.7; 46–75*	*19*	*463*	*36*	*–12.76*	*–13.02*	*incon-clusive*	uncertain interpretation of age profile
Suka 016.2	9059.2	mortar		21.6	579	37	–7.88	–10.94		
Suka 016.3	9059.3	mortar		22.4	568	43	–11.56	–12.7		
Suka 016.4	9059.4	mortar		21.6	703	34	–12.77	–12.88		
Suka 016.5	9059.5	mortar		16.1	778	35	[–13]			
Suka 016C	9057	charcoal			681	38	–24.98			
Suka 034.1	*7570.1*	*mortar*	*4.6; 46–75*	*16.9*	*451*	*43*	*–13.5*	*–18.11*	*incon-clusive*	uncertain interpretation of age profile
Suka 034.2	7570.2	mortar		27.7	743	39	–8.06	–15.49		
Suka 034.3	7570.3	mortar		23.1	728	39	–10.11	–17.36		
Suka 034.4	7570.4	mortar		20.6	835	33	–10.74	–16.25		
Suka 034.5	7570.5	mortar		11.7	1275	38	–10.78	–16.14		
VÅRDÖ CHURCH										
Unit: nave, east gable *(conclusive)*										
Vaka 001.1	*8947.1*	*mortar*	*4.9; 76–150*	*18.5*	*287*	*36*	*–21.01*	*–21.56*	*incon-clusive*	heavy contamination
Vaka 001.2	8947.2	mortar		17.1	857	40	–4.79	–16.16		
Vaka 001.3	8947.3	mortar		19.4	933	50	–11.06	–19		
Vaka 001.4	8947.4	mortar		17.1	905	55	–11.78	–19.36		
Vaka 001.3.1	8947.3.1	mortar	5.2; 46–75	9.5	331	37	–16.22	–20.64		
Vaka 001.3.2	8947.3.2	mortar		17.8	503	37	–12.61	–20.14		
Vaka 002.1	*8948.1*	*mortar*	*5.0; 76–150*	*18.9*	*319*	*43*	*[–24.23]*	*[–29.52]*	*incon-clusive*	heavy contamination
Vaka 002.2	8948.2	mortar		18.2	979	45	[–2.35]	[–15.98]		
Vaka 002.3	8948.3	mortar		18.2	1274	47	–9.12	–18.65		
Vaka 002.4	8948.4	mortar		17.9	1258	42	–10.09	–19.15		
Vaka 002.5	8948.5	mortar		27.2	1167	44	–11.25	–19.26		
Vaka 002.3.1	8948.3.1	mortar	5.1; 46–75	10.3	524	31	–16.72	–20.86		
Vaka 002.3.2	8948.3.2	mortar		22.6	686	43	–11.04	–19.86		
Vaka 003.1	*8949.1*	*mortar*	*3.8; 76–150*	*18.0*	*240*	*90*	*–16.36*	*–19.91*	*incon-clusive*	heavy contamination
Vaka 003.2	8949.2	mortar		21.4	1611	32	–2.88	–14.14		
Vaka 003.3	8949.3	mortar		17.0	2181	36	–6.71	–15.6		
Vaka 003.4	8949.4	mortar		16.5	1586	36	–8.02	–16.8		

Appendix Dated mortal samples and fractions. *(Continued)*

Sample	Lab nr Aarhus (AAR-#)	Type	C yield (%); grain-size fraction (µm)	Fraction size (%)	^{14}C age (BP)	± 1 σ	$\delta^{13}C$ ‰ VPDB	$\delta^{18}O$ ‰ VPDB	Criteria	Comments
Vaka 003.5	8949.5	mortar		27.5	1495	55	–9.58	–17.13		
Vaka 005C	9056	charcoal			394	41	–26.04			
Vaka 005.1	**13006.1**	**mortar**	**4.0; 46–75**	**11.5**	**415**	**37**	**–20.34**	**–22.5**	**CIV**	agrees with embedded charcoal (Vaka 005C)
Vaka 005.2	13006.2	mortar		14.7	702	32	–9.24	–18.44		
Vaka 005.3	13006.3	mortar		13.3	1156	28	–7.78	–17.17		
Vaka 005.4	13006.4	mortar		27.7	1951	34		–17.4		
Dendro: AD 1470–75										