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Dendroarchaeological evidence of early medieval water mill technology

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A B S T R A C T

The use of hydropower provides an important technical advancement over hand-operated grain mills, which steadily increased over large parts of Europe from the early Middle Ages onwards. Since written information on the technical design of early medieval water mills is generally missing, archaeological evidence may provide unique insights into their evolution. Well-preserved wooden finds from continental Europe are, however, extremely rare. Here we present dendroarchaeological results from an exceptional number of structural elements of the Audun-le-Tiche water mill in northern France. Taxonomical identification, tree-ring dating and observations of technical features provide a detailed picture of milling technology as early as the Carolingian period in the mid-9th century. A well-preserved waterwheel segment allows the reconstruction of an undershot start-and-float wheel. Numerous wooden paddles reveal a technological evolution from one-piece paddles to composite forms. Placing our results in the context of other early medieval mills, suggests a rather uniform consruction design within, though different beyond the Frankish Empire. This study provides a detailed description of early medieval water milling technology that possibly contributed to the success of agriculture as well as cultural and economic growth of the Carolingian Empire.

1. Introduction

The processing of grain for food production is essential in all sedentary cultures. The use of hydropower provides a decisive technical advancement over hand-operated grain mills. Water mills are the first machines in a narrow sense, since their drive does not rely on human or animal labour. They represent one of the most important technical achievements of mankind. In pre-industrial times the use of hydromechanic power was applied for various production processes, among other things, for grinding grain (Lucas, 2005). In the Early Middle Ages with an essentially agricultural economy, this must be considered as the main use of water mills. From this period on, a steady increase of water mill use can be observed inside, as well as outside the former Roman provinces (e.g. Rynne, 2015; Czycz, 1998; Böhme, 1999b).

The first evidence of water-powered mills in Central Europe derives from written sources for the Roman period (e.g. Böhme, 1999a). From the Early Middle Ages on, the written sources accumulate, which has been regarded as an indication of a technical innovation boost in the early Middle Ages among experts of technical history for a long time (Bloch, 1935; Mumford, 1934; Wikander, 1984, recapitulatory Lucas, 2005). More recent studies on sites and finds from the roman provinces, which are interpreted

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as water mills (e.g. Gähwiler and Speck, 1991; Harding, 2013; Castella et al., 1994 Böhme, 1999a; Maisant, 1994; Champagne et al., 1997), in turn, suggest a milling tradition from antiquity onwards. In recent years, a greater number of roman sites have been excavated, leaving no doubts about the existence of water mills in roman times (recapitulatory Brun, 2016).

Despite the controversial debate on whether the roots of Central European milling tradition reach back to roman or early medieval times, the prominent role of water mills in the Early Middle Ages manifested in various written sources from the 6th and 7th century AD, e.g. Gregory of Tours‘ Liber vitae patrum, 18,2 (James, 1991), the Fundatio monasterii Aquicinctini (Waitz, 1883), the Vitae sanctae Brigidae (Hochegger, 2009) as well as law regulations (e.g. Lex Salica, 6th c. AD, Lex Ripuaria, 7th c. AD, Edictus Rotharii, 643 AD (Rivers Th, 1986; Azzara and Gasparri, 2005). Although the written sources on water-powered flour mills consolidate in the Early Middle Ages, the number archaeologically documented mills in Central Europe from this period remains limited (Lorquet, 1994; Czycz, 1998; Höckmann, 1994; Kind, 2007; Rügner, 2013; Liebert, 2015; Rollier et al., 2016; Rohmer et al., 2016; Viau, 2016).

The structural remnants of water mills are mostly found in waterlogged sediments, which means an increased probability of preserved wooden structures in relatively large amounts. The waterlogged environment prevents decomposition by aerobic microorganisms and strongly slows down the biodegradation. Under such circumstances, woods can survive for millennia (Tegel et al., 2012). The saturation with water leaves the outer shape of the artefact intact for technological observations and allows for microscopic identification of species.

Numerous parameters such as water volume, flow rate, seasonal or year-round usability, agricultural catchment area, traffic connection and local ownership structures have defined a location suitable for setting up a water mill. Therefore, in many cases a mill site was used in several phases or periods. Archaeological discoveries of mill sites frequently present pile groups without recognisable structures or ground plans. Notably wooden parts from the rising structure (e.g. parts of the roof or wooden partitions) have often been exposed to dislocations caused by water stream and the shifting of river banks and scattered randomly across the excavation site.

Dendroarchaeological studies, based on technomorphology and dendrochronological dating, deliver annually resolved, absolute data. This precision of dating makes it possible to identify individual phases of construction within one mill site. Other dendrological observations provide information on the timber used (e.g. species selection, tree age and growth rates). On the preserved wooden remains, constructional solutions can be recognised. Based on the wood species utilised and technical details, we can provide a differentiated picture of contemporary milling technology. This is all the more important, since no iconographical sources for the appearance and design of water mills exist for the early Middle Ages, i.e. the period 500–1000 AD, roughly between the disintegration of the Roman Empire and the comprehensive implementation of milling technology in Central Europe (Berthold, 2016). Fundamental economic and technological directions have been set during this timespan, yet little is known about the development of mills. Therefore, the present study aims to fill this knowledge gap.

Here, we present the dendroarchaeological analysis of a Carolingian water mill from Audun-le-Tiche, Dép. Moselle (F). Thanks to its excellent conservation condition, remnants of the mill building and technical elements such as parts of the waterwheel, as well as numerous paddles provide unique insights. With a multidisziplinary approach from archaeological, dendrochronological and technical perspective, we broach various fields of humanities and sciences and place our local results in a wider, European context.

2. Material and methods

North of the village of Audun-le Tiche, close to the border between France and Luxembourg, structures of wood were discovered in 1995 at the banks of the Alzette River (Rohmer, 1996). Overall, 328 wooden objects were excavated on the site (Rohmer et al., 2016). A total of 183 samples were taken for dendroarchaeological studies. The material includes round piles from the mill building, split wood piles, mostly from the revetment of the mill race and construction elements such as pegs, a segment of the waterwheel and numerous paddles.

All investigations were carried out on the excavated objects prior to any stabilisation treatment. In most cases, samples with a thickness of about 4 cm were prepared for dendrochronological analysis. For the most significant pieces, stabilisation treatment was carried out post analysis at the Grenoble Nuclear Research Center (France). After the analyses, all samples were preserved in the musée de la Tour aux Puces at Thionville (France).

The identification of wood species was performed on all wood samples taken. Thin sections in tangential and radial orientation as well as cross sections were analysed under a transmitted light microscope with magnification 40× to 400×. The taxonomical classification followed standard identification keys (Schweingruber, 2011; Grosser, 2007).

In the interest of museum presentation, the wheel segment and some of the best-preserved paddles were not part of the dendrochronological analysis. Therefore, dendrochronological analysis focused on 100 samples, 86 of oak and 14 of beech. The samples were cut along the cross section to obtain an undistorted ring pattern. For better visibility, the sample surface was prepared with razor blades and if necessary, stained with chalk to highlight the vessels. Ring-width measurements were performed, using binocular microscopes, measuring table and the software PAST4 (www.sciem.com). The tree-ring series were cross-correlated and synchronised with regional and supraregional reference chronologies and dated by acknowledged statistical methods and visual verification (Baillie and Pilcher, 1973; Baillie, 1982).

3. Results

3.1. Taxonomy

A total of six species could be anatomically distinguished (Fig. 2). The microscopic species identification of 183 samples show a majority of oak (*Quercus sp.*) wood used for the construction of the mill. The other important species for construction is beech (*Fagus sylvatica*). Other species have been used for piles and logs found in the immediate vicinity of the mill. Five individuals were identified as pomaceous trees (*Maloideae*). Hornbeam (*Carpinus betulus*) was identified in three cases. Furthermore, three long timbers found in horizontal position represent lightweight wood species. Two examples of poplar (*Populus sp.*) and one of willow (*Salix sp.*) were identified.

3.2. Dendrochronology

A total of 77 samples could be dated, 67 of which are oak series and ten beech. The measured tree-ring width series allowed a generation of a mean chronology of 242 years for oak and 298 years for beech (Fig. 3A and B). These chronologies were correlated and synchronised with regional reference chronologies between 708 and 949 AD for oak and between 625 and 922 AD for beech based on high statistical significance (Fig. 3A and B).

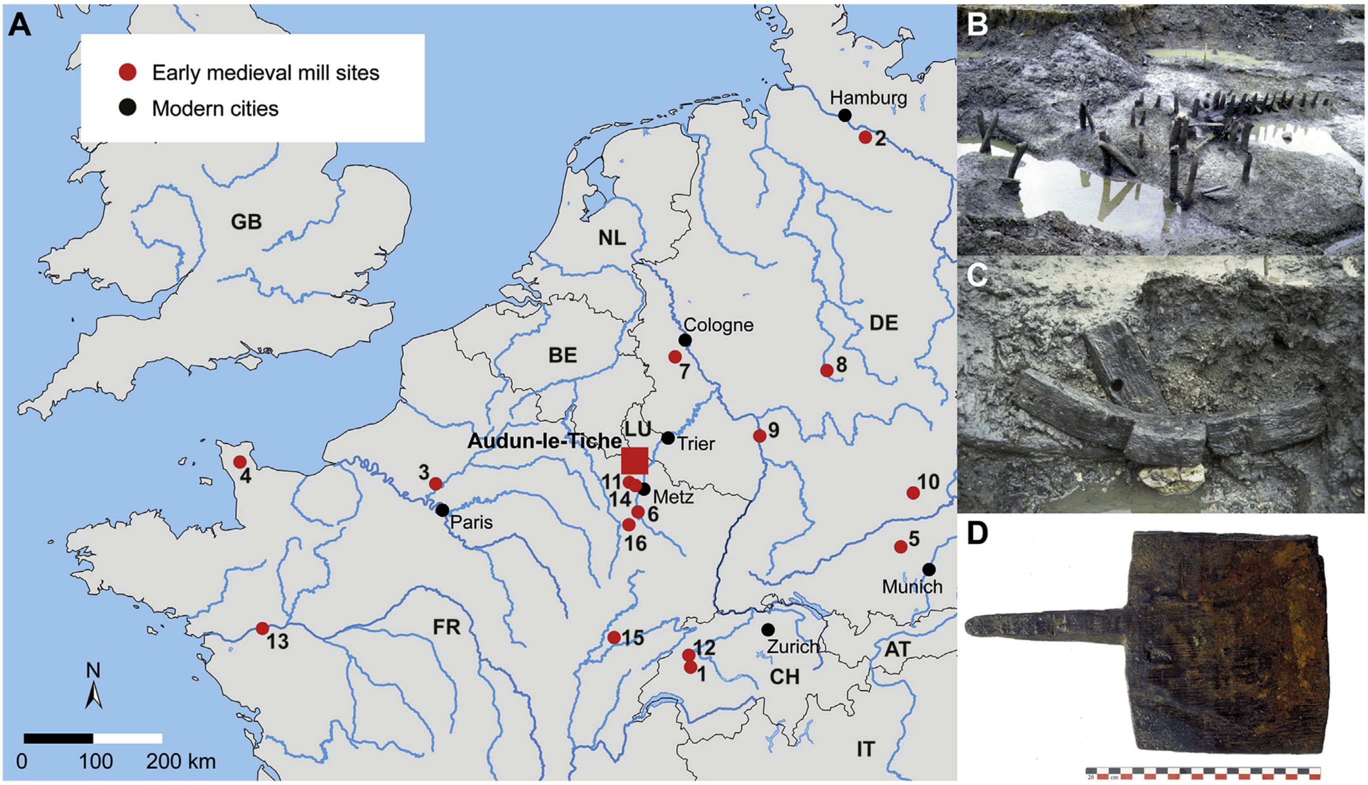

Fig. 1. **A** Archaeological sites with early medieval water mills in Central Europe (* only millstones): 1* Avenches (Blanc and Castella, 2016), 2 Bardowick (Krüger, 1934), 3 Belle-Église (Lorquet, 1994), 4 Colomby (Bernard et al., 2016), 5 Dasing (Czycz, 2016), 6* Dieulouard (Gucker, 2016), 7 Erftstadt-Niederberg (Rügner, 2013), 8 Fulda (Kind, 2007), 9 Gimbsheim (Höckmann, 1994), 10 Großhöbing (Liebert, 2015), 11* Hatrize (Galland et al., 2016), 12 La Mottaz (Pillonel and Plumettaz, 2016), 13 Marillais (Viau, 2016), 14* Prény (Galland et al., 2016), 15 Thervay (Rollier et al., 2016), 16* Toul (Galland, 2016). **B** On-site photography during the excavation. **C** *in situ*-photography of the waterwheel segment. **D** Photography of paddle No. 2013.

Dendrochronological analyses on structural elements still in their original position show a first construction phase for the mill building in 840 AD (Fig. 4B). Over the following years, frequent repairs and adjustments can be recorded through more samples with wanes. The latest date for the construction of the mill is 851 AD. This date is confirmed by eight samples of split wood piles with wane from the mill race, indicating extensive repairs. Of the 51 analysed paddles 42 have been dated. Produced from radially split boards, these elements have a characteristically great number of tree rings. The mean segment length (MSL) for oak paddles was calculated as 76.5 rings, for beech it was even higher with 95.9 rings. 20 oak paddles still showed sapwood. For the most recent date (949 AD) no sapwood was preserved. Therefore, only a heartwood dating was possible, leading to a *terminus post quem*. The earliest felling date possible corresponds with the year 959 AD.

Regarding beech, recent studies have shown that this species is well suited for dendrochronological dating and dendroclimatological analyses, due to its sensitivity in growth (e.g. Tegel et al., 2014). Three beech boards from the southern part of the excavation site (No. 10, 13 and 14) show very similar growth patterns and thus most probably were produced from the same tree. Apart from visual matching, this is demonstrated by extraordinarily high *Gleichläufigkeit* (GL) between 82.1% and 85.2% and t-values between 18.5 and 20.8 according to Baillie and Pilcher (TBP). With one of the boards, remnants of the wane were preserved, dating the felling to 845 AD. This corresponds well with the oak datings from the mill structure. Aside from these construction timbers, seven paddles could be dated. In one case, the waney edge was preserved. This allowed a precise dating for paddle No. 2014 (TBP 8.81, GL 71.6% with the site chronology for beech). With a felling date of 787 AD it is the oldest paddle found in Audun-le-Tiche. At the same time it provides the important evidence of an 8th century mill facility on the Alzette River. All other six paddles show no wane, providing *termini post quem*. However, they stand for a continuous use of beech for paddle production throughout the 9th and the beginning of the 10th century.

3.3. Wood technology

Two wheel segments were found in Audun-le-Tiche (Rohmer et al., 2016). Only one of the segments had been in use, the other, is a semi-finished work in progress (see below). Both objects belong to the same basic wheel type. The first waterwheel segment was discovered on the berm separating two basins (Fig. 2B). The segment was manufactured from beech wood and measures 72 cm on its convex and 65 cm on the concave side. The cross section is 8×6 cm at one end, 7.5×6 cm at the other end and of 11×6.5 cm in its central part. The size and curved form allow conclusions to the wheel dimensions and design: A circle consisting of 10 such "T-shaped" segments put together in alternating orientation form a start-and-float wheel with a diameter of 146 cm (Fig. 5).

The segment was connected to the adjacent ones using two round pins, 2.3 cm in diameter, and two pegs with a rectangular profile of 2.5 by 3.5 cm to secure the construction. Remains of all these connecting elements were still preserved *in situ*. Three pin holes on the outer face of the wheel with a diameter of 2.5 cm were the counterparts of the paddle tenons. Fragments of the tenons are still preserved in all three holes, one of them was additionally secured with a wedge. As may be seen from the number of holes and their distance to each other (23 cm), the complete wheel

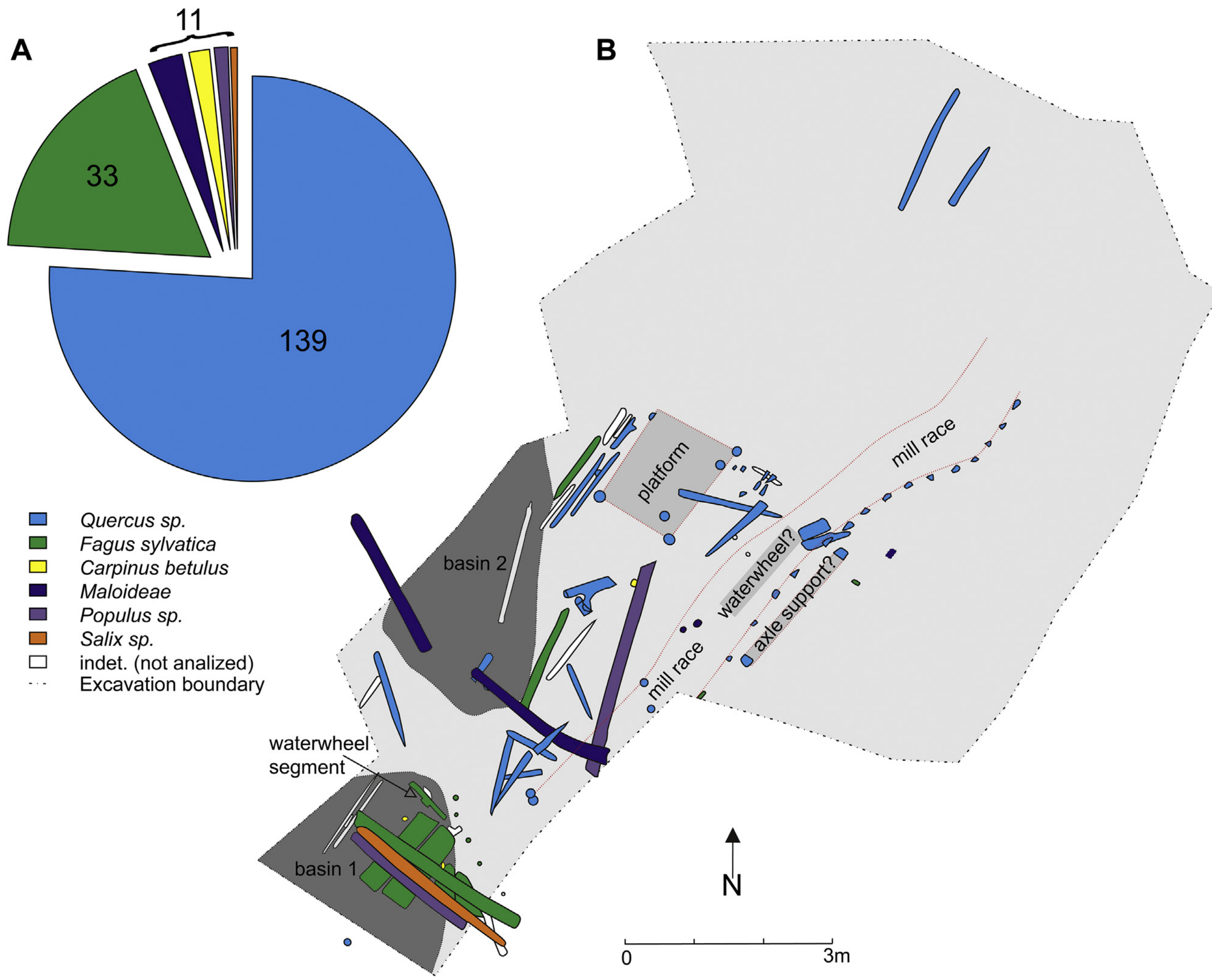

Fig. 2. A Proportional distribution of wood species (with total numbers). **B** Spatial distribution on the excavation site. Map basis: Rohmer et al., 2016, 308, Fig. 6.

contained 20 paddles.

The second wheel segment is a roughly formed object also processed from beech. The 68.5 cm long curved object, which has been shaped angularly from a half-timber and has a width of 9.5 cm and a thickness of 7.5 cm (Rohmer et al., 2016). Through the course of the curve the piece can be supplemented to a wheel with 120–130 cm diameter from 8 similar segments. Hence, it is certain that the semi-finished segment was originally planned for another water wheel extra to the abovementioned wheel segment.

A total of 121 fragmented paddles were found, frequently fractured along the fibre (Rohmer et al., 2016). They were spread over the entire excavation site. 104 of the objects seem to be made according to the same model (Fig. 6B, type 1). Manufactured from one piece of wood, a rectangular-shaped paddle extends in a rectangular to cylindrical tenon. With widths of 15–20 cm and lengths between 16 and 34 cm there is some variation in the paddle size, whereas all tenons show more or less the same dimensions, conditional on the diameter of the pin holes of the waterwheel. Most paddles have their tenon placed centrally but some tenons are eccentric. The reason for these two types of paddles is the position of the pin holes on the wheel rim. Every other hole deviates from the rim center (Fig. 6C). A smaller group of 17 paddles follow another design (Fig. 6B, type 2). They consist of a rectangular paddle board connected to a separate stave with two small pegs. The paddle boards for both types were radially split from the trunks of oak and beech. One end of the paddle is always planar, the other end is almost always slightly bevelled. It is likely that this bevel was facing the current to facilitate the 'intake' of water.

Alongside these water mill parts, numerous other wooden objects were analysed. Their distinct function is not definable. Pins, pegs and wedges of various dimensions and profile were found. They were predominantly manufactured from oak but also from beech.

4. Discussion

Oak was used for the vast majority of wooden objects found in Audun-le-Tiche. The material is tough, elastic and durable. Oak is moderately difficult to process, but is easy to split and has little shrinkage. Up to modern times it has been used as timber in all areas of interior and exterior construction, bridge construction and hydraulic engineering as well as shipbuilding. Beech is the second most important species in Audun. The wood is short-fibered, has low bearing capacities and elasticity and has a tendency to crack and warp. But by contrast beech is also heavy, hard, pressure-resistant but is easy to split and to process. It is this combination of properties, that made beech preferentially used. Other species used furthermore indicate a selection of dense and hard species for

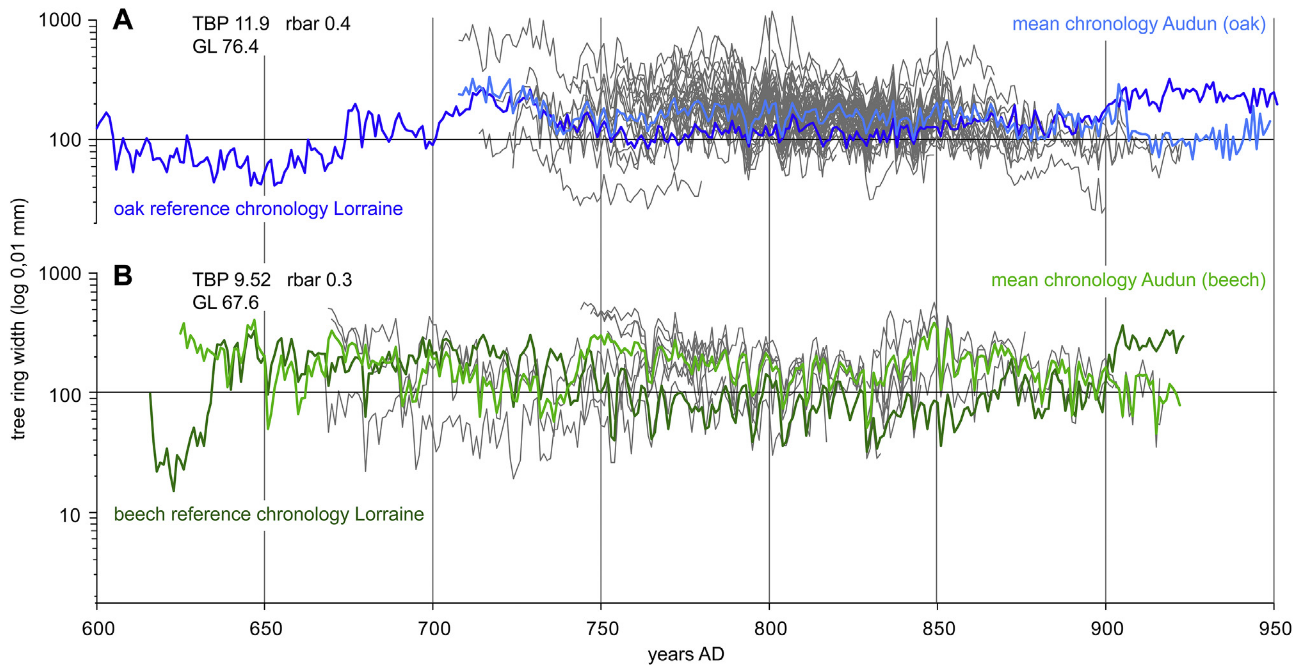

Fig. 3. **A** Site chronology for oak (light blue) in synchronisation with regional reference chronology (Tegel et al., 2010), single tree ring sequences in gray. **B** Site chronology for beech (light green) in synchronisation with regional reference chronology (Tegel and Peytreman, 2011), single tree ring sequences in gray. TBP … t-value according to Baillie and Pilcher (1973), GL … *Gleichläufigkeit*, rbar … inter-series correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the water mill. The diffuse-porous wood of pomaceous trees has a fine structure, is moderately heavy but hard and dense. Hornbeam is the heaviest indigenous species in Central Europe, known for its hardness and mechanical strength. With only three objects lightweight wood played a subordinate role for the construction.

Dendrochronological analysis provides strong evidence towards the construction of a Carolingian water mill in Audun-le-Tiche in the year 840 AD. This can be determined through the absolute dating of sample No. 66. The last ring formed evinced the wane, the pile was part of the mill platform. The date is confirmed by various samples with sapwood, but without waney edge (Fig. 4B). Continuous repairs until 851 AD are indicated by several samples with wane. All construction timbers found *in situ* were felled within this time span of only eleven years. All other dendrochronological data derive from wooden objects in secondary position, mostly paddles. Further tree-ring analyses revealed the presence of paddles between the late 8th century and the second half of the 10th century. This proves the presence of mills in the immediate vicinity on the Alzette River throughout the Carolingian period.

Oberservations of tool marks, cross-sections and cutting give us some detailed information about the manufacturing process. The perforations on the wheel show, that aside from axes or adzes, at least one chisel (max. blade width 2.5 cm) and two augers (bores 2.3 cm and 2.5 cm) were used. The second wheel segment has not been finished and therefore doesn't have any perforations. Nevertheless, it reveals the state of a semi-finished product from a naturally bent half timber. Some of the fragmented pins and pegs could have served as cogs or staves in the lantern-wheel. Nine pegs show tool marks of a fine blade knife. The absence of traces of wear contradicts a function as parts of the transmission gear, a functional context with the mill building seems more likely. Eight objects are suggested to be wooden hammers or mallets. Systematically, one end shows distinct traces of wear due to the repetitive mechanical shock of hammering.

The two wheel segments found in Audun-le-Tiche are not the only examples known from archaeological excavations. Another example from the Central European Early Middle Ages was found in Dasing, Bavaria (southern Germany), and dated to 696/697 AD (Czycz, 1993, 2016). It was made of birch wood (*Betula sp.*) and is reconstructed with a wheel diameter of approx. 1.60 m and a total number of 24 paddles. All three wheels belong to the same basic wheel type consisting of several segments, into which the paddles are tapped with simple plug-in connections. However, they show different technical details:

The remnants of the Dasing wheel indicate a suspension with four strongly dimensioned spokes. For the Audun wheel, there is no evidence of the fastening to the wheel shaft. The reduced thickness on the overlapping sections suggests a joint on the thicker middle section. As there are no signs of this on the preserved segment, we suggest a system of joints with mortised arms on every second segment connecting the wheel with the axle tree. Thus, obtained reconstruction models show five spokes (Fig. 5C). The existence of wheel fastenings with an uneven number of spokes is unequivocally proven by the find of an early 11th century axle tree with seven spokes in Colomby (Bernard et al., 2016).

The relatively high number of paddle finds can be explained by two factors: on the one hand, a drive wheel is equipped with approximately 20 paddles. On the other hand, the paddles are to be seen as consumables of the milling mechanism, which had to be replaced regularly. With oak, sapwood is weaker and less durable than heartwood. The observation of sapwood on several oak paddles indicates they only were in use for a short time. All paddles were produced from oak and beech wood. Beech has a low durability and dimensional stability but both taxa are distinguished by good cleaving properties. This shows that the shaping and dimensional accuracy of the paddle was of secondary importance and was ranked behind the ease of processing the raw material.

The dimensions of paddles found at Audun-le-Tiche overall vary strongly, for whole pieces between 15 and 20 cm in width and from 16 to 34 cm in length. The thickness varies less, between 1.5 and

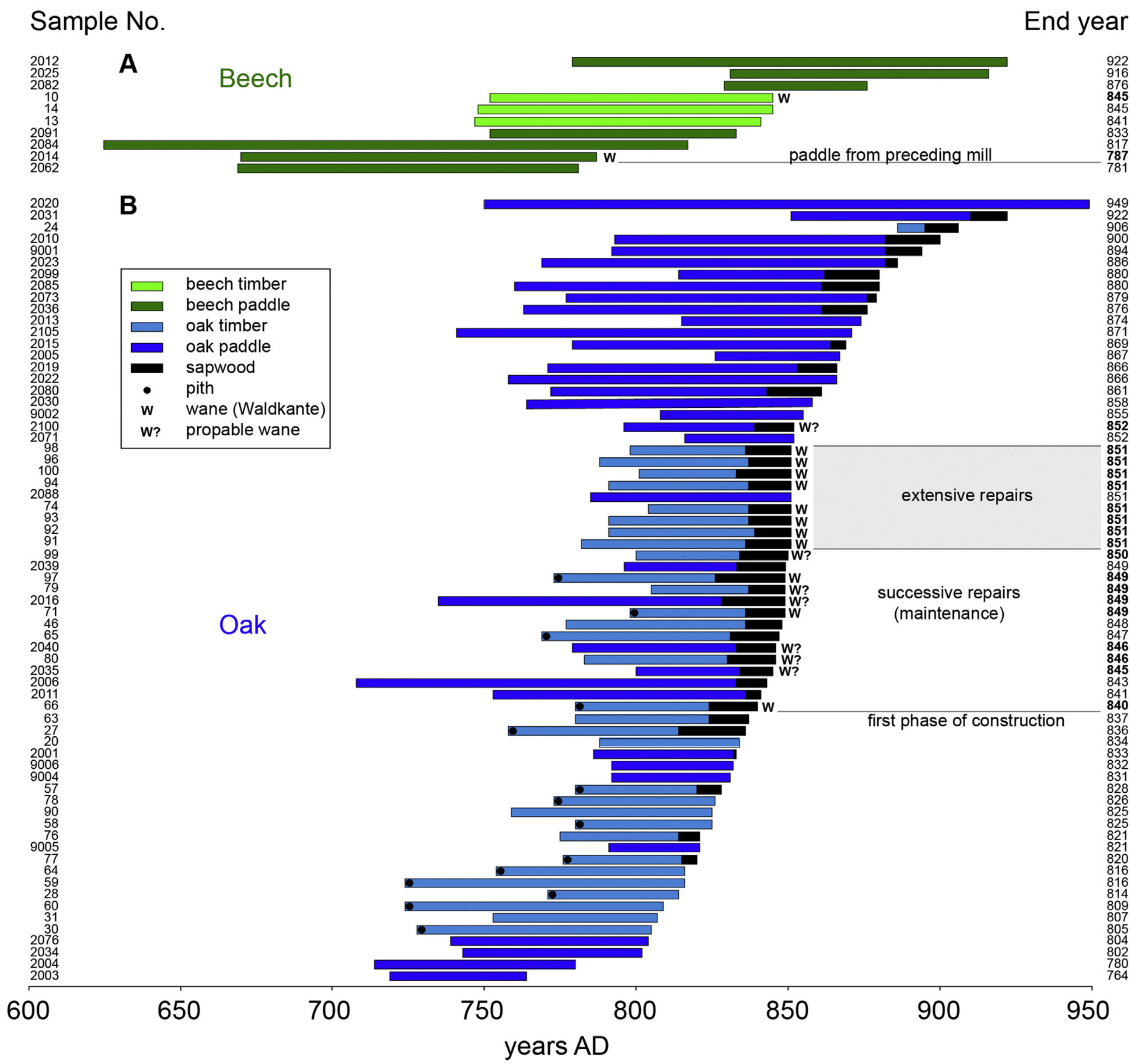

Fig. 4. **A** Bar graphs of dated beech paddles (dark green) and timber (light green). **B** Bar graphs of dated oak paddles (dark blue) and timber (light blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2 cm. These variables suggest that they originate from different wheels. Excavations have also revealed the presence of paddles upstream of the milling facility, proving the existence of other mills that operated along the Alzette in the same period. The similarity of the paddles indicates that all wheels belong to the same type as the ones discovered.

Due to the frequent occurrence of paddles around water mills on archaeological sites, they are important objects in terms of typo-chronological information. The hypothesis of beech being used for paddles in younger phases (Liebert, 2015) cannot be verified for Audun-le-Tiche, regarding the wide range of datings from c. 8th-10th (Fig. 4A).

The good data set though allows us to recognize a chronological succession of paddle shapes. One-piece paddles (Type 1) can be distinguished from those which consist of a paddle board and a separate shaft fixed with pins (Type 2). An overview of dated paddles shows a change in the paddle shape from type 1 to type 2 towards the end of the early Middle Ages. The earliest examples of composite paddles appear in the 10th century. In the course of the high middle ages, type 2 eventually prevails (Mille, 2016). This development wasn't abrupt, the diffusion of the dendrochronological dating shows a temporary co-existence of both paddle types. The orientation of the fibre on type 2 paddles is crosswise to the rotation axis. This allows the processing of much wider paddles than type 1, where the width is limited to the half stem diameter. This might be an argument for the transition.

Paddle type 1 occurs both in Merovingian and Carolingian periods. It can be regarded as symptomatic for central Europe during the Early Middle Ages. Within type 1, various details can be observed (Liebert, 2015), a further typological classification does not appear to be of any relevance in view of the diversity of details. However, one fundamental difference related to the technical design of the wheel construction is the position of the shaft. The wheel construction requires an alternation of paddles with

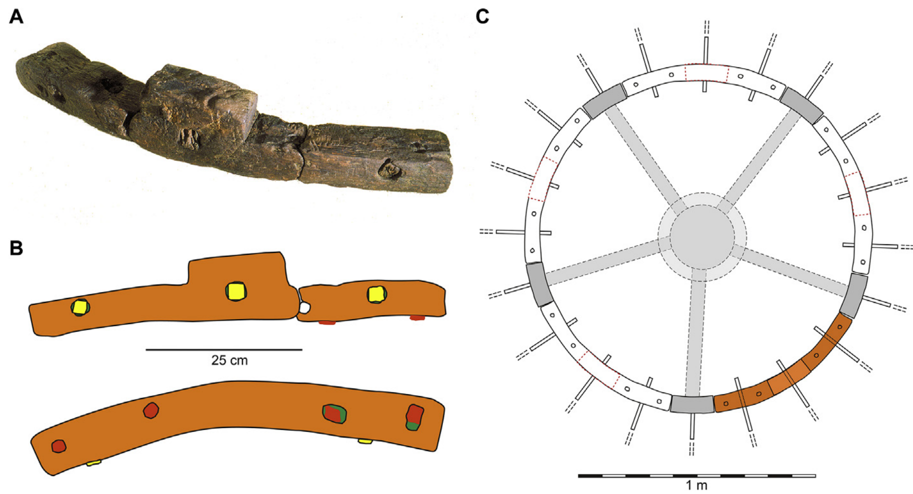

Fig. 5. **A** Photography of the wheel segment. **B** Technical drawing of the wheel segment according to P. Rohmer (Rohmer et al., 2016, 313, Fig. 13). **C** Reconstruction of the waterwheel. Orange segment according to P. Mille (Rohmer et al., 2016, 314, Fig. 15), axle tree diameter based on the find from Colomby, La Perruque (Bernard et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

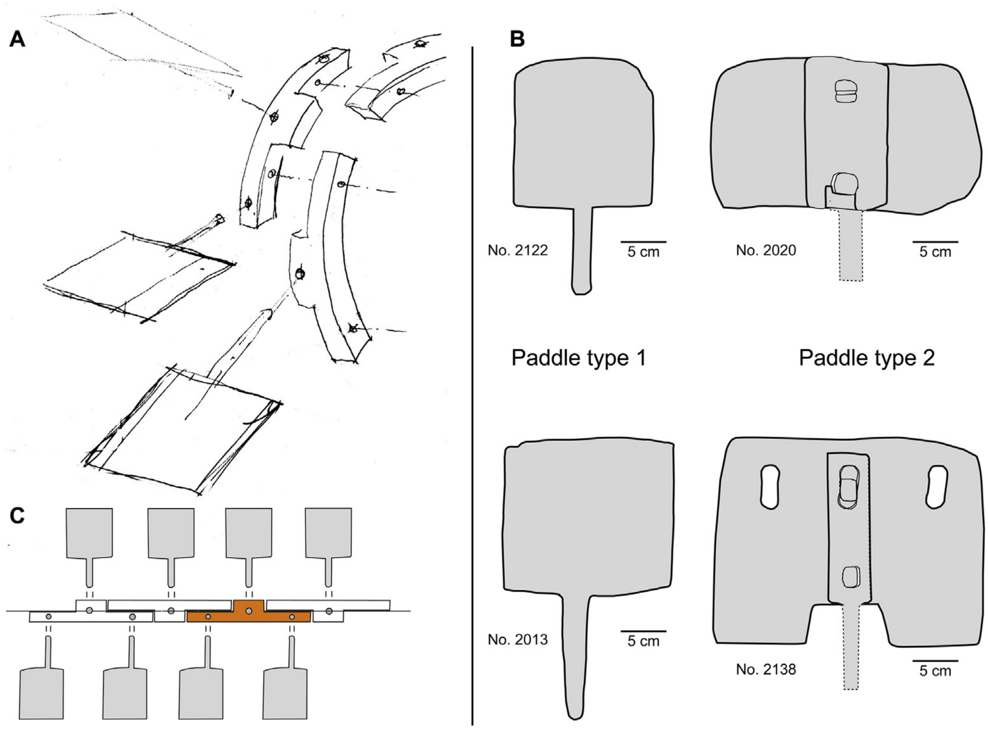

Fig. 6. **A** Assembly of the waterwheel, draft by J. Rebmann, Mannheim. **B** Paddle types found in Audun-le-Tiche. One-piece paddles with symmetric/asymmetric tenon (type 1) and composite paddles (type 2). **C** Alternation of symmetric and asymmetric paddles (schematic representation).

symmetrical and asymmetrical shafts (Fig. 6C). This explanation was only possible with the discovery of the wheel segment from Audun-le-Tiche (Rohmer, 1996). The find is all the more important since it is possible to infer the existence of corresponding wheel constructions even without the remains of the waterwheel itself. In Großhöbing (Liebert, 2015, type 5) a representative of this type was dendrochronologically dated to 720 ± 10 AD and thus occupies wheel constructions corresponding to Audun already for the Merovingian period.

A typological difference can also be observed in the composite paddles (Fig. 6B, type 2). While early representatives of this type have a simple rectangular paddle board (Kind, 2007; Rohmer et al., 2016), another variant shows a peg-sided trapezoidal recess (Viau, 2016). This form sustains into the High Middle Age, as confirmed by finds from the 12 t h century mills from Thervay (Rollier et al., 2016) and Großhöbing (Liebert, 2015, type 8). An undated paddle found in Audun-le-Tiche (No. 2138, Fig. 6B) shows the same recess, suggesting a possible successor mill in high medieval times. From a constructive point of view, these recesses are revealing because they reflect the outer width of the associated waterwheel.

4.1. Applications of water power

The general opinion in the field of history of technology constitutes a diversification of mills in high or late medieval times (Bulach, 2006; Clemens and Matheus, 2001). First iconographical and written sources for other purposes than milling grain appear in high medieval times (Lucas, 2005). In the further course of the Middle Ages, hammers or mallets, driven by a camshaft were used for various purposes e.g. fulling woollen textiles, the pressing of the can in tannery processes, pounding ore in metallurgy and crushing seeds for oil production (Lucas, 2005). In later periods, up to the 20th century, more and more production fields intensified the use of water powered hammers.

For Audun-le-Tiche, where flax (*Linum usitatissimum*) and hemp (*Cannabis sativa)* were found in two separate basins (Rohmer et al., 2016), the existence of wooden mallets (Rohmer, 1996) gives a strong argument for the use of milling energy for the purpose of textile production already in early medieval times.

Considering other archaeologically excavated water mills, there is some evidence for a multi-purpose use. Archaeobotanical analyses in Dasing already explained a significant amount of flax with a retting pond around the mill structure (Küster, 1993). A necessary precondition for all these applications of water power is the conversion from rotatory to reciprocating motion, i.e. an up-and-down motion through the use of a cam drive equipped with cams or lifters. Two large wooden pegs with characteristic traces of wear from the early medieval phases 9 and 10 in Großhöbing are interpreted as lifters of a stamp mill (Liebert, 2015, 205). The evidence of a roof over a length of 6.0 m for these construction phases supports this interpretation.

4.2. Early medieval invention

All documented water mills from the early medieval period in Central Europe are vertical undershot start-and-float wheels.

Other regions show a prevalence of horizontal mills, for example Ireland (Rynne, 2015). In contrast to early medieval mills, all reconstructable examples from the roman period in Central Europe feature breastshot (Schuchany and Winet, 2016) or low-breastshot (Blanc and Castella, 2016) bucket wheels. Hence, roman vertical waterwheels show a distinctively different technical design than the wheels known from early medieval times. The different form of the wheel with rims requires other types of paddles or floats (e.g. Schuchany and Winet, 2016). The abovementioned paddle forms are known from Merovingian times onwards (Liebert, 2015). Therefore, we can expect, that this form of paddles is an independent invention of the early medieval period.

4.3. Lifespan of mill sites

The mill structure at Audun-le-Tiche shows sucessive repairs over it's short lifespan of eleven years. By contrast, the wide spreading dendrochronological data from paddles prove the existence of milling facilities for at least 180 years between 787 and 959 AD. Several other documented cases suggest that a mill site was used much longer than the individual mill building. For example, alongside the early medieval mills excavated in Großhöbing (D), late-antique structures of the fourth century were found (Liebert, 2015). At the Swiss site of Avenches – En Chaplix, less than 400 m from the roman mill structures, there is evidence for a medieval water mill, dating to the 8th – 10th century (Blanc and Castella, 2016).

There also are several examples of a local consistency through the early middle ages and into the high medieval period. In Marillais (F) remnants of water mills dating from the 7th - 10th century were found (Viau, 2016). In Thervay (F) remains of a high-medieval mill of the 12th century are located in the immediate vicinity of a Carolingian mill of the 9th/10th century (Rollier et al., 2016). The site of Großhöbing also shows wooden remains of mills from the 12th century (Liebert, 2015).

5. Conclusions

Water driven mills played a great socio-economic role in the agriculturally based society of the Early Middle Ages. Various legal codes from Merovinigan times distinctly mention water mills. From the Carolingian period on, a shift in the legal ownership of water-mills into the hand of religious institutions, due to donations, can be observed all over Central Europe (Squatriti, 1998). Alongside this “clericalisation” (Squatriti, 1998, 144), however, secular *potentates* also occur as owners and portion-holders of mills.

The Carolingian water mill from Audun-le-Tiche represents the common type of early medieval milling facility in the Frankish heartland. It shows a small working platform for the mill building and a drive system consisting of an undershot start-and-float wheel with paddles in single mortise and tenon joints. The comparison with other water mills points to an independent development of this uniform design for the Early Middle Ages. It is noticeable, that most archaeological evidence for early medieval water mills derives from the Carolingian period. Rare examples from Merovingian times from Dasing, Großhöbing and Marillais though display the same constructive elements (Czycz, 1998; Liebert, 2015; Viau, 2016).

The rare preservation and the extensive temporal and spatial distribution of early medieval mill sites complicate the comparison of technological aspects. On one hand, individual structural solutions adapted to the local topography, and on the other, the varying states of research in different regions of Europe make it impossible to create a viable model for the development and spreading history of water-mill technology in the early medieval period.

To the present state of the research, the water milling technique in the early Middle Ages on the European mainland north of the Alps seems to be limited to the western Central European regions (Fig. 1A). A spread to the east takes place in the High Middle Ages. In many regions (such as Slovakia, the Czech Republic and Silesia in southern Poland) the earliest mentions of mills occur in the 12th century. Up to the High Middle Ages the technique of water mills has spread throughout Europe, as evidenced by the condensation of historical sources in the 13th century (Jeute, 2015; Galusová, 2015).

Author contributions

B.M. designed and coordinated the study with input from W.T. U·B. P.R. and UE.S. P.R. did the archaeological fieldwork. B.M. and W.T. analysed the material. All authors contributed to writing the paper.

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