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ORCID®
Alexander Reis, https://orcid.org/0000-0003-3805-1121
Sebastian Vehlken https://orcid.org/0009-0006-5344-7318
Klaus Eickel https://orcid.org/0000-0002-5700-2029
Pia Götz https://orcid.org/0009-0007-6134-6581

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Magnetic resonance techniques in cultural heritage research

Magnetic resonance imaging (MRI) techniques are perhaps best known for their role in medical imaging. However, the transdisciplinary conference “MRI for Cultural Heritage Objects” discussed MRI’s great potential also for examining the so-called ‘Bremen Cog’ and similar cultural heritage objects made of organic material. Jointly organized by Fraunhofer Institute for Digital Medicine MEVIS (MEVIS), the Center for Materials and Processes at the University of Bremen (MAPEX) and the German Maritime Museum (DSM), and supported by the U Bremen Research Alliance, the conference assembled researchers from a variety of disciplines on December 7-8, 2023 on the premises of Bremerhaven University of Applied Sciences. The aim of the conference was to exchange the latest findings on the technical applicability of magnetic resonance methods to various biomaterials from the historical-archaeological field as well as to the analysis of conservation substances. Such transdisciplinary approaches offer the opportunity to further explore the spectrum of technical methods by applying them to ‘unconventional objects for analysis, and to create novel relations to cultural-historical research questions.

Cultural heritage institutions such as the DSM are interested in methods for the “in-depth exploration” of objects. Since MRI does not use ionizing radiation and does not require special sample preparation, it is non-destructive in its application to (fragile) cultural heritage objects. Such non-invasive methods allow detailed structural analyses of sensitive objects – especially waterlogged archaeological wood. In this way, material changes in condition can also be effectively monitored. At the conference, this was summed up in a tongue-in-cheek statement: “Whilst in cultural heritage research people love artifacts, in medical imaging they hate them!”

However, the “operational images” (Krämer 2009; Parikka 2023) produced by MRI and CT (computer tomography) not only provide additional data on objects, but can also be used as digital media formats for museum presentations, making objects from the past even more tangible and easier to experience. In this way, MRI and CT help to “understand the entire object,” as Dirk Leder (NLD Lower Saxony State Office for the Preservation of Monuments) put it in his presentation. The main objective of the conference was to determine the current state of research on the use of MRI technologies as an approach for the exploration and conservation of historical and archaeological objects, which can function in a complementary way to already increasingly established procedures such as CT methods. Based on some preliminary work on this topic (Kanazawa 2017; Mori et al. 2021; Longo et al. 2023), the participants discussed the epistemic and application-oriented possibilities of MRI methods in the perspective of follow-up research to pilot and intensify transdisciplinary cooperation between cultural heritage institutions and scientific research institutions in this field.

Archaeological wood in Europe is generally very well preserved in a waterlogged, oxygen-free environment. In this environment, the cells of the wood are filled with water so that they retain their shape and are only slowly destroyed by anaerobic bacteria. When waterlogged wood dries out after excavation, the cells usually collapse due to evaporation of the water. The contraction forces during evaporation then deform the finds in an uncontrolled manner. They shrink and crack as important structures are broken down. Degradation occurs from the outside to the inside, so that different degrees of degradation can occur: from severely degraded edges and transition areas to intact cores, with the severely degraded outer areas being particularly vulnerable to collapse. Prior stabilization is necessary for the presentation of the objects in the museum. For this purpose, special procedures are used to impregnate the objects with preservatives before final drying. Established methods include preservation with the melamine resin Kauramin 800 (BASF) or impregnation with polyethylene glycol (PEG) followed by freeze-drying. The aim of conservation thus is to transform the wood into a stable, dry state while changing it as little as possible so that it is permanently preserved and available for research and exhibition. The success of the conservation is determined in the course of this by various measurement parameters – such as shrinkage and anti-shrink efficiency (ASE).

Ingrid Stelzner and Markus Wittköpper (LEIZA Leibniz Centre for Archaeology in Mainz) presented the reference collection of conserved archaeological wood samples (Wittköpper et al. 2016), which was established at LEIZA and is available online at www.rgzm.de/kur. This collection includes samples preserved using different methods such as alcohol-ether resin, melamine formaldehyde (Kauramin 800), lactitol/trehalose, polyethylene glycol impregnation with different molecular sizes and subsequent freeze-drying, sucrose and silicone oil. The volume changes of the samples were recorded using 3D structured-light scans before and after preservation. The documentation of the internal structure of the wood by CT revealed collapse, splitting and cracks as damage patterns, which can therefore be taken into account when assessing the conservation methods and provide information on improvements to the methods (Fig. 1-3; Stelzner et al. 2024). Investigations on the initial state of waterlogged wood using MRI clearly showed the improvements in the visibility of the inner structure compared to other methods (Stelzner and a. 2022). It turns out that some preservation methods perform better than others in terms of volume stabilization. The best results are achieved in particular by preservation with polyethylene glycol and freeze-drying, Kauramin 800 or the alcohol-ether-resin-method.

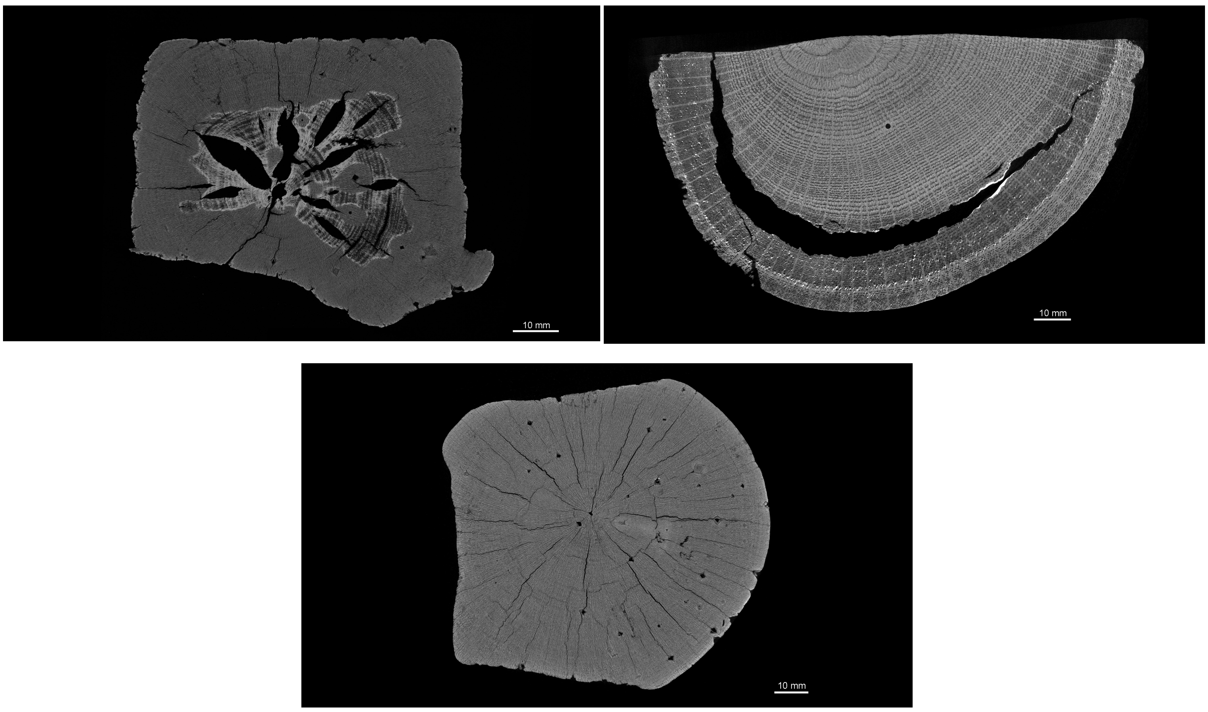

Fig. 1-3. left to right to bottom: Damage patterns collapse, fissures, cracks in CT scan (Stelzner et al. 2024).

Dirk Leder and Utz Böhner (NLD), Ekkehard Küstermann (University of Bremen), Mathias Günther (MEVIS) and Susanne Boretius (DPZ German Primate Center in Göttingen) contributed their experience with MRI scans of waterlogged and dry-preserved wooden artefacts of the Palaeolithic finds from

Schöningen (Fig. 4). Schöningen is located in the Harz foreland, where lignite was mined until 2016. Since the end of open-cast mining, a research excavation has been carried out there. Thousands of stone artifacts, hundreds of wooden fragments, over eighty bone tools and of prey remains from Stone Age hunter-gatherers have been discovered so far. The *Schöningen 13 II-4* site is a lakeshore where a large number of wooden artifacts were left behind around 300,000 years ago. The objects include at least ten spears, seven throwing sticks, more than 30 small tools and more than 100 pieces of work waste, which have been excellently preserved under anaerobic conditions and with the addition of calcareous water (Leder et al. 2024).

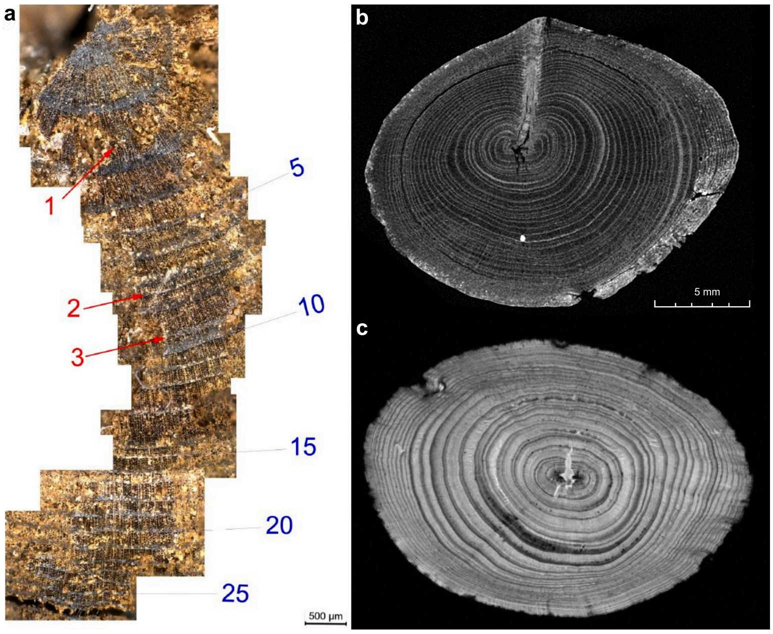

Fig. 4. Testing various examination methods on the wood artifacts. They allow insights into the growth conditions of the raw material. These are stored in the respective growth rings. a) Traditional invasive thin section or incision (M. Sietz, NLD). b) non-destructive µCT scan (Waygate Technologies, NLD). c) non-destructive MRI scan (S. Boretius, DPZ); Graphics: D. Leder, NLD.

Fig. 5. A series of cross-sections from MRI scans of this throwing stick sharpened on both sides illustrates not only the growth rings but also the processing of the artifact, which can be seen, for example, in angular cross-sections. Furthermore, so-called compression wood is noticeable, which leads to asymmetrical growth and confirms that this hunting tool was made from a branch (Cross sections: Waygate Technologies, NLD; photo Throwing stick: V. Minkus, NLD; Graphics: A. Milks/D. Leder, NLD).

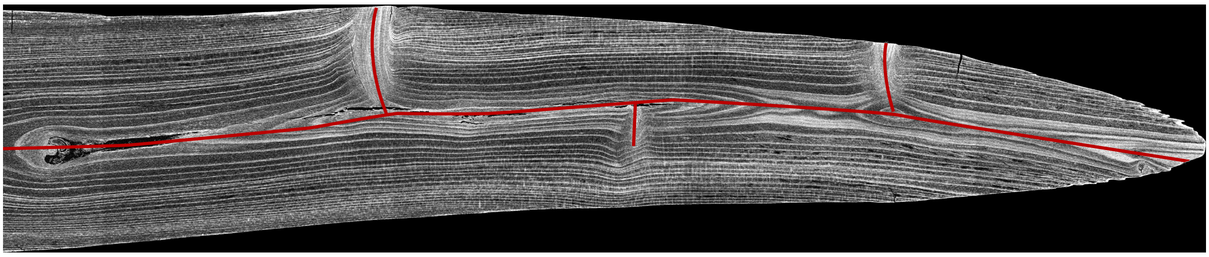

Fig. 6. The longitudinal MRI scan through the wood shows the pith in the center (horizontal line) and the direction of growth of the branches (red vertical lines). The direction of growth influences the processing of the wood (Waygate Technologies; Graphics: D. Leder, NLD)

Only non-destructive methods are used to examine the wood technology, such as 3D microscopy to detect traces of processing in the detailed area of the surfaces. In the case of waterlogged wood, high-resolution MRI scans are particularly good at visualizing the growth rings and growth conditions of the spruce and pine used to make the spears (Fig. 5-6). High-resolution µCT-scans can also be used on surfaces and in cross-sections of preserved wood (Milks et al. 2023).

Beyond the usual medical field of application, which only covers a subset of possible MRI device concepts, recent technical improvements resulted in novel designs for specific applications in other fields. For instance, medium-sized and small, often portable magnetic resonance (MR) systems are nowadays used in industrial environments such as the development and production of polymers, porous materials and foodstuffs (Fig. 7-8). Philipp Mörchel's presentation of research at Fraunhofer IIS in Würzburg was an exemplarily showcase of these broadening application spectra. At Fraunhofer IIS, materials are analyzed and characterized by MR methods with regard to molecular dynamic processes (Haddad et al. 2021). This technique also has great potential for the analysis of cultural artifacts, as MR effects allow conclusions to be drawn about the proportion of bound and free water in wood samples without the need for advanced imaging techniques.

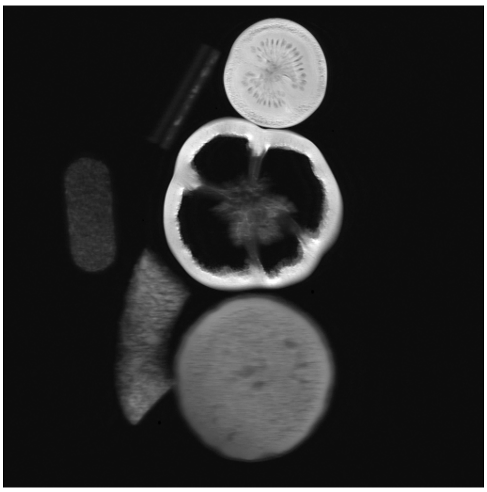

Fig. 7-8. left to right: Photography and MRI of various food. The signal intensity, which makes up the image contrast, is mainly dependent on the water content and the consistency - i.e. how firmly the water is bound - of the pixel in the object being examined (P. Mörchel, Fraunhofer IIS).

At Forschungszentrum Jülich, Johannes Kochs, Marco Meixner and Carel Windt have developed a mobile device for low-field MRI imaging of plants. The device is robust and allows the outdoor use in various environments. The magnetic field is generated by an open permanent magnet. This magnet is large enough to enclose stems of living plants which can be placed in its middle without damaging them. One disadvantage of the open C-shaped magnet design, however, is the limited homogeneity. This disadvantage was compensated for by the use of bespoke so-called MRI sequences. These are kind of programs how the MRI systems generates images. The experts from Forschungszentrum Jülich, for example, used a multi-spin echo sequences with short echo times and a large number of echoes. In combination with specifically developed low-impedance gradient coils and compact amplifiers the mobile and open MRI system could achieve high sub-millimeter spatial resolution. The mobility and functionality of the device (weight 45 kg) was tested during measurements on the trunk of an apple tree in an orchard at an ambient temperature of 7°C and on a beech tree in a greenhouse during leaf emergence in spring (Fig. 9-12; Windt et al. 2021; Meixner et al. 2021; Herold et al. 2006).

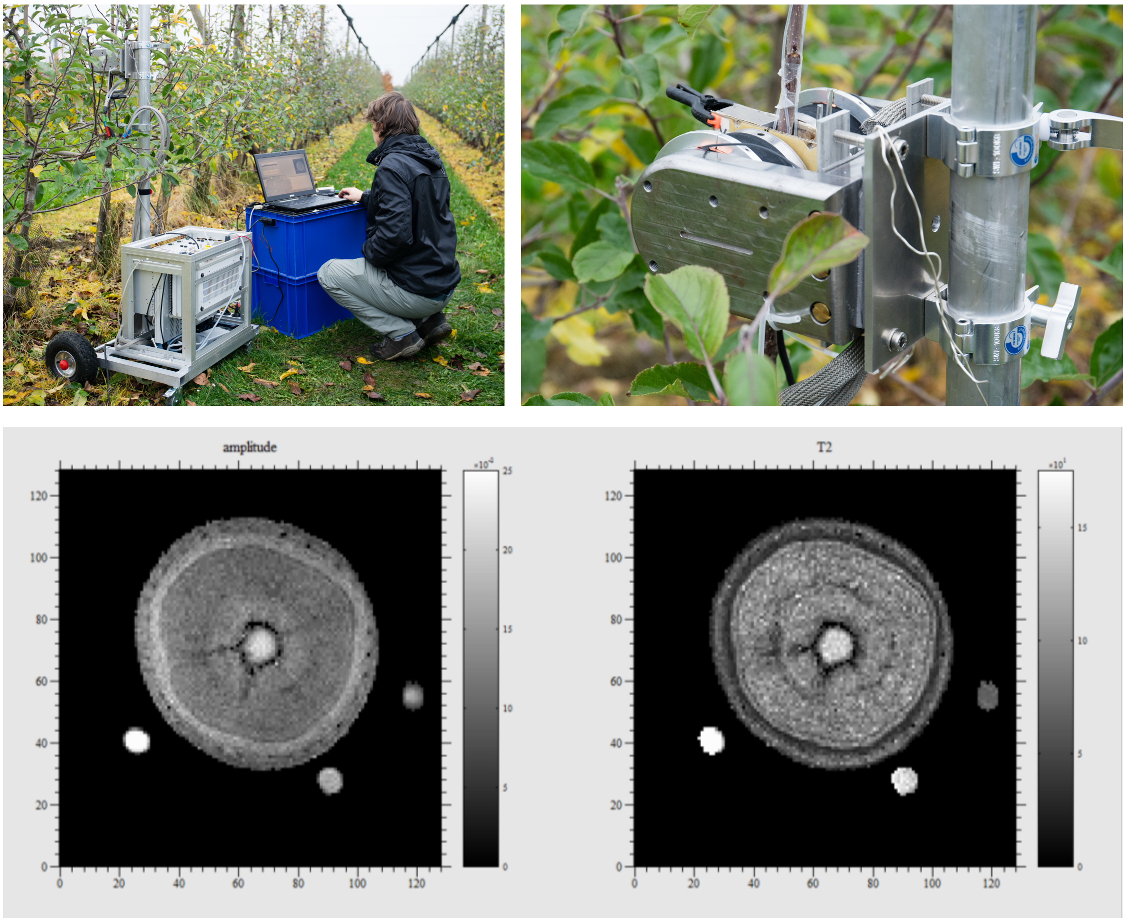

Fig. 9-12. Test measurements on the trunk of an apple tree in an orchard. Fig. 11 and 12 (bottom) show water content (amplitude) and mobility of water (T2 relaxation time) in the trunk of the apple tree (C. Windt/M. Meixner, Forschungszentrum Jülich).

Due to Bremen's maritime history, timber finds are frequently made during archaeological investigations accompanying construction work in the city (Bischop 2023). However, it was not until the 20th century that efforts were made to preserve these finds, as Dieter Bischop (Bremen State Archaeology Department) showed. In 1858, during the construction of the commercial port of Bremerhaven, a large shipwreck was found that was similarly well-preserved to the Bremen Cog: it was a coastal sailing ship – initially interpreted as a Roman legionary ship – that had been filled with stones and deliberately sunk in a tidal bend in 1673. Today, however, apart from the ship's documentation in contemporary drawings, nothing physical remains of it after the site was cleared for firewood.

In Bremen's old town smaller and larger wooden finds have come to light on various occasions, such as parts of timber-framed buildings or Deuchel pipes, i.e. water pipes made from drilled-out tree trunks (Fig. 13). Among the finds of watercraft, Weser barges dating back to the Carolingian period and dugout canoes, which could also have been components of ferries, are particularly noteworthy (Fig. 14). Wooden substructures of early modern riverbank quays, for example the ones dating from 1532 which were found during the excavation at the Radio Bremen construction site (Fig. 15), or even parts of wooden bank reinforcements, which may also include reused parts of ships, are very frequently preserved in the riverbank area. Oak beams from half-timbered buildings date back to the High Middle Ages, and among the finds of goods from medieval household, turned and coopered vessels are particularly well represented (Fig. 16).

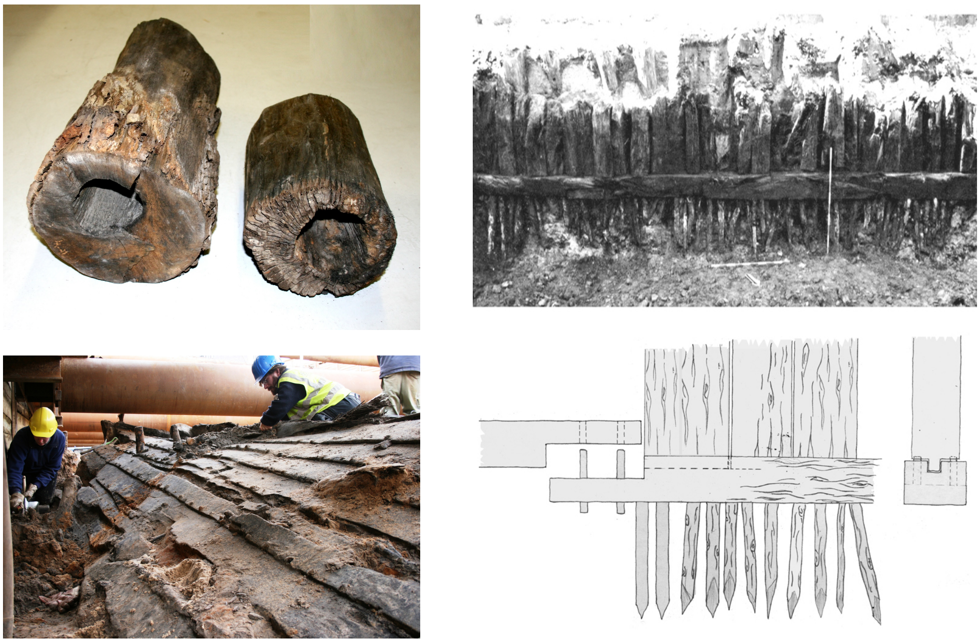

Fig. 13-15. top left to bottom left to right: Deuchel pipes. Quay from 1532. Embankment used for bank reinforcement (Landesarchäologie Bremen/D. Bischop, Landesarchäologie Bremen).

There are also remains of weapons, such as longbows (Fig. 17) or so-called kidney daggers. A frame of a hand mirror from the later 13th century was found in a layer of a fill in the Böttcherstraße. Turned furniture components, a pocket sundial (Fig. 18), an animal figurine, a comb and parts of wooden soles, so-called “Trippen”, come from a backfill of the city ditch from around 1600. Another outstanding find is a fragment of a diptych with remains of a painting, which was discovered in a well during the excavation in the area of the building site of the Atlantic Grand Hotel on Bredenplatz. The well is dendro-dated to around 1220 (Fig. 19). In 2007 and 2023 in particular, under the supervision of Bremen State Archaeology, features and finds were documented and recovered at Teerhof that prove the area’s usage as a building site for ships in the late Middle Ages (Zwick/Bischop 2007). Furthermore, structures were documented that can be interpreted as parts of slipways. Among the objects are shipwrights’ tools and caulking clamps, which were used in almost identical form on the Bremen Cog.

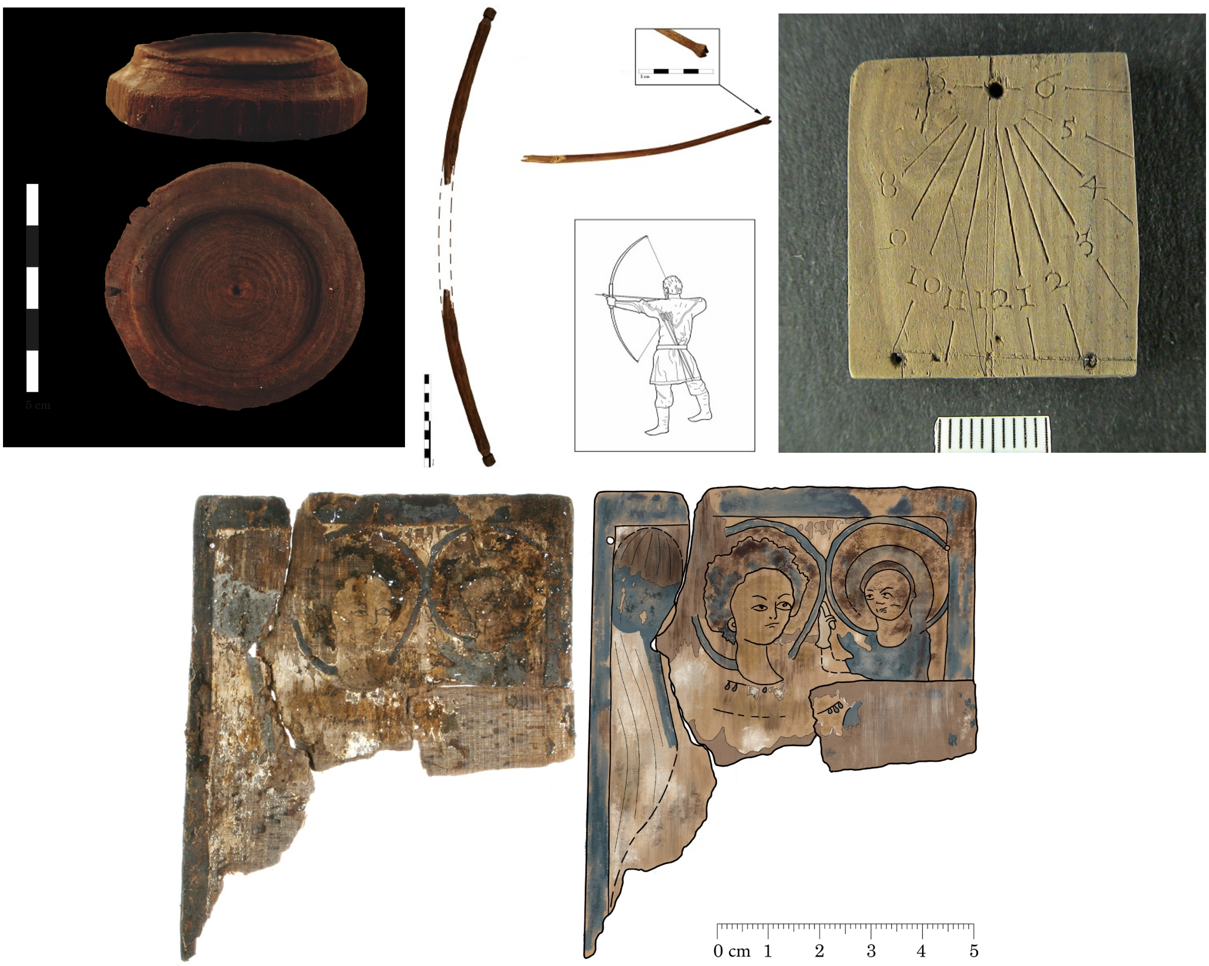

Fig. 16-19. top left to right to bottom: Turned vessel lid. Fragments of longbows. Early modern pocket sundial. (bottom) Fragments of a high medieval diptych painted with a Marian scene (Landesarchäologie Bremen (Fig. 16); J. Schmidt, Landesarchäologie Bremen (Fig. 17+19); C. C. von Fick (Fig. 18), Landesarchäologie Bremen).

Not surprisingly, the conference was also strongly related to the Bremen Cog at the DSM, not least because the history of this ship find can be perceived as a pioneering case for testing museum conservation techniques for large wooden objects, especially with regard to the use of PEG for the conservation of archaeological waterlogged wood. Over the last two decades, the early development and scientific evaluation of such preservation methods has been followed by novel computer-supported approaches in the field of preventive conservation of large archaeological objects. For example, Amandine Colson (DENKMAL3D, Vechta) who dedicated her PhD project to such methods of preventive conservation, presented the relevance of condition monitoring for the prevention of damage – especially in the case of deformation and geometric changes (Colson 2023). Preventive measures are particularly important for large objects, where high costs can be incurred if appropriate action is not taken in time. Although there is no shortage of examples and initiatives from other European museums, research remains to be carried out into which standardized procedures, devices and equipment enable this monitoring – such as the moisture content or the load distribution and vibration of the wood - in a timely and effective manner. According to Colson, museum professionals should always search for inspiration aside from well-trodden paths and try to adapt approaches and methods that have been tried and tested elsewhere to the specifics of museum objects. With this mindset, 2017 saw the founding of the European working group 'Monitoring of Preserved Ships' with 17 participating institutions from nine countries. An excellent example of current research in this field is the project on the optimized conservation of archaeological waterlogged wood with the help of 3D monitoring (OptiKons), led by Colson. Its aim is to use optical 3D measurement technology to detect the decisive moment when archaeological wet wood deforms while still in the conservation basin, in order to enable early and appropriate conservation measures.

The Institute for Applied Photogrammetry and Geoinformatics at the Jade University of Applied Sciences Wilhelmshaven/Oldenburg/Elsfleth developed a measurement concept in a research collaboration with the DSM to determine the geometric deformations of the Bremen Cog while maintaining the museum's operations over the long term. This transdisciplinary concept, developed from measurement technology and restoration, has been implemented since 2020 using photogrammetric measurement technology in combination with a basic network and suitable analysis methods have been developed (Fig. 20; Colson et al. 2019, Hastedt et al. 2019, Schmik et al. 2019).

Despite advanced digital analysis, microscopic and micromorphological examinations and chemical characterization of wood remain crucial for determining the type of wood and its degree of decomposition, as Jana Gelbrich (IWT Leibniz Institute for Materials Engineering) in Bremen pointed out. Starting with the question of which aspects can be determined to provide a reliable basis for decisions regarding the conservation of archaeological waterlogged wood

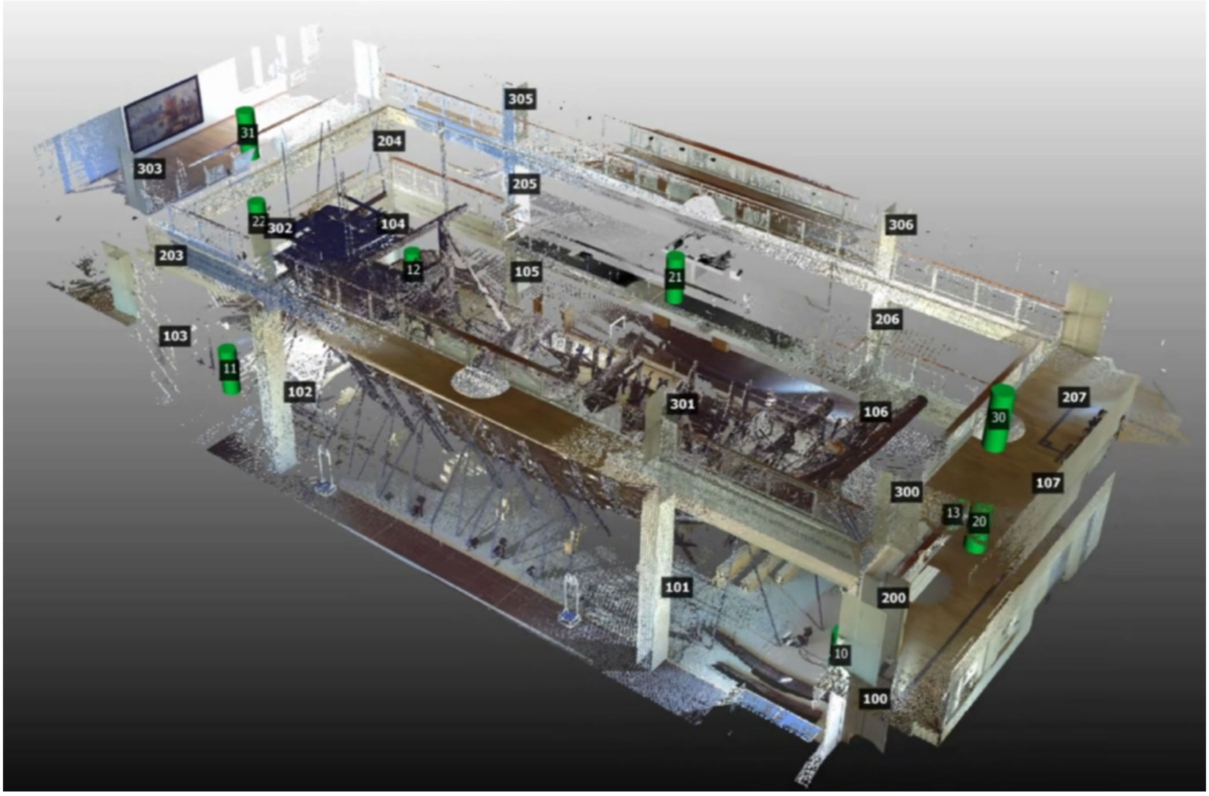

Fig. 20. Measurement setup for the network measurement on the Bremen Cog (IAPG Jade Hochschule Oldenburg).

finds, Gelbrich explained which methods are particularly suitable for this purpose. She thereby focused on species identification, moisture profiles, and micromorphological and chemical characterization of wood. With regard to digital methods, the talk comparatively evaluated CT, MR, and FTIR (Fourier transform infrared spectrometer) approaches, using – among other things – incidental finds from the Bremen Cog, for example a rod network (Fig. 21; Gelbrich et al. 2023). The challenge in all of these investigations is to ensure that the metadata resulting from the analyses are always created in an interdisciplinary and multidisciplinary manner, so that they can be easily used for both historical and material sciences (Fig. 22-24).

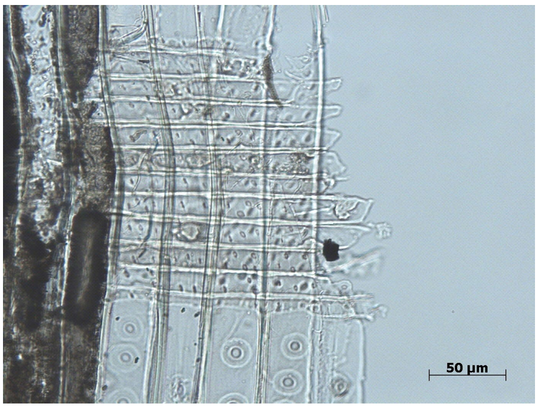

Fig. 21. Small find from the Bremen Cog (?). Typical cell wall perforations in the intersection field of wood ray and fiber cells (tracheids) of a spruce (Picea abies) (J. Gelbrich, IWT Leibniz-Institute for Materials Engineering).

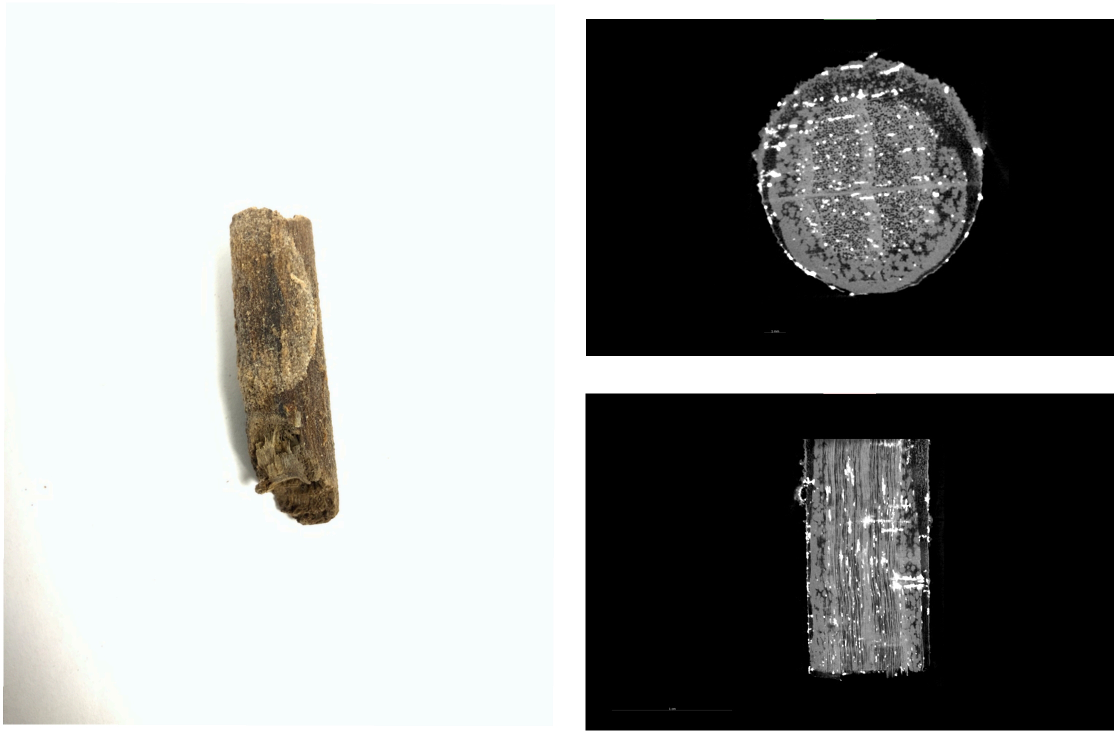

Fig. 22-24. By-find of the Bremen Cog (?). Hardwood, treated with a stabilizing agent. left: Photograph. upper right: µCT shows round cross-section due to processing. Outer areas with more decomposed cell structures; mineral infiltrations (light areas) along the wood rays in the CT scan of the cross section (Fig. 23) and longitudinal section (Fig. 24, lower right) (P. Götz, MAPEX Center for Materials and Processes, University Bremen).

In a lively exchange with engineering and technical science perspectives contributed by the co-organizers from MEVIS and MAPEX as well as researchers from the MRI community, future-oriented potentials from the extensive toolbox of imaging and material analysis were discussed. The presentation by Wolf-Achim Kahl (MAPEX) and Ekkehard Küstermann (University of Bremen) explicitly brought together a spectrum of possible complementary or combined applications of CT and MR methods for the visualization of complex structures of cultural heritage objects (Fig. 25-26; Häuser et al. 2022; Kahl et al. 2020; Kahl/ Ramminger 2012). The speakers exemplarily emphasized the knowledge potential of three-dimensional virtual objects generated from density data. Küstermann also suggested microbiological references in addition to the aforementioned structural and chemical aspects. Both speakers also pleaded for a 'dynamic' interpretation of transdisciplinarity: Whilst calls for 'standard solutions', i.e. the development of universal easy-to-use MR applications for the cultural heritage sector, were understandable, they challenged this sort of 'customer understanding' of uni-directed know-how import from MINT to the Humanities. Rather, transdisciplinarity should be understood as a continuous dialogue between academic disciplines which unfolds in a reciprocal way along and around interesting (and also problematic) 'cases', i.e. cultural heritage objects.

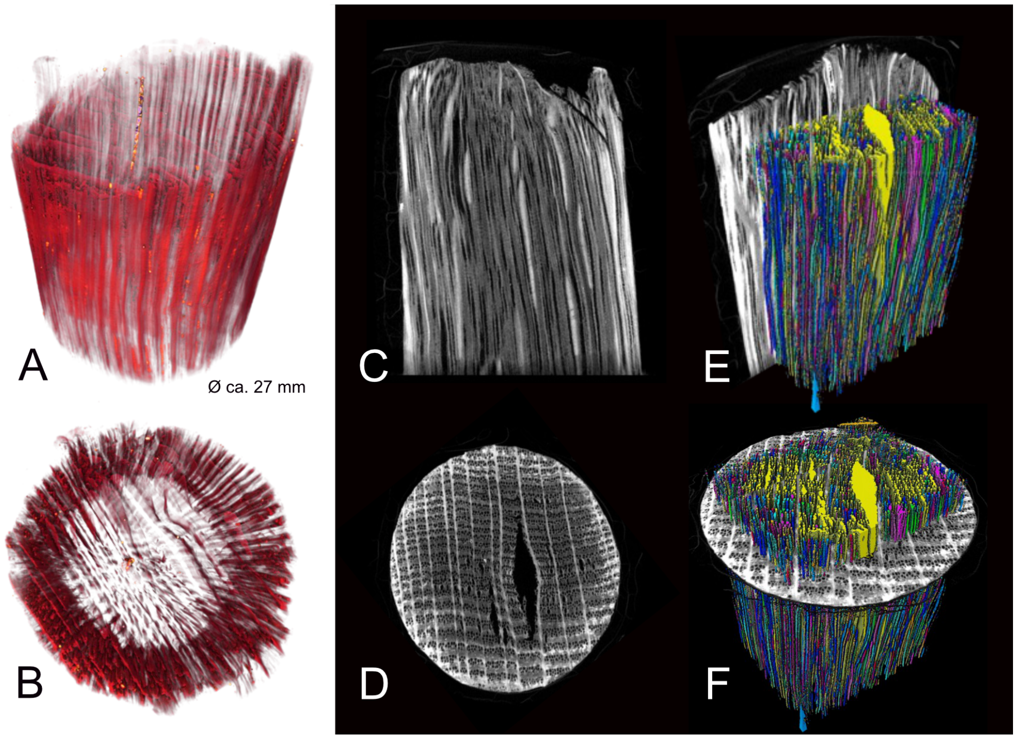

Fig. 25. Bremen Cog. Visualization and image analysis of a wooden nail using X-ray microtomography (CT). A and B: Semi-transparent representation of the effectiveness of the polyethylene glycol impregnation in the wood body; C and D: Gray scale representation of the different densities of differently impregnated wood areas (light and dark gray) and of air (black); E and F: Highlighting of the pore structure of the wood by individual coloring of separated cavities (W.-A. Kahl, MAPEX Center for Materials and Processes, University of Bremen).

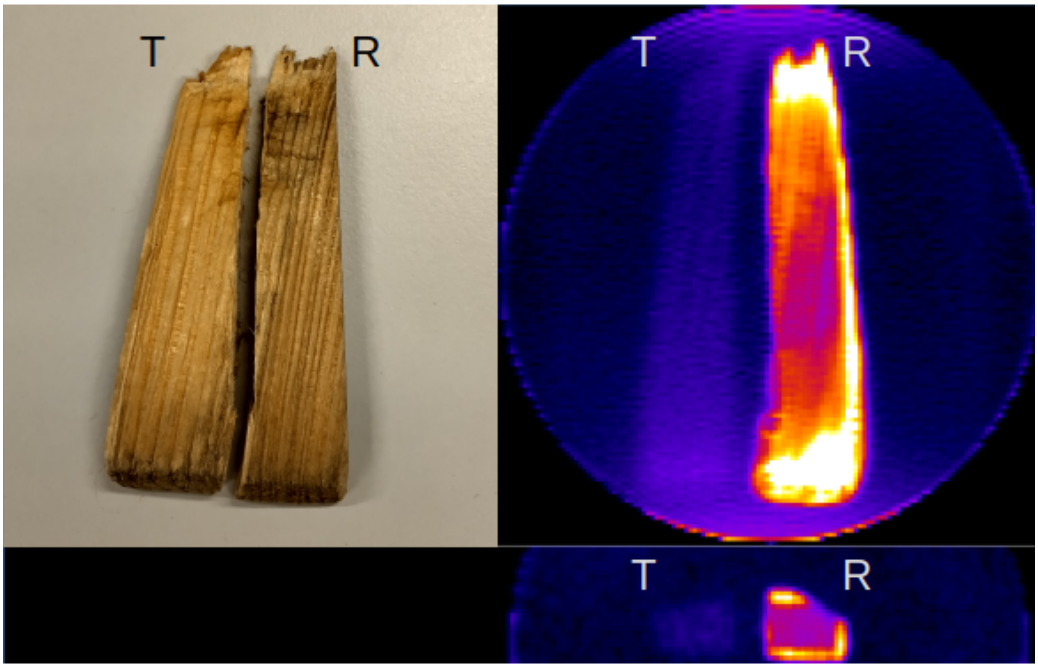

Fig. 26. Comparison of a dry (T) and a rehydrated (R) piece of wood. Left: The left half (T) of the piece of wood is dry, while the right half has been rehydrated in tap water (R). Right: In MR images (ZTE method, 3D data set with isotropic resolution of 0.78 mm), the dry wood (T) is barely visible, while in the rehydrated part (R) the locally different water absorption is clearly visible. False color representation to visualize the large signal differences (E. Küstermann, University of Bremen, Working group In-vivo-MR).

This bald statement once again reformulated the main concern of the entire conference. The initiators of conference thus consider it very positive that already in the concluding discussion roundtable, the transdisciplinary discussion started being translated into specific follow-up projects. For instance, these revolve around the question as to what extent elastographic MRI measurement methods could be applied to archaeological timbers, and to what potential magnetic resonance methods – even aside from a focus on computer-based visualization techniques – hold for timbers that have already been preserved. Piloting studies that are already being carried out on finds from both the Bremen Cog and on objects from excavations of the Lower Saxony State Archaeology Department explore the applicability of rehydration for preserved wood, and whether MR contrast mechanisms can be effective. Last but not least, the interest expressed after the conference by other international cooperation partners from the DSM's network of maritime museums and the field of maritime archaeology to add MR technologies to their toolbox in order to gain an even better understanding of the “entire object” speaks for a transdisciplinary verve that came to stay.

Bibliography

Bischop 2023
D. Bischop, Bauen über den Fluss – Hochmittelalterliche Bauhölzer unter einer Steinkammer im Bremer Martiniviertel. In: D. Rieger (Hrsg.), Vom Ende her denken. Beiträge zur Archäologie im Hanseraum und darüber hinaus. Festschrift Manfred Schneider (Rahden/Westf. 2023) 23–37.

Colson 2023
A. Colson, Spatial monitoring of the Bremen Cog - Long-term preservation of archaeological wooden ships in museums. Schriften aus der Fakultät Geistes- und Kulturwissenschaften der Otto-Friedrich-Universität Bamberg (Bamberg 2023).

Gelbrich et al. 2012
J. Gelbrich/C. Mai/H. Militz, Evaluation of bacterial wood degradation by Fourier-Transform-Infrared (FTIR) measurements, Journal of Cultural Heritage 13, 2012, 135–138.

Gelbrich et al. 2008
J. Gelbrich/C. Mai/H. Militz, Chemical changes in wood degraded by bacteria, International Biodeterioration and Biodegradation 61 (1), 24–32.

Ghavidel et al. 2022
A. Ghavidel/Amin, J./Miklós, B./Gelbrich, J./Morell, J. J./Sandu, I./Hosseinpourpia, R., Degradation assessment of archaeological oak (Quercus spp.) bu-

ried under oxygen.limited condition, Holzforschung 2022 (published online January 4, 2023). https://doi.org/10.1515/hf-2022-0168

Ghavidel et al. 2021
A. Ghavidel/R. Hosseinpourpia/J. Gelbrich/M. Bak/I. Sandu, Microstructural and Chemical Characteristics of Archaeological White Elm (Ulmus laevis P.) and Poplar (Populus spp.). Applied Sciences 2021, 11, 10271. https://doi.org/10.3390/app112110271

Ghavidel et al. 2020
A. Ghavidel/J. Gelbrich/A. Kugo/V. Vasilache/I. Sandu, Investigation of Archaeological European White Elm (Ulmus laevis) for Identifying and Characterizing the Kind of Biological Degradation. Heritage 2020, 3, 1083–1093. https://doi.org/10.3390/heritage3040060

Hastedt et al. 2019
H. Hastedt/T. Luhmann/A. Colson, Large-volume photogrammetric deformation monitoring of the Bremen Cog. 4th Joint International Symposium on Deformation Monitoring (Athen 2019). https://fig.net/resources/proceedings/2019/04_JISDM2019/89.pdf

Haddad et al. 2021
D. Haddad/Ph. Mörchel/M. Hildenbrand/K.-H. Hiller, Selected Magnetic Resonance applications for non-destructive material testing. tm – Technisches Messen 88 (1), 2021, 17–23. https://doi.org/10.1515/teme-2019-0149

Häuser et al. 2022
L. Häuser/J. Erben/G. Pillot/S.Kerzenmacher/W. Dreher/E. Küstermann, In vivo characterization of electroactive biofilms inside porous electrodes with MR Imaging, RSC Advances 12, 2021, 17784–17793. https://doi.org/10.1039/d2ra01162j

Herold et al. 2006
V. Herold/P. Mörchel/C. Faber/E. Rommel/A. Haase/P. M. Jakob. In vivo quantitative three-dimensional motion mapping of the murine myocardium with PC-MRI at 17.6 T. Magnetic Resonance in Medicine 55 (5), 2006, 1058–1064. https://doi.org/10.1002/mrm.20866

Kahl et al. 2020
W.-A. Kahl/T. Yuan/T. Bollermann/W. Bach/C. Fischer, Crystal surface reactivity analysis using a combined approach of X-ray micro-computed tomography and vertical scanning interferometry. American Journal of Science 320 (1), 2020, 27–52. https://doi.org/10.2475/01.2020.03

Kahl et al. 2012
W.-A. Kahl/B. Ramminger, Non-destructive fabric analysis of prehistoric potte-

ry using high-resolution X-ray microtomography: a pilot study on the late Mesolithic to Neolithic site Hamburg-Boberg. Journal of Archaeological Science 39, 2012, 2206–2219.

Kanazawa et al. 2017
Y. Kanazawa, Internal evaluation of impregnation treatment of waterlogged wood; relation between concentration of internal materials and relaxation time using magnetic resonance imaging. Magnetic Resonance Imaging 38, 2017, 196–201.

Krämer 2009
S. Krämer, Operative Bildlichkeit. Von der ‚Grammatologie' zu einer ‚Diagrammatologie'? Reflexionen über erkennendes ‚Sehen'. In: M. Heßler/D. Mersch (Hrsg.), Logik des Bildlichen: Zur Kritik der ikonischen Vernunft (Bielefeld 2009), 94–122. https://doi.org/10.1515/9783839410516-003

Leder et al. 2024
D. Leder/J. Lehmann/A. Milks/T. Koddenberg/M. Sietz/M. Vogel/U. Böhner/T. Terberger, The wooden artifacts from Schöningen's Spear Horizon and their place in human evolutions. Proceedings of the National Academy of Science of the United States of America 121, No. 15, 2024.
https://doi.org/10.1073/pnas.2320484121

Longo et al. 2023
S. Longo/F. Egizi/V. Stagno/ M.G. di Trani/G. Marchelletta/T. Gili/E. Fazio/G. Favero/S. Capuani, A Multi-Parametric Investigation on Waterlogged Wood Using a Magnetic Resonance Imaging Clinical Scanner. Forests 14 (2), 2023, 276. https://doi.org/10.3390/f14020276

Meixner 2021
M. Meixner, Development of low-field and mobile MRI devices and methods to monitor xylem emboli in trees.
https://mediatum.ub.tum.de/doc/1611470/1611470.pdf

Meixner et al. 2020
M. Meixner/J. Kochs/P. Foerst, C. Windt, An integrated magnetic resonance plant imager for mobile use in greenhouse and field. Journal of magnetic resonance 323, 2021. https://doi.org/10.1016/j.jmr.2020.106879

Milks et al. 2023
A. Milks/J. Lehmann/D. Leder/M. Sietz/T. Koddenberg/U. Böhner/V. Wachtendorf/T. Terberger, A double-pointed wooden throwing stick from Schöningen, Germany: Results and new insights from a multianalytical study. Plos one 18 (7). https://doi.org/10.1371/journal.pone.0287719

Mori et al. 2021
M. Mori/S. Kuhara/K. Kobayashi/S. Suzuki, Nondestructive visualization of polyethylene glycol impregnation in wood using ultrashort echo time 3D imaging. Journal of Cultural Heritage, 50, 2021, 43–48.
https://doi.org/10.1016/j.culher.2021.05.008

Muskalla/Wittköpper 2009
W. Muskalla/M. Wittköpper, Das KUR Projekt "Massenfunde in archäologischen Sammlungen". Restaurierung und Archäologie 2, 2009, 133–136.

Parikka 2023
J. Parikka, Operational Images: From the Visual to the Invisual (Minneapolis 2023). https://doi.org/10.5749/9781452970929

Schmik et al. 2018
J. Schmik/A. Colson/H. Hastedt/T. Luhmann, Photogrammetrisches Monitoring und Deformationsanalyse der Bremer Hanse-Kogge. In: Th. Luhmann/Ch. Schumacher (Hrsg.), Photogrammetrie, Laserscanning, Optische 3D-Messtechnik – Beiträge der Oldenburger 3D-Tage 2018 (Offenbach, Berlin 2018) 42–54.

Stelzner et al. 2024
J. Stelzner/D. Gwerder/I. Stelzner/P. Schuetz, Cross-sectional images from x-ray computed tomography (XCT) of conserved archaeological samples. https://doi.org/10.5281/zenodo.12690015

Stelzner et al. 2022
J. Stelzner/I. Stelzner/J. Martinez-Garcia/D. Gwerder/M. Wittkoepper/W. Muskalla/A. Cramer/G. Heinz/M. Egg/P. Schuetz. Stabilisation of waterlogged archaeological wood – The application of structured-light 3D scanning and micro computed tomography for analysing dimensional changes. Heritage Science 10, 2022, 1–25. https://doi.org/10.1186/s40494-022-00686-6

Windt et al. 2021
C. Windt/M. Nabel/J. Kochs/S. Jahnke/U. Schurr, A Mobile NMR Sensor and Relaxometric Method to Non-destructively Monitor Water and Dry Matter Content in Plants. Frontiers in Plant Science 12, 2021.
https://doi.org/10.3389/fpls.2021.617768

Wittköpper et al. 2016
M. Wittköpper/W. Muskalla/S. Brather/A. Le Boedec-Moesgard/S. Gebhadt/S. Klonk/C. André/K. Schmidt-Ott/W. Smith, The KUR (conservation and restauration) project - a comparison of different methods to preserve waterlogged wood. In: T. Grant/C. Cook (Hrsg.), Proceedings of the 12th ICOM-CC Group on Wet Organic Archaeological Materials Conference, Istanbul,13-17 May 2013 (Paris 2016), 134–143.

Zwick/Bischop 2007
D. Zwick/D. Bischop, Werften und Wracks am Weserufer: Vorbericht über die Grabung Beluga auf dem Teerhof 2007. Bremer Archäologische Blätter 7, 2005–2008, 93–110.