

**Lateglacial environmental transformations in northern Europe
evidenced by high-resolution palynology and tephrochronology
from Lake Bølling and the Nahe palaeolake.
New insights into terminology, vegetation development and
human-environmental interaction.**

Dissertation in fulfilment of the requirements for the doctoral degree at the
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submitted by

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Foreword.....	5
1. Introduction to the Lateglacial in Schleswig-Holstein.....	7
1.1 Lateglacial archaeological background.....	9
1.2 Lateglacial vegetation history in Schleswig-Holstein – a brief overview.....	13
1.2.1 The discovery of Lateglacial flora.....	14
1.2.2 Palynological research from its introduction to the work of Hartmut Usinger.....	14
1.2.3 The work of Hartmut Usinger.....	16
1.2.4 Recent palynological research and the status quo.....	19
2. Lateglacial environmental transformations in northern Europe – the project.....	20
2.1 The initial thought – objectives and obstacles.....	20
2.2 Project objective.....	22
2.3 Main questions.....	24
2.3.1 Terminology of Lateglacial research.....	24
2.3.2 Lateglacial vegetation history.....	24
2.3.3 Lateglacial human-environmental interaction.....	25
2.4 Concept.....	25
2.4.1 Defining the frame (Appendix I).....	25
2.4.2 Connecting Europe (Appendix II).....	26
2.4.3 Comprehending the record – date the dirt (Appendix III).....	26
2.4.4 Pollen, plants and pioneers (Appendix IV).....	27
2.3.1 Transformation and adaptation (Appendix V).....	27
3. Methodological background.....	28
3.1 Entanglements of Lateglacial terminology.....	28
3.2 Human indicators in pollen diagrams.....	36
4. Summary of papers/ appendices.....	41
4.1 Appendix I.....	41
4.2 Appendix II.....	41
4.3 Appendix III.....	42
4.4 Appendix IV.....	43
4.5 Appendix V.....	44
5. Conclusion and perspective.....	45
6. Acknowledgement.....	49
7. Deutsche Zusammenfassung.....	51
8. References.....	61
9. Appendix I-V.....	73

Foreword

This dissertation is based on the synthesis of the following five papers, presented as appendices I-V.

- Appendix I: Krüger, S. and Damrath, M.
In search of the Bølling–Oscillation: a new high resolution pollen record from the locus classicus Lake Bølling, Denmark.
Vegetation History and Archaeobotany 29 (2), 2019, 189-211.
<https://doi.org/10.1007/s00334-019-00736-3>
- Appendix II: Krüger, S. and van den Bogaard, C.
Small shards and long distances – three cryptotephra layers from the Nahe palaeolake including the first discovery of Laacher See Tephra in Schleswig-Holstein (Germany).
Journal of Quaternary Science 36 (1), 2020, 8-19.
<https://doi.org/10.1002/jqs.3264>
- Appendix III: Dreibrodt, S., Krüger, S., Weber, J., Feeser, I.
Limnological response to the Laacher See eruption (LSE) in an annually laminated Allerød sediment sequence from the Nahe palaeolake, northern Germany.
Boreas 2020.
<https://doi.org/10.1111/bor.12468>. ISSN 0300-9483
- Appendix IV: Krüger, S., Mortensen, M.F. and Dörfler, W.
Sequence completed – palynological investigations on Lateglacial/Early Holocene environmental changes recorded in sequentially laminated lacustrine sediments of the Nahe palaeolake in Schleswig-Holstein, Germany.
Review of Palaeobotany and Palynology (280) 2020.
<https://doi.org/10.1016/j.revpalbo.2020.104271>
- Appendix V: Krüger, S.
Of birches, smoke and reindeer dung – tracing human-environmental interactions palynologically in sediments from the Nahe palaeolake.
Journal of Archaeological Science: Reports (32) 2020.
<https://doi.org/10.1016/j.jasrep.2020.102370>

This Ph.D. project is part of the project B1- *Pioneers of the North: Transitions and transformations in Northern Europe evidenced by high resolution datasets (c. 15,000-9,500 BCE)* of the CRC 1266 *Scales of Transformation* at the Centre for Baltic and Scandinavian Archaeology (ZBSA) Schleswig and Kiel University (CAU).

During the three years of contract as a Ph.D. at the ZBSA I have been enrolled at the Institute of Pre- and Protohistoric Archaeology at Kiel University. The analyses have mainly been carried out at the palynological laboratory (CAU), headed by Dr. Walter Dörfler. The work has been supervised by Priv.-Doz. Dr. habil. Berit V. Eriksen, ZBSA and Prof. Dr. Wiebke Kirleis, CAU.

1. Introduction to the Lateglacial in Schleswig-Holstein

The Weichselian Lateglacial, which is referred to as *the Lateglacial*, designates a period of time between about 14,650 and 11,600 cal yr BP (Litt et al. 2007; Litt and Stebich 1999; Magny et al. 2006; Rasmussen et al. 2006). This period, the transition from the end of the Pleistocene to the Holocene, is a key period for the understanding of transformation processes at different scales, because the Lateglacial featured continuously and profoundly changing environmental conditions that in turn were regionally and locally manifested in very diverse ways. The period was characterised by rapid climatic alterations, and accordingly high pressure to adapt and transforming requirements for all forms of life. In order to classify the Lateglacial into comprehensible periods the event stratigraphy was proposed by the INTIMATE Group based on fluctuations in oxygen isotope concentrations in Greenland ice core records (Björck et al. 1998; Rasmussen et al. 2006; 2014; Seierstad et al. 2014). Consequently, the Lateglacial is divided into the Glacial Interstadial 1 (GI-1), which is further subdivided, and the following Glacial Stadial 1 (GS-1). Both are defined in an absolute chronological framework. The GI-1 is one of 24 cyclic thermal fluctuations during the Weichselian within the last 110,000 years and is characterised by warmer atmospheric conditions (Bond et al. 1999; Dansgaard et al. 1993). The following GS-1 event represents a return to stadial cold and predominantly dry conditions. The abrupt termination of the GS-1 indicated in climatic proxies is succeeded by the Holocene and thus by the comparatively exceptionally long warm period in which we still live today.

Even before the subdivision on the basis of climatic data, it was discovered in disciplines such as geology or pollen analysis that the Holocene was preceded by stadial periods which were punctually interrupted by climatically more favourable phases (Hartz and Milthers 1901; Iversen 1942). In those respective early pioneer studies, undisturbed sediment sequences were rarely analysed and there was practically no possibility of correlation. For this reason, certain concepts were introduced that describe the same or similar phenomena (Bølling-Oscillation by Iversen, 1942; Meiendorf-Interval by Menke, 1968). Due to the application of the similar terms in different disciplines and in connection with the respective progress, a confusing and misleading terminology of the Lateglacial emerged, which still today leads to misunderstandings and requires further clarification.

For research into the Lateglacial, the territory of the northernmost German federal state – Schleswig-Holstein – is most applicable, because the area literally represented a bridge between Scandinavia and northern central Europe for humans, animals and plants since the melting of the Fennoscandian Ice Sheet (fig 1). Advance and retreat phases of the glacier shaped the landscape of Schleswig-Holstein several times and thereby created an edaphic segmentation, which has been a decisive factor for the

distribution of the vegetation since the beginning of the Lateglacial until today (Behre 2008; Overbeck 1975).

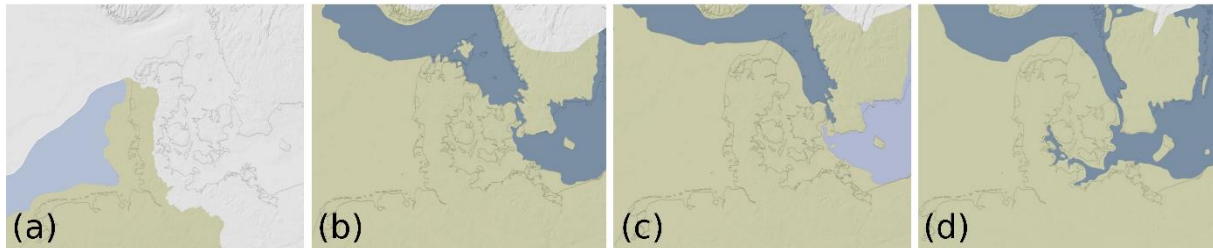


Figure 1: Overview on the distribution of land mass, glaciers and sea during (a) the Lateglacial Maximum, (b) the Meiendorf period, (c) the Allerød period and (d) the Dryas 3 period. Map compiled by ZBSA after Andrén et al. (2011); Björck (1995); Brooks et al. (2011); Bouncristiani and Campy (2004); Calvet et al. (2011); Caille et al. (2013); Clark et al. (2004); Clark et al. (2012); Edwards and Brooks (2008); Gibbard and Clark (2011); Gobejishvili et al. (2011); Harff et al. (2017); Hughes et al. (2016); Jakobsson et al. (2007); Lambeck and Purcell (2005); Larsen et al. (2013); Lemke et al. (2002) Lericolais (2017); Lunkka et al. (2012); Matoshko (2011); Moscon et al. (2015); Pasanen et al. (2010); Rinterknecht et al. (2018); Patton et al. (2017); Seguinot et al. (2018); Sejrup et al. (2016); Stroeven et al. (2016); Subetto et al. (2017); Ureda et al. (2011); Vassiljev and Saarse (2013); Weaver et al. (2003); Westley and Edwards (2017); Zasadni and Kłapyta (2014).

Numerous botanical and above all pollen analyses in Schleswig-Holstein investigated the post-glacial forest history, but also to a considerable degree the vegetative re-colonisation of soils after deglaciation (Aletsee 1959; Fischer-Brenzon 1891; Tidelski 1929; 1960; Usinger 1975).

Various pollen profiles of different complexity, resolution and scope were produced. On the one hand this diversity in records can be related to the respective progress in the discipline. On the other hand, this is due to the suitability of peats and lake sediments investigated. Still, there is no analysis available on a sediment sequence that was deposited continuously during the whole Lateglacial, which in turn is mainly conditioned by a common hiatus (Usinger 1981a) or by effects subsequent to deep thawing processes of dead ice (pers. com. I. Feeser; Gripp 1964). Therefore, the present state of knowledge concerning Lateglacial vegetation history in Schleswig-Holstein is based on a patchwork of numerous analyses with different temporal scope (cf. below).

This patchwork also includes the circumstance that there is no absolutely dated biostratigraphy of the Lateglacial in the study area due to the availability of only a few ^{14}C dates of individual pollen profiles. Furthermore, it has not been possible to correlate and compare even the high-resolution diagrams using event stratigraphy due to the lack of detected volcanic ash layers.

Consequently, this results in a definition of specific requirements for new palynological investigations of Lateglacial depositions that mainly concern the respective pollen archives. This includes that:

- (i) the investigated sediments have been deposited continuously throughout the Lateglacial and,
- (ii) hence, have not been affected by the common hiatus (Usinger 1981a).

- (iii) It should be possible to construct a robust age-depth-model (based on the absolute dating of a number of botanical macrofossils),
- (iv) and to connect the produced biostratigraphy to the event stratigraphy in order to correlate the new profile with important European key sites.

There are rather numerous Lateglacial pollen profiles from Schleswig-Holstein when contrasted to other regions in northern Germany. However, comparatively few of these represent on- or near-site analyses relative to archaeological contexts (Bokelmann et al. 1983; Schütrumpf 1935; 1937; 1943; 1958b; Usinger 1998). This fact means that a close linkage between hunter-gatherer research and palaeo-environmental investigations is absent in most cases. Consequently, a fifth desirable requirement for a new palynological analysis can be defined:

- (v) There is a need for high-resolution palaeo-environmental investigations close to a former Lateglacial camp site that has been proven archaeologically.

Certainly, the reflection of human-environmental interaction has been regarded as very difficult, and hardly possible in many cases, and is therefore still discussed (Behre 1988; Bos and Janssen 1996; Iversen 1941; Mortensen et al. 2014b; Sobkowiak-Tabaka et al. 2017).

However, the investigation of a sediment sequence that meets all formulated five requirements would inherit a high potential to palynologically trace Palaeolithic human action. A possible positive result would immensely contribute to our understanding of Palaeolithic anthropogenic activity especially with regard to environmental transformations as potential triggers for changing human behavior.

From the above three general desiderata in Lateglacial research can be concluded. These concern Lateglacial terminology, Lateglacial vegetation history as well as Lateglacial human-environment interaction. The mentioned three aspects are the starting point for this thesis.

1.1 Lateglacial archaeological background

When intending to finally investigate human-environmental interaction, it is necessary to start by summarizing the archaeological background. Therefore, a brief overview of the current knowledge on archaeologically defined Lateglacial cultural groups is given below.

In general there are four major cultural groups (often also referred to as techno-complexes) distinguished by archaeological research for the Lateglacial in Schleswig-Holstein. These are the Hamburgian, Federmesser-Gruppen (FMG), Brommian and Ahrensburgian (fig. 2). Associated lithic inventories do also occur in mixed assemblages which has often complicated a chronological

classification of sites. However, archaeologists today have a sound understanding of the temporal order of the respective cultures.

The first people to colonize the North European Plain and hence also the area of investigation after the Lateglacial Maximum (LGM) are assigned to the Hamburgian (Clausen 1998; Eriksen 2000; 2002; Fischer 1991; Grimm and Weber 2008; Tromnau 1975). The available ^{14}C dates for the Hamburgian correspond to the time between GI-1e and GI-1c₁ (Grimm and Weber 2008). In the Nahe palaeolake record (i.e. NAH record in the following) this equals roughly the temporal extend of the (biostratigraphic) Meiendorf period as well as the Dryas 1 period (Appendix IV). Hence, suggested by the environmental record and the archaeological find assemblages, those people were hunter-gatherers mainly of the grass and partly shrub dominated tundra. Considering the subsistence strategy, archaeological finds with a proportionally high amount of reindeer bones and antlers (*Rangifer tarandus*) indicate that hunting of these animals was an integrated and important part of the annual cycle. This is particularly demonstrated by the type locality of the Hamburgian (fig. 3) – the Ahrensburg tunnel valley (Bratlund 1996; Rust and Gripp 1937). Shouldered points and Zinken belong to the typical lithic assemblage (Terberger 2006; Tromnau 1981).

Within the Hamburgian, archaeologists differentiate between two phases. The first and elder is the classical Hamburgian phase. The second, however, is referred to as Havelte phase with its characteristic Havelte-type tanged points (Grimm and Weber 2008; Hartz 1987; Hartz 2013; Schwabedissen 1937; Schwantes 1932; Terberger 2006; Tromnau 1981).

It has been suggested that the Havelte group is a north-western development of the classical Hamburgian (Clausen 1998; Grimm and Weber 2008). With respect to the pollen record of Lake Hämelsee, Grimm and Weber (2008) identified a distinct pattern of reflected increased shrub abundance that corresponds to the appearance of the Havelte phase. However, whether this cultural shift can be ascribed to environmental changes, remains unclear.

The youngest archaeological finds associated with the Havelte phase date to the GI-1c₁ and hence, correspond to ages known from the first dated finds of the FMG (Eriksen 2002). Still, there is debate about the emergence of FMG and as to whether this shift in find assemblages reflects migration processes or autochthonous developments (Burau, unpubl.; Grimm and Weber 2008; Riede 2009). Nevertheless, the appearance of finds associated with the FMG apparently also corresponds to the time of the first Lateglacial evidence of trees in the area of investigation (Appendix IV).

In between the GI-1c and GI-1a a shift from the first occurrences of trees to open and later dense woodlands occurs around the Nahe palaeolake. The developments of at least open woodlands is significant for this time period between northern Germany and Denmark (Appendix IV; Merkt and Müller 1999; Mortensen et al. 2011). Based on this transformed landscape it is not surprising that the archaeologically traced subsistence of the FMG is based on elk (*Alces alces*), giant deer (*Megaloceros*

giganteus), red deer (*Cervus elaphus*) and horses (*Equus sp.*) (Riede et al. 2010). Typical lithic artefacts associated with FMG inventories are especially curve-backed points (Schwabedissen 1954).

The Laacher See Volcano erupted during the GI-1a, approximately around 12,940 cal yr BP (Bronk Ramsey et al. 2015; Schmincke et al. 1999; van den Bogaard and Schmincke 1984). This event had a massive regional environmental impact (Litt et al. 2003; Schmincke et al. 1999). Still the question remains, if hunter-gatherers roaming the area of investigation far north of the eruptive centre witnessed any environmental changes at all. Judged from the NAH record at least, only changes in the aquatic ecosystem could be traced. These concern mainly fluctuations in algae and diatom frequencies but could also have triggered a change in fish species composition with respect to the shifting pH-values.

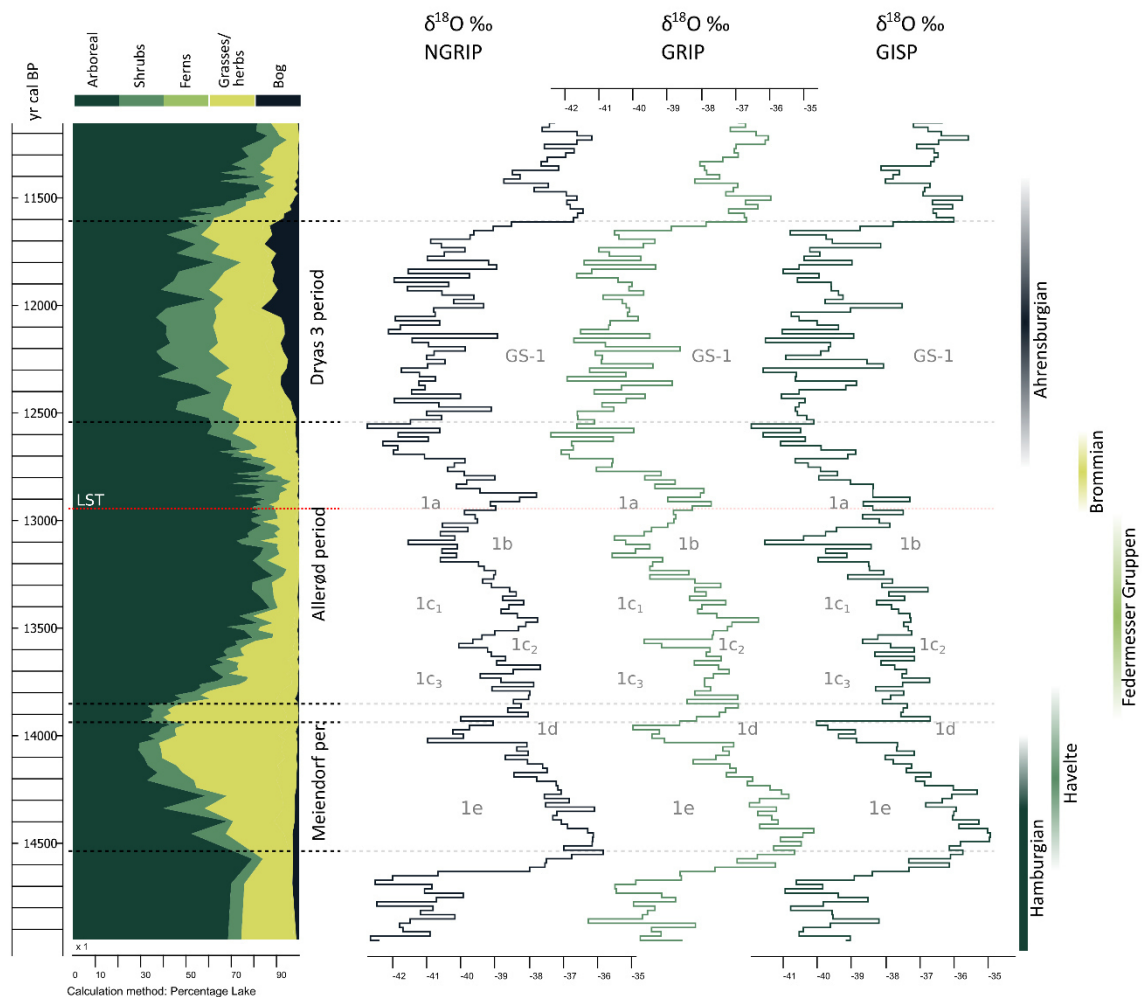


Figure 2: Approximate dating of archaeologically defined cultures at the area of Schleswig-Holstein, age-correlated to the GISP, GRIP and NGRIP $\delta^{18}\text{O}$ data sets (GICC05modelext timescale for the ice cores and resampled data series after Rasmussen et al. 2014 and Seierstad et al. 2014). A composite pollen profile of the Lateglacial NAH sequence including major pollen assemblage zones and the depth of the Laacher See Tephra (LST) are given below.

This in turn would potentially be recognisable by Lateglacial hunter-gatherers but remains a hypothesis. However, there are no alterations in the composition of the upland vegetation reflected (Appendix II, III and IV).

An apparent cluster of radiocarbon dates led Riede (2007) to formulate the hypothesis that the Laacher See Eruption can be seen as chronological divide between FMG and the Brommian in northern central Europe (Riede 2016; Riede and Bazely 2009; Riede et al. 2010; Riede and Wheeler 2009).

Sites associated with the Brommian in turn, date to the later part of the GI-1 (1a) and the beginning of the GS-1. Typical lithic inventories include especially large tanged-points but also several burin types and end-scrapers (Eriksen 2000; Weber et al. 2011). In contrast to the FMG Brommian sites are concentrated within the young morainic area of northern Germany and Denmark (Eriksen 2000; 2002; Fischer et al. 2013). For these areas Mortensen et al. (2014a) recently demonstrated the presence of woodland (mainly including *Betula sp.*, *Populus sp.*, *Juniperus sp.* – and *Pinus sp.* in southern regions). The edaphic trichotomy of e.g. Schleswig-Holstein conditioned that apart from woodland there were further ecosystems to exploit in a geographically rather small area. Therefore, it was possible to hunt reindeer in treeless sandur and old morainic areas to the west and north-west as well as elk or giant deer in the eastern and southern younger morainic regions that were characterized by a patchwork of woodland and open areas (Aaris-Sørensen 2009; Mortensen et al. 2014a).

With the emergence of the GS-1 strong environmental changes towards more stadial conditions took place, including the shift from woodland to shrub dominated tundra in many parts of Schleswig-Holstein. People living under these harsher conditions are associated with the Ahrensburgian (Eriksen 2000; 2002; Grimm et al in prep.; Weber et al. 2011). These Ahrensburgian hunter-gatherers were roaming a tundra dominated, yet extremely patchy environment. To the west heather (*Calluna sp.*), crowberry (*Empetrum sp. cf. nigrum*) and grass communities were dispersed across the sandur plains. In sheltered areas, such as the northern shore of the Nahe palaeolake, other slopes directed towards the south or riparian areas of rivers, birch trees (*Betula pubescens*) survived the cold GS-1 (Appendix IV). To the east Juniper (*Juniperus sp. cf. communis*) but also mugwort (*Artemisia sp.*) and Chenopodiaceae characterized the vegetation of the landscape. Towards south-eastern areas also different kinds of woodland persisted¹. These diverse accessible ecosystems highlight the potential of Lateglacial landscapes regarding nutrition and subsistence strategies especially during this stadial period that archaeology has not yet been able to comprehend completely.

¹ Light birch-pine woodland in Mecklenburg (Theuerkauf and Joosten 2012), and pine (*Pinus sp. cf. sylvestris*) dominated forests in the Brandenburg area (Kobe et al. 2019).

As for the Hamburgian, also the type locality for the Ahrensburgian is situated in the wider focus area of this thesis – the Ahrensburg tunnel valley (fig. 3). Here, enormous amounts of bones indicate that migrating reindeer herds were one important component of the subsistence strategy (Bratlund 1996; Kollau 1943; Rust 1943).

Most indicative for the Ahrensburgian inventories are characteristic small tanged points as well as Zonhoven points with oblique truncation (Grimm and Weber 2008).

Only 18 km to the north of the Ahrensburg tunnel valley lies the archaeological site Nahe LA11 (fig. 3) at an elevated position on top of a moraine directly at the shore of Lake Itzstedt and the Nahe palaeolake. In southern Schleswig-Holstein this close proximity of sites like Nahe LA11 or Stellmoor LA190 highlights the extraordinary suitability of investigations into human-environmental interaction, especially of the Ahrensburgian, with the sediments of the Nahe palaeolake. This is further referred to in Appendix IV and especially in Appendix V.

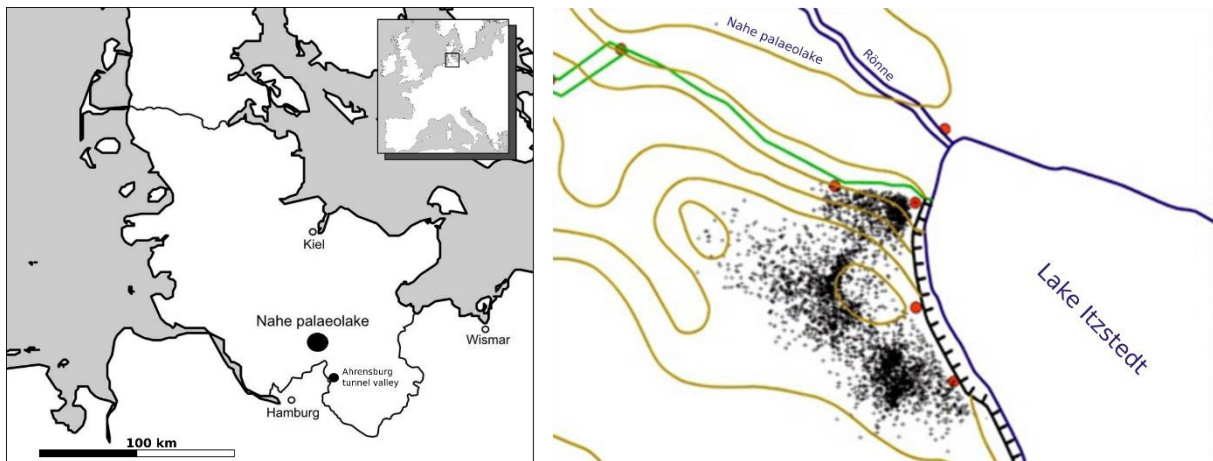


Figure 3: Left – Map of the location of the Nahe palaeolake and the Ahrensburg tunnel valley. Right – three flint concentrations of the site Nahe LA11 in elevated position close to the shore of Lake Itzstedt and the Nahe palaeolake (former shoreline in green).

1.2 Lateglacial vegetation history in Schleswig-Holstein – a brief overview

Investigations into Lateglacial vegetation developments in Schleswig-Holstein have a long-standing tradition shaped by a number of prominent palynologists and botanists, such as Rudolf Schütrumpf, Fritz-Rudolf Averdieck or Burchard Menke. Especially the work of Hartmut Usinger contributed significantly to our understanding of Lateglacial vegetation dynamics in Schleswig-Holstein. However, research tradition, understanding and progress are in general naturally also bound to Jutland and Denmark. Therefore, the work of e.g. Knud Jessen and Johannes Iversen are equally fundamental.

1.2.1 The discovery of Lateglacial flora

Deposits of Lateglacial flora have been known in Schleswig-Holstein even before the introduction of pollen analysis. A profound overview on the early detection of Lateglacial plant macrofossils is given by Franz Firbas (1949) as well as Fritz Theodor Overbeck (1975). These include investigations in Schleswig-Holstein (Fischer-Brenzon 1891; Gagel 1915; Nathorst 1891; Range 1903) but also the detection of an important Lateglacial *locus classicus* on Sealand (Denmark) with international implications for further research into the Lateglacial – the Allerød location (Hartz 1912; Hartz and Milthers 1901).

Based on these pioneer investigations it was clear already in the beginning of the 20th century that these botanical macrofossils found embedded in glacial till as well as organic gyttja sediments in sum indicate shifting climatic regimes that conditioned profound changes in the composition of the vegetation.

1.2.2 Palynological research from its introduction to the work of Hartmut Usinger

In the years after the official introduction of pollen analysis by Lennart von Post (1916), investigations mainly concerned the reconstruction of Holocene forest history in Schleswig-Holstein (Kolumbe 1932; Koppe and Kolumbe 1926; Schröder 1935; 1937; Tidelski 1929). This, however, was contrasted by Danish research. The botanist and geologist Knud Jessen published his thesis on *Bog investigations in north-east Sealand*² (Jessen 1920). Therein he analysed six sediment sequences of bogs from around Copenhagen that also included Lateglacial depositions. Later, in 1935, Jessen published his *Summary of Pollen-Diagrammatical Zones* and thereby proposed the first pollen analytical zonation of the Lateglacial defining also the corresponding main geological features (Jessen 1935).

Contemporaneously, a close linkage between prehistory and pollen analysis was established in general. Firbas, who gave an overview on Lateglacial vegetation development in southern, central and northern Germany, included a chapter on the integration of Lateglacial vegetation dynamics into prehistoric periodization. He was aware of the archaeological data deficiency, yet he assumed that there could be no doubt about the age of e.g. the *Magdalénien* (and *Hamburgian* in Schleswig-Holstein) and its association with arctic-alpine and steppe-like flora (Firbas 1935a; 1935b).

When Alfred Rust started excavating at the famous site of Meiendorf close to Hamburg (Rust and Gripp 1937), Rudolf Schütrumpf was asked to carry out pollen analyses. The aim was to link cultural history to vegetation development. The combination of a pollen-percentage diagram with depth information on cultural layers should provide a relative age estimation of hunter-gatherers in the area (Schütrumpf 1936; 1937). *A treeless tundra covered the ground during the time of the reindeer hunters*

² Original title: *Moseundersøgelse i det nordøstlige Sjælland*

of Meiendorf [Hamburgian]. The trees had not migrated yet, narrow dwarf birches and crawling willow-shrub-stands were intermitted by larger grasslands and a rampant moss flora³. By using pollen analysis, Schütrumpf proved that Hamburgian finds from Meiendorf and from the nearby site of Stellmoor date roughly to the same period of time (Schütrumpf 1943).

Just a year before that Iversen (1942) presented his work on a sediment sequence from Lake Bølling in northern Jutland (see Appendix I; fig. 4). He realized that the pollen profile from this site reached further back in time as previously published diagrams. The results led him to propose a climatic *Bølling-Oscillation* prior to the Allerød period, thereby extending the Lateglacial classification established by Jessen (1920).

By the 1940s discussion started whether the name pollen analysis would still be satisfactory because the method included the analysis of spores and ferns, mosses and other micro remains such as charcoal particles. Therefore, the term palynology⁴ was introduced (Hyde and Williams 1944).

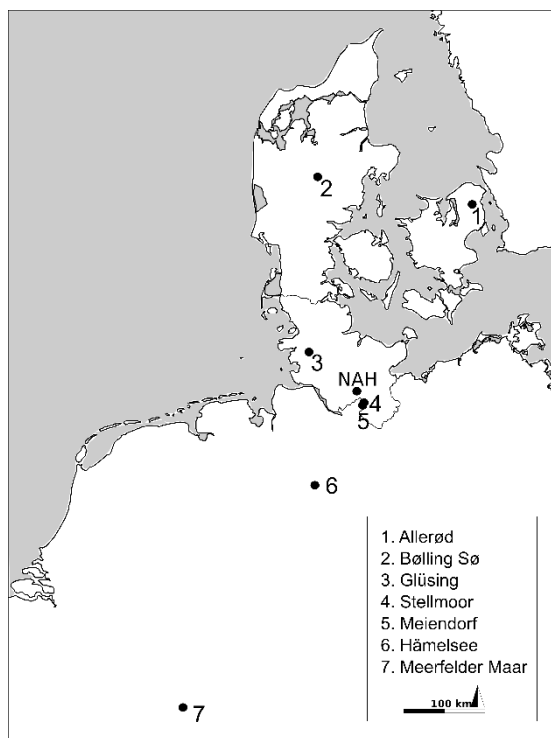


Figure 4: Important key sites for Lateglacial palynological research as mentioned in the text.

During the 1950s, the work of Heinz Schmitz (1952) filled a gap in Lateglacial vegetation research by publishing a pollen diagram from Travemünde that spanned almost the whole Lateglacial. Based on this work and the previous diagrams provided by Schütrumpf, Schmitz consequently reviewed Overbeck's zonation for Lateglacial pollen diagrams in Lower Saxony (Overbeck and Schneider 1938) and applied it to Schleswig-Holstein (Schmitz 1953). Furthermore, he suggested to use different pollen stratigraphical events as marker horizons for absolute chronology (Schmitz 1955). The synopsis-diagram given for Holstein by Schmitz (1955) was embraced and directly confirmed by the work of Fritz Tidelski (1955) on the location Schlüsbecker Moor.

In addition to detailed investigations into vegetation history by Fritz-Rudolf Averdieck (1957) and Ludwig Aletsee (1959) also summaries and general overviews on Lateglacial vegetation history were published (Firbas 1949; 1952; Schütrumpf 1955). Therein, the role of the collaboration between

³ „Waldfreie Tundra bedeckte den Boden zur Zeit der Meiendorfer Rentierjäger. Die Bäume waren noch nicht wieder eingewandert, niedrige Zwergbirken und dicht am Boden kriechende Polarweidengebüsche wurden von größeren Grasflächen mit üppiger Moosflora durchbrochen.“ (Schütrumpf 1937, 42).

⁴ Palynology: [gr.] *παλυνω* (palyno) = strew/ sprinkle; *παλή* (palé) = fine flour; [lat.] *pollen* = flour/dust.

palynology and archaeology has extensively been emphasized. In this respect, Schütrumpf authored two more palynological contributions to archaeological investigations in 1958 (Schütrumpf 1958a; 1958b), following his earlier pioneer work (Schütrumpf 1935; 1936; 1937; 1943).

During the 1960s, only few more Lateglacial pollen profiles were compiled (Tidelski 1960; Vogel 1963). With important implications Burchard Menke (1968) suggested the subdivision of the earliest part of the Lateglacial, discussing an early climatic amelioration prior to the *Bølling-Oscillation sensu Iversen* based on the Glüsing and Stellmoor diagram (after Schütrumpf 1943). The comparison with other pollen diagrams from Schleswig-Holstein led him to suggest the local term *Meiendorf-Interval* for the earliest period of the Lateglacial, thereby not realizing that he was describing local vegetation characteristics that biostratigraphically correlated to the *Bølling-Oscillation* as defined by Iversen (see Appendix I).

In the early 1970s, Averdieck et al. (1972) conducted age determinations of lake sediments from Segeberger See and Overbeck (1975) published his seminal *Botanical and geological study of Bogs*⁵. In the same year, Hartmut Usinger finished his thesis on two Lateglacial pollen profiles (Usinger 1975) and thereby led the way regarding Lateglacial palynology in Schleswig-Holstein.

1.2.3 The work of Hartmut Usinger

Already with his dissertation *Pollen analytical and stratigraphical investigations of two lateglacial depositions in Schleswig-Holstein* (Usinger 1975)⁶, which deals in detail with pollen-size-frequency-distributions, Usinger established a standard method for his further investigations. This statistical method of pollen-size-frequency-distribution contributed significantly to our knowledge of the reforestation processes after the LGM. Additionally, one of the most valuable achievements of Hartmut Usinger is without doubt his meticulously precise work on coring equipment and its permanent development which he started early in his carrier. The modified Livingston-piston corer (Mingram et al. 2007), known as *Usinger-corer*, is used world-wide – further also to obtain the sediments analysed in this thesis.

In the 1970s and early 1980s, different papers by Usinger addressed the *Bølling-Interstadial* (Usinger 1978a; 1978b; 1981b; 1981c; 1985), later emphasising to refrain from utilizing this term (Usinger 1998). He reviewed multiple pollen diagrams, criticized their chronological classification and provided suggestions to correct their reading (Usinger 1978b; 1985). Based on this work, he stressed that many pollen profiles from northern Europe have potentially been misinterpreted. He suggested that the

⁵ Original title: *Botanisch-geologische Moorkunde*

⁶ Original title: *Pollenanalytische und stratigraphische Untersuchungen an zwei Spätglazial-Vorkommen in Schleswig-Holstein*

Bølling-Oscillation sensu Iversen needs to be equated with the early Allerød period and supported this assumption with a variety of studies.

Usinger often emphasized the importance of bio- and lithostratigraphic aspects for a correct interpretation of Lateglacial pollen profiles that are specifically indicative when intending to identify phases of transformation (Usinger 1981a; 1985). Therefore, his work was dedicated to the vegetation development of the Allerød period during the 1980s (Usinger 1985; Usinger and Wolf 1982) and to a *common hiatus of Lateglacial lake sediments*⁷ (Usinger 1981a) that he had identified during many of his fieldwork campaigns (Usinger unpubl.).

Apart from Usinger's work, only Menke (in Bock et al. 1985) and Averdieck (in Bokelmann et al. 1983) provided a few further palynological Lateglacial investigations during this time.

Especially between 1980 and 1990 Usinger analysed various sediment sequences from all over Schleswig-Holstein and also beyond. This included an extremely detailed analysis from the Stellmoor location, but like most of the pollen profiles created during this time, this has never been published.

One exception is the publication of the palynological results from Meerfelder Maar (Rheinland-Pfalz), where Usinger (1982) presented a pollen profile on a complete sediment sequence of the Lateglacial and Early Holocene representing a key site in Lateglacial research in central Europe (Litt et al. 2001).

Only in his most recent article, Usinger began focussing more on the Early Holocene and the Preboreal Oscillation (PBO) rather than on questions concerning the Pleistocene (Usinger 2004).

A linkage to archaeology and archaeological questions grew from a close cooperation between Hartmut Usinger and Ingo Clausen from the Archaeological State Department Schleswig-Holstein (ALSH). In this context, various reports and collaborations at important archaeological sites from the Lateglacial were established (e.g. Ahrenshöft – Usinger (1998), Stellmoor – Usinger, unpubl., Nahe – Usinger unpubl.).

⁷ Original title: *Ein weit verbreiteter Hiatus in spätglazialen Seesedimenten*

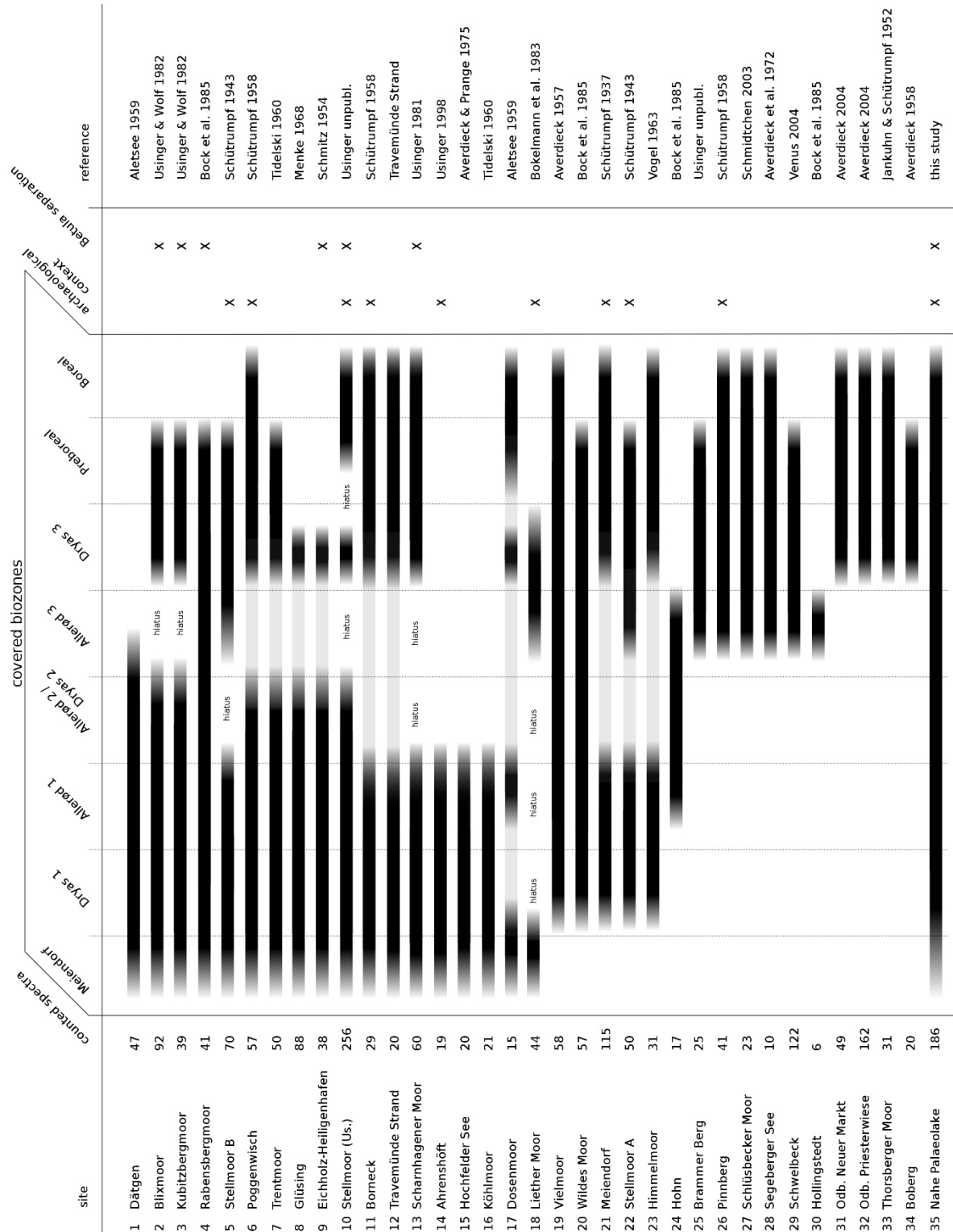


Figure 5: Compilation of palynological investigations of Lateglacial sediments in the area of Schleswig-Holstein. Black bars indicate which Lateglacial biozones are covered by the respective pollen profile.

1.2.4 Recent palynological research and the status quo

The last decades of palynological research into the Lateglacial in the area of Schleswig-Holstein have strongly been influenced by Usinger's work. However, most recent investigations by Fritz-Rudolf Averdieck (2004) and Jörg Venus (2004) approach the Lateglacial only to a very limited extend. Since their contributions, no palynological analyses of Lateglacial sediments have been accomplished.

In 2008 Oliver Nelle and Walter Dörfler (2008) compiled the available data and provided an overview of the general pollen assemblage zones and for Schleswig-Holstein with basic information on the Lateglacial. Their paper was grounded on Usinger's work and represents the current state of research into Lateglacial vegetation history in Schleswig-Holstein.

As mentioned above, this current state of knowledge is based on the combination of various pollen profiles of different temporal scope and resolution. The respective patchwork of analyses is displayed in figure 5. Therein, all available pollen records from Schleswig-Holstein are included that at least feature parts of the Lateglacial. The records have been classified again according to biostratigraphy as applied in this thesis (see Appendix I and IV) in order to create a basis for comparison. Here, especially the division of the Allerød period is challenging. On the one hand this is due to the hiatus as described by Usinger (1981a). On the other hand this is also related to the resolution of the respective analyses that often did not allow to further subdivide the Allerød period. The inequality in records requires that the apparent hiatuses observable in the Allerød 2 and Allerød 3 period are partly artificial.

Nevertheless, it is apparent from the overview in figure 5 that there is a need for a modern investigation of a new and suitable archive to establish a comprehensible biostratigraphy of the whole Lateglacial to Early Holocene in Schleswig-Holstein.

2. Lateglacial environmental transformations in northern Europe – the project

2.1 The initial thought – objectives and obstacles

The original project was entitled *Estimated subsistence potential of Lateglacial landscapes*. The processing and evaluation of the legacy data of Hartmut Usinger was an essential part as well as a palynological investigation of a suitable archive. With reference to the title, the planned third step was originally to estimate the nutritional potential of the landscape.

The reconstruction of plants used by humans during the Lateglacial is challenging due to the lack of data and the so far predominantly archaeologically evidenced use of animal resources (c.f. Bratlund (1990), Aaris-Sørensen et al. (2007) or Wild (2017)). Nevertheless, it is clear that *past hunter-gatherers may have used a range of plants and methods of plant utilisation of which we have little or no knowledge...* (Hather and Mason 2002, 3). Due to predominantly taphonomic reasons, it is hardly possible to draw conclusions about the nutritional potential of a landscape for humans. Therefore, the calculation of the food requirements of recent reindeer and moose was initially intended to answer the question of how many animals could be fed per km² and how high the corresponding nutritional potential of the individual landscapes of Schleswig-Holstein was in different periods of the Lateglacial. In order to achieve this, several maps should be created based on the collected data and the existing pollen profiles (fig. 6). For this reason, all available pollen profiles showing at least parts of the Lateglacial were digitalised and thus standardised in the preliminary stages of this thesis. Each vegetation map was to cover a time slice of about 500 years. This frame had to be chosen in order to utilize the very diverse temporal resolution of the pollen profiles.

Finally, the diverse mosaic and the transformation of vegetation through time should be visible on the maps. The maps should further provide the data basis for the assessment of the food potential, which should be done as follows:

Through intensive discussions with Prof. Felix Müller (Institute for Natural Resource Conservation, Department of Ecosystem Management), the project idea developed to estimate the food potential of a Lateglacial landscape on the basis of data on palaeovegetation. The objective was the simple transfer of methods already used in modern field research. Within the RENMAN project (Forbes et al. 2006; Kumpula 2006) satellite images were used to distinguish between open soils, lichen-, grasses- and shrub cover based on colour and shading, that resulted in percentage values. On this basis, the biomass of an area was calculated (Colpaert et al. 2003; Falldorf et al. 2014).

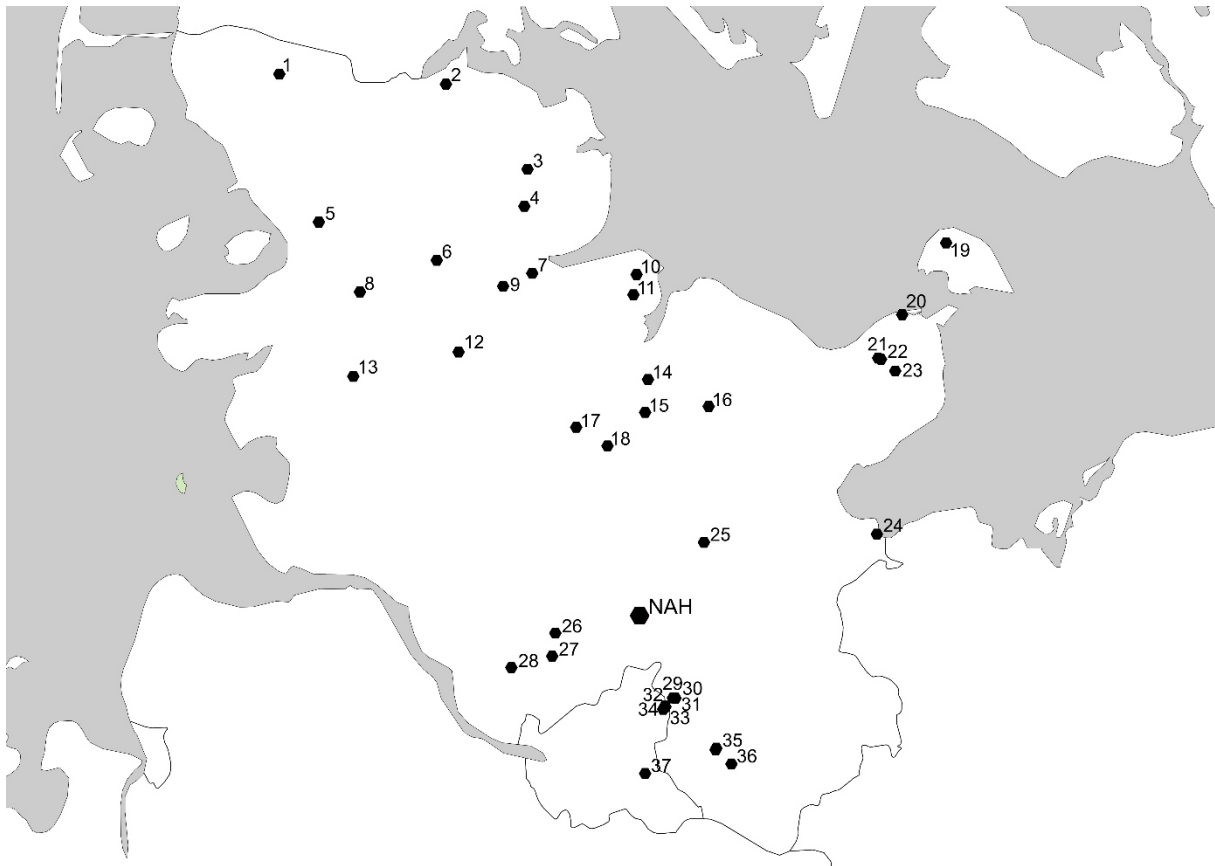


Figure 6: Map of Schleswig-Holstein displaying the locations of pollen records compiled in this thesis and the location of the Nahe palaeolake (red). **1** – Rabensbergmoor (Bock et al. 1985); **2** – Blixmoor (Usinger and Wolf 1982); **3** – Thorsberger Moor (Jankuhn and Schütrumpf 1952); **4** – Ulsnis (Schröder 1935); **5** – Ahrenshöft (Usinger 1998); **6** – Hollingstedt (Bock et al. 1985); **7** – Köhlmoor (Tidelski 1960); **8** – Wildes Moor/Schwabstedt (Bock et al. 1985); **9** – Brammer Berg (Usinger unpubl.); **10** – Scharnhagener Moor (Usinger 1981b); **11** – Kubitzbergmoor (Usinger and Wolf 1982); **12** – Hohn (Bock et al. 1985); **13** – Glüsing (Menke 1968); **14** – Schlüsbecker Moor (Usinger unpubl.); **15** – Hochfelder See (Averdieck and Prange 1975); **16** – Trentmoor/Brennacker (Tidelski 1960); **17** – Dätgen (Großes Moor) (Aletsee 1959); **18** – Dosenmoor (Aletsee 1959); **19** – Trimbok (Venus 2004); **20** – Eichholz/Heiligenhafen (Usinger unpubl.); **21** – Oldenburg i.H. Neuer Markt (Averdieck 2004); **22** – Schwelbeck (Venus 2004); **23** – Oldenburg i.H. Priesterwiese (Averdieck 2004); **24** – Travemünde Strand (Schmitz 1952); **25** – Segeberger See (Averdieck et al. 1972); **26** – Vielmoor (Averdieck 1957); **27** – Himmelmoor (Vogel 1963); **28** – Esinger Moor/Liether Moor (Bokelmann et al. 1983; Usinger 1981c); **29** – Pinnberg (Schütrumpf 1958a); **30** – Borneck (Schütrumpf 1958b); **31** – Poggenwisch (Schütrumpf 1958b); **32** – Meiendorf (Schütrumpf 1937); **33/34** – Stellmoor A/B (Schütrumpf 1943); **35/36/37** – Sachsenwald-Ro./Sachsenwald-T./Boberg (Averdieck 1958).

In order to transfer this to the context of palaeovegetation and to estimate a food potential, the pollen data from all over Schleswig-Holstein should be used to replace the satellite images.

Only after contact with Timo Kumpula (University of Eastern Finland, Department of Geographical and Historical Studies) it turned out that for a reliable calculation of the biomass, additional field inspections would be necessary to document the corresponding species populations in the field in detail and over longer periods of time. As this was retrospectively not possible, i.e. for the palaeo-environmental data, a calculation could not be carried out.

To avoid this obstacle and still provide data on the nutritional potential of the landscape, a direct reference to the main hunting game of the cold phases of the Lateglacial (*Rangifer tarandus*) should be made. Here, the essential premise remained that lichens are a major food resource for reindeer during winter and early spring (Horstkotte and Moen 2019; Lent and Klein 1988; Staaland et al. 1993). In more humid areas of Fennoscandia these are replaced by mosses (Kumpula 2006). As demonstrated by Bjune (2000) with reindeer faeces, lichens (or mosses, in areas where they replace lichens) contribute up to 90% of the animals winter forage intakes.

Lichens have only scarcely been recorded palynologically so far (Favero-Longo et al. 2014) and the question emerged as to how and whether lichens from Lateglacial samples can be detected at all. In a study, ten different recent lichen species from Norway were sent to the ZBSA. In the palynological laboratory of the Institute of Pre- and Protohistoric Archaeology at Kiel University, four species were selected for palynological treatment.

The compilation of specimen included *Flavocetraria nivalis* (snow lichen / shrub lichen), *Alectoria ochroleuca* (shrub lichen of alpine areas), *Cladonia portentosa* (known as reindeer lichen) and *Cladonia stellaris* (forms continuous mats over large areas of the ground in boreal forests and arctic regions). Nevertheless, it was not clear whether sporangia (enclosure in which spores are formed) were attached to the sampled species.

The sample preparation followed standard techniques following Fægri and Iversen (1989), Acetolysis after Erdtman (1960). The addition of exotic markers according to Stockmarr (1971) was omitted, as plant parts were prepared directly and no concentration calculation would be necessary. The use of the ultrasonic disintegrator and sieving with a mesh size of 6 µm as well as the use of hydrofluoric acid (HF) was further deliberately avoided in order to preserve and detect as many and as small botanical macrofossils as possible. The four samples with laboratory numbers 22303, 22304, 22305 and 22306 have been archived in the palynological laboratory.

Lichens are a symbiosis of fungi (mycobiont) and either algae (photobiont) or cyanobacteria (cyanobiont) (Nash III 1996). Therefore it was expected that spores could be found in the prepared samples.

The evaluation of the samples showed that even after the examination of at least three slides per sample not a single spore could be found. As a result, the attempt to detect lichens (spores) as a potentially important food source for reindeer directly in the pollen samples was cancelled. The subsequent restructuring of the project resulted in the five-part concept presented below.

2.2 Project objective

Archaeological investigations and surveys conducted for many years in the former lakeshore area of the Nahe palaeolake (Kreis Segeberg, Schleswig-Holstein) revealed not only Late Palaeolithic lithic

artefacts but also preserved organic material in the form of reindeer bones and antlers (Weber et al. 2011; Wild 2017). The typological dating of the artefacts, as well as the radiocarbon dating of antlers, resulted in a Lateglacial dating and thus document one of the few Lateglacial sites with organic preservation in northern Germany.

The preliminary investigations of Hartmut Usinger in the area of the Nahe palaeolake revealed that sediments deposited during the Lateglacial partially feature annual lamination and still rest undisturbed in the deepest part of the former lake basin. In combination with the proximity to an archaeologically confirmed Palaeolithic hunting site, the Nahe palaeolake (NAH) is, hence, an excellent location for interdisciplinary investigations of the Lateglacial vegetation history and the Palaeolithic human-environmental interaction. Therefore, the main objectives of this Ph.D. project were the following:

- Firstly to process legacy data by Hartmut Usinger in order to contribute to the static discussion of Lateglacial terminology with the aim of a better comprehension of existing difficulties and challenges.
- Secondly, to enhance our knowledge of Lateglacial vegetation history (through the main analysis on sediments from the Nahe palaeolake), whereby a robust absolute-chronological framework (based on ^{14}C dates, varve counting and tephra layers) would allow for a comparison of the established local and regional biostratigraphy (based on pollen and botanical macrofossils) with important European key sites.
- Thirdly, the evaluation of the obtained record with regard to potential reflections of human action and further, the creation of an explanatory model in order to evaluate possible changes and transformation processes in human interaction with the environment.

The general research strategy was to work on the legacy data of Hartmut Usinger and to build up a comprehensive dataset of Lateglacial pollen profiles from Schleswig-Holstein until the permission for sediment corings at the Nahe palaeolake were granted. Following the coring campaign in October 2017, palynological, geological and geochemical analyses were performed. The varve countings were carried out by Stefan Dreibrodt (CRC-F2), additional XRF scans and organic biomarker analysis was processed by Jan Weber (CRC-E1). Early in this Ph.D. project it was possible to learn the processing and analyses techniques of tephrochronology that subsequently were applied to the sediment sequences on the basis of pollen stratigraphic events. The necessary analyses on the geochemical composition of shards was carried out by Christel van den Bogaard (GEOMAR, Kiel). The results will be published in the articles belonging to this thesis in cooperation with the respective colleagues.

2.3 Main questions

The main questions of this thesis concern three aspects:

1. Lateglacial terminology
2. Lateglacial vegetation history
3. Lateglacial human-environment-interaction

2.3.1 Terminology of Lateglacial research

Within the context of this Ph.D. project I had been granted access to the comprehensive legacy data of Hartmut Usinger. It contained an unpublished dataset from a 1982 drilling campaign at Bølling Sø (Denmark). Therefore the focus at the beginning of the project was set on the following questions:

- Can the processing of the Bølling Sø's data set make a valuable contribution to the static discussion of general Lateglacial terminology by approaching the original and main characteristics of the term *Bølling* at the type locality?
- Can this data set be the basis for a subsequent main investigation at the Nahe palaeolake by contributing a comprehensive biostratigraphical terminology?

The same data set allowed a comparison of the methods to separate birch pollen-types. Consequently, the following questions arose:

- Are there any differences between the results of the two methods of separating birch pollen-types (pollen-size-frequency-distribution/approximation approach and fixed threshold) when applying them to the same data set?
- Is the separation of birch pollen types of the Bølling Sø data set able to clarify potential earlier misinterpretations?

2.3.2 Lateglacial vegetation history

From the beginning of the Ph.D. project the question prevailed whether a pollen archive could be found that fulfilled the requirements mentioned at the beginning. In the context of the processing of the legacy of Hartmut Usinger it became clear that the Nahe palaeolake (NAH) is extraordinarily well suited. After a coring campaign in October 2017 the sediments from the NAH location were subject to intensive palynological analyses. Based on this new dataset the following questions were formulated:

- Can a high-resolution pollen profile contribute to improve the previously valid regional pollen zones (Usinger 1985)?
- Can traces of volcanic eruptions be found in the sediment sequence that allow to directly correlate the NAH record with European key sites?

- How fast do phases of vegetative transformations occur?
- How do the first reliable evidence of trees (i.e. tree birches) date at the NAH location?
- Can riparian forests be assumed for Schleswig-Holstein during the cold phases?
- What additional information can be gained from the record of non-pollen-palynomorphs and charcoal particle size classes?

2.3.3 Lateglacial human-environmental interaction

The proximity to the Palaeolithic archaeological site Nahe LA11 favours the investigation of the following questions concerning palynological anthropogenic indicators:

- How fast do environment changes occur and how fast are humans confronted with adaptation pressure?
- Is human-environmental interaction reflected in the palynological record?
- In which way is it reflected and what are plausible causes?
- How can we explain changes within proxies of human action?
- Can identified phases of human-environmental interaction be clearly assigned to archaeologically defined cultures?

2.4 Concept

The three question blocks will be discussed in five manuscripts. The respective objectives and their general context is briefly presented below.

2.4.1 Defining the frame (Appendix I)

A fundamental and general discussion of the terminology and concepts of Lateglacial designations has been attempted several times (De Klerk 2004; Mangerud et al. 1974; Usinger 1985). Although of meticulous profoundness, they have led to an even greater diversity in the use of terms. Therefore, a further discussion must refrain from providing new terms or new definitions and should instead concentrate on the most basic existing terms in use. The already mentioned previously unpublished data set by Hartmut Usingers from Bølling Sø (Denmark) provides such an opportunity. The data set allows a comprehensive investigation of the origin of the Bølling-Oscillation *sensu* Iversen (1942). In this part of the thesis the data set will be processed and discussed in order to address used concepts directly with data from the type locality. In this way, a contribution to the rigid discourse of terminology can be made. This resulting terminology is applied to all following investigations.

The further four parts are based on the analysis of the sediments deriving from the Nahe palaeolake. Each of them represents an independent study (tephrostratigraphy, sedimentology and chronology, vegetation history) or a discussion of specific proxies (human-environmental interaction).

2.4.2 Connecting Europe (Appendix II)

Volcanic ash layers represent chronological markers in sediment archives. From the Lateglacial and early Holocene there are numerous known tephra layers that have been deposited in lakes and bogs of Northern Europe (Borobol, Penifiler, Laacher See, Vedde, Askja, Hässeldala, Saksunarvatn; Blockley et al. 2014; Pyne-O'Donnell et al. 2008; Wastegård et al. 2018). However, except for the evidence of the Vedde Ash in an archaeological context (Ahrenshöft, Housley et al. ,2012), there are no known ash layers from investigated sediments deposited during the Lateglacial in Schleswig-Holstein. As a result, it has not yet been possible to directly compare regional pollen profiles in a European context using event stratigraphy.

In order to learn the processing technique and quantification of Cryptotephra shards on the one hand and to put the NAH data set into the European context and thus into value on the other hand, the sediment was examined for volcanic ash layers in this part of the thesis.

2.4.3 Comprehending depositions – date the dirt (Appendix III)

An important requirement for the interpretation of the palynological record is a complete and undisturbed sediment sequence and a robust chronology. In cooperation with the F2 and E1 subprojects of the SFB 1266⁸, an age-depth model based on radiocarbon dates, volcanic ash layers and varve counting has been created.

Considering the undisturbed sedimentation without recognizable hiatuses and sequentially annual lamination (the only investigated in Schleswig-Holstein so far) the preconditions were excellent for further sedimentological investigations based on a geochemical method (XRF).

This part of the thesis provides the age-depth model (ADM) of the record and contributes to the understanding of sedimentation as well as changing climatic conditions. Primary author of the manuscript is Stefan Dreibrodt. My contribution to this article consisted mainly of discussing the palynological data of the laminated section, identifying pollen events that in analogy could be used as further dates for the ADM and proof reading.

⁸ F2: Socio-environmental transformations and interdependencies; E1: Transformations in early Greek societies and landscapes.

2.4.4 Pollen, plants and pioneers (Appendix IV)

This part of the thesis comprises the palynological analysis. The undisturbed and partly annually laminated sediments for the first time allow creating a complete profile of the Lateglacial in Schleswig-Holstein. This contributes to clarify existing ambiguities in the vegetation history of Schleswig-Holstein. The reconstruction of the vegetation history is supported by information from the analysis of botanical macrofossils.

The study connects former local and regional pollen profiles and builds bridges between records from Scandinavia and northern central Europe via the existing event stratigraphy. The high resolution of the record and a robust age-depth model allows to (i) improve our understanding of the vegetation history, (ii) record the temporal framework, (iii) better understand transformations within the vegetation, and (iv) provide a base for a comparison of these transformations.

2.4.5 Transformation and adaptation (Appendix V)

The study of human interaction with the environment prior to the Neolithic period has for long been perceived as difficult (Behre 1981; Bos and Janssen 1996; Iversen 1941). For the actual palynological assessment of Palaeolithic human action several prerequisites are required, all of which are fulfilled at the NAH location.

For the first time in a Lateglacial context, charcoal particles and non-pollen-palynomorphs are considered in a palynological study in Schleswig-Holstein. Based on these selected proxies and additional archaeological information, a discussion of human interaction with the changing environment is given. Here, not only the proximity of the coring location to one of the rare Palaeolithic sites with organic preservation is decisive, but also the short distance to the eponymous Ahrensburg tunnel valley.

This part of the thesis discusses indicators of human-environmental interaction and proposes an explanatory model to describe adaptation processes triggered by environmental changes at the Pleistocene-Holocene transition.

3. Methodological background

3.1 Entanglements of Lateglacial terminology

Current knowledge about environmental conditions and transformations of the Lateglacial is based on a variety of data sets from ice-core, marine and terrestrial records (Brauer et al. 1999; Hoek 1997; Hoek et al. 1999; Iversen 1942; Johnson et al. 1992; Litt et al. 2001; Lotter 2001; Mortensen et al. 2011; Müller and Stein 2014; Overbeck 1975; Schütrumpf 1935; Usinger 1975; 1982; 1985; Van Geel 1989). They are united by their temporal scope but also by the seemingly insoluble historical bag of terms used differently between countries and scientific schools. The different terms utilized for Lateglacial periods, phases, biozones, chonozones or oscillations thereby suggest a temporal correlation across disciplines that is inexistent (tab. 1).

In this context, even terms of a conceptual unit – such as biostratigraphy – are used in different ways. Designations such as *Meiendorf*, *Allerød* or *Bølling* were (Firbas 1949; Litt and Stebich 1999; Menke 1968; Merkt and Müller 1999; Overbeck 1975) and are still used (Kobe et al. 2019; Mortensen et al. 2014b) as well as redefined (Usinger 1985), contributing to a confusion of terms that can hardly be resolved. This is supplemented by the use of epithets such as younger, older or oldest (Iversen 1954), as well as early and late (Hoek 1997; Van Geel 1989).

The attempt to thoroughly approach the complex entanglement of Lateglacial terms has already been made by Pim De Klerk (2004). In his article, De Klerk demanded to see a dataset from the Lake Bølling that Usinger had referred to in different papers and personal communication since 1982 (Usinger 1985; Usinger and Wolf 1982) but that in the same time had never been published.

For the present work, this specific dataset had been available. Based on the previously unpublished data set of Lake Bølling, Appendix I refers in detail to a key aspect of the terminological obstacle. At this point the research-historical entanglements of the terms and their origins, but in particular the effects of the resulting misunderstandings, will be dealt with exemplarily.

There are four central terms in the Lateglacial biostratigraphy: *Meiendorf*, *Allerød*, *Bølling* and *Dryas*, each featuring an epithet. The original connotation of the terms is listed in the following overview:

term	discipline	original connotation	reference
Dryas-[...]	Geology/ Botany	Clayey sediments containing arctic flora including prominent fossils of <i>Dryas octopetala</i> were referred to as <i>Dryas-clay</i> . The period that was expected to have large proportions of corresponding plant communities (summarized as <i>Dryas flora</i>) was labelled <i>Dryas-zone</i> .	(Sernander 1894)
Allerød-[...]	Geology/ Botany	Originally <i>Allerød-Oscillation</i> . Organic gyttja or peat containing macrofossils of tree birches. Organic layers are underlayed and	(Hartz and Milthers 1901) (Hartz 1912)

		overlayed by clayey deposits including macrofossils of the <i>Dryas flora</i> .	
Bølling-[...]	Palynology	Originally Bølling-Oscillation . <i>Betula</i> pollen peak (originally interpreted as <i>B. alba</i> /tree birch pollen-type) prior to the <i>Betula</i> pollen increase of the Allerød-Oscillation (that in turn had never been specified at the type locality Allerød).	(Iversen 1942)
Meiendorf-[...]	Palynology	Originally Meiendorf-Intervall . Increase in <i>Betula</i> type pollen and <i>Artemisia</i> before the tree birch expansion of the Bølling sensu Iversen (although the Bølling period forms part of the Allerød-Oscillation in the Glüsing and Stellmoor profile at which the term Meiendorf-Interval is defined).	(Menke 1968)

According to Hedberg (1976) and the international stratigraphic guide, the fossil content of the sediments determines their biostratigraphical designation. In this sense all of the four terms are biostratigraphic terms and should only be used in this context. Biostratigraphic terms in turn are valid only locally and in some cases regionally, as the content of fossil bearing strata is dependent on available soils and their quality, migration speed of plants and climatic conditions (Firbas 1949). This specific fact – the limited range of terms – is the core of confusion.

When the Allerød-Oscillation was recognized by Nikolaj Hartz and Vilhelm Milthers (1901) and finally labelled as such by Hartz (1912), the term referred to local geological characteristics and the macrofossil content of strata⁹. Based on these information and on investigations of Alfred Gabriel Nathorst (1891) into Lateglacial depositions from southern Scandinavia, Knud Jessen proposed regional characteristics of Allerød deposits and the Allerød period in 1935. In his *Summary of Pollendiagrammatical Zones* characteristic pollen features were defined that he suspected to be generally valid for Northern Jutland. These assumptions, however, were not based on a pollen profile from the Allerød location, but based on a pollen profile from Brøndum bog (fig. 7). Jessen's classification, and hence geographical extension of the term Allerød, is another aspect of subsequent misunderstandings. With his overview on pollen zones Jessen defined key characteristics, but pollen analysis was never carried out on sediments from the Allerød type locality on Sealand. It follows that the actual pollen analytical characteristics of the Allerød-Oscillation were never determined and from then on remained a matter of interpretation.

⁹ The macrofossil content did not specifically relate only to plant macrofossils but also to fauna. A decisive component of the Allerød gyttja should be bones of elk, whereas *Dryas* clays could be identified by the presence of reindeer bones (Hartz 1912).

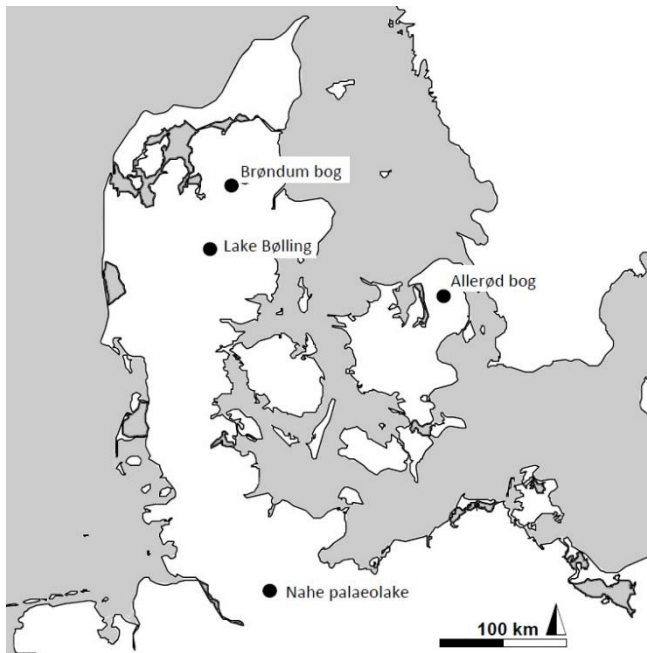


Figure 7: Overview on the locations of important type localities and geographical relation to Brøndum bog and the Nahe palaeolake.

The increasing number of investigations resulted in compilations and overviews that are still in use today (Firbas 1949; 1952; Overbeck 1975). In such an overview Firbas (1949) applied Lateglacial pollen zones as introduced by Jessen (1935) to the whole of Germany and partly beyond. Since that time the classification of periods based on specific pollen features and the respective designations were regarded as fixed. This partly still today legitimizes term use, extensions and redefinitions.

A representative example of unjustified and misleading use of designations is the work of Fletcher et al. (2007) from Portugal. A

Lateglacial pollen profile from the Algarve assigns a pollen zone to *the Allerød*, in which an extensive spread of oak forests predominates (inferred from maxima in *Quercus* evergreen type pollen and *Quercus* deciduous type pollen), although without any relation to the Allerød-period *sensu* Jessen.

Fletcher et al. (2007) do not refer to this pollen zone as Allerød phase or period, but as *Allerød chronozone*¹⁰. This classification is made as the climate was temperate and the landscape extensively forested but first and foremost because it corresponds to the time interval given for the respective chronozone (Fletcher et al. 2007).

The use of the term Allerød chronozone follows the work of Mangerud et al. (1974). It was already clear in the 1970s that the terminologies used in Lateglacial research, despite of lithostratigraphic, biostratigraphic or morphological, climatological or chronological assignment, needed correlation and common classification. Mangerud et al. (1974) mainly used pollen profiles of northern Europe and the boundaries of the pollen zones attributed to e.g. the Allerød-Oscillation (Iversen 1942; 1954; Menke 1968; Van der Hammen et al. 1971). Ages were interpolated from the few available ¹⁴C dates of the pollen profiles to finally create units – chronozones. They suggested a simultaneity that did not exist. The more serious problem was that the names of the chronozones (Allerød-Chronozone; Bølling-Chronozone, etc.) were now linked to absolute ages and no longer to the original contents. Since the introduction of this linkage the terms were used worldwide as demonstrated in the work of Fletcher

¹⁰ In the original publication referred to as *PAB* (pollen assemblage biozone).

et al. (2007). The following table gives an impression of the different use of the terms in different disciplines, regions and their respective dating:

used term	discipline./stratigr.	geographical scale	absolute age	reference
Bølling-Oscillation	Palynology	northern Jutland	-	(Iversen 1942)
Bølling-Oscillation	Palynology	The Netherlands	-	(Van der Hammen 1951)
Bølling-Interstadial	Palynology	Schleswig-Holstein	10,500-10,100 BC	(Menke 1968)
Bølling Chronozone	Chronostratigraphy	Scandinavia	13,000-12,000 BP	(Mangerud et al. 1974)
Bølling Interstadial	Palynology	Bornholm	-	(Usinger 1978a)
Bølling <i>sensu lato</i>	Palynol./Biostrat.	The Netherlands	12,900-12,100 ± 100 BP	(Van Geel 1989)
Bølling <i>sensu stricto</i>	Palynol./Biostrat.	The Netherlands	12,400-12,100 ± 100 BP	(Van Geel 1989)
Bølling	Palynol./Biostrat.	The Netherlands	12,450-12,100 BP	(Hoek 1997)
Bølling	Palynol./Biostrat.	N Lower Saxony	13,620-13,520 cal BP	(Merkt and Müller 1999)
Bølling biozone	Palynol./Biostrat.	Eifel region	13,670-13,540 varve yr. BP	(Litt and Stebich 1999)
Bølling Chronozone*	Palynol./Biostrat.	Europe	13,000-11,800 BP	(Jacomet and Kreuz 1999)
Bølling-Interstadial*	Geology/Biostrat.	Lower Saxony	13,730-13,480 cal BP	(Pott 2005)
Bølling Horizon	Climatol./Ice cores	north. Hemisph.	14,692-14,075 b2k	(Rasmussen et al. 2006)
Bølling-Interstadial	Geology/Biostrat.	Germany	13,670-13,540 varve yr. BP	(Litt et al. 2007)
Bølling-Interstadial	Palynol./Biostrat.	Jutland	14,700-14.100 cal yr. BP	(Mortensen et al. 2011)
Bølling period*	Palynol./Biostrat.	The Netherlands	12,400-12,000 BP	(Cappers and Neef 2012)
Bølling period	Palynol./Biostrat.	Falster	14,200-14,000 cal yr. BP	(Mortensen et al. 2014b)
Allerød-Oscillation	Geology/Botany	Jutland	-	(Hartz 1912)
Allerød-Interstadial	Palynology	Schleswig-Holstein	9,800-9,000 BC	(Menke 1968)
Allerød Chronozone	Chronostratigraphy	Scandinavia	11,800-11,000 BP	(Mangerud et al. 1974)
Allerød	Palynol./Biostrat.	Schleswig-Holstein	-	(Usinger and Wolf 1982)
Allerød	Palynol./Biostrat.	The Netherlands	11,900-10,950 BP	(Hoek 1997)
Allerød-Interstadial	Palynol./Biostrat.	Schleswig-Holstein	-	(Usinger 1998)
Allerød period	Palynol./Biostrat.	N Lower Saxony	13,260-12740 cal yr. BP	(Merkt and Müller 1999)
Allerød biozone	Palynol./Biostrat.	Eifel region	13,350-12,680 varve yr. BP	(Litt and Stebich 1999)
Allerød Chronozone*	Palynol./Biostrat.	Europe	11,800-11,000 BP	(Jacomet and Kreuz 1999)
Allerød-Interstadial*	Geology/Biostrat.	Lower Saxony	13,350-12,700 cal BP	(Pott 2005)
Allerød Interstadial	Palynology	Schleswig-Holstein	11,700-10,700 cal yr. BC	(Nelle and Dörfler 2008)
Allerød period	Palynol./Biostrat.	Jutland	14,000-12,800 cal yr. BP	(Mortensen et al. 2011)
Allerød period*	Palynol./Biostrat.	The Netherlands	11,800-10,800 BP	(Cappers and Neef 2012)
Allerød period	Palynol./Biostrat.	Falster	13,800-12,600 cal yr. BP	(Mortensen et al. 2014b)
Bølling-Allerød Complex	Palynology	Schleswig-Holstein	-	(Usinger 1985)
Bølling-Allerød Oscillation	Climat./Palynol.	North America	13,000-11,000 yr ¹⁴ C yr. BP	(Yu and Eicher 1998)
Bølling-Ållerød Interstadial	Climatology	India	15,200-11,700 ka BP	(Sinha et al. 2005)
Bølling-Allerød Interst. Compl.	Palynology	Europe	-	(Simikova 2005)
Bølling-Allerød period	Climatology	East Africa	14,200-13,200 kyr BP	(Tierney and Russell 2007)
Bølling-Allerød period	Climatology	Indonesia/Austral.	14,700-13,000 kyr BP	(Mohtadi et al. 2011)
Bølling/ Allerød Interstadial	Biostratigraphy	Bering Land Bridge	14,900-12,900 yr. BP	(Wooller et al. 2018)

Table 1: Term overview. *Biostratigraphy* implies that apart from palynological results also macrofossils, foraminifers, or chironomids have been used. Terms marked with * are published textbook terms.

Unclear designations of terms create even more confusion when used in interdisciplinary research. Finally, this also has important and often unrecognized effects on archaeology and can be explained as follows:

In each of the original publications (Bølling-Oscillation, Allerød-Oscillation, Meindorf-Interval) it is assumed that climatically more favourable periods caused the observed vegetation developments (Hartz 1912; Iversen 1942; Menke 1968). The importance of the role of climate is indicated by the chosen epithets – *Oscillation* and *Interval*.

Although these terms were clearly linked to biostratigraphic developments, they were used in climatostratigraphy. Before the introduction of event stratigraphy by the INTIMATE Group (Björck et al. 1998), identified phases of the Lateglacial Interstadial were supplemented or equated by common terms of Quaternary research (Dansgaard et al. 1993; Johnson et al. 1992; fig 8).

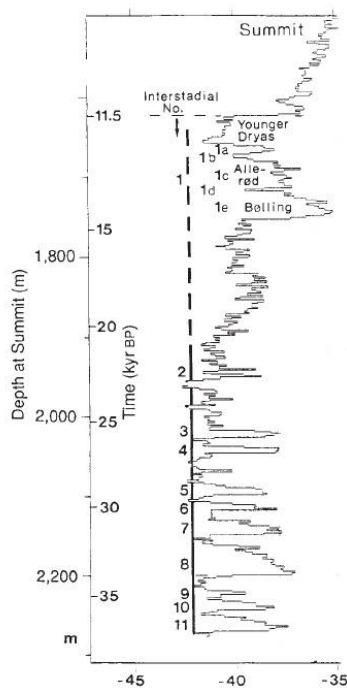


Figure 8: Part of the Summit $\delta^{18}\text{O}$ profile as given in Johnson et al. (1992).

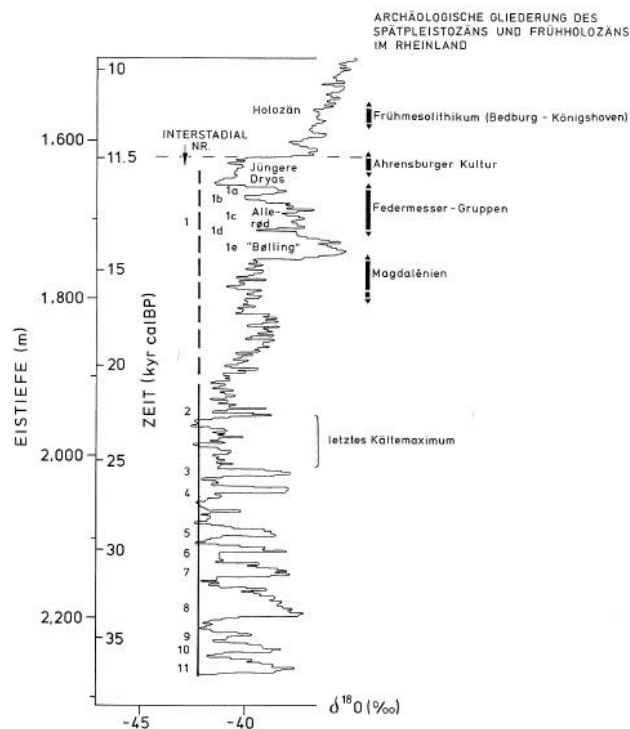


Figure 9: Figure as given in Street et al. (1994), modified after Johnson et al. (1992) and including archaeologically defined cultures.

Considering that ice core isotopic data is partly valid globally, but only for one hemisphere, it would be justified to equate the Bølling-Oscillation *sensu* Iversen (1942) with the GI-1e (Dansgaard et al. 1993; Johnson et al. 1992) at the Bølling type locality (Appendix I). This justification would arise from the fact that the local and regional vegetation changes, which are summarised by Iversen (1942) under Bølling-Oscillation, are predominantly local and regional consequences of climatic alterations.

A generalisation, i.e. a supra-regional or even continental equation of GI-1e with Bølling-Oscillation is, however, not justified, but is suggested by figures in corresponding publications (Dansgaard et al. 1993; Johnson et al. 1992).

Prehistoric archaeology in particular cooperates closely with various natural sciences. Traditionally, archaeological research has also used terms of biostratigraphy in order to correlate archaeologically defined cultures with relative chronologies (Schütrumpf 1935; 1936; 1937; 1943; 1958a; 1958b; Usinger 1998). As research progressed, however, these relative chronological phases in archaeology were transferred to absolute chronological periods. The possibility of correlating radiocarbon-dated archaeological finds directly with an absolute chronology and also with climatic events is a milestone in prehistoric research. However, the use of the original biostratigraphic designations has even more profound effects here.

Back to our chain of entanglement, the article *Absolute chronology of the late Palaeolithic and early Mesolithic in northern Rheinland*¹¹ (Street et al. 1994) can be given as an example in archaeology.

In the paper, archaeological ¹⁴C data is connected with the climatic phases as recorded in the Summit ice core data (Johnson et al. 1992). For the subsequent periodization, terms such as *Beginning Bölling Interstadial* and their absolute dating were taken directly from the publication by Johnson et al. (1992), including the equation with climatically defined phases and events (GI-1e, GI-1c to 1a). At this point the terms *Allerød* and *Bølling*¹² are loaded with dating and reconstructed climatic conditions (fig. 9). For archaeological research, this results in two phases that are labelled *Bølling-Zeit* and *Allerød-Zeit*. These designations have an absolute chronological frame and thus can be correlated with climatic events and phases. The problem is that biostratigraphically derived terms (*Allerød/Allerød-[...]* and *Bølling/Bölling-[...]*) are not used as such, but as a concept of environmental conditions (regional climate, fauna, vegetation) in an absolute chronological framework, detached from a geographical scale and especially detached from the respective conceptual problems and original contents of designations. This is exemplary for the use of the terms in archaeological research of the Lateglacial until today.

By Street et al. (1994) the *Allerød-Zeit* is correlated with the GI-1c₃ to GI-1a based on the Summit ice core data. Other, also more recent studies by e.g. Riede et al. (2010) correlate the *Allerød* with the GI-1c₁ to GI-1a by separating an early phase of the *Allerød* (by a cooler phase, GI-1c₂) with *Bølling* (GI-1c₃), based on the NGRIP ice core data. These two articles may serve as examples for the entanglement of terms at an even higher level, i.e. if archaeology were to make a comparison between *sites of Allerød*

¹¹ Original title: Absolute Chronologie des späten Paläolithikums und Frühmesolithikums im nördlichen Rheinland

¹² In the publication (Street et al. 1994) terms have inconsequently been spelled as *Allerød* and *Bølling* as well as *Alleröd* and *Bölling*.

age^{13} across a geographically larger area. In addition to the problem of temporal comparability, there is the fact that no uniform ecosystems are compared in a supra-regional, or even continental comparison.

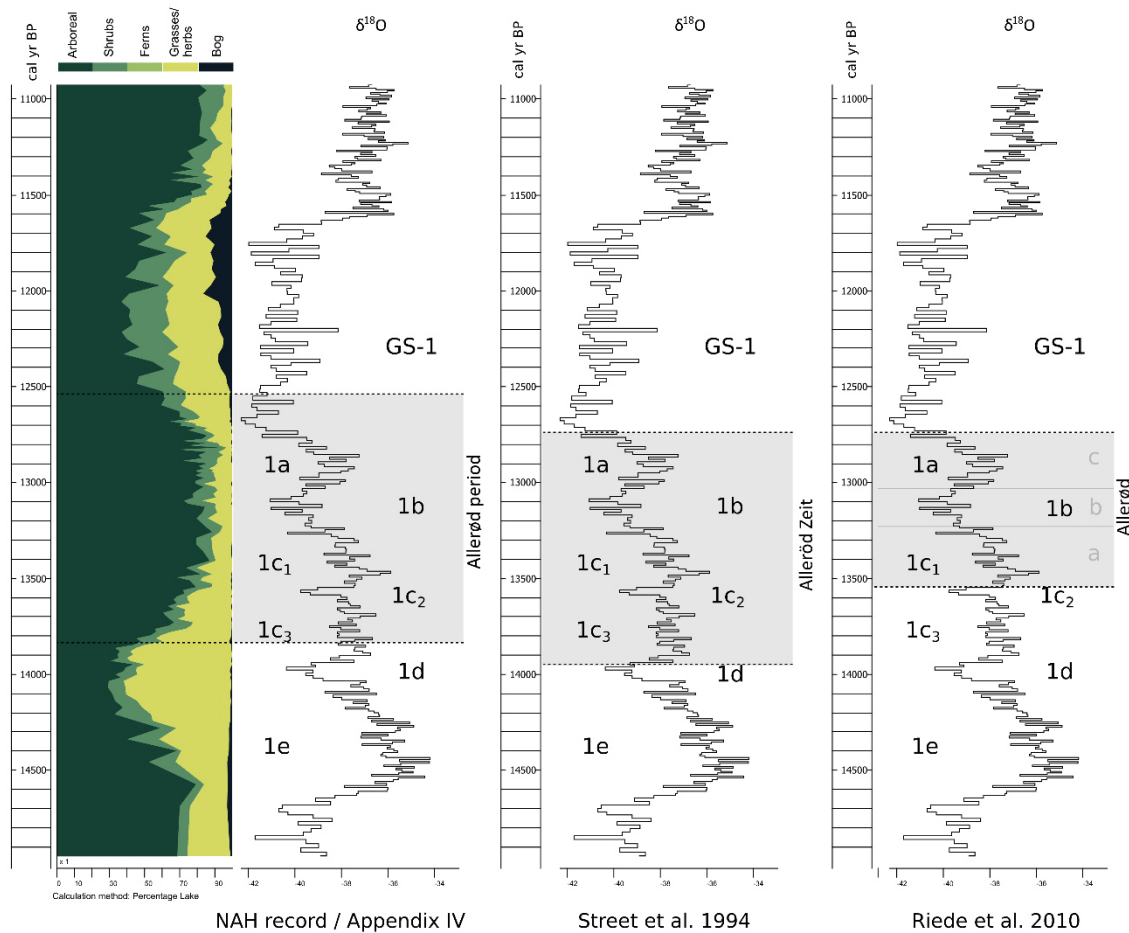


Figure 10: Composite pollen profile of the NAH sequence between 11,000 and 15,000 cal yr BP age-correlated with the GRIP $\delta^{18}O$ data (GICC05modelext timescale for the GRIP ice core and resampled data series after Rasmussen et al. (2014) and Seierstad et al. (2014)). Marked areas show temporal extend of the respective terms according to climatic data as given by the different authors.

According to the assumed vegetation Street et al. (1994) divide the Lateglacial interstadial into an open phase (Bølling) and a forested phase (Allerød). This equation highlights a further generalisation often used in archaeology. In this case climatic oscillations, as traced by isotopic data, are temporally equated with vegetation types. Of course the natural vegetation does react rapidly to strong climatic alterations. However, a time lag exists between climatic changes and the palynologically reflected responses of the vegetation (Hoek 2001). This in turn is related to migration speed of plants, the distance from their pleniglacial refugia, their resilience, soil development or erosion and actual

¹³ "allerødzeitliche Fundstellen"

regional effects of climatic changes (Firbas 1949). As demonstrated in figure 10, this results in the fact that the designation Allerød-period does not statically refer to a temporally fixed climatic oscillation. Chronology-based comparisons show that the biostratigraphically defined Allerød-period at the NAH location is reflected approximately 100 years after the beginning of the GI-1c₃. At the same time the Allerød-period does extend far into the GS-1 and, hence, to a time about 150 years after the termination of the GI-1a.

Such time lags do differ with regard to the investigated location. Also uncertainties in respective age-depth models are possible causes of false correlation and misinterpretations. Nevertheless, the circumstance of a delayed response of the vegetation to climatic shifts – especially deteriorating shifts – should be considered in future archaeological research.

If the boundaries of the Allerød-period were set strictly according to the definition based on the type locality (Hartz 1912; Hartz and Milthers 1901) at each examined location, gyttja and peat formations with first evidence of tree birches are absolute-chronologically very different in the respective regions. Referring this back to the given example (Street et al. 1994), organic gyttja depositions including first macrofossils of tree birches are recorded in the Neuwied Basin by around the GI-1e (Wiethold and Baales 2002). Note that comparable findings are observable in Denmark or Schleswig-Holstein not before the GI-1c (Appendix IV; Mortensen et al. 2011; 2014a; 2014b).

From the above, as well as from table 1 and figure 10, it can be deduced that a comparison of *Allerød-aged* or *Bølling-aged* strata, find spectra or vegetation should not be made (Eriksen 2002). This is for the simple reason that for each individual location it must first be clarified which temporal frame and which contents are linked to it. In principle, this should be clear from the terms themselves – a characteristic that has been lost over time and the application in different disciplines across a geographically large area.

The event stratigraphy proposed by the INTIMATE Group (Björck et al. 1998; Rasmussen et al. 2006; Rasmussen et al. 2014; Seierstad et al. 2014) could offer a solution to these entanglements and the inevitable misunderstandings. Climatic and thus global events are temporally almost synchronous. But as already shown by e.g. Rasmussen et al. (2006) there is an uncertainty in every ice core timescale. As a result, climatic phases, (e.g. the deviation of the Glacial Interstadial 1) are not congruent with each other when compared between different ice core data sets (see fig. 2 in 1.1 Lateglacial archaeological background). Additionally, other absolutely dated environmental investigations (palynological, sedimentological, geochemical and radiometric dating) have uncertainties.

Therefore, archaeological research needs to use environmental and climatic data with caution when intending to contextualize ¹⁴C dated cultural groups.

If archaeological investigations still aim at referring to phases of vegetation development and thus historically burdened terms of biostratigraphy, a palynological near-site investigation is imperative in order to justify the terminologies used in individual cases and to confront results with the original content of designations. In a wider European context, however, it is generally not advisable to use them.

Moreover, it is always desirable to carry out analysis on cryptotephra. In this way the record can be integrated even more precisely into event stratigraphy. The investigations of the Nahe palaeolake sediments provide an example of how event stratigraphy and biostratigraphic terms can be used in an unchanged original context, even in relation to archaeological investigations (Appendix II and IV). The general application of terms in this thesis is explained in Appendix VI.

3.2 Human indicators in pollen diagrams

Almost every human action had and still has effects on the natural environment. Initiated by the work of Firbas (1937) and Iversen (1941), pollen analysts were subsequently not only focusing on vegetation history but also on the definition of anthropogenic pollen indicators to define human driven vegetation changes (Behre 1986; Behre 1992 and literature cited therein).

Today, classical anthropogenic indicators are divided into primary and secondary anthropogenic pollen indicators (Behre 1988; Cappers and Neef 2012; Jacomet and Kreuz 1999). As mostly crops are assigned to the former it is evident that these classical pollen indicators of human activity are linked to cultivation. This fact limits their applicability temporally to the beginning of the Neolithic period. The impact of prehistoric man prior to the Neolithic period was, however, regarded as minor and nearly undetectable:

The primitive cultures of the Early Stone Age could have but little effect on the forest growth. The hunters had their paths as the animals their tracks; and just as the vegetation around bird colonies receives its character from the manure supplied to it, that in the immediate vicinity of Mesolithic settlement was characterized by midden plants. Man's influence on the vegetation did not extend far: the virgin forest closed in a few paces outside the settlement, and there nature alone determined what was to grow (Iversen 1941, 20).

However, in a later section of his fundamental work *Land occupation in Denmark's Stone Age*, Iversen (1941, 20-68) highlights the indicative value of Chenopodiaceae pollen in connection with the Mesolithic Gudenå culture. Iversen assumes that human action is not only reflected by the occurrence of Cereal pollen (cultivation) but also by the reduction of arboreal pollen (AP) (landscape opening) and specific non-arboreal pollen types (NAP) to which e.g. the family of Chenopodiaceae is assigned.

Chenopodiaceae are considered secondary anthropogenic pollen indicators (Behre 1988; Cappers and Neef 2012; Jacomet and Kreuz 1999). The obstacle with many of these secondary indicators and especially with Chenopodiaceae pollen is that the respective plants also belong to the natural (nitrogenous) bank vegetation of lakes and rivers (Behre 1981). Therefore, in absence of primary indicators – which would be the case in Early Holocene and Lateglacial records – only a coincidence of several contemporary rising values of secondary indicators could potentially be interpreted as anthropogenic. From this, three general statements can be made for reflections of pre-Neolithic human activity in pollen profiles:

1. The foraging way of life has an ephemeral character regarding the impact on the natural vegetation. Therefore it needs to be discussed whether a short-termed stay of hunter-gatherer groups at one site will affect the pollen rain of the subsequent vegetation period at all.
2. If the former is the case, it will only be possible to detect such minor alterations in the pollen composition if (i) an analysis is carried out at very high resolution, (ii) a sampled archive has a comparably small catchment area and hence prevents the effect that regional pollen input dominates and blurs the local pollen input and (iii) the camp site lies close to the sampled archive (Bos and Janssen 1996; Hicks 1988).
3. Secondary pollen indicators have so far been applicable in forested (mainly Holocene) environments (Bos and Urz 2003; Kamerling et al. 2016; Wolters et al. 2005). Only few investigations considered secondary indicators in open areas (Aronsson 1991; Aronsson 1994; Hicks 1993). Therefore, the questions arises whether (i) secondary anthropogenic indicators are applicable also in open Lateglacial woodland and tundra landscapes and (ii) what other microfossils can be indicative of anthropogenic activity.

With respect to the latter, the vegetation of Lateglacial northern central Europe is dominated by shrub or grass tundra in different phases. Several secondary anthropogenic pollen indicators are part of these tundra communities (Poaceae, Chenopodiaceae, Caryophyllaceae; Plantaginaceae, *Juniperus* sp., *Artemisia* sp., *Rumex* sp.) during the colder periods and recorded in the pollen spectrum at even high levels (Appendix IV; Hoek et al. 1999; Merkt and Müller 1999; Mortensen et al. 2011; Schütrumpf 1943; Usinger 1985). Other species as *Urtica* sp. or *Filipendula* sp., that are nitrophytes and hence promising indicators of human presence, occur naturally during more moderate climatic phases of the Lateglacial Interstadial (Appendix IV; Usinger 2004). Further species that are considered secondary indicators (*Centaurea cyanus*, *Agrostemma* sp.) are in turn not recorded at all, as they are predominantly associated with arable fields and hence cultivation.

For the interpretation of a Lateglacial pollen profile regarding the reflection of human action only a very limited number of pollen types therewith remains indicative. Nevertheless, the spread of the

corresponding plants can generally also be attributed to natural processes and is mostly related to climate. As pollen analysis alone cannot provide sufficiently reliable evidence on anthropogenic activity, palynology needs to utilize further microfossils.

Such can be NPPs that are more and more routinely recorded during a palynological analysis. A group of direct anthropogenic indicators among NPPs are different chitinous egg cuticles of parasites (e.g. *Trichuris trichiura*) (Van Geel et al. 2003). However, early records of eggs of intestinal parasite whipworms do not outdate the Neolithic period (Le Bailly et al. 2007). Higher quantities would require equally high abundances of the culture media (human faeces) and are mainly known from latrines of the roman, medieval or modern era (Bosi et al. 2011; Brinkkemper and van Haaster 2012; Fernandes et al. 2005). Nevertheless, comparable high concentrations of excrements are not expectable in a Lateglacial context and around seasonal Palaeolithic or Mesolithic camp sites. Hence, egg cuticles cannot be excluded as human indicator but are unlikely to occur in Lateglacial/ Early Holocene records. In contrast to that there is a large group of coprophilous fungal spores that do occur in palynological records of Pleistocene as well as Holocene records (Bos et al. 2013; Van Geel et al. 2007). In Mid to Late Holocene contexts, these can e.g. provide evidence on pastoralism or wood pasture (Feeser and O'Connell 2009; Richardson 2001). If recorded in early Holocene or Lateglacial depositions, fungal spores can at least indicate presence of large herbivores (Bos et al. 2005). As these fungal spores are mostly but not exclusively coprophilous (Perrotti and van Asperen 2018; Van Geel and Aptroot 2006) every case study needs to discuss their indicative value in the respective context (Appendix V).

Certainly, the presence of large herbivores does not synchronously suggest human presence. People and their interaction with these herbivores (hunting or even domestication) needs to be substantiated further by interdisciplinary archaeological and scientific investigations, including palynological proxies. Especially in the case of Lateglacial and early Holocene contexts, charcoal particles may represent a further proxy.

Unfortunately, the record of charcoal particles in palynological investigations is still no standard procedure. On the one hand, this might be conditioned by the focus of palaeo-environmentalists to vegetation history. On the other hand, a record of charcoal particles might often be neglected due to the lack of identification standards. But if recorded, the indicative value of charcoal particles needs to be discussed carefully (Appendix IV and V).

Fire is considered a key characteristic of even early human activity, indicating that charcoal particles feature a high indicative value when investigating human-environmental interaction.

Nevertheless, wildfires have naturally occurred since the Palaeozoic Era (345 mya) (Falcon-Lang 2000; Scott 2000), representing a key process in the natural ecosystem (Pausas and Keeley 2009). Natural inflammation can have several different causes. These include volcanic activity and, in regions with

high altitude differences, also inflammation due to sparks caused by rock-fall. However, lightning strikes are considered the main cause of repeated natural inflammation (Nash and Johnson 1996; Patterson et al. 1987; Tinner et al. 1998; Tipping 1996). Therefore, the key challenge in the interpretation of charcoal particle abundances in pollen profiles is to distinguish between anthropogenic and naturally induced fires.

In principle, palynology allows to differentiate between large scale and small scale fires. As demonstrated by Edwards (1990) or Edwards et al. (2000) evidence on large scale fire regimes can only be provided by the analysis of various sediment sequences of a specific area that cover equal time periods.

With respect to large scale fires, especially since the 1970s, interest into Early to Mid-Holocene landscape openings by means of fire increased. In areas across Ireland (Warren et al. 2014), Scotland (Edwards 1990; Tipping 1996) or Scandinavia (Selsing 2016), the respective record of charcoal particles in different regional pollen profiles show identical events. These observations led to the conclusion of extensive wildfires. Additionally, it was assumed that these are reflections of hunter-gatherer activities – burning of landscapes for the purpose of improving hunting yields. This is reasonable, as analogies are also known from ethnography (Behre 1988; Jacobi et al. 1976; Mellars 1976; Welinder 1983). With regard to these analogies, the hypothesis of a deliberate Mesolithic landscape -, environment- or woodland management is recently gaining even more attention and underlines the significance of charcoal particles in pollen samples (Bos et al. 2005; Mason 2000; Scherjon et al. 2015; Selsing 2016; Warren et al. 2014).

Apart from these Holocene examples, large scale fires are also known from the Lateglacial. The rapid cooling at the end of the GI-1a resulted in huge amounts of dead biomass, dispersed across northern central Europe (Appendix IV). This dead organic material fueled enormous fire regimes that in turn are traceable in a variety of archives across the continent – known as Usselo horizons (Crombé 2019; Kaiser 2003; Kaiser et al. 2009; Tolksdorf et al. 2014; Van der Hammen 1951; Van der Hammen and Van Geel 2008). Yet, assuming human action as a cause of large scale fires can be discussed, but neither proven nor falsified with certainty in either Lateglacial or Holocene contexts.

In contrast, small scale fires can easily be interpreted as reflections of anthropogenic interaction with the environment in case of interlinked archaeological investigations. This had already successfully been done at Holocene sites like Star Carr (Day and Mellars 1994) and Hohen Viecheln (Schmitz 1961), as well as at Lateglacial sites like Lubrza (Sobkowiak-Tabaka et al. 2017), Hasselø (Mortensen et al. 2014b), or the Nahe palaeolake (Appendix V). At all these sites the charcoal record does not reflect woodland burning, but rather small scale fires as hearth fires or, in some cases, burning of reeds to provide better access to lakes and rivers.

A further general difficulty in interpreting the charcoal record is the way to present the data. In many of the above mentioned pollen profiles charcoal particle abundances are given as charcoal to pollen ratios. As mentioned by William Patterson et al. (1987), Richard Tipping (1996) or Kevin Edwards et al. (2000) values calculated on pollen sum, as concentration or influx (accumulation rates) result in similar qualitative patterns. This, however, only holds true for samples taken from Holocene depositions and not for absolute quantities. How challenging, or potentially misleading, an interpretation of the charcoal to pollen ratios in Lateglacial contexts can be, is revealed by the assumptions of Lotte Selsing (2018)¹⁴. Therefore, different taphonomic processes need to be considered when referring to Lateglacial depositions (e.g. further and different erosional processes compared to Holocene depositions) but especially the way of calculating the raw data.

Additionally, in case of indications for a landscape opening that coincides with alterations in charcoal particle abundances climate must be considered as a primary driving force before assuming human intervention.

To sum up, four conclusions can be drawn with respect to human indicators in Lateglacial pollen profiles:

- The sediment archive needs to fulfill several important preconditions in order to enable an investigation of Lateglacial human-environment interaction (see introduction or Appendix V).
- Even if there is large consensus about the indicative value of charcoal particles, human action must be documented by other microfossils or proxies.
- In a set of multiple proxies, indicative values need to be discussed in detail and individually to exclude possible circular reasoning.
- Reasonable conclusions can only be drawn if archaeological evidence supports the hypotheses.

The requirements to the investigated archive in order to detect human action have been fulfilled at the investigated sediments of the Nahe palaeolake. Therefore, the respective microfossils that have been used as indicative for human action are discussed in detail in Appendix V.

¹⁴ The assumptions are based on charcoal to pollen ratios in the early Lateglacial. Selsing proposes forest opening and landscape management by large scale fires in an area that featured tundra and grasslands but no trees (Birks et al. 2005).

4. Summary of papers/ appendices

4.1 Appendix I:

In search of the Bølling-Oscillation – a new high-resolution pollen record from the locus classicus Lake Bølling, Denmark - Sascha Krüger and Martin Damrath

Vegetation History and Archaeobotany (29/2) 2019, 189-211. <https://doi.org/10.1007/s00334-019-00736-3>

In 1982 Hartmut Usinger investigated a sediment sequence that originated from a prominent locus classicus in Lateglacial terminology – Lake Bølling. The results had never been published and were used for this article. The main focus is set on two different aspects. The first is the separation of birch-pollen types by applying a fixed threshold. Also, a pollen size frequency distribution (approximation approach) is prepared in order to compare the general outcomes of both methods. In a second step, the separation of birch pollen types allows for a detailed investigation of the main characteristics of the Bølling-Oscillation *sensu* Iversen (1942).

The results show that the reprocessed data can immensely refine Iversen's pollen zones. A clear dominance of *Betula nana* pollen-types during the Bølling-Oscillation is demonstrated. The proximity of the coring location to former sediment investigations by Iversen (1942) as well as Bennike et al. (2004) render it possible to directly correlate the different data sets according to depth. The combination of the here presented pollen profile and the radiocarbon dates given by Bennike et al. (2004) indicates that the Bølling-Oscillation coincides with the GI-1e. Hence, the record reveals that Iversen's original assumption concerning the existence of a climatic oscillation prior to the Allerød can indeed be confirmed at the locus classicus. By discussing these results and its implication for terminology this paper contributes to fundamental aspects of Lateglacial research.

4.2 Appendix II:

Small shards and long distances – three cryptotephra layers from the Nahe palaeolake including the first discovery of the Laacher See Tephra in Schleswig-Holstein (Germany) - Sascha Krüger and Christel van den Bogaard

Journal of Quaternary Science 36 (1), 2020, 8-19. <https://doi.org/10.1002/jqs.3264>

Tephra layers are important chronological markers in sediment sequences. As these volcanic ash layers represent single events, an attempt was made to identify tephra layers as additional chronological horizons supplementing radiocarbon dating of macrofossils on sediments from the Nahe palaeolake.

To increase the probability of detecting cryptotephra and synchronously avoid an unnecessary processing of the whole sediment sequence, a targeted search for specific volcanic events was conducted based on pollen stratigraphy.

The targeted search yielded a total of three cryptotephra layers. These include the Holocene Saksunarvatn Ash, the Lateglacial Vedde Ash and the Laacher See Tephra. A geochemical investigation using LA-ICP-MS of hand-picked shards confirmed their classification. Therefore, this manuscript presents the first geochemically confirmed find of Laacher See Tephra in Schleswig-Holstein – extending the so far detected ash fan further to the North-West. These finds enable direct stratigraphical correlations to be made and underline the potential of the site for further investigations into the location of deposited cryptotephra layers.

4.3 Appendix III:

Limnological response to the Laacher See eruption (LSE) in an annually laminated Allerød sediment sequence from the Nahe palaeolake (northern Germany) - Stefan Dreibrodt, Sascha Krüger, Jan Weber, Ingo Feeser

Boreas 2020. <https://doi.org/10.1111/bor.12468>. ISSN 0300-9483

Sediment cores from the Nahe palaeolake revealed the so far only known annually laminated Lateglacial sediment sequence from Schleswig-Holstein. This 53 cm sequence spans mainly the (biostratigraphic) Allerød period as well as parts of the Dryas 3 period and includes the deposition of the Laacher See Tephra. Based on radiocarbon dates, cryptotephra layers and varve counting, an age-depth model for the NAH sequence is presented.

High-resolution geochemical investigations revealed that increased allochthonous inputs into the lake system lasted for four years following the eruptive event of the Laacher See Volcano. Subsequently, 60 years of lower bioproductivity and another 60 years of increased bioproductivity within the lake system can be inferred from the record. 240 years after the eruption of the Laacher See volcano the lamination terminated. The termination in turn is a reflection of the beginning stadial period (GS-1).

A combined study of the NAH record and records from Lake Meerfelder Maar (Brauer et al. 2008) and Lake Kråkenes (Baldini et al. 2018) support the hypothesis that westerly wind systems shifted southwards in different pace: 40-120 years after the LST about 12 km/year; 120-200 years after the LST about 5 km/year.

4.4 Appendix IV:

Sequence completed – palynological investigations on Lateglacial/ Early Holocene environmental changes recorded in sequentially laminated lacustrine sediments of the Nahe palaeolake in Schleswig-Holstein, Germany. - Sascha Krüger, Morten Fischer Mortensen, Walter Dörfler

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Despite being one of the most studied areas regarding the Lateglacial, no biostratigraphy covering the complete Lateglacial and Early Holocene period have been recovered so far in Schleswig-Holstein. This fact is mainly conditioned by climatically caused hiatuses in various sediment archives. However, sediments deriving from the deepest part of the former Nahe palaeolake have not been effected. By analyzing and discussing these sediments, this paper presents the first complete Lateglacial to Early Holocene pollen profile from Schleswig-Holstein.

The special strength of the presented sequence is expressed in (i) undisturbed sediments , (ii) palynologically investigated sequentially annual laminated limnic sediments of the Lateglacial in Schleswig-Holstein, (iii) radiocarbon dating of botanical macrofossils and (iii) three geochemically confirmed cryptotephra layers (Laacher See Tephra, Vedde Ash and Saksunarvatn Ash) providing excellent age control and allowing for a Europe-wide connection via event-stratigraphy.

The most fundamental environmental change or transformation observable in the record is the transition from tundra to woodland. In fact this shift occurred twice within the record (during the Lateglacial and very Early Holocene). The excellent age control enables the evaluation of the temporal scale of these environmental transformations (Dryas 1-Allerød transition and Dryas 3-Preboreal transition) and allows to compare them. A comparison is done in order to address the question of how fast transformations of the vegetation did occur. This is important, as apparently identical changes in the pollen composition visible in the pollen diagram actually reflect different steps of the primary succession. These different steps in turn can only be revealed by considering the temporal scale.

Furthermore, a comparison with datasets from Lake Hämelsee (Merkt and Müller 1999) and Slotseng (Mortensen et al. 2011) highlight the bridging function of pollen profiles from Schleswig-Holstein for research into Lateglacial vegetation history on a geographically larger scale. As the NAH dataset fits perfectly into existing records it allows to substantially enrich our spatial and temporal understanding of vegetation developments.

4.5 Appendix V:

Of birches, smoke and reindeer dung – tracing human-environmental interactions palynologically in sediments from the Nahe palaeolake - Sascha Krüger

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Sediments from the Nahe palaeolake in Schleswig-Holstein provided the first continuous and high-resolution palynological record in the direct vicinity of a Lateglacial archaeological site in northern Germany.

The aim of this paper is to discuss the indicative value of selected indicators of human-environmental interaction in the NAH record. High charcoal particle frequencies in different size classes and coinciding fungal spores reveal a remarkable pattern at the transition from the Dryas 3 to the Preboreal period that correspond to the archaeological record. This coincidence of proxies led to the definition of a *transformation phase* at the Pleistocene-Holocene transition, between 11,650 and 11,520 cal yr BP.

The palynological record revealed climatically driven rapid changes of the vegetation at the Pleistocene-Holocene transition. Fastly increasing plant availability (qualitatively and quantitatively) caused seasonally prolonged presence of reindeer in the area, which is reflected in the record of coprophilous fungal spores. The positively altered availability of the main game animal resulted in temporally prolonged hunting activities by Late Palaeolithic hunter-gatherers. These activities are in turn reflected in the charcoal particle record as well as the archaeological record.

Hence, the respective *transformation phase* palynologically mirrors environmentally triggered adaptation processes of humans and animals at the Pleistocene-Holocene transition.

5. Conclusion and perspective

This thesis contributes to the understanding of Lateglacial environmental developments and transformations as well as vegetation history in the area of Schleswig-Holstein based on a sediment sequence from the Nahe palaeolake. It is demonstrated how anthropogenic activity and human-environmental interaction is reflected in the palynological record. Further, this thesis investigates and clarifies entanglements of Lateglacial terminology by processing legacy data of Hartmut Usinger. The main contribution of this work to Lateglacial research can be summarized in the following four statements.

[1] Firstly, this work contributes to the clarification of Lateglacial terminology with regard to the Bølling-Oscillation by analysing legacy data from the locus classicus. The clarification is achieved by providing unequivocal evidence that Iversen's original assumption from 1942 can be confirmed. This assumption concerns a climatic oscillation prior to the Allerød *sensu* Hartz (1912) that conditioned Lateglacial vegetation changes. Additionally, the presented work demonstrates that the Bølling-Oscillation can regionally be correlated to the climatic GI-1e event (Björck et al. 1998). Furthermore, the statistical analyses of the dataset revealed that it generally makes no difference which method of birch-pollen type separation (approximation approach or fixed threshold) is applied.

The investigations of the legacy data form the terminological as well as methodological background for the analysis carried out in this thesis. These concern the sediments from the Nahe palaeolake (NAH), to which the other three general statements refer.

[2] Secondly, based on investigations of the NAH sediment sequence it is demonstrated that one of the identified cryptotephra layers can be geochemically associated with the eruption of the Laacher See Volcano. This represents the first find of the Laacher See Tephra north-west of Lake Hämelsee and hence a find location far outside the previously known ash fall out zone. The data indicate that the ash fall out effected the aquatic ecosystem by changing the trophic state for about 120 years subsequent to the eruption. However, palynological investigations demonstrate that the ash fall out – in this area only on a microscopic scale – had no effect on the upland vegetation in Schleswig-Holstein. Further geochemical evidence is also given for the identification of the Vedde Ash as well as the Saksunarvatn Ash.

[3] Thirdly, the presented pollen profile of the NAH record is the first in Schleswig-Holstein that (i) spans the whole Lateglacial to early Holocene period without being effected by a hiatus, (ii) includes sediment investigations by geochemical methods on Lateglacial laminated sequences, (iii) includes Lateglacial tephra layers as chronological markers, (iv) provides a robust age-depth model even in the Lateglacial section of the profile, (v) includes the quantification of charcoal size-classes and NPP types

and (vi) whose analysed sediment sequence originates from a coring location close to an archaeologically confirmed site of Lateglacial hunter-gatherers.

Furthermore, a comparison of apparently similar pollen features (here the *Betula pubescens*-type pollen curve at the transitions of Dryas 1-Allerød and Dryas 3-Preboreal) was carried out on a temporal basis. The comparison revealed that the speed of transformations of the vegetation at that time was different. Within a comparable temporal dimension different steps of the primary succession were reached that in turn are not as different when looking at the pollen spectrum and percentage diagram alone. This highlights how challenging it is to compare seemingly resembling alterations of the vegetation and their characteristics even within one record.

[4] Finally, one main hypothesis of this thesis is the formulation of a *transformation phase* between 11,670 and 11,520 cal yr BP. The discussion of the record for this temporal interval clearly demonstrates that environmental changes caused seasonally prolonged stays of reindeer in the surrounding of the Nahe palaeolake that in turn resulted in an adapted hunting behaviour of potentially Ahrensburgian foragers (intensified or seasonally prolonged) at the Pleistocene-Holocene transition. Hence, this work is the first to discuss and successfully apply several palynological proxies for human activity in connection with the archaeological record in the area of Schleswig-Holstein during the Lateglacial to Early Holocene.

The presented results underline the potential of the Nahe palaeolake for future research. For a better understanding of the natural ecosystem additional investigations into vegetation history would be desirable. Still specific periods of the Lateglacial, such as the Meiendorf period or Drays 1 period, should be analysed in higher resolution. However, not only palynology but also isotope geochemistry (e.g. wax lipids, Weber and Schwark 2019) may contribute to e.g. the question of the absolute dating of the Lateglacial migration of tree birches.

As only 18% of the palynologically analysed sequence has been subject to cryptotephra analysis, it would be desirable to increase the number of tephra layers by applying further targeted searches. However, as could be demonstrated based on the NAH cryptotephra record, also investigations into cryptotephra layers at other locations, such as the biostratigraphic type locality Allerød (Denmark), are both desirable and promising. These future investigations may further clarify confusions of Lateglacial terminology.

The re-analysis of the Bølling data set originally obtained by Hartmut Usinger demonstrated the large potential of legacy data sets. Future investigations should focus on processing, digitalizing and publishing these precious but often forgotten records. Localities, which might be mentioned as preliminary investigations in legacy data, should be given more attention. The value of such archives

for interdisciplinary research can even be increased by comparing the coring localities with recent archaeological databases. Hence, potential suitable archives for research into human-environmental interaction, such as the Nahe palaeolake, can be identified.

Generally, when investigating human-environmental interaction, regardless of their chronological classification, archive size is a crucial factor for the identification of past anthropogenic activity.

Therefore, future work should concentrate on small kettle holes such as the Tyrsted locality (Denmark). At that site, archaeological evidence on the shore of the former water body proves human presence and provides a relative chronological classification by typological classification of the artefacts found (Borup and Krog Nielsen 2017). The time period could be investigated by palynology in highest possible resolution. Small kettle holes are advantageous as the input of pollen is absolutely dominated by local input and a potential reflection of human activity is significantly less masked by regional pollen and particle inputs.

The very early Lateglacial – or in archaeological terms, the early Hamburgian culture – the younger morainic area of northern and north-eastern Germany still represents a sterile archaeological area. No finds pertaining to this techno-complex are known so far (Terberger 2006; Terberger and Lübke 2005). This could equally be representing the current state of research, but it is remarkable that Hamburgian finds have not been made north of the maximum extend of glaciers of the Pommeranian stage. It has been suggested that these regions were unsuitable for hunting and gathering as the area could have been characterized by an unpassable network of water bodies (I. Clausen pers. comm. referring to H. Usinger). Based on this presumed archaeological emptiness this region would be predestined for palaeo-environmental investigations as reflected early Lateglacial changes in the ecosystem (including fires) would exclusively be naturally caused. This in turn would provide a background for interpretations of records in other areas with focus on human-environmental interaction by providing a figurative blue print.

Lastly, but most importantly regarding the interpretation of the NAH record, would be future investigations into sediments from the Ahrensburg tunnel valley. The proposed *transformation phase* would potentially be reflected on even larger scales with respect to the archaeological find assemblage. In this way a comparison to the NAH record could confirm the suggested hypothesis.

In other words, a modern high-resolution palynological investigation of the Ahrensburg tunnel valley probably represents the most promising basis for investigating the reflection of Lateglacial human action in northern central Europe, and, accordingly, this represents a most prominent research desideratum.

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7. Deutsche Zusammenfassung

Transformationen der spätglazialen Umwelt im nördlichen Europa basierend auf hochauflösenden palynologischen und tephrochronologischen Untersuchungen vom Bølling Sø und dem Nahe Paläosee. Neue Einblicke in Terminologie, Vegetationsentwicklung und Mensch-Umwelt-Interaktion.

Einleitung

Das Weichselspätglazial, synonym bezeichnet mit *Spätglazial*, bezeichnet einen zeitlichen Abschnitt der zwischen 14.650 und 11.600 cal yr BP einzuordnen ist (Litt et al. 2007; Litt and Stebich 1999; Magny et al. 2006; Rasmussen et al. 2006). Dieser Zeitbereich, der Übergang der erdgeschichtlichen Perioden des ausgehenden Pleistozäns zum Holozän, repräsentiert eine Schlüsselperiode in unserem heutigen Verständnis von Transformationsprozessen der Umwelt auf unterschiedlichen Ebenen. Dies liegt darin begründet, dass das Spätglazial fundamentalen sowie sich kontinuierlich wandelnden Veränderungen unterworfen war, die sich jedoch gebunden an den geographischen Raum unterschiedlich manifestierten. Das Spätglazial ist generell charakterisiert durch rapide klimatische Wandel, hohen Anpassungsdruck und stark alternierende Anforderungen für alle Lebensformen.

Um das Spätglazial in schlüssige Perioden zu untergliedern, wurde eine Einteilung durch die INTIMATE Group vorgeschlagen, welche sich nach Veränderungen der Sauerstoffisotopenkonzentrationen in den Schichtungen der Bohrkerne aus dem Grönländischen Eis richtet (Björck et al. 1998; Rasmussen et al. 2006; Rasmussen et al. 2014; Seierstad et al. 2014). Deren zur Folge wird das Spätglazial in das Glaziale Interstadial 1 (GI-1) – mit weiterer Unterteilung – und das darauffolgende Glaziale Stadial 1 (GS-1) gegliedert. Das GI-1 ist eines von 24 zyklisch auftretenden Temperaturfluktuationen während des Weichselglazials innerhalb der letzten 110.000 Jahre und von wärmeren atmosphärischen Bedingungen geprägt (Bond et al. 1999; Dansgaard et al. 1993). Das anschließende GS-1 repräsentiert eine Rückkehr zu stadialen, d.h. kalten und überwiegend trockenen Bedingungen. Auf das abrupte Ende des GS-1 folgt das Holozän mit der außerordentlich langen Warmzeit, in der wir heute leben.

Bereits vor der Unterteilung des Spätglazials auf Basis klimatischer Daten wurde in unterschiedlichen Disziplinen erkannt, dass dem Holozän Kaltzeiten vorausgingen, welche periodisch von Phasen günstigeren, d.h. wärmeren klimatischen Bedingungen unterbrochen wurden (Hartz 1912; Hartz and Milthers 1901; Iversen 1942). In Pionierarbeiten der Geologie und Palynologie wurden jedoch kaum ungestörte und kontinuierlich abgelagerte Sedimentsequenzen untersucht, wie sie Eisbohrkerne darstellen. Darüber hinaus bestand keine Möglichkeit, Korrelationen zwischen verschiedenen Untersuchungsergebnissen sicher herzustellen. Aus diesem Grunde wurden im Laufe des 20.

Jahrhunderts unterschiedliche Konzepte für Phasen des Spätglazials vorgeschlagen, welche auf denselben Phänomenen basierten (z.B. Bølling-Oscillation *sensu* Iversen (1942) und Meiendorf-Intervall *sensu* Menke (1968)). Die Verwendung der Begrifflichkeiten in unterschiedlichen Disziplinen und wissenschaftlichen Schulen führte zu einer nur schwer durchdringbaren Terminologie des Spätglazials, welche heute noch zu Missverständnissen führt und dringend weiterer Aufklärung bedarf. Für Untersuchungen des Spätglazials ist das Gebiet des nördlichsten deutschen Bundeslandes Schleswig-Holstein bestens geeignet. Seit dem Abschmelzen des der Fennoskandischen Gletscher entwickelte sich dieses Gebiet zur Brücke zwischen dem nördlichen Mitteleuropa und Skandinavien für Mensch, Fauna und Flora. Unterschiedliche Vorstoß- und Rückzugsphasen der Gletscher formten die Landschaft Schleswig-Holsteins und kreierten eine edaphische Dreiteilung, welche seither die Verbreitung der Vegetation bestimmt (Behre 2008; Overbeck 1975).

Zahlreiche botanische und pollenanalytische Arbeiten untersuchten die Entwicklung der Vegetation in Schleswig-Holstein nach der Eisfreiwerdung (Aletsee 1959; Fischer-Brenzon 1891; Tidelski 1929; Tidelski 1960). Dabei entstand eine Vielzahl an Pollenprofilen unterschiedlichster Komplexität, zeitlicher Auflösung und Fokussierung. Bis heute sind keine Untersuchungen publiziert worden, die an kontinuierlich abgelagerten Sedimenten des Spätglazials und frühen Holozäns durchgeführt wurden. Dies liegt Usinger (1981) zur Folge zum einen darin begründet, dass Seespiegelschwankungen zu Unterbrechungen bzw. starken Umlagerungen der Stratifizierung im Sediment führten. Zum anderen ist das Tieftauen von sedimentbedeckten Gletschereisblöcken (sog. Toteis) bis in das frühe Holozän hinein im Jungmoränengebiet für Störungen und Abbrüche in der Sedimentationsfolge verantwortlich (Gripp 1964). Aus diesen Gründen ist unser derzeitiges Verständnis der Vegetationsentwicklung in Schleswig-Holstein aufgebaut auf einer Art Flickenteppich unterschiedlicher Analysen mit ungleicher zeitlicher Tiefe und Auflösung.

Dieser Flickenteppich beinhaltet überdies den Umstand, dass keine absolut datierte Biostratigraphie des Spätglazials im Untersuchungsgebiet existiert, bedingt durch die geringe Anzahl von einzelnen Radiokarbondatierungen in wenigen Pollenprofilen.

Des Weiteren war es bisher nicht möglich, auch hochaufgelöste Diagramme über die Eventstratigraphie mit internationalen Schlüsselstandorten, wie dem Meerfelder Maar, D (Litt and Stebich 1999), dem Hämelsee, D (Merkt and Müller 1999), Kråkenesvatnet, NOR (Birks and Birks 2008) oder Slotseng, DK (Mortensen et al. 2011) zu korrelieren. Schlussendlich entstanden damit Schwierigkeiten, welche auch die Terminologie beeinflussten.

Als Konsequenz aus dem Obengenannten lassen sich vier Anforderungen für eine neue palynologische Untersuchung des Spätglazials formulieren, welche das untersuchte geologische Archiv betreffen:

- (i) Die untersuchten Sedimente sind kontinuierlich während des Spätglazials und frühen Holozäns abgelagert.
- (ii) Folglich sind sie nicht beeinträchtigt durch den von Usinger beschriebenen weitverbreiteten Hiatus.
- (iii) Es sollte ein belastbares Altersmodell auf Basis von ^{14}C -Datierungen botanischer Großreste erstellbar sein.
- (iv) Ergebnisse der Biostratigraphie sollten über die Eventstratigraphie mit Schlüsselstandorten zu korrelieren sein.

Aus dem Gebiet des heutigen Schleswig-Holsteins sind im nationalen Vergleich zahlreiche Spätglazialprofile vorhanden. Im Gegensatz dazu sind davon nur wenige Profile in einen archäologischen Kontext eingebunden, d.h. Untersuchungen an oder nahe eines archäologisch gesicherten Fundplatzes (Bokelmann et al. 1983; Schütrumpf 1935; 1937; 1943; 1958a; 1958b; Usinger 1998). Dieser Umstand bedingt, dass eine Verknüpfung von archäologischer Erforschung von Jägern und Sammlern mit Untersuchungen der Paläoumwelt nur selten gegeben ist. Daraus lässt sich bei einer neuen Untersuchung eine weitere Anforderung an ein geologisches Archiv ableiten:

- (v) Es muss gewährleistet sein, dass sich ein archäologisch gesicherter Aufenthaltsplatz spätglazialer Jäger und Sammler in unmittelbarer Nähe zum Bohrpunkt befindet.

Die Reflexion spätglazialer und frühholozäner menschlicher Aktivität im Pollenprofil gilt gemeinhin als sehr schwierig. Einzelne Indikatoren wurden und werden in der Fachliteratur diskutiert (Behre 1988; Bos and Janssen 1996; Iversen 1941; Mortensen et al. 2014; Sobkowiak-Tabaka et al. 2017). Die Untersuchung einer Sedimentsequenz aus einem geologischen Archiv, welches alle zuvor genannten Voraussetzung erfüllt, hätte daher das Potenzial zu dieser Diskussion beizutragen. Eine solche Analyse würde unser bisheriges Wissen über menschliche Interaktion mit der Umwelt erweitern, insbesondere in Bezug auf Umweltveränderungen als Auslöser für Änderungen in menschlichen Verhalten.

Aus dem Oben genannten lassen sich schließlich drei Desiderata der Spätglazialforschung zusammenfassen. Diese betreffen:

1. spätglaziale Terminologie
2. spätglaziale Vegetationsgeschichte
3. spätglaziale menschliche Interaktion mit der Umwelt

Die genannten drei Aspekte sind die Hauptthematik dieser Arbeit.

Konzept

Aus den drei Hauptthemen wurde ein fünfteiliges Konzept erarbeitet, mit dem Ziel, fünf eigenständige Publikationen zu erstellen. Sie sind diesem Rahmentext als Appendices I bis V angefügt und werden im Folgenden kurz vorgestellt.

Der Aspekt der Terminologie wurde auf Grundlage des umfassenden Nachlasses des Paläobotanikers Hartmut Usinger (+2015) untersucht. Ein bisher unpublizierter Datensatz Usingers vom Bølling Sø (Dänemark) ermöglichte eine detaillierte Ergründung des Ursprunges der Bølling-Oscillation *sensu* Iversen direkt an erhobenen Daten der Typuslokalität. Grundlegende Fragen zur Terminologie werden beantwortet und sind Voraussetzung für die nachfolgenden Untersuchungen.

Die anschließenden Manuskripte sind Ergebnisse eigener Untersuchungen an Sedimenten des Nahe Paläosees (Kr. Segeberg). Durch intensive Voruntersuchungen Usingers war bekannt, dass sich aus dem verlandeten Seebecken Sedimente gewinnen lassen, die die oben genannten Kriterien erfüllen. Außerdem befand sich ein archäologisch untersuchter Fundplatz spätglazialer Jäger und Sammler am Ufer des Nahe Paläosees.

Die Sedimente wurden palynologisch, geochemisch, und hinsichtlich vulkanischer Aschelagen untersucht. Die Aufbereitungstechnik und Auszählung von Kryptotephra war dabei ein methodischer Schwerpunkt. Aschelagen sind chronologische Marker und wurden in spätglazialen Sedimenten Schleswig-Holsteins bisher nicht nachgewiesen. Die Interpretation des Datensatzes führt zu der geforderten verifizierten Chronologie.

In Zusammenarbeit mit dem F2 und E1 Projekt des SFB 1266 entstand ein Altersmodell, das auf Radiokarbonaten, identifizierten vulkanischen Aschelagen und Warvenzählungen beruht. Der dritte Teil der Thesis liefert daher das Altersmodell der Untersuchung und trägt zum Verständnis der Sedimentations- und Umweltbedingungen bei.

Die Ergebnisse der palynologischen Untersuchung der Sedimente werden im vierten Manuskriptteil abgehandelt. Die ungestörten und teilweise jahresgeschichteten Ablagerungen erlauben, dass bei einer solchen Analyse ein Pollenprofil entsteht, welches bestehende Fragen zur Vegetationsgeschichte des Spätglazials in Schleswig-Holstein beantwortet. Die Rekonstruktion der Vegetation wird unterstützt durch Informationen aus der Analyse botanischer Makroreste. Die Interpretation, Diskussion und Kontextualisierung des Datensatzes basiert auf hier gezeigten Untersuchungen zur Terminologie und dem erstellten Altersmodell.

Schließlich wird im fünften Manuskript auf den Aspekt der menschlichen Interaktion mit der Umwelt eingegangen. Auf Basis gesonderter Betrachtungen ausgewählter Indikatoren (Holzkohlepartikel Größenklassen und Non-Pollen-Palynomorphe/NPPs) – welche erstmals in palynologischen Untersuchungen des Spätglazials in Schleswig-Holstein angewendet werden – und in Zusammenspiel

mit archäologischen Informationen wird die Reflexion menschlichen Handelns im Pollenprofil diskutiert.

Ergebnisse

Appendix I

Im Jahre 1982 untersuchte Hartmut Usinger eine Sedimentsequenz einer Typuslokalität des Spätglazials – dem Bølling Sø in Dänemark. Die Ergebnisse der palynologischen Untersuchung wurden bisher nicht publiziert und bilden die Grundlage der weiterführenden Untersuchungen. Der Fokus ruht dabei auf zwei unterschiedlichen Aspekten.

Der erste Aspekt betrachtet die Unterscheidung der Birkenpollentypen auf Basis eines festgesetzten Grenzwertes der Pollenkorngroße (21,5 µm) und einer statistischen Separierung (Approximation durch theoretische Mischverteilung) mit dem Ziel, die generellen Ergebnisse beider Methoden miteinander zu vergleichen. Dies geschieht, da für eine Interpretation spätglazialer Pollendiagramme mit hohem Birkenpollenanteil entscheidend ist, ob sie eher Reflexionen baumloser Tundren, oder Baumbirken-beherrschter Wälder sind. In den meisten Diagrammen des Spätglazials aus Skandinavien und der Nordeuropäischen Tiefebene wurde bisher auf eine Trennung verzichtet.

Der zweite Aspekt nutzt die Ergebnisse der Birkenpollentrennung für eine genauere Untersuchung der von Iversen (1942) beschriebenen Bølling-Oscillation.

Eine klare Dominanz des Zwergbirkenpollentyps während der Bølling-Oscillation wird aufgezeigt. Die geographische Nähe des Bohrstandortes zum ehemaligen Bohrstandort Iversens (1942) und später Bennikes et al. (2004) von teilweise weniger als einem Meter ermöglicht eine direkte stratigraphische Korrelierung. Zusammen mit den von Bennike et al. (2004) gewonnenen Radiokarbonaten zeigt sich eine zeitliche Übereinstimmung der Bølling-Oszillation mit GI-1e (Glaziales Interstadial-1e). Damit werden Iversens Annahmen einer klimatischen Oszillation vor der Allerød Periode zum ersten Mal an der Typuslokalität bestätigt. Die Anwendung der Ergebnisse auf die Terminologie leistet einen wichtigen Beitrag zur Erforschung des Spätglazials.

Appendix II

Vulkanische Aschelagen sind hervorragende chronologische Marker in Sedimentsequenzen, da sie häufig gut datierbare Einzelevents repräsentieren. Auf Grund der hohen Aussagekraft wurde der erfolgreiche Versuch unternommen, Kryptotephralagen in den Sedimenten des Nahe Paäosees nachzuweisen.

Vulkanasche des Spätglazials ist auf dem Gebiet des heutigen Schleswig-Holsteins nur aus einer einzigen Untersuchung bekannt (Housley et al. 2012). Bei dieser handelt es sich um die Vedde Asche,

welche in einem archäologischen Kontext und nicht in einer gesicherten Biostratigraphie identifiziert wurde.

Um die Wahrscheinlichkeit der Entdeckung von Kryptotephra zu erhöhen und gleichzeitig die unnötige Aufbereitung der gesamten Sedimentsequenz zu vermeiden, wurde eine gezielte Suche anhand pollenstratigraphischer Charakteristiken durchgeführt.

Die Suche erstreckte sich auf spätglaziale und frühholozäne Sequenzen und ergab die erwarteten drei Kryptotephrahorizonte. Dabei handelt es sich um die frühholozäne Saksunarvatn Asche (etwa 10264 ± 47 cal yr BP) sowie die spätglaziale Vedde Asche (etwa 12040 ± 35 cal yr BP) und die Laacher See Tephra (etwa 12937 ± 23 cal yr BP). Die Untersuchung der geochemischen Zusammensetzung einzelner Kryptotephra-Scherben bestätigte deren Ansprache.

Damit können zum ersten Mal frühholozäne und spätglaziale Vulkanaschen in einer Sequenz aus Schleswig-Holstein nachgewiesen werden. Gleichzeitig ist dies der erste geochemisch bestätigte Fund der Laacher See Tephra in Schleswig-Holstein, welches die bisher bekannte Ausbreitung des Aschefächers nach Nordwesten erweitert (Riede 2007; Riede et al. 2011).

Die Aschelagen ermöglichen direkte stratigraphische Korrelationen zu Europäischen Schlüsselstandorten und tragen drei wichtige chronologische Marker zum Altersmodell bei. Des Weiteren unterstreichen sie das Potenzial der Sedimente aus dem Nahe Paläosee für zukünftige Untersuchungen.

Appendix III

Sedimentbohrungen aus dem Nahe Paläosee förderten die bisher in Schleswig-Holstein einzig bekannten jahresgeschichteten Ablagerungen des Spätglazials zu Tage. Die 53 cm mächtigen laminierten Ablagerungen (716 Warven) umfassen biostratigraphisch weite Teile der Allerød Periode sowie einen Teil der beginnenden Dryas 3 Periode und die Ablagerung der Laacher See Tephra.

Basierend auf den zuvor identifizierten Aschelagen, zwölf Radiokarbondaten und der Warvenzählung wird ein Altersmodell des NAH-Datensatzes vorgelegt.

Die Ergebnisse der geochemischen und sedimentologischen Untersuchungen zeigen eine unmittelbare Reaktion des Seesystems auf die Eruption des Laacher See Vulkans. Unwetter und Starkregenereignisse sind wahrscheinliche Auslöser stärkerer Erosion der Ufersedimente und vermehrtem Eintrag aus dem Einzugsgebiet des Sees in den ersten vier Jahren nach der Eruption. Eine Versauerung des Seesystems bis 50 Jahre nach dem Ausbruch ist das Resultat des eingetragenen schwefelhaltigen Aerosols.

Die erhobenen Daten belegen das Einsetzen stärkerer Westwinde für ab 120 Jahren nach der Eruption. Die südliche Verlagerung der starken Winde ist für eine frühere Phase (40 Jahre nach LSE) in Norwegen und für eine spätere Phase (200 Jahre nach LSE) für Südwestdeutschland belegt. Basierend auf den

Ergebnissen lässt sich eine Änderung in der Geschwindigkeit der Verlagerung der Westwinde feststellen: 40-120 Jahre nach der LST ca. 12 km/Jahr, 120-200 Jahre nach der LST ca. 5 km/Jahr.

Appendix IV

Obwohl Schleswig-Holstein eine der am meisten untersuchten Regionen der Spätglazialforschung in Deutschland ist, wurde bisher keine Biostratigraphie vorgelegt, die das komplette Spätglazial und frühe Holozän umfasst. Dieser Umstand liegt überwiegend in Seespiegelschwankungen und einem resultierenden Hiatus am Übergang der Allerød Periode zur Dryas 3 Periode begründet (Usinger 1981). Nur wenige Seen waren davon nicht betroffen. Zu diesen gehören Ablagerungen des Nahe Paläosees. Mit der Diskussion der palynologischen Untersuchungen einer Sequenz des Nahe Paläosees legt dieser Artikel das erste komplette Pollenprofil des Spätglazials und frühen Holozäns in Schleswig-Holstein vor. Durch die Besonderheit der kontinuierlichen Ablagerungen mit jahreszeitlicher Schichtung und dem Vorhandensein der Kryptotephralagen konnte im Zusammenspiel mit Radiokarbonaten an botanischen Großresten eine belastbare Altersbestimmung erfolgen.

Dieses Altersmodell ermöglicht eine zeitliche Abgrenzung sowie den Vergleich von Umweltveränderungen und Transformationsprozessen innerhalb des NAH-Datensatzes. Deshalb wird hier der Dryas 1-Allerød-Übergang mit dem Dryas 3-Präboreal-Übergang verglichen. Der Vergleich legt nahe, dass vermeintliche Koinzidenzen der Übergänge im Pollenprofil irreführend sein können, zumal sich Geschwindigkeit und Grad der Umweltveränderung innerhalb ähnlicher Zeitspannen stark unterscheiden.

Aus den vorgelegten Ergebnissen der Pollenanalyse und den Untersuchungen zur Terminologie folgt, dass die bisher gültigen regionalen Pollenzonen Usingers umdefiniert werden müssen.

Darüber hinaus demonstriert ein Vergleich mit Datensätzen aus dem Hämelsee (Merkt and Müller 1999) und Slotseng (Mortensen et al. 2011) die Brückenfunktion Schleswig-Holsteinischer Datensätze zwischen Mitteleuropa und Skandinavien in Bezug auf die Erforschung der spätglazialen Vegetationsgeschichte in einem größeren geographischen Rahmen. Der NAH-Datensatz fügt sich nahezu nahtlos in bestehende Datensätze und ist dabei im Stande, unser räumliches und zeitliches Verständnis der Vegetationsentwicklung weiter zu verfeinern.

Appendix V

Untersuchungen an einer Sedimentsequenz aus dem Nahe Paläosee zeigten das erste hochaufgelöste Pollenprofil des Spätglazials nahe eines archäologischen Fundplatzes in Schleswig-Holstein. Auf Grundlage dieses Datensatzes ist das Ziel dieses Artikels, den indikativen Wert der angewandten Anzeiger einer Mensch-Umwelt-Interaktion zu diskutieren. Darüber hinaus wird ein Erklärungsmodell erstellt, für die Summe aus archäologischen Funden und der Interpretation der Proxies.

Am Übergang des Pleistozäns zum Holozän (NAH-5b zu NAH 6a) korrelieren erhöhte Werte in den unterschiedlichen Holzkohlepartikel-Größenklassen und koprophilen Pilzsporen zeitlich mit Radiokarbondatierungen archäologischer Funde (Wild 2017). Gleichzeitig ist dem Datensatz eine rapide Transformation der Umwelt von Sträucher-dominierte Tundra hin zu einem lichten Birkenwald abzulesen. Diese Beobachtungen führen zur Formulierung einer Transformationsphase, die auf die Zeit zwischen 11.650 und 11.520 cal BP fällt.

Die stetig wachsende Verfügbarkeit und Diversität der Flora führte wahrscheinlich zu saisonal verlängerten Aufenthalten von Rentieren in der Region während der Transformationsphase. Deren Präsenz ist durch archäologische Funde, aber auch Maxima in den Werten der koprophilen Pilzsporen belegt.

Die längere Verfügbarkeit des Hauptjagdwildes hatte zur Folge, dass auch Jäger und Sammler ihre saisonal begrenzten Aktivitäten in der Region verlängerten bzw. verstärkten. Diese werden durch Maxima in den Holzkohle-Größenklassen angezeigt und sind sehr wahrscheinlich auf Lagerfeuer zurückzuführen.

Archäologisch sind jene Jäger und Sammler der Ahrensburger Kultur zuzuordnen, wie tausende Flintartefakte des Fundplatzes belegen (Weber et al. 2011). Ein Fortbestehen der Ahrensburger Kultur bis in das frühe Holozän hinein ist auch im nahegelegenen Ahrensburger Tunneltal nachgewiesen. Ein in diesem Artikel neubewerteter Datensatz von Stellmoor (Schütrumpf 1943) mit direkter stratigraphischer Einordnung der Fundschicht in das Pollenprofil zeigt zweifelsfrei an, dass ein Fundhorizont mit der Ausbreitung des lichten Birkenwaldes in der Region zusammenfällt. Die Neubewertung des Datensatzes von Stellmoor und der Datensatz aus dem Nahe Paläosee legen den Schluss nahe, dass erst mit bzw. nach der Präborealen Oszillation die Indikatoren menschlicher Aktivität abbrechen.

Zusammenfassend ist die formulierte Transformationsphase eine palynologische Reflexion der Anpassungsprozesse von Mensch, Fauna und Flora am Übergang vom Pleistozän zum Holozän.

Zusammenfassung und Perspektive

Diese Dissertation soll zum Verständnis der spätglazialen Umweltentwicklungen und -veränderungen auf dem Gebiet des heutigen Schleswig-Holsteins beitragen, basierend auf interdisziplinären Analysen an Sedimenten des Nahe Paläosees. Dabei wird veranschaulicht, wie anthropogene Aktivität und menschliche Interaktion mit der Umwelt palynologisch reflektiert wird.

Vorangestellt wurde eine Aufarbeitung zur Terminologie des Spätglazials basierend auf einem unpublizierten Datensatz von Hartmut Usinger. Der wissenschaftliche Beitrag dieser Dissertation kann in den folgenden vier Feststellungen zusammengefasst werden.

Als erster essenzieller wissenschaftlicher Zugewinn aus dieser Arbeit kann der Beitrag zur Aufklärung der Verstrickungen spätglazialer terminologischer Konzepte gesehen werden. Dieser Beitrag basiert auf der Aufarbeitung und Diskussion eines unpublizierten Datensatz Hartmut Usingers vom Bølling Sø (Dänemark) und liefert zweifelsfreie Belege dafür, dass eine viel kritisierte Annahme Iversen (1942) bestätigt werden kann. Diese bezieht sich auf eine palynologische Reflektion einer klimatischen Schwankung vor der von Hartz (1912) beschriebenen Allerød-Oscillation. Darüber hinaus demonstriert der vorgelegte Datensatz, dass die von Iversen definierte Bølling-Oscillation mit dem GI-1e zusammenfällt.

Die Untersuchungen der Daten aus dem Nachlass von Hartmut Usinger bildet den terminologischen und methodischen Ausgangspunkt der Hauptanalyse. Diese interdisziplinäre Analyse (palynologisch, geologisch, geochemisch) wurde an Sedimenten aus dem Nahe Paläosee (Kr. Segeberg) vorgenommen und resultiert in den weiteren Beiträgen dieser Arbeit.

Der zweite wissenschaftliche Zugewinn dieser Dissertation ist der tephrochronologische Beitrag der Arbeit. Dabei ist hervorzuheben, dass die Laacher See Tephra (LST) zum ersten Mal in Schleswig-Holstein geochemisch bestätigt wurde. Somit liefert diese Arbeit den ersten Nachweis der LST nordwestlich des Hämelsees und folglich einen Fundpunkt weit außerhalb des bisher bekannten Aschefächers. Obwohl das Seesystem deutliche Änderungen durch den Eintrag aus der Eruption erfährt, zeigt sich im Pollenprofil keine Auswirkung des Vulkanausbruchs auf die Landpflanzen der Region. Neben der LST konnten auch die Vedde Asche und die Saksunarvatn Asche geochemisch nachgewiesen werden.

Als dritter wichtiger Beitrag ist das Pollenprofil des Nahe Paläosees zu nennen. Der palynologische Datensatz ist der erste in Schleswig-Holstein, welcher

- (i) das gesamte Spätglazial und frühe Holozän überspannt, ohne durch einen Hiatus beeinträchtigt zu sein,
- (ii) jahresgeschichtete spätglaziale Ablagerungen enthält,
- (iii) spätglaziale Tephralagen als zusätzliche chronologische Marker beinhaltet,

- (iv) ein belastbares Zeit-Tiefen-Modell auch für den spätglazialen Abschnitt liefert,
- (v) neben Pollentypen auch Holzkohle-Größenklassen und NPPs quantifiziert,
- (vi) und dessen analysierte Sedimentsequenz einem Bohrpunkt entstammt, der nahe an einem archäologisch gesicherten Fundplatz spätglazialer Jäger und Sammler liegt.

Ausgehend von diesem neuen Datensatz ist der vierte wissenschaftliche Beitrag dieser Arbeit die Formulierung der Transformationsphase im Zeitbereich zwischen etwa 11.650 und 11.520 cal BP. Das Zusammenwirken aus palynologischen und archäologischen Untersuchungen legen den Schluss nahe, dass Umweltveränderungen am Übergang des Pleistozäns zum Holozän saisonal verlängerte Aufenthalte von Rentieren in der Region zur Folge hatten. Diese resultierten wahrscheinlich in einem veränderten Jagdverhalten der kontemporären Jäger und Sammler (saisonal längere Präsenz, oder Intensivierung der Jagd).

Zusätzliche Untersuchungen zur Vegetationsentwicklung bleiben wünschenswert und sind besonders in Bezug auf das frühe Spätglazial (Meiendorf Periode und Dryas 1 Periode) in bspw. höherer palynologischer Auflösung notwendig. In Zusammenhang mit der spätglazialen Migration der Baumbirken sind überdies auch geochemische Analysen (Wachslipide) vielversprechend, um eine noch genauere Datierung der ersten Bäume in der Region vornehmen zu können.

Nur etwa 18% der palynologisch untersuchten Sequenz sind einer Suche nach Kryptotephralagen unterzogen worden. Es ist bekannt, dass neben den identifizierten Tephren zahlreiche weitere Aschefächer spätglazialer und frühholozäner Eruptionen über das Untersuchungsgebiet verweht wurden (Blockley et al. 2014; Pyne-O'Donnell et al. 2008; Wastegård et al. 2018). Demzufolge ist eine weitere gezielte Suche nach Vulkanaschelagen aussichtsreich.

Um die erzielten Ergebnisse insbesondere in Bezug auf die *Transformationsphase* zu überprüfen, sind neue Untersuchungen an Sedimenten des Ahrensburger Tunneltals ebenso notwendig wie wünschenswert. Betrachtet man die umfangreichen archäologischen Funde des Ahrensburger Tunneltals, sind die hier vorgestellten Charakteristiken der Transformationsphase möglicherweise dort stärker ausgeprägt als im Nahe Paläosee.

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Appendix I



In search of the Bølling-Oscillation: a new high resolution pollen record from the *locus classicus* Lake Bølling, Denmark

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Abstract

In a paper from 1942 Johannes Iversen described a warm phase prior to the Allerød warming from lake Bølling in western Denmark and thereby extended the common classification of Lateglacial biostratigraphy. Iversen's assumptions concerning the Bølling-Oscillation were based on sedimentological features and high *Betula* (birch) pollen values in two pollen samples prior to the onset of the Allerød warming. Questions regarding the nature of the Bølling warming later became a discussion due to the expansion of terms into different fields and especially with advances in palynology. To further refine the knowledge on the Bølling-Oscillation, Hartmut Usinger investigated the *locus classicus* in 1982. The method of pollen-size-frequency distribution was applied on birch pollen in order to distinguish between *B. nana*- and *B. pubescens*-type pollen, however, the results were never published and got lost over time. Therefore, these data are presented here and the method as described by Usinger (Pollenanalytische und stratigraphische Untersuchungen an zwei Spätglazial-Vorkommen in Schleswig-Holstein, 1975, Danm Geol Unders Årbog, 1977:5–29, 1978a, Pollen Spores 23:389–432, 1981b) is performed on the reassembled dataset again. In order to solve existing ambiguities in Lateglacial terminology, especially concerning the terms Bølling and Meiendorf, we used the data originally compiled by Usinger to discuss it against the background of the previous work by Iversen. Furthermore, the dataset enabled a comparison of different ways to determine between different *Betula* pollen types. The general focus is set on the distinction of *Betula* pollen types in order to shed light on the question of the migration of tree birches into northern Europe, especially before the Allerød warming. The results show that the dataset can immensely refine Iversen's pollen zones. A clear dominance of dwarf birch pollen during the Bølling-Oscillation is demonstrated. Furthermore, the record reveals that Iversen's assumption concerning the existence of a climatic oscillation prior to the Allerød warming can be confirmed at the *locus classicus*.

Keywords Bølling-Oscillation · Palynology · Lateglacial · Pollen-size-frequency-distribution

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Introduction

To classify periods according to key sites has been common practice in archaeology as well as in palynology. However, progressing knowledge often resulted in repeated amendments of terms and has consequently led to misinterpretations and a lack of clarity. The terminology of Lateglacial biostratigraphy in northern Europe especially underwent various revisions and adjustments. In this respect, the term Bølling has been redefined almost beyond recognition, as indicated by the terms Bølling-Oscillation (Iversen 1942, 1954, 1973; van der Hammen 1951), Bølling-Zeit (Overbeck 1975), Bølling Interstadial (Usinger 1978b; van Geel et al. 1989), Bølling-Allerød complex (Usinger 1985; Friedrich et al. 2001), Bølling/Allerød Interstadial (Wooller et al. 2018) or Bølling-Allerød-Interstadial-Complex (Simikova

and Puzachenko 2005)—referring to stratigraphy, chronozones or biozones.

In 1942, Iversen extended the common classification of Lateglacial biostratigraphy (Hartz and Milthers 1901; Jessen 1935) based on pollen analyses from Lake Bølling, Denmark. There, he found a climatic oscillation prior to the Allerød warming and named it Bølling-Oscillation (Iversen 1942). The interpretation rested on sediment features and especially on a twofold *Betula* pollen peak reflecting the first spread of tree birches in Denmark after the deglaciation. This interpretation led to a subdivision of the zonation by Jessen (1935). The given zone I was divided into subzone Ia (Oldest Dryas), Ib (Bølling-Oscillation) and Ic (Older Dryas), the latter representing the stadial period between the Bølling- and Allerød-Oscillation (Iversen 1947, 1954). It has been stated by Björck et al. (1998) and later by de Klerk (2004b) that terms such as oldest, older and younger are inappropriate as descriptive epithets for periodic terms. For reasons of comparability, these have still been used here, as well as the terms Dryas 1–3.

Since then, biostratigraphic classifications have been extended to terms including radiocarbon ages and climatostratigraphic elements (Mangerud et al. 1974; Donner 1995; Björck et al. 1998). The expansion of the terms (*Meiendorf*, *Bølling*, *Allerød*, *Dryas*) into different fields led consequently to further misunderstandings and misinterpretations. In particular Mangerud et al. (1974) intended to shed light on this ambiguity regarding terminology and suggested a chronostratigraphic scheme (for further reading and discussion see also: Usinger 1985; Donner 1995; Hoek 1997, 2009; Björck et al. 1998; de Klerk 2004b; Litt et al. 2007). There were different attempts to introduce new terms for biostratigraphy (Menke 1968; Usinger 1985, 1998; de Klerk 2004a) and for event stratigraphy (Johnson et al. 1992; Dansgaard et al. 1993; Björck et al. 1998), the latter inheriting the strength of being equally applicable to a variety of records, but the principles of Lateglacial terminology, especially concerning the term Bølling, remained rather confusing.

Furthermore, a disparity in the application of terms between countries became established. On the one hand the term Bølling describes biostratigraphically the first warmer phase of the Allerød-Interstadial (used in this paper sensu Usinger 1998) in northern Germany. The term Bølling includes the subsequent spread of *Betula*, encompassing tree-sized species (Usinger and Wolf 1982; Usinger 1985, 1998; Nelle and Dörfler 2008). It is equal to the Allerød-a sensu Usinger (1981a) or the *Juniperus-Betula nana-B. pubescens*-PAZ sensu Usinger (1985). On the other hand, Bølling-Oscillation or Bølling period in Denmark is understood chronologically as an independent Interstadial equivalent to the Meiendorf-Interstadial sensu Menke (in Menke 1968; Bock et al. 1985). It is biostratigraphically

characterized by increasing values of heliophilous plants (*B. nana*, *Dryas octopetala*, *Salix*, *Hippophaë*, *Juniperus*, *Artemisia*) and is understood as the first warmer period of the Lateglacial (Bennike et al. 2004; Litt et al. 2007; Mortensen et al. 2011).

The pure number of publications including reinterpretations, adjustments and revisions of Lateglacial terminology make it redundant to add another definition or to further divide the existing framework. But, if there is the intention to approach the main features of the term Bølling, it is necessary to include new palynological data into the discussion. As pointed out by de Klerk (2004b, p 276) "... The most detailed pollen analysis of the Bøllingsø was carried out by H. Usinger on a new core which is still unpublished with the exception of only a few pollen curves (Usinger 1985)". Since then the publication of the palynological investigation and macrofossil analysis still remained a desideratum. As Usinger targeted the distinction between *B. nana*- and *B. pubescens*-type pollen by size-frequency distribution, the results presented here shed light on the migration of tree birches in that area—a crucial point of Iversen's interpretation (Iversen 1942). Therefore, it is one objective of this paper to provide unpublished palynological and macrofossil data from Lake Bølling. Consequently, this allows for the discussion of existing ambiguities in the terminology of the Lateglacial, especially with regard to the term Bølling.

The determination of *Betula* pollen is essential to interpret Lateglacial pollen diagrams and to comprehend Lateglacial reforestation processes and vegetation dynamics. However, fossil European *Betula* pollen originate either from tree birches (*Betula pendula* ROTH/*B. pubescens* EHRH.) or shrubby birches (*Betula nana* L./*B. nana* ssp. *exilis* SUKACZEV/*B. humilis* SCHRANK). Based on phytogeographic considerations some of these species can be excluded spatially and temporally (Usinger 1975). In addition, Usinger (1981a) argued that Lateglacial *Betula* pollen precipitation predominately consisted of *B. nana* and *B. pubescens* based on multiple Lateglacial pollen and macrofossil datasets.

In the case of separating these *Betula* species palynologically, two different approaches are prevailing. On the one hand, there is morphological distinction (Welten 1944; Pragłowski 1962, 1966; Blackmore et al. 2003). It is argued by Blackmore et al. (2003) that this approach is indeed possible requiring extremely careful comparison. However, the visual assessment of *Betula* pollen types has its limitations. As Firbas (1949), Birks (1968) and Mäkelä (1996) pointed out, it is hardly repeatable and inadequate as an objective research method.

On the other hand, there are attempts to separate pollen by grain-size. This method is based on the measurements of equatorial diameter or additionally of its ratio to pore height (Welten 1944; Eneroth 1951; Andersen 1961, 1970, 1980; Birks 1968; Usinger 1975; Gordon and Prentice 1977;

Kolstrup 1982). Grain sizes of different *Betula* species are approximately normally distributed (Usinger 1975, 1978b, 1981a; Karlsdóttir et al. 2007). The average grain size of *B. nana* is distinctly smaller than the grain size of *B. pubescens* (*B. nana*, 24 μm ; *B. pubescens* ssp. *pubescens*, 27 μm ; *B. pubescens* ssp. *tortuosa*, 30 μm —Blackmore et al. 2003; *B. nana*, 24.5 μm ; *B. pubescens*, 30.8 μm —Beug 2004). The grain size distribution of Lateglacial *Betula* pollen precipitation is consequently either normally distributed (if just one species is present) or a compound distribution of two normally distributed components with different average values (Usinger 1981b).

The applicability of grain size measurements as a distinctive feature between tree and dwarf birch pollen leads to a common use of a fixed threshold (Kolstrup 1982; Karlsdóttir et al. 2007; Mortensen et al. 2011). In contrast to this method, Usinger applied the statistical method of evaluation of size-frequency distribution/approximation approach (Usinger 1975, 1978a, b, 1981b; Andersen 1980). As shown by different studies an absolute separation is not possible due to an overlap in grain-size distribution.

Beyond that it is important to note that the distinction is made between pollen types and not ultimately between species. In this respect pollen types are displayed in small CAPITALS following de Klerk (2004b) to separate them from plant taxa. However, we assume that potential errors are statistically irrelevant.

Location

Lake Bølling is situated in central Jutland, Denmark. The lake basin, roughly circular in outline and about 2 km in diameter, is part of a valley adjacent to the main stationary line of the Weichselian ice sheet during the last glacial maximum (Fig. 1). The valley was formed during the early Lateglacial by a meltwater stream (Brandt 1954). The area was drained in 1870 for peat cutting and agricultural purposes (Stockmarr 1975; Bennike et al. 2004) before it was restored again between 2004 and 2005. The site cored by Usinger is close to Iversen's original coring site from the 1940s and was determined by Bennike et al. (2004) as 56°10'35.4"N, 9°22'20.9"E.

Material

On the 30th of June 1981, Usinger used a modified Livingston piston-corer (Mingram et al. 2007) to extract nine different sediment cores, each with a maximum depth of four metres. Three of them were cored in an overlapping sequence to enable interruption-free analyses. Boreholes VII

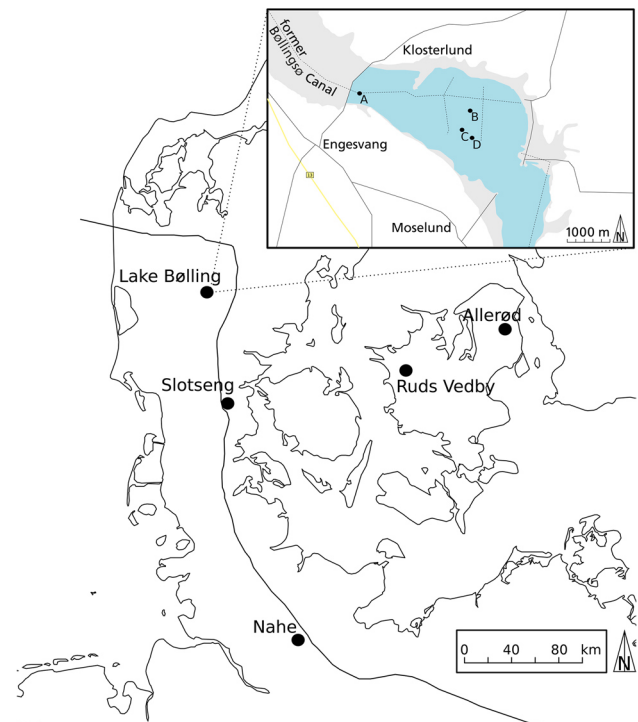


Fig. 1 Map of Denmark with important locations as mentioned in the text. Allerød—Hartz and Milthers (1901), Slotseng—Mortensen et al. (2011); Ruds Vedby—Krog (1954), Nahe—Krüger unpublished; the detailed map shows the restored Lake Bølling within the melt water valley as well as the former Bøllingsø canal. Location A—investigations by Stockmarr (1975), B—approximate location of the core analysed by Brandt (1954), C—excavation by Krog in 1960; D—Iversen (1942)/Bennike et al. (2004)/present study. Blue colour indicates renaturated lake area

and IX with an offset of 30 cm were chosen for palynological investigations.

According to a number of previous analyses of sediments from Lake Bølling the complex Lateglacial stratigraphy of the site (Iversen 1942, 1947; Stockmarr 1975) could easily be correlated with a sequence analysed by Bennike et al. (2004).

The chosen sediment sequence for pollen analysis is shown in Table 1. The sequence reaches glacial till in the bottom section at 390 cm depth. This is followed by irregularly layered sandy, silty and clayey gyttja up to 370 cm and by different layers of sand as well as clayey and silty calcareous gyttja of predominantly yellowish-grey colour up to 246 cm. A layer of sandy and clayey gyttja with very sharp upper and lower boundaries follows up. This layer spans about four cm and has been interpreted by Usinger as a single event representing a hiatus. Different thick layers of calcareous gyttja interspersed with layers of fine sand and dark brown detritus gyttja are overlaying the probable hiatus (up to 165 cm). These are succeeded by blackish fine

Table 1 Lithology of Lake Bølling sediments

Depth (cm)	Lithology
0–30	Peat
30–45	Dark brown gyttja
45–130	Dark grey gyttja
130–165	Blackish fine detrital gyttja
165–170	Grey-brown calcareous gyttja, irregularly layered with organic detritus and sand
170–190	Grey-brown detritus gyttja/organic detritus with sand
190–242	Grey-brown calcareous gyttja, irregularly layered with coarse sand
242–246	Sandy, clayey gyttja (sharp boundaries; <i>hiatus</i>)
246–280	Yellowish-grey calcareous gyttja
280–308	Yellowish-grey calcareous gyttja, with numerous thin sandy (thickest at 308.0 cm) and laminated clayey layers
308–332	Greyish clayey-silty gyttja, irregularly thin sand layers
332–338	Clayey sand layer
338–387	Irregularly layered sandy silty and clayey gyttja
387–390	Coarse sand mixed with fine gravel

detrital gyttja (130 cm), dark grey and brown gyttja (30 cm) and finally peat.

Methods

Sampling and sample treatment

Pollen sampling and sample preparation had already been carried out in the early 1980s by H. Usinger. He analysed a total of 89 samples that are presented here, spanning almost the whole Lateglacial and the early Holocene. Sample preparation was carried out according to standard techniques of the 1980s (Erdtman 1960; Fægri and Iversen 1964). *Lycopodium* spore tablets were added to each sample to calculate pollen concentrations (Stockmarr 1971). Additionally, approximately 10 g of sediment per sample were subjected to loss on ignition (LOI). The sediments were analysed for organic matter and CaCO₃ according to the methods described by Dean (1974).

The gyttja, silt and sand layers were sampled at least at 2.5 cm intervals for pollen samples. The alternating thin layers of gyttja and sand (190–240 cm) that probably date to the Dryas 3 have been sampled at 5 cm intervals. Pollen counting was performed by H. Usinger at a total magnification of $\times 400$ for routine counting and $\times 160$ for scanning for rare types. A total pollen sum of at least 300 TTP (total terrestrial pollen, here excluding Cyperaceae) for pollen-poor samples and ≥ 650 TTP for average samples was achieved. Pollen grains were identified with the help of literature (Erdtman et al. 1963; Fægri and Iversen 1964) and the reference collection of the Botanical Institute at Kiel University (Germany). Pollen of thermophilous taxa such as *Alnus*, *Corylus*, *Ilex aquifolium*, *Picea*, *Quercus*, *Tilia*, *Ulmus* and *Viscum*

album were regarded as rebedded/exotic if present in the Lateglacial deposits.

Additional pollen slides of each sample were visually scanned for *Betula* pollen by H. Usinger. The equatorial diameter of pollen was measured to enable a separation of species by pollen-size-frequency distribution. For each sample at least 120 measurements were made by H. Usinger.

Apart from that, samples of 10 cm³ were wet sieved at 0.4, 0.2 and 0.1 mm to achieve material for a macrofossil analysis. Macrofossils were identified by H. Usinger and counted at 10- $\times 40$ magnification. The reference collection of the Botanical Institute at Kiel University was further consulted. Macrofossils are presented as numbers per 10 cm³.

The macrofossil record as well as the handwritten pollen counting and scanning sheets have been compiled again and digitalized for this study by the authors.

Here, pollen-size-frequency distributions were used to determine theoretical compound distributions of *Betula* species. The computation for the present study was done in Excel 2016.

The pollen diagrams were constructed using the CountPol software developed by I. Feeser, Kiel University (Germany). Percentage values shown in the diagrams are based on the total terrestrial pollen sum—on the arboreal pollen sum (AP) and pollen of non-arboreal plants from dry grounds (NAP, upland vegetation). Pollen and spores of water plants and Cyperaceae were excluded. The diagrams were imported to Inkscape (v. 0.91–1) where minor changes have been made. Zone boundaries were placed at marked changes in pollen and LOI assemblages, as well as according to the results from PEARSON's coefficient of skewness and pollen concentration.

The processing of Usinger's legacy data revealed that the preparation forms including sample weight and

volume of each sample have been lost over time. Usinger performed the sampling consistently according to a uniform protocol (W. Dörfler personal communication). As the number of added *Lycopodium* spore tablets and counted spores are known, the calculation of the pollen concentrations has been obtained by assuming a uniform sample volume and weight (1.5 ml/1.5 g per sample).

Determination of *Betula* species

The pollen analytical determination of *Betula* sp. was attempted by two different methods. The first was by morphologically distinguishing a *B. pubescens*- and a *B. nana*-type (Blackmore et al. 2003; Beug 2004). Based on phytogeographic considerations, pollen and macrofossil datasets of *B. pubescens* pollen dominate the tree-birch pollen precipitation (Usinger 1981a, b), although *B. pendula* cannot be fully excluded. Hence, a *B. pubescens*-type is used here, including the species of *B. pendula* and *B. pubescens* (Blackmore et al. 2003; Beug 2004).

The second method was the evaluation of characteristics and parameters of pollen-size-frequency distributions.

With the first method a determination of *Betula* pollen based on morphologic differences was made after Tersmä (1951) as well as Erdtman et al. (1961). Generically developed pollen grains can be distinguished but the amount of intermediary pollen remains considerable, leaving space for subjective decisions (Usinger 1978b). In this respect, it was necessary to utilize the approximation approach as described by Usinger (1975, 1978b, 1981b; ‘Approximation through theoretical compound distribution’). Only triporate pollen grains lying in polar view were used during the visual scanning. The pollen size was distinguished by measuring the major dimension (distance from the outside tip of the pore to the outer margin of the facing wall). For the pollen-size-frequency distribution, the pollen size was classified in μm steps. However, this microscopic work had been carried out by Usinger between 1982 and 1983 and recorded on counting sheets. Those were compiled and digitalized for the present study. In order to obtain statistically significant results (minimum of 200 *Betula* pollen grains, depending on the preservation), two samples were combined. Statistical parameters were used as follows:

D is the modal value

H is the relative frequency, $0 \leq H \leq 1$

Q is the relative difference of average pollen size of two species, $Q = \bar{x}_2 / \bar{x}_1$ when $\bar{x}_2 > \bar{x}_1$

s is the statistical dispersion; standard deviation

Sp is the Pearson’s coefficient of skewness, $Sp = (\bar{x} - D)/s$

V is the coefficient of variation, $V = s/\bar{x}$

\bar{x} is the mean; average pollen size

Pearson’s coefficient of skewness

The use of PEARSON’S coefficient of skewness (Sp) to separate *B. nana* from *B. pubescens* has already widely been discussed by Usinger (1975). The principle is based on the assumption that pollen grains feature the same size alterations when subjected to the same physical and chemical processes (Sachs 1971; Usinger 1975, 1978b, 1981b). The principle utilizes the circumstance that the modal value D and the arithmetic average \bar{x} do not coincide in asymmetrical distributions. In this article, the skewness of a displayed curve can reveal compound distributions, successions or changes of dominance in pollen precipitation.

Approximation through theoretical compound distribution

The algorithm is premised on the assumption that the distribution is a compound distribution of two normally distributed (and always the same) components with different mean values. Differences between the distributions are substantially based on differences in mix-ratios of the two components.

Given that the assumption is true, \bar{x}_1 and \bar{x}_2 are the mean values (average pollen sizes) and s_1 and s_2 the standard deviation of the two component distributions. The mix-ratio of the component distributions is defined by their relative frequency, for which $H_1 + H_2 = 1$ applies. The compound distribution can be described with the function

$$p(x) = \frac{H_1}{s_1 \sqrt{2\pi}} e^{-\frac{(x-\bar{x}_1)^2}{2s_1^2}} + \frac{1-H_1}{s_2 \sqrt{2\pi}} e^{-\frac{(x-\bar{x}_2)^2}{2s_2^2}}, \quad (1)$$

when only H_1 is altered (Usinger 1978b, 1981b). Thereby $p(x)$ stands for pollen-frequency of size x . The relative frequency H_1 is determined by minimizing the mean squared error between the compound distribution and the normalized pollen-frequency-distribution $\bar{n}(x)$

$$H_1 = \arg \min_{H_1 \in [0,1]} \sum_x [p(x) - \bar{n}(x)]^2 \quad (2)$$

In this work, H_1 is calculated through an exhaustive search with a step size of 0.01. In addition to H_1 , only \bar{x}_1 is varied with a step size of 0.1 μm . The second mean \bar{x}_2 results from $Q = 1.19$, which is assumed to be constant (Usinger 1975; Karlsdóttir et al. 2007). The standard deviation of each component distribution results from a constant coefficient of variation $V = 0.072$ (Usinger 1975, 1978b, 1981b).

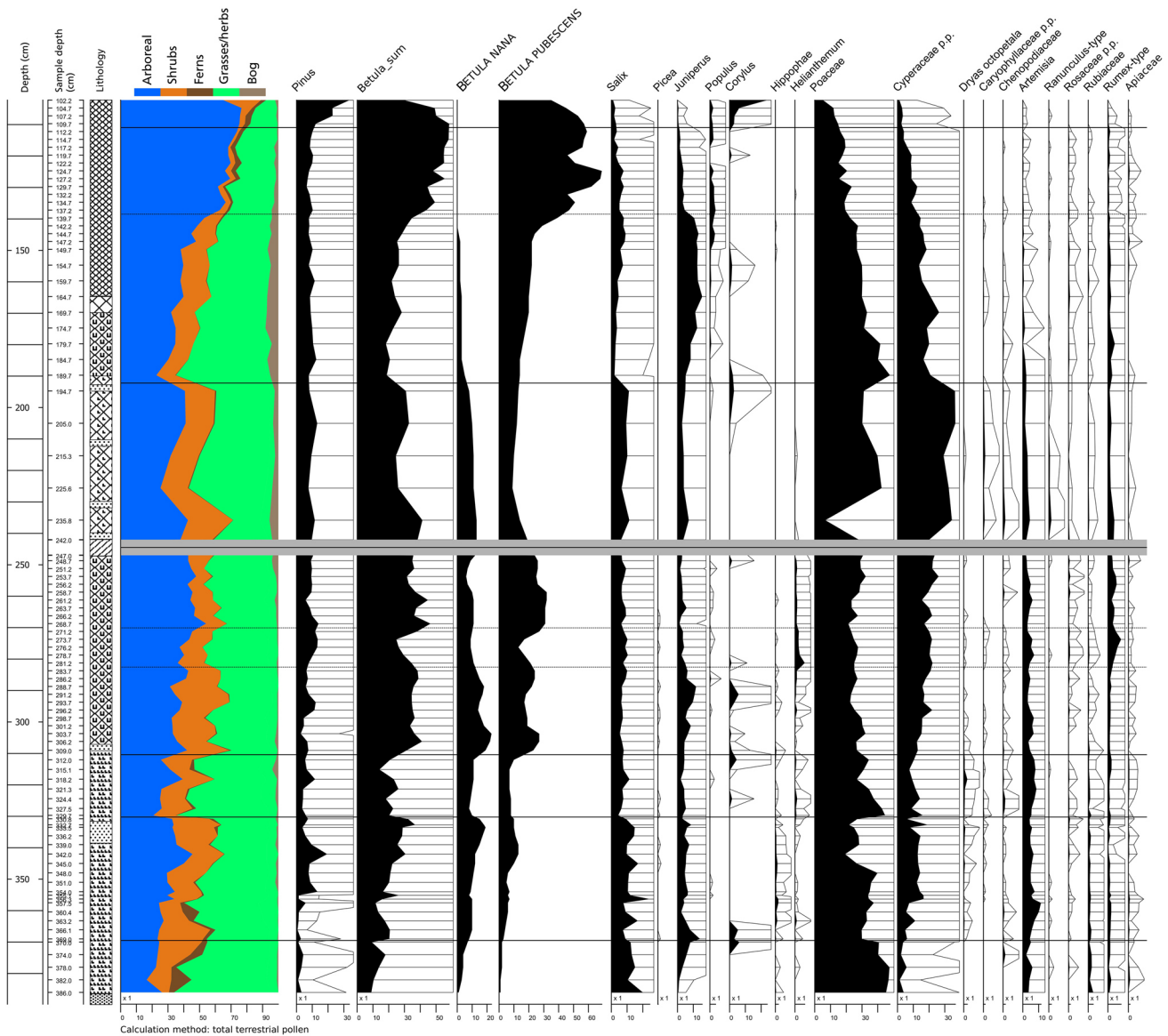


Fig. 2 Pollen percentage diagram showing selected taxa. The sum used for calculation is TTP excluding Cyperaceae. The dashed line indicates $\times 10$ exaggeration for improved reading. The grey horizontal bar indicates a hiatus

The relative frequency is used to determine the amount of *B. PUBESCENS* and *B. NANA* pollen in the total terrestrial pollen sum. Missing frequency values, due to the combination of two samples, were determined by linear interpolation. The results were smoothed with a moving average filter of length 3.

Distinction of *Betula* species by a fixed threshold

The detailed and comprehensive handwritten dataset by Usinger rendered it possible to retrospectively apply a fixed threshold in order to separate *Betula* sp. Usinger recorded

size classes of *Betula* pollen, by measuring the maximum diameter of the pollen grain, in $1 \mu\text{m}$ -steps. In this respect a fixed threshold at $21.5 \mu\text{m}$ was applied, following Mortensen et al. (2011), Karlsdóttir et al. (2007) and Kolstrup (1982).

Dating

As the investigations by Usinger in 1982 did not include the dating of macrofossils, a later study by Bennike et al. (2004) aimed at obtaining datable material. Further dates were provided by Sarmaja-Korjonen et al. (2006) deriving from the same fieldwork campaign. However, the datings

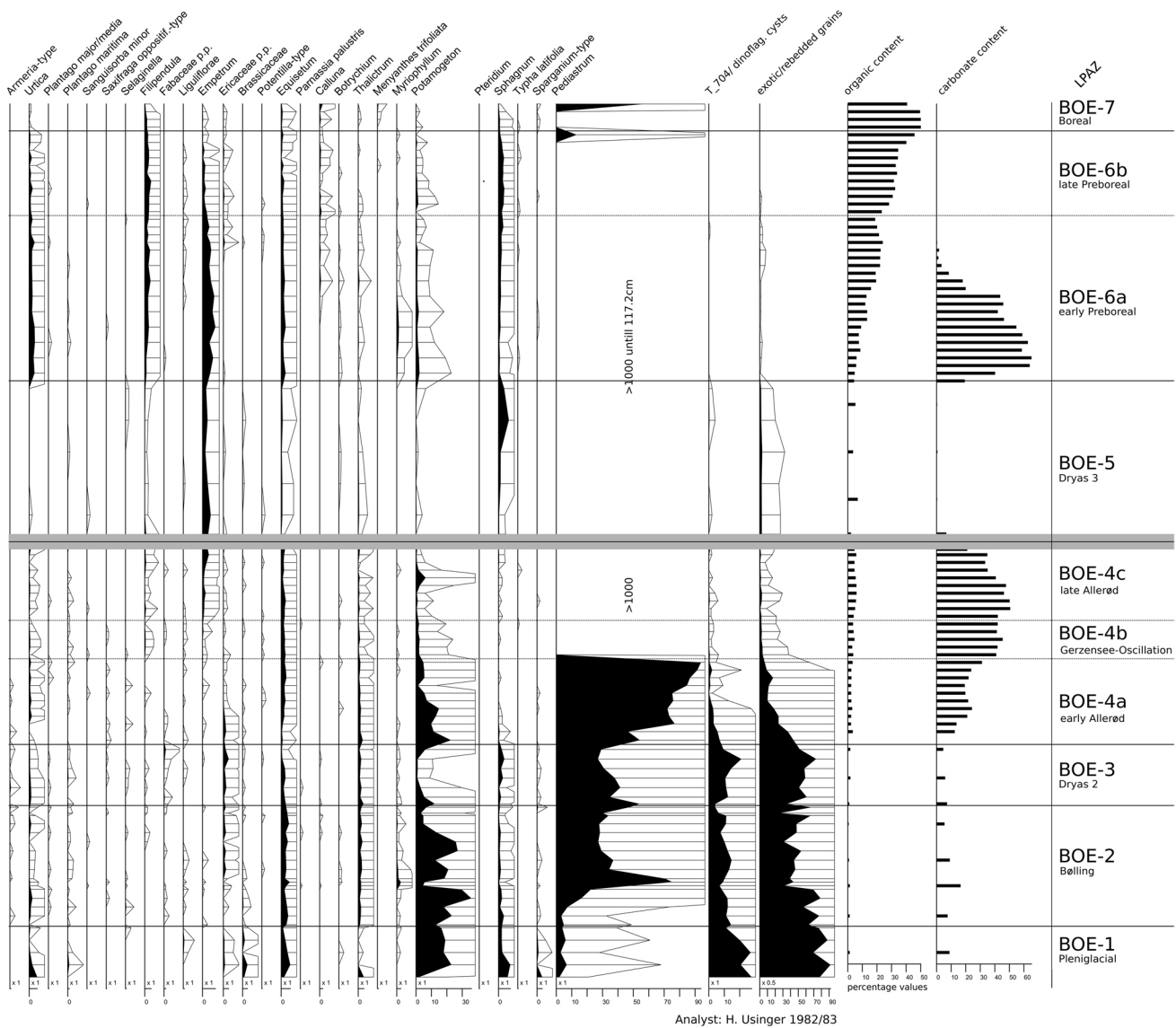


Fig. 2 (continued)

only allowed for a rather fragile age-depth model (O. Benike personal communication). Macrofossils from Usinger’s original analysis for potential new datings are unfortunately not existent. For this reason the present study neglects to set up an age-depth model and is based solely on palynostratigraphy and biostratigraphy.

Results and environmental synthesis

The pollen diagram of Lake Bølling is based on 89 pollen spectra between 102.2 and 386 cm below the surface. The diagram was divided into seven pollen assemblage zones (PAZ; BOE-1 to BOE-7), which further included five

subzones. The general development in the pollen record is described in ESM Table 1. The pollen diagram showing percentage values calculated on TTP is shown in Fig. 2. Besides *B. NANA* and *B. PUBESCENS* curves also a *Betula* sum curve has been added for improved reading. A simplified concentration diagram is depicted in Fig. 3a, b.

The diagram displaying the coefficient of variation, PEARSON’S coefficient of skewness, the approximation approach and the fixed threshold can be seen in Fig. 4a–e. The use of the approximation approach in the uppermost samples of the record (Fig. 4c) was regarded as redundant. The sediment is of clear Holocene origin and, therefore, a calculation has not been made.

The preservation of macrofossils was predominantly good. 27 samples were analysed in total and the results are

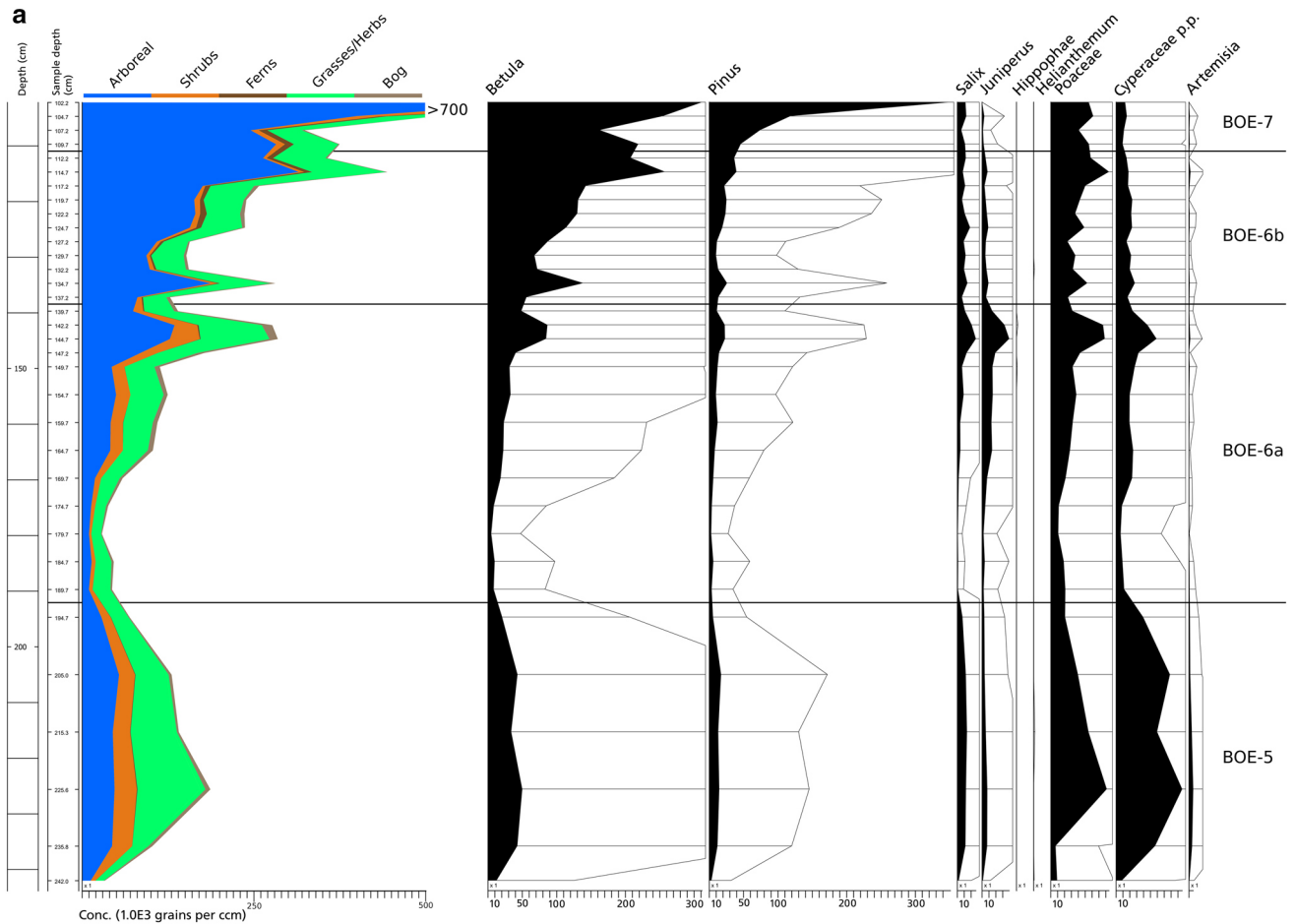


Fig. 3 **a** Diagram showing pollen concentration per cm^3 sediment of selected taxa and sum concentration between Dryas 3 and early Boreal period. **b** Diagram showing pollen concentration per cm^3 sedi-

ment of selected taxa and sum concentration between Dryas 1 and late Allerød period

given in Fig. 5. PAZs have been added at corresponding depths for improved reading.

Determination of *Betula* species by statistical methods

Coefficient of variation and PEARSON'S skewness

The coefficient of variation for a record of a single species would constantly remain below 0.09 as shown by Usinger (1975). However, the coefficient of variation within the first Sect. (1) of Fig. 4a remains constantly above 0.09 and in most cases even significantly above 0.11. As suggested by Usinger (1975, 1978b, 1981b) it can be concluded that values > 0.09 with certainty result from a compound distribution of at least two species with different average pollen sizes.

Within the second Sect. (2) the values predominantly undershoot the value 0.09 indicating that only one *Betula*

species is present within the record. However, on the other hand it needs to be considered that this section displays the later Preboreal and early Boreal period (see 'Environmental synthesis' below). A mixture of *B. pubescens*, *B. pendula* and potential hybrids could affect the result within the early Holocene. Still, this possible source of error can be neglected, as the focus is set on the Lateglacial part of the record.

PEARSON'S coefficient of skewness for a record of a single species can always be characterized as approximately symmetric. In this respect asymmetry suggests a compound distribution (Usinger 1978b), indicating that all five defined sections of Fig. 4b show the presence of at least two *Betula* species within the record.

In a detailed study, Usinger (1975) could show that skew values above $+ 0.3$ are equivalent to a compound distribution dominated by *B. nana*, with significant participation of *B. pubescens*. To the opposite skew values below $- 0.15$ indicate compound distributions dominated

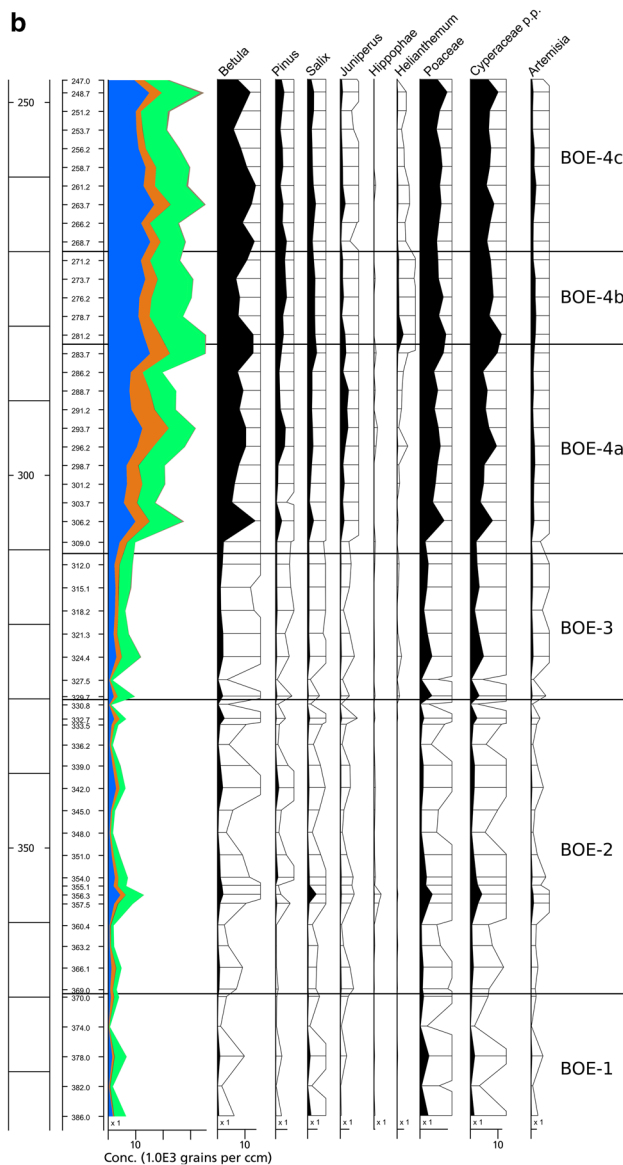


Fig. 3 (continued)

by *B. pubescens*, with significant participation of *B. nana* (Usinger 1975, 1978b; Andersen 1980).

PEARSON'S coefficient skewness in section one (1) of Fig. 4b significantly undershoots the value of + 0.3 towards only the very end of the section. It can be inferred that the compound distribution of this section is without doubt dominated by *B. NANA*.

Section two (2) displays highly fluctuating values that clearly exceed and undershoot the set thresholds of -0.15 and $+0.3$. PEARSON'S coefficient of skewness is highly dependent on the modal value *D*. *D* does not differ distinctly in section two. The quantity of size-distributions between 21 and 25 μm are almost equal. This results in a strongly varying coefficient of skewness and can be

interpreted as a shift of dominance between *B. NANA* and *B. PUBESCENS*.

Within section three (3) the values have stopped fluctuating. They constantly stay below -0.15 indicating a clear dominance of *B. PUBESCENS*. This presumed dominance ends at the observed hiatus.

The lower part of section four (4) only contains five samples (depth 244.5–200.0 cm). An increasing tendency is obvious, indicating another possible shift in dominance, but the amount of samples is insufficient for a statistically relevant conclusion. Within the upper part of section four (200.0–244.5 cm) the values undershoot the threshold of -1.5 again. Considering that the blackish gyttja is of early Holocene origin, the regained dominance of *B. PUBESCENS* is not surprising.

Finally, section five (5) contains values that lie well between the thresholds showing no clear tendency. Considering the lithology again, this should not be interpreted as another shift in dominance between *B. PUBESCENS* and *B. NANA*. As stated above, it is more likely that the values display a compound distribution of *B. pubescens* and *B. pendula* (including possible hybrids), the latter being also highly relevant for early Holocene reforestation (Usinger and Wolf 1982).

Determination of *Betula* species by approximation approach

The method was applied in particular to focus on the earlier parts of the Lateglacial. As can be seen in Fig. 4c the approximation approach yielded distinct results. Especially within the assemblage zones BOE-1 to BOE-4c tendencies and dominances could be clarified.

A dominance of *B. NANA* within BOE-1 to BOE-2 is clear. This includes a first maximum that needs to be discussed against the background of the first Lateglacial interstadial (see 'Environmental synthesis' and 'Approaching the term Bølling'). Furthermore, the beginning of the Allerød-Interstadial and a following shift in dominance between *B. NANA* and *B. PUBESCENS* can easily be noticed from the results (BOE-4a to 4c).

Potential sources of error concerning the approximation approach have been discussed in detail by Usinger (1975, 1978b). Still the question remains whether curve-fitting, interpolation and averaging will result in reliable outcomes. However, a comparison with actual pollen counts as well as macrofossils will contribute to answering that question.

It must be clear that a high resolution is imperative for conducting this application in order to detect small scale changes also. Nevertheless, the method is highly time-consuming and it is therefore recommended to only use it in case of research questions referring specifically to *Betula*.

Two ways of determination: a brief comparison

The results of the determination of *B. NANA* by a fixed threshold (Fig. 4d) and by approximation approach (Fig. 4c) are compared in Fig. 4e. The similarities in the course of the curves and the coincidence of tendencies are apparent. This implies that the results of the approximation approach are less effected by potential sources of error than expected. However, it becomes clear that the morphological distinction (fixed threshold) yielded smaller percentages for *B. NANA* throughout the Lateglacial part of the diagram. In this respect, Usinger (1978b) suspected that the limits for *B. NANA* concerning the threshold have been set too narrowly.

As the focus of this paper is set on the earlier parts of the Lateglacial period in order to look at the relation of tree and dwarf birches it was necessary to apply the approximation approach. Only in this way was it possible to achieve a distinct result.

Whether one or the other method is applied generally draws no distinction with regard to the question of the migration of tree birches. Proof for the actual local presence of species can only be provided by macrofossils (Birks and Birks 2000) or wax lipids (Schwark et al. 2002; van den Bos et al. 2018).

Environmental synthesis

The environmental synthesis comprises the results and discussion of the pollen analysis (depicted as percentages in Fig. 2 and as concentrations in Fig. 3a, b) and the macrofossil record (Fig. 5). Palynological work by Iversen (1942), Krog (1954), Stockmarr (1975), de Klerk (2004b), Usinger (1975, 1981a, b, 1985) and Mortensen et al. (2011) is further consulted. Additionally, LOI values are incorporated, inheriting a high explanatory potential between the onset of the first Lateglacial interstadial and the end of the Allerød-Interstadial (Mortensen et al. 2014a). In order to prove the presence of species, macrofossil records of previous local analyses by Brandt (1954) and Bennike et al. (2004) are included as well.

BOE-1 (cf. Pleniglacial/Dryas 1) 386.0–369.5 cm

The environmental conditions of the Lake Bølling area before the onset of the first Lateglacial interstadial are characterized by diverse erosional processes. This can be inferred from high amounts of rebedded pollen grains with maxima of 90% and high abundances of dinoflagellate cysts > 20% (Bakker and van Smeerdijk 1982). Additionally, a pollen concentration below 1000 pollen grains per cm³ sediment, and irregular layers of sand embedded in a silty and clayey gyttja of 90% minerogenic content in sum suggest

periglacial conditions with high aeolian activity, permafrost and solifluction.

The heterogeneous aquatic flora is composed of different species of *Pediastrum*, *Potamogeton praelongus* (Brandt 1954), *P. perfoliatus* and *P. filiformis* (Bennike et al. 2004). Those species are unlikely to have been competing with each other due to a wide ecological amplitude. The high abundance of *Potamogeton* sp. within the pollen spectrum as well as within the macrofossils suggest that their distribution was favoured by clear water conditions. Their ecological requirements indicate that the water levels were rather low.

At the telmatic zone of the lake *Equisetum* sp., *Sparganium* sp. and Cyperaceae were prevailing.

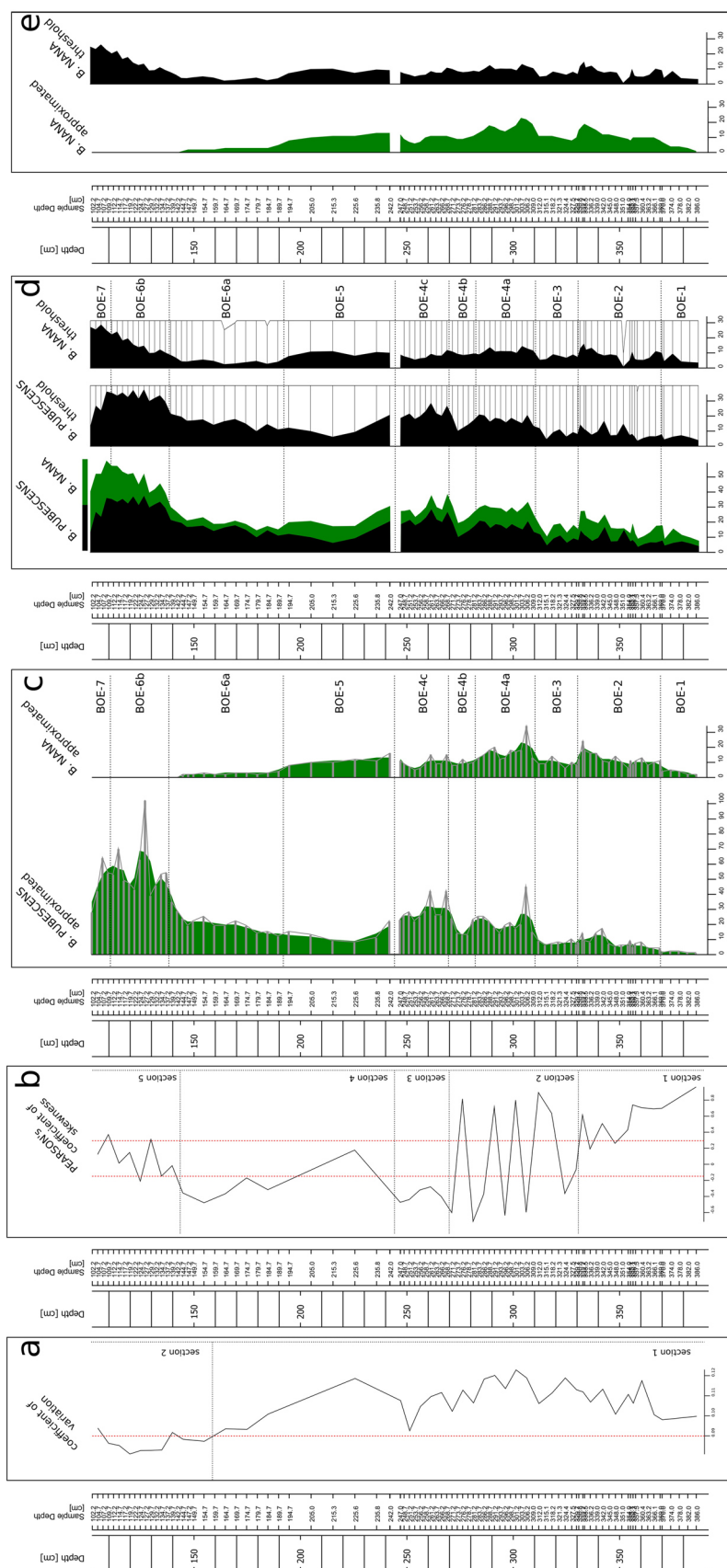
Some of the first pioneer species to spread on the dry raw soils were dwarf shrubs such as *Salix* sp. (cf. *polaris*, cf. *herbacea*) and *B. nana* that were also the dominating tree/shrub pollen types as well as dry land macrofossils (Brandt 1954; Bennike et al. 2004). Towards the end of the assemblage zone, *Juniperus*-type pollen became abundant indicating a minor spread on the raw sandy soils. It is likely that juniper plants, if actually present, grew close to the ground. All branches that protruded beyond the winter snow cover would have been withered and eroded when the ground was frozen (Overbeck 1975). This can also be assumed for dwarf birches and willows. However, a rather sparse local vegetation can be deduced from the pollen concentration. It was generally dominated by Poaceae but also other light-demanding herbaceous plants such as *Artemisia* sp., *Rumex* sp., *Urtica* sp. as well as Rubiaceae and Apiaceae.

Iversen (1942) emphasized that the high amount of reworked material may have resulted in a pure secondary pollen record originating from meltwater. Additionally, Bennike et al. (2004) also highlight a possible impairment of the interpretation caused by re-depositional processes. However, a pleniglacial interpretation of this assemblage zone is in line with vegetation records from The Netherlands (Hoek 2001; Bos et al. 2006), northern Germany (Usinger 1985; de Klerk 2002) and Denmark (Mortensen et al. 2011) probably due to a relatively sparse vegetation and thereby high erosion.

BOE-2 (cf. Meiendorf sensu Menke/Bølling-Oscillation sensu Iversen) 369.5–330.0 cm

The variety and abundance of aquatic species in this assemblage zone mark a warming. *Potamogeton praelongus*, *P. perfoliatus* and *P. filiformis* are dominant, while Characeae macrofossils have also been found in large quantities (Brandt 1954; Bennike et al. 2004). Additionally, *Pediastrum* sp. in high abundances, *Menyanthes trifoliata* and *Myriophyllum verticillatum* are present in the pollen samples.

Fig. 4 **a** The coefficient of variation according to depth including division into two sections. Red dotted line indicates threshold at 0.09; **b** PEARSON'S coefficient of skewness according to depth including division into five sections. Red dotted lines indicate thresholds at - 0.15 and 0.3; **c** Approximated *B. PUBESCENS* and *B. NANA* pollen. Grey bars and grey line indicate results per sample. Green curve depicts combined samples smoothed with a moving average filter; **d** Sum curve and separate curves of *B. PUBESCENS* and *B. NANA* pollen resulting from separation by fixed threshold; **e** The comparison of *B. NANA* pollen according to approximation [green] and fixed threshold [black]



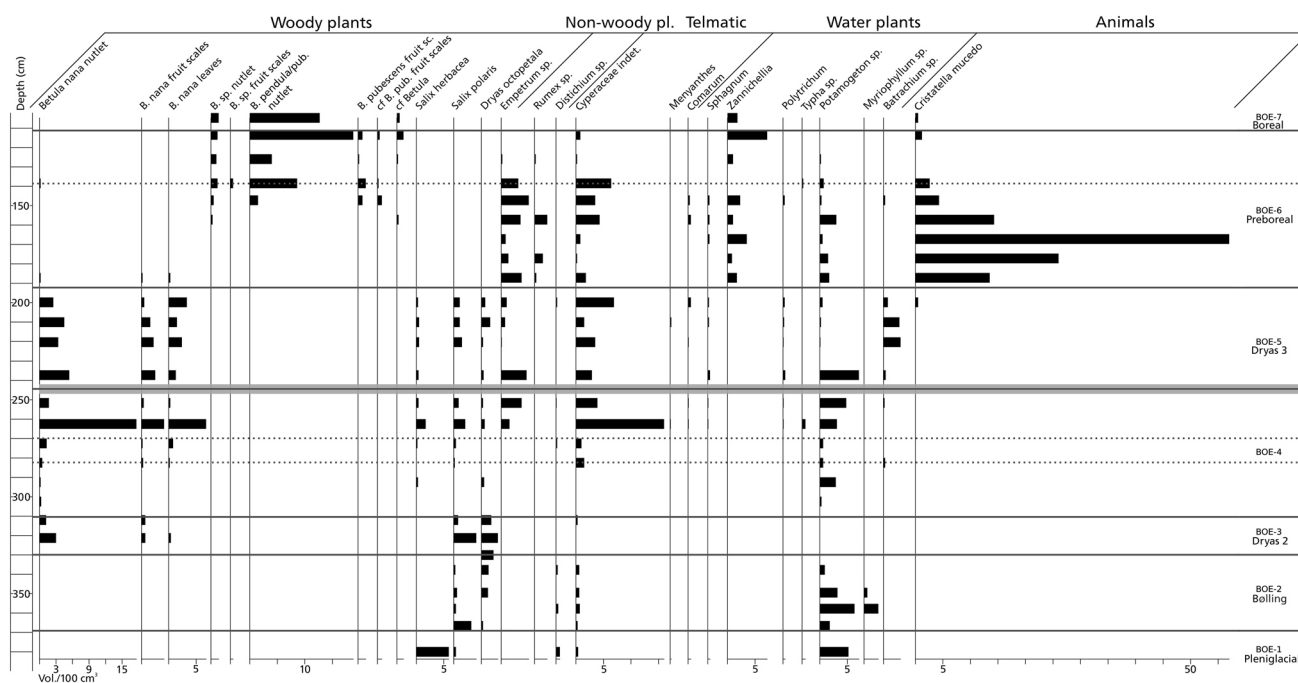


Fig. 5 Diagram showing macrofossil concentrations per 10 cm³ sediment. The taxa remains are seeds and fruits, unless otherwise specified

The aquatic ecosystem—that might have responded much faster to environmental changes than the vegetation on dry grounds (Iversen 1973; Sarmaja-Korjonen et al. 2006)—could have been impacted by in-wash of minerogenic matter and rapid sedimentation as indicated by several thin sandy layers embedded in silty and clayey gyttja. The spread of aquatic species had potentially even been slowed down in this way (Bennike et al. 2004) but the overall increase in aquatic productivity could explain an increase in carbonate content of the sediment.

Still, high percentages of exotic pollen indicate unstable conditions in the area but the amount of those grains has been reduced by half. The same is valid for rearrangement-indicating dinoflagellate cysts that are a major component of the marine environment. As marine influence can be excluded for this stage of the Pleistocene at the research area, their abundance within the record could be a sign of meltwater outflow or secondary deposition (Bakker and van Smeerdijk 1982). Again, this still suggests diverse environmental processes, most likely aeolian activity and meltwater-erosion, but not as pronounced as before.

The percentage increase of the heliophilous *Artemisia* sp. as well as *B. NANA* and *Hippophaë* mark the beginning of assemblage zone BOE-2 and hence, of the Lateglacial (van der Hammen 1951; Iversen 1954; Menke 1968; van Geel et al. 1989; Hoek 1997; de Klerk 2008). Synchronously with the increase in variety of aquatic species, the influx of calcium carbonate in the sediment also increases. Calcareous raw soils in particular favoured the spread of

Hippophaë cf. *ramnoides* in the area. Even if the distribution of *Hippophaë* was not as significant as in parts of northern Germany (Dätgen, Großes Moor—Aletsee 1959; Kubitzbergmoor—Usinger 1975; Eichholz-Niederung—Usinger 1978b), two maxima can be observed within the PAZ. Mortensen et al. (2011) also reported on a double peak of *Hippophaë ramnoides* at Slotseng, South Jutland. However, as common sea buckthorn is insect pollinated even low amounts of pollen can indicate a strong local distribution (Firbas 1949; Overbeck 1975; Søgaaard et al. 2018).

Throughout the assemblage zone an increase in *Betula* pollen is apparent. The approximation approach revealed that *B. NANA* pollen was dominating. This result is supported by *B. nana* macrofossils that prove its existence in the area (Brandt 1954). Apart from that, increasing amounts of *B. PUBESCENS* pollen cannot be ignored. As suggested by Bennike et al. (2004) and supported by the present study (Fig. 5), macrofossils of *B. pubescens* exclusively occur in the upper parts of the sediment that can be correlated to the early Holocene. Against this background long distance transport needs to be discussed. Airborne *Betula* pollen easily crosses distances of 2000 km under favourable wind conditions (Hjelmroos 1991, 1992; Wallin et al. 1991). However the glacial refugia of tree birches can be expected much further to the south (Litt and Stebich 1999; Mortensen et al. 2014a). It is therefore presumed that the amount of recorded *B. PUBESCENS* pollen consists of a mixture of rebedded pollen, potentially wrongly recorded *B. NANA* pollen, but first and foremost of airborne pollen. The assumption contradicts the

suggestion of Iversen (1942) who interpreted a first *Betula* pollen peak as the Lateglacial migration of tree birches (see ‘Comparison with Iversen’s diagram’ below).

Still, a rather sparse local vegetation can be inferred from the pollen concentration. However, *Hippophaë* sp. and *Juniperus* sp. were present in small local populations consolidating the soil and slowing down erosional processes (de Klerk 2008). As their seeds are distributed by birds (Gillham 1970) their maximum distribution occurred before that of *B. nana*. Stands of *B. nana* became abundant towards the end of the assemblage zone to the disadvantage of especially Poaceae. *Salix* cf. *polaris* was also common as indicated by macrofossils (Brandt 1954; Bennike et al. 2004). An increase in the variety of herbaceous plants within BOE-2 is proven by macrofossils of *Saxifraga oppositifolia*, *Dryas octopetala*, *Rumex tenuifolius*, *Potentilla* sp., *Minuartia* sp., and *Cerastium* sp. that partly have been found within the pollen spectrum as well. Furthermore, there is pollen evidence of *Helianthemum* sp., *Armeria* sp., *Plantago major/medica*, *P. maritima*, Caryophyllaceae, Rosaceae, Rubiaceae, Apiaceae and Fabaceae, supporting the interpretation of a vegetation with an open character.

The assignment of the spread of *Hippophaë* sp., *Artemisia* sp., *Helianthemum* sp. etc. to a separate phase has been suggested by e.g. Menke (1968; Merkt and Müller 1999). This is followed by a general decrease in NAP and a general *Betula* pollen maximum. This division could easily be made for the dataset presented and assemblage zone BOE-2. Nevertheless, it has been omitted as this part of the record mirrors a succession favoured by warmer conditions, here presumed to reflect one biostratigraphic unit. The results for BOE-2 show that they meet the (biostratigraphic) characteristics described for the Meiendorf-Interstadial (Bock et al. 1985) as well as for the Bølling-Oscillation (Iversen 1942). The latter did originally not include *Hippophaë* sp. but it was highlighted as the first pioneer shrub of Lateglacial Denmark later on (Iversen 1973). As a result, it is generally proposed here to equate the terms *Meiendorf* and *Bølling* (-biozone) as it is already common practice (Donner 1995; Bennike et al. 2004; Mortensen et al. 2011).

BOE-3 (cf. Older Dryas/Dryas 2) 330.0–310.5 cm

A general decrease in arboreal and shrub pollen contrasted by a steep increase in NAP marks the beginning of PAZ BOE-3. The amount of exotic/rebedded pollen grains increases to > 60% once again, as does the number of dinoflagellate cysts, indicating increased erosional processes in the area. Several thin layers of sand embedded in clayey-silty gyttja allude to the same process.

The aquatic ecosystem had probably been affected by colder and therewith less favourable conditions. Pollen evidence of *Potamogeton* sp. reduces to a minimum.

Synchronously, the macrofossil record confirms less variable aquatic biodiversity with only few finds of *Potamogeton perfoliatus* and *P. filiformis* (Brandt 1954; Bennike et al. 2004).

Pollen evidence of *B. NANA*, *B. PUBESCENS*, *Salix* sp. and *Hippophaë* sp. decreases and also the amount of *B. nana* macrofossils is low (Brandt 1954; Bennike et al. 2004). However, the first macrofossil of *B. nana* of the present study appears in the record. In contrast to that, a wide range of heliophilous herbs is present, including a maximum distribution of species that prefer dry and often calcareous and basic soils such as *Dryas octopetala*, *Helianthemum* sp., *Artemisia* sp., *Armeria* sp. and *Rumex* sp. An apparent maximum amount of *Dryas octopetala* macrofossils as well as few finds of *Saxifraga oppositifolia*, *Rumex tenuifolius*, *Potentilla* sp., *Minuartia* sp. and *Cerastium* sp. in connection with the pollen results point out that the vegetation was still dominated by light-demanding species.

The general pollen concentration almost doubled within BOE-3. The major part of the increase in concentration is determined by Poaceae. According to that, the decrease in *B. NANA*, *B. PUBESCENS*, *Salix* sp. and *Hippophaë* sp. in the percentage diagram can potentially be explained by calculation effects. A decrease in pollen percentages is not in line with a decrease in pollen concentrations. This effect has also been reported at Slotseng (Mortensen et al. 2011). This can be a result of increased local distribution of Poaceae as well as increased pollen amounts deriving from long distance transport.

BOE-4a (cf. early Allerød period) 310.5–282 cm

The onset of the Allerød-Interstadial can be detected through a variety of proxies. A change in sediment from clayey-silty gyttja to a yellowish calcareous gyttja partly showing lamination suggests less erosion and more stable conditions within the lake. A steep decrease in exotic/rebedded pollen and dinoflagellate cysts allude to the same process.

Synchronously, a strong increase in carbonate content of the sediment is in line with a diversification of aquatic species. Especially the amounts of Characeae point to an increased precipitation of calcium carbonate (Hoek et al. 1999). Occurrences of *Potamogeton filiformis*, *P. praelongus*, *P. perfoliatus*, *Batrachium* sp. (Brandt 1954) and *Callitriche hermaphroditica*, as well as an increase in general Cladoceran concentrations (Bennike et al. 2004) and fair amounts of *Potamogeton* sp. pollen and increasing values of *Pediastrum* sp., indicate increased aquatic productivity through a possible growing nutrient input (Sarmaja-Korjonen et al. 2006).

The change in the environment is also reflected in pollen concentration. While the percentages remain unaltered, the overall concentration almost triples. Within the pollen

samples maxima of *B. PUBESCENS* and *B. NANA* are significant at the beginning of the assemblage zone, the latter showing general decreasing tendencies after the maximum. Once again the spread of *B. nana* is reflected in the macrofossil record to the same extent, whereas evidence of tree birches is still lacking (Brandt 1954; Bennike et al. 2004).

Within the early Allerød period the northern limit of tree birch dispersal has expanded northwards. Pollen and macrofossil evidence suggest scattered stands of tree birches in the area of Hamburg in the early Allerød period (Overbeck 1975; Usinger 1985). In accordance with this shift also the increased influx of *B. PUBESCENS* pollen is assumed to derive from long distance transported pollen and not from local stands.

The total amount of arboreal and shrub pollen rises to about 50%. However, the presence of *Selaginella selaginoides* (Bennike et al. 2004), Caryophyllaceae, *Salix herbacea* (Brandt 1954) and pollen evidence of Chenopodiaceae, *Urtica* sp., *Artemisia* sp., *Rumex* sp. and *Helianthemum* sp. still suggest open pioneer vegetation conditions consisting of low growing species and potentially sub-arctic conditions.

The similarities of the pollen abundances described by Usinger (1985)—cf. *Juniperus-Betula nana-Betula pubescens*-PAZ—for the early Allerød period are obvious. In particular, the delayed maximum of *Juniperus*-type pollen, which can also be observed in the diagram from Ruds Vedby, Sealand (Krog 1954), highlights an association with the early Allerød period.

The Allerød—as chronozone, climatic unit or biozone—is a period of constant fluctuations. These fluctuations have been recorded in a variety of archives such as the Greenland ice cores (Björck et al. 1998; Lowe et al. 2008; Blockley et al. 2014) as well as lake sediments from e.g. The Netherlands, Germany, Denmark and Belgium (Reinberg basin/N. Germany—de Klerk et al. 2008; Hämelsee/N. Germany—Merkt and Müller 1999; Meerfelder Maar/W. Germany—Litt and Stebich 1999; Holzmaar/W. Germany—Leroy et al. 2000; Slotseng/Denmark—Mortensen et al. 2011; Hasselø/Denmark—Mortensen et al. 2014c; Moervaart/NW. Belgium—Bos et al. 2017; Gulickshof/S. Netherlands—Hoek et al. 1999).

It is evident that even subzone BOE-4a could potentially be further divided. Between 302 and 290 cm there is a decrease in *B. NANA*, *B. PUBESCENS* and in carbonate content of the sediment that correspond to short-termed increases in Poaceae, *Artemisia* sp. and *Pinus* sp. In this respect, also the following *Juniperus* sp. increase and decrease can be explained if one assumes this to reflect a succession with another *Betula* pollen maximum towards the end of assemblage zone BOE-4a. Following this, one could argue that a short termed climatic setback can potentially be found within this PAZ, which would resemble biozone Dryas 2/cf. Older Dryas as used by Usinger (1975) or Litt et al. (2001).

This would further imply that the previous subzone including a *B. NANA* and *B. PUBESCENS* maximum could be linked to what has been called Bølling/Bölling/Boelling in German research context (Usinger 1985; Litt and Stebich 1999; Merkt and Müller 1999; Litt et al. 2001; Nelle and Dörfler 2008). However, this fluctuation is much less pronounced than the following Gerzensee-Oscillation within the pollen record. The resolution seems still too low to finally evaluate this event. Therefore, a subdivision has been neglected.

BOE-4b (cf. Gerzensee-Oscillation) 282–269.9 cm

Assemblage zone BOE-4b is characterized by a marked decrease in *Betula* pollen. This is, however, much more pronounced for *B. PUBESCENS* pollen than for *B. NANA* pollen. At the same time, maximum values of *Pinus*, *Rumex* sp., *Artemisia* sp. and *Helianthemum* sp. can be observed, indicating that the assemblage zone reflects the Gerzensee-Oscillation (Björck et al. 1998; Lotter et al. 2000) and hence, the intra-Allerød cold period (Björck et al. 1998; Andersen et al. 2000; Bennike et al. 2004; Mortensen et al. 2011).

This short-termed event is not visually reflected in the sediment but an increase in carbonate content is apparent. In how far the aquatic ecosystem was affected cannot be evaluated because the analysis of macrofossils has not been conducted on a comparable time resolution. However, pollen of *Potamogeton* sp. is still present and *Pediastrum* sp. is continuously represented in high abundances within the diagram, suggesting minor or no variation.

It can be assumed that fluctuations in pollen composition are more dependent on a change in long distance transport (*Pinus*, *B. PUBESCENS*) and in local pollen production due to the cold (Mortensen et al. 2011) than in local vegetation change. Still, an open vegetation is prevailing whereby cold and dry tolerant species as e.g. *Helianthemum* sp., *Artemisia* sp. and *Rumex* sp. are temporarily benefitting from a short-term temperature set-back (Björck et al. 1998).

BOE-4c (cf. late Allerød period) 269.9–247 cm

The increase of *B. PUBESCENS* pollen marks the beginning of assemblage zone BOE-4c. At the same time, *B. NANA* pollen is constantly decreasing although still being reflected in the macrofossil record (Brandt 1954; Bennike et al. 2004). Due to the lack of macrofossils, a presence of tree birches is doubted. This assumption is in line with a study by Mortensen et al. (2014a) and Bennike and Mortensen (2018), who suggested that tree birches did not migrate before the middle/late Allerød period to Denmark. Furthermore, a migration is restricted to areas where calcareous depositions of the glaciers are found forming areas of high field capacity (Mortensen et al. 2014a)—further to the east of Lake Bølling. The sandy soils around Lake Bølling

remained a tree-less open landscape vegetated by heathland throughout the Lateglacial. It is likely that the increase in *B. PUBESCENS* pollen influx mainly derives from migrating tree birches to eastern Jutland that, however, did not expand into the clayey sandy soils of the Lake Bølling area (Theuerkauf and Joosten 2009).

The upland vegetation almost remained unaltered. A low growing and light-demanding plant-community consisting of Poaceae species, *Artemisia* sp., *Helianthemum* sp. and *Rumex* sp. dominated the landscape. Still, scattered groups of shrubs such as *B. nana* (Bennike et al. 2004), *Salix* sp. and *Juniperus* sp. were present. Additionally, an increasing abundance of *Empetrum nigrum* can be inferred from pollen and macrofossil data (Brandt 1954; Bennike et al. 2004). The dispersal of *E. nigrum*, an acidophilic dwarf shrub, indicates a leaching of the carbonates in the soil as well as an enrichment in humus (Bennike et al. 2004). The overall picture corresponds to the reconstruction by Mortensen et al. (2014a) who assume open heathland vegetation in the investigated area.

Hiatus 247 and 242 cm

A layer of sandy to clayey gyttja with extremely sharp boundaries has been identified as an event causing a hiatus in the sediment record. The same is observed by Bennike et al. (2004) who report on a grey detritus gyttja with very sharp boundaries and a layer of grey well-sorted medium sand in correlating depths. As previously suggested by Usinger (1981a), such abrupt changes and the absence of transitional sediments point to a hiatus. These hiatuses have been associated with water level changes, which cannot be excluded for the coring site at Lake Bølling as well. These changes were caused by more arid climate during the Dryas 3 period (Bakke et al. 2009). This implies that reworked Allerød material needs to be considered when interpreting the assemblage zone of the following Dryas 3. The temporal extend of the hiatus is unknown.

BOE-5 (cf. Younger Dryas/Dryas 3) 242–192.2 cm

The most significant change in contrast to the previous assemblage zone is reflected in the pollen concentration. General pollen influx has increased six-fold due to erosion. This circumstance is described by Usinger (1981a) as characteristic for the hiatus between Allerød and Dryas 3 sediments. The macrofossil record likewise shows clear signs of soil erosion through the presence of in-washed *Cenococcum geophilum* sclerotia (Bennike et al. 2004; Krüger et al. 2017).

Synchronously with sand layers occurring within the gyttja, the abrupt decrease of calcium carbonates in the

sediment is a characteristic sediment feature of the Dryas 3 (Hoek et al. 1999; van Asch et al. 2012a, b; Bos et al. 2017).

An increase in Poaceae pollen and consistently high values for *Artemisia* sp., *Helianthemum* sp. and *Rumex* sp. together with the frequent occurrences of *Selaginella selaginoides* and *Dryas octopetala* point to the presence of an open pioneer vegetation (Bennike et al. 2004). Furthermore, high abundances of *B. NANA*, *Salix polaris* and *S. herbacea* within the macrofossil record (Brandt 1954; Bennike et al. 2004) emphasize the level of distribution of dwarf shrubs in the landscape within the PAZ.

Large quantities of Cyperaceae indet. and *Carex* sp. macrofossils (Brandt 1954; Bennike et al. 2004) correspond to maximum Cyperaceae pollen values. Consequently, sedges were abundant in the telmatic zone and the closer surroundings of the lake.

BOE-6a (cf. early Preboreal) 192.2–138.5 cm

The transition towards the Holocene is reflected in a variety of proxies. At the beginning of the assemblage zone a marked increase in carbonate content of the sediment is apparent probably suggesting higher aquatic productivity through higher temperatures. This can be inferred especially from Cladoceran analysis by Bennike et al. (2004). Again, a diversification of aquatic species can be observed in the macrofossil record, including Characeae, *Potamogeton filiformis*, *P. perfoliatus* and *Zannichellia palustris* (Bennike et al. 2004). The palynological evidence from *Potamogeton* sp., *Myriophyllum* sp. and *Pediastrum* sp. indicates the same process.

The onset of the Holocene provided more stable conditions within the lake. Less than 1% exotic/rebedded pollen grains and a lack of dinoflagellate cysts are the result of almost unimpeded sedimentation.

Within the assemblage zone a change in sediment towards a detrital gyttja is reflected in the increase of organic sediment content. This can be explained by an increase in organic production within the lake resulting from diversification and higher amounts of aquatic species.

Whilst the proportion of Poaceae is halved, other heliophilous species such as *Artemisia* sp. and *Rumex* sp. remain continuously present. Thermophilous species such as *Urtica* sp. and *Filipendula* sp. become abundant, indicating warmer climatic conditions. The disappearance of *B. nana* and the continuous lack of tree birches in the lake area promoted the spread of *Juniperus* sp. especially. Whether *Juniperus* sp. was still low-growing or reaching medium heights—as assumed for a comparable vegetation type during Dryas 3 in northern Germany with scattered trees or groups of trees/high shrubs at favourable sites (Usinger 2004)—cannot be finally evaluated.

The increased quantities of *Empetrum*-type pollen and the abundance of *E. nigrum* remains within the macrofossil record (Bennike et al. 2004) still indicate rather poor soil conditions. This has also been interpreted as corresponding well to a more oceanic climate (Hoek 1997; Usinger 2004; Mortensen et al. 2014b, c).

However, the Preboreal Oscillation (Behre 1967; Björck et al. 1998; Usinger 2004) cannot be seen in the record, presumably due to low sample resolution in this part of the sequence.

BOE-6b (cf. late Preboreal) 138.5–108.7 cm

A marked change in vegetation can be assumed by the beginning of assemblage zone BOE-6b. Steeply increasing values of *B. PUBESCENS* correspond to *B. pubescens* finds within the macrofossil record (Bennike et al. 2004). This is equivalent to the migration of tree birches to the Lake Bølling area. The assumption is supported by a significant increase in organic sediment content that has previously been interpreted as a sign of a more widespread woodland (Mortensen et al. 2014a). Zero values for *B. NANA* are artificial. As the sediment was of clear Holocene origin, the calculation was omitted resulting in zero values for *B. NANA*. *B. nana* probably grew as an understorey but the lack of macrofossils make a widespread distribution rather unlikely.

The migration of tree birches into the lake area affected the distribution of *Juniperus* sp. especially. A marked decrease suggests that the majority of *Juniperus* sp. stands were shaded out by the higher-growing birches. Poaceae were affected to the same extent. However, tree birches probably formed a relatively light open woodland with the presence of the thermophilous and heliophilous *Filipendula* sp. and *Urtica* sp.

The rising temperatures are reflected in the pollen concentrations and by increased number of species. Values more than double from 16,000 to 37,000 pollen grains per cm³ of sediment. Favourable growing conditions can be attributed to improved soil conditions and soil formation in the area, as also reflected in a decline in *Empetrum*-type pollen.

BOE-7 (cf. early Boreal) 108.7–102.2 cm

Within assemblage zone BOE-7 total percentages for grasses and herbs decrease to below 10%. At the same time a marked increase in *Corylus*-type pollen can be observed, here interpreted as the beginning of the characteristic boreal *Corylus* maximum (Firbas 1949; Overbeck 1975; Odgaard 1994). Furthermore, this is associated with an increase in *Pinus*-type pollen. Whether pine was already present or whether the rising curve just results from increased long-distance transport cannot be evaluated due to a lack of macrofossils.

A denser-growing woodland can be inferred from declining percentages of *Artemisia* sp., *Urtica* sp. and *Rumex* sp., only *Filipendula* sp. was still abundant. The species spreads even under medium shade conditions. It is also likely that the pollen originated from *F. ulmaria* that grows rather in wet meadows.

Detrital gyttja with an organic content of $\geq 30\%$ is characteristic for early Holocene lake sediments in northern Germany and Denmark (Reinberg basin/N. Germany—de Klerk et al. 2008; Hasselø/Denmark—Mortensen et al. 2014c). This corresponds to the further increase of pollen concentrations within the assemblage zone.

Approaching the term Bølling

Comparison with Iversen's diagram

The investigation of Lake Bølling by Iversen took several stages (1941—Holocene sequence; 1942—Lateglacial/early Holocene sequence; 1947—same diagram as published in 1942; 1954—Lateglacial periodic overview; 1973—simplified overview Pleistocene-Holocene). These originated from different palynological datasets based on cores from 1936, 1939 and 1946 (de Klerk 2004b). Following Bennike et al. (2004) the material presented here derives from a location very close to Iversen's original coring site. Therefore, a comparison with the dataset from 1936 (Iversen 1942) is performed.

Figure 6 displays the comparison of the two datasets. The diagram to the left is an extract from the diagram discussed above. The diagram to the right shows the Iversen dataset from 1936. Nine decisive taxa were chosen for comparison (following Iversen 1942, p 138). The calculation is based on TTP excluding Cyperaceae, as it is common practice in recent Lateglacial palynology (Mortensen et al. 2011; for further discussion see: Schütrumpf 1955; Fægri and Iversen 1964; Iversen 1973; Janssen and Ijzermans-Lutgerhorst 1973; Usinger 1975; de Klerk 2004b). It should be noted, that *Pinus*-type pollen grains of zone 1c in Iversen's diagram were originally not included because of being regarded as rebedded grains (Iversen 1947). Nevertheless, they are included in the displayed diagram because it cannot finally be decided whether they are the result of re-depositional processes or increased long-distance transport.

The given zonation is displayed according to original descriptions. For reasons of assumed spatial vicinity, the depths have been directly correlated. As a result, clear similarities are apparent from depth-correlation alone. This becomes even more apparent when comparing the PAZs.

The juxtaposition of the lowermost assemblage zones (BOE-1 and 1a) revealed no clear accordance. This is not surprising for three reasons. Firstly, Iversen's zone 1a consists of only two pollen samples that, secondly, have an

Present study

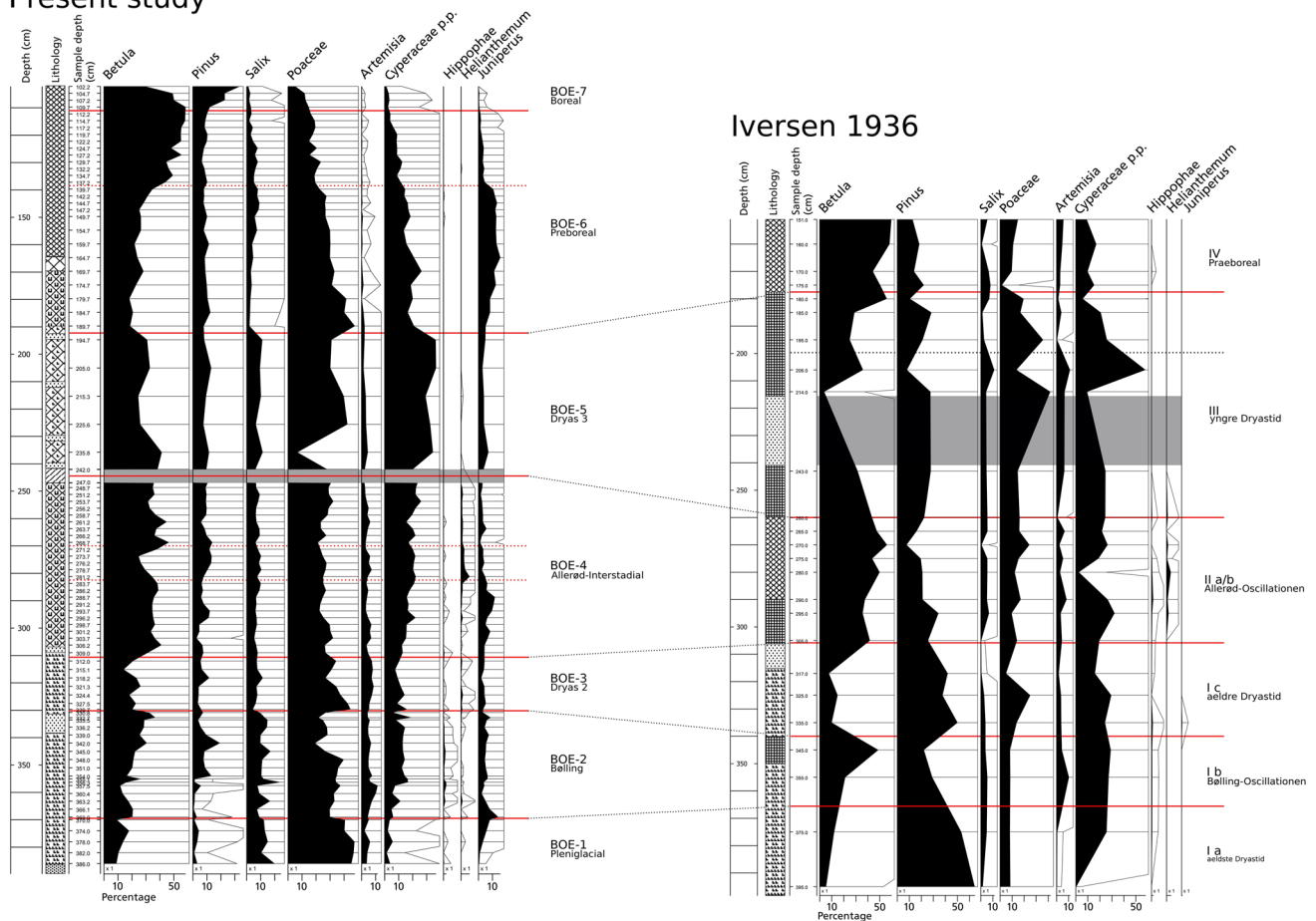


Fig. 6 Depth correlation of selected taxa from the present dataset [left] and the pollen diagram as given by Iversen (1942) from an analysis of 1936 [right]. PAZ according to original publications. Grey bars indicate hiatus

extremely low pollen sum (72 and 118 TTP) which is lower than the samples of BOE-1 (200–300 TTP). Thirdly, Iversen subtracted potentially rebedded pollen grains in the pollen samples below assemblage zone III (Iversen 1942), which might highly influence the displayed curves.

A correlation becomes apparent by comparing BOE-2 and zone 1b—Iversen’s Bølling-Oscillation. Even though also zone 1b only consists of two pollen samples, both diagrams show similar tendencies and percentage values. *Artemisia* values rise in both cases to about 10% before *Betula* reaches maximum values. The increase in *Artemisia* values is for BOE-2 and in general assumed to reflect the onset of the Lateglacial (Iversen 1947; van der Hammen 1951; Overbeck 1975; Usinger 1985).

Iversen assumed that the *Betula* maximum of zone 1b reflects a mixture of *B. nana* and *B. pubescens* with a clear dominance of the latter (Iversen 1942, 1954). As discussed above, this peak in *Betula* mainly consists of *B. nana* pollen and also the only *Betula* macrofossils within the record are *B. nana* (Brandt 1954; Bennike et al. 2004). It had been

assumed before that Iversen mainly determined *B. nana* pollen (Andersen 1980; Usinger 1985, 1998; de Klerk 2004b) but for the first time this can be shown for the *locus classicus* by the approximation approach on a detailed dataset.

It is conspicuous that *Juniperus*-type pollen is not present in Iversen’s record with only one single exception. Working on Lake Bølling, Iversen generated three different datasets that were available for the present study. A chronological comparison of the datasets shows that total *Juniperus*-type pollen amounts increase over time. Therefore, it is likely to assume that Iversen did not recognize the very thin-walled and often torn *Juniperus*-type pollen grains in the first place, and hence they were not recorded. Difficulties in distinguishing *Hippophaë* pollen can be assumed to the same extent (Troels-Smith et al. 2018).

Furthermore, it has been argued for northern Germany that the maximum of *B. nana* pollen is followed by a maximum of *Hippophaë* pollen, in sum defining the *Betula-nana-Hippophaë*-PAZ (sensu Usinger), and hence equalling a first Lateglacial Interstadial (Usinger 1985). Based on that,

Usinger (1985, 1998) reinterpreted the results of Iversen and concluded that there could not have been a pre-Allerød Interstadial sensu Iversen for Denmark. However, a comparison of Iversen's zone 1b with the present study and results from the well dated site of Slotseng (Mortensen et al. 2011)—that had not been available to Usinger—shows that a slightly pronounced double maximum of *Hippophaë* pollen before the B. NANA pollen maximum was potentially common on clayey calcareous soils within the first Lateglacial interstadial in Denmark. This would imply that Iversen did indeed find a climatic oscillation that pre-dates the Allerød period.

Within assemblage zones BOE-3 and 1c correspondingly low values for *Betula* associated with a peak in Poaceae can be observed as well as decreasing *Salix* values. The similarity becomes even more apparent by looking at the lithology. The boundary between 1c and 2 was not drawn halfway between the samples (depth 317 and 305 cm) as commonly done. Here, Iversen directed his attention to a layer of sand in between the samples that is also reflected in the lithology of the present study.

The Allerød period is reflected in BOE-4 and zone 2. In both cases, *Betula* values are fluctuating around 40%. Furthermore, there is a surprisingly good match in *Helianthemum*. Maximum values are again found at almost the same depths (280 and 278 cm).

Assemblage zones BOE-4 and BOE-5 are separated by a hiatus of unknown temporal extent. Iversen neither displayed nor wrote about a hiatus within zone 3. Nevertheless, the given lithology reflects a wide layer of sand that can explain the huge distance between Iversen's samples (from 214 to 243). Indeed, BOE-5 and zone 3 have independently been determined to represent the Dryas 3.

The onset of the Holocene is expressed by generally increasing values of *Betula*, a sharp decrease in *Salix*, a decrease in *Artemisia* and a decreasing overall tendency of Poaceae values within BOE-6. However, this would again correspond well with Iversen's diagram if the boundary between zone 3 and 4 was shifted downwards to between depths 195 and 206 cm (see dotted line, Fig. 6; de Klerk 2004b).

The challenge in correlating the diagrams arises from the different taxonomical and temporal resolutions. However, it can be seen that the overall correspondence between the diagrams in displayed pollen values and lithology is justified. As a result, the strength of the presented dataset lies within its ability to show the biostratigraphical units defined by Iversen (1942) in much higher resolution together with a statistical separation of *Betula* pollen.

Consequently, it can be inferred that Iversen's interpretation of zone 1b as an independent climatic oscillation before the Allerød can be confirmed with one constraint. This would be that the Bølling-Oscillation sensu Iversen does

not reflect the migration of tree birches, as hitherto assumed (Andersen 1980; Usinger 1985, 1998; de Klerk 2004b).

The biostratigraphical term Bølling—a comment

In 1942 Iversen made two important conclusions from his data. Firstly, he stated that there is a climatic oscillation prior to the Allerød period and that chronozone was named according to the analysed locality—Lake Bølling. Secondly, he linked his assumption to the first spread of tree birches after deglaciation—hence a biozone. Both assumptions were equally essential for Iversen's definition (Iversen 1954).

However, Usinger emphasized the latter part of Iversen's assumption. He pointed out that there could not have been a pre-Allerød-Interstadial sensu Iversen for Denmark based on comparisons to other diagrams and the migration of tree birches (Usinger 1985, 1998). Another diagram from the Lake Bølling area—Bøllingsö Canal 2 (Stockmarr 1975)—corresponds to the lower sections of Iversen's diagram. Supported by disputable radiocarbon dates, Stockmarr (1975) interpreted the diagram *Bøllingsö Canal 2* as beginning with the Allerød-Interstadial. Years before that Krog (1954) published pollen data from Ruds Vedby—a location further away on Sealand. Therein zonal division was conducted according to Jessen (1935) and the strongly fluctuating percentages of *Betula* are interpreted as belonging to the Allerød (Krog 1954). Based on this, Usinger (1985) recommended a reinterpretation of the Bølling pollen zone (Bølling-Oscillation, Zone 1b) as defined by Iversen (Iversen 1942). All diagrams forming the basis for Usinger's assumption show a very low sample density at the decisive depths (Stockmarr 1975, p. 8 samples per 30 cm; Iversen 1942, pp. 3–4 samples per 50 cm; Krog 1954, p. 5 samples per 20 cm). Thus, it remains generally questionable whether some important changes in vegetation composition have been recorded at all. Following Usinger, the Bølling pollen zone sensu Iversen would designate palynologically the early Allerød-Interstadial. This assumption would be justified if Iversen had linked the Bølling-Oscillation solely to the migration of tree birches. Nevertheless, Usinger's suggestion was resumed by Litt and Stebich (1999). It was largely accepted from that time on and partly applied for Germany (Merkt and Müller 1999; Litt et al. 2001; Nelle and Dörfler 2008).

In contrast to that, Iversen's first assumption was highlighted in Danish Lateglacial research. Here, the term is applied as resembling the first part of the Lateglacial Interstadial (Mangerud et al. 1974; Andersen 1980; Kolstrup 1982; Kolstrup and Buchardt 1982; Donner 1995; Bennike et al. 2004; Mortensen et al. 2011, 2014b, c). At the same time, it is widely accepted that the migration of birch species does not occur before the middle to late Allerød period on favourable soils (Mortensen et al. 2014a). Therefore, the *rule of priority* should be applied here, as Iversen was the first to

name an oscillation prior to the Allerød that is reflected in biostratigraphy. Even if the content of the biostratigraphic term has not withstood the expansion of knowledge and hence has been altered, it is well justified to apply the term as currently done in Denmark and Scandinavia. Furthermore, it is used in exactly the same manner in e.g. France (Pastre et al. 2003; Peyron et al. 2005), Switzerland (Küttel and Lotter 1987), Poland (Majecka et al. 2018), The Netherlands (Bohncke and Wijmstra 1988; Hoek 2001, 2009), or Belgium (Bos et al. 2017, 2018). To use the term biostratigraphically as a designation for the first Lateglacial interstadial becomes even more legitimate in the context of the presented data.

The application of the term Bølling as the first part of the Allerød period in Germany is reasonable when referring only to the migration of birch species (Usinger 1985). At the same time, this is the source of confusion because of Iversen's twofold assumption concerning the Bølling-Oscillation and the introduction of the local term Meiendorf-Interval/ Interstadial for north-western Germany (Menke 1968; Bock et al. 1985). Therefore, we suggest here that terms are not altered further, but the term Bølling is abolished within the early Allerød period as currently done in German Lateglacial research contexts (Usinger 1998).

Additionally, we recommend the use of the terms Meiendorf (regionally for northern Germany as introduced by Menke (1968) and Bølling (Denmark) equally as expressions for the first interstadial of the Lateglacial. The contents of both terms correspond to the main features of the *Hippophaë-Betula nana*-PAZ defined by Usinger (1985). Bølling: ... *er dog stadig dækket af Tundravegetation (Græsser, Halvgræsser, Artemisia, Pil og Dværgebirk). Fyr mangler.* (Iversen 1942)—it is assumed that *Hippophaë* pollen was not consistently recognised by Iversen; Meiendorf: ... *unter dem Bølling-Interstadial [in this case equal to Allerød-a sensu Usinger 1981b] existiert ein schwach (durch Zwergbirke und Sanddorn) gekennzeichnetes „Meiendorf-Interstadial“* (Menke in Bock et al. 1985).

The utilization of two terms makes sense, as the climatic amelioration of the interstadial is reflected differently in the prevailing vegetation due to the delayed succession in the areas resulting from geographical and edaphic conditions as well as distance to plant refugia.

It is argued that the Weichselian Lateglacial can climatically be divided into three independent interstadials (GI-1a, 1c and 1e; Björck et al. 1998). This division also corresponds palynostratigraphically to the Meerfelder Maar sequence (Litt and Stebich 1999) where the second interstadial period (GI-1c) is equated with the term Bølling.

Bennike et al. (2004) published ^{14}C -data of macrofossils from a sediment sequence that also originates from the immediate vicinity of Iversen's original drilling site. These data thus can be correlated with the material presented

here with regard to the depth. There are three radiocarbon dates for macrofossils from 330 to 332 cm (AAR-7442: $12,470 \pm 90$ y BP), 260–262 cm (AAR-7443: $12,590 \pm 80$ y BP) and 366–368 cm (AAR-7444: $12,510 \pm 100$ y BP) below the surface. With respect to the depth of the presented sequence all of them are biostratigraphically part of BOE-2 and chronologically well within the given range of the first Interstadial—GI-1e (Björck et al. 1998)—and thus not within GI-1c. However, biostratigraphy is by its nature a sequence of sediment with a defined biological content, regardless of absolute dating. Clearly, it is essential to contextualize palaeoenvironmental records chronologically, but we should refrain from mixing chronozones and biozones in future research.

Conclusions and outlook

This study presents data originally compiled by Usinger to solve existing ambiguities in Lateglacial terminology especially concerning the terms Bølling and Meiendorf in order to discuss it against the background of the previous work by Iversen. A Lateglacial pollen sequence from the *locus classicus* Lake Bølling (Denmark) is presented spanning all Lateglacial and early Holocene biozones—with the exception of a hiatus. The study includes a separation of *Betula* pollen types that has been conducted in two different ways—by fixed threshold and by approximation approach. The results of the separation suggest that it is imperative to use only high resolution datasets when applying the approximation approach in order to obtain a reliable outcome. Nevertheless, the method is highly time-consuming and therefore its use is recommended exclusively in the case of research questions referring specifically to *Betula*. We show that there is tententially little distinction whichever method of separation is applied.

The palynological results are discussed against the original dataset published by Iversen (1942, 1947, 1954). The geographical proximity of Iversen's original coring site and the high resolution of the presented analysis permits the possibility of re-evaluating the origin of the Bølling-Oscillation sensu Iversen. This study confirms Iversen's interpretation of zone 1b as an independent climatic oscillation before the Allerød with one constraint. This is that the Bølling-Oscillation sensu Iversen does not reflect the migration of local tree birches, as had been previously assumed (Usinger 1985, 1998). However, a statistical comparison with well dated Lateglacial pollen sequences should be performed in the future.

Furthermore, we recommend utilizing the terms Meiendorf (regionally for northern Germany) and Bølling (for Denmark) equally as biostratigraphical expressions for the

first interstadial of the Lateglacial, as is an already common habit in Lateglacial palynology. To prevent further confusion the term Bølling should be abolished as a designation for the early Allerød period in German pollen diagrams.

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Appendix II

Small shards and long distances — three cryptotephra layers from the Nahe palaeolake including the first discovery of Laacher See Tephra in Schleswig-Holstein (Germany)

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ABSTRACT: Investigations of Lateglacial to Early Holocene lake sediments from the Nahe palaeolake (northern Germany) provided a high-resolution palynological record. To increase the temporal resolution of the record a targeted search for cryptotephra was carried out on the basis of pollen stratigraphy. Three cryptotephra horizons were detected and geochemically identified as G10ka series tephra (a Saksunarvatn Ash), Vedde Ash and Laacher See Tephra. Here we present the first geochemically confirmed finding of the ash from the Laacher See Eruption in Schleswig-Holstein—extending the so far detected fallout fan of the eruption further to the north-west. These finds enable direct stratigraphical correlations and underline the potential of the site for further investigations.

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KEYWORDS: cryptotephra; Laacher See Tephra; Saksunarvatn Ash; Vedde Ash

Introduction

Schleswig-Holstein, the northernmost German federal state, holds a key position in palaeo-environmental as well as archaeological research of the Lateglacial and Early Holocene. This is due to the fact that the region provided a north-facing corridor after the retreat of the glaciers. Despite numerous palaeo-environmental investigations (Krüger *et al.* 2020 and literature cited therein), a correlation of the individual records is difficult because age modelling is mainly missing, or because of hiatuses (Usinger 1981). The analyses of sediment cores from the Nahe palaeolake (NAH; Dreibrodt *et al.* 2020; Krüger *et al.* 2020) fill a gap in Lateglacial/Early Holocene palaeo-environmental research in Schleswig-Holstein. For the first time a complete Lateglacial to Early Holocene sequence is described without being affected by the Allerød–Younger Dryas hiatus that had been documented for numerous lake sediments in northern Germany and Denmark (Krüger and Damrath 2019; Bennike *et al.* 2004; Usinger 1981). Furthermore, a sequence of the sediment is annually laminated, allowing for a high resolution of the temporal scale (Dreibrodt *et al.* 2020). Therefore, an attempt was made to identify tephra layers as additional chronological horizons to supplement radiocarbon dating of macrofossils, as volcanic ash layers mainly represent single events. This would, moreover, provide the opportunity to directly correlate the record with important European key sites of Lateglacial–Early Holocene research. However, while recording and describing the NAH sediment sequence, no visible ash horizons could be detected.

The advancements in search techniques for non-visible volcanic ash beds, or cryptotephra, have widened the possibilities of searching for additional chronological markers in sediment archives (Blockley *et al.* 2005; Lowe and Hunt 2001; Turney 1998;

Turney *et al.* 2004). In this way the detection of non-visible tephra horizons has been extended to further distal sites throughout Europe (Blockley *et al.* 2007; Bramham-Law *et al.* 2013; Hafliðason *et al.* 2018; Lane *et al.* 2012b; Larsson and Wastegård 2018; Wastegård and Boyle 2012; Wastegård *et al.* 2000; Wulf *et al.* 2013). Palaeo-environmental studies provide the possibility of combining specific tephra horizons with pollen stratigraphy. Conversely, this implies that pollen stratigraphy can be used to locate the position of non-visible ash beds in sediment sequences. To successively increase the temporal resolution of the NAH sediment record a targeted search for well-dated cryptotephra horizons was performed based on their expected position in pollen stratigraphy. We aimed at searching for cryptotephra of the Vedde Ash (VA) and Laacher See Tephra (LST). Apparently, the Saksunarvatn Ash (SA) is the product of a series of eruptions in the Grímsvötn system and hence, does not represent one fixed event date (Davies *et al.* 2012; Harning *et al.* 2018; Óladóttir *et al.* 2020). However, this study also attempts to identify the SA/G10ka series tephra at least as an event interval (Óladóttir *et al.* 2020).

The SA was erupted in the Grímsvötn volcanic system in the Eastern Volcanic Zone on Iceland. The ash has been described from numerous sites in Northern Europe from Iceland, the British Isles, Norway, the Faroe Islands, Greenland and the North Atlantic (Birks *et al.* 1996; Björck *et al.* 1992; Grönvold *et al.* 1995; Harning *et al.* 2018; Mangerud *et al.* 1984; Timms *et al.* 2017). In Germany, the ash has been recorded at Potremser Moor in Mecklenburg Western Pomerania (Bramham-Law *et al.* 2013) and in Schleswig-Holstein at two locations 30 and 50 km north-east of the Nahe palaeolake, Lake Plußsee and Lake Muggesfeld (Merkt *et al.* 1993). Furthermore, the visual evaluation of thin sections from Lake Belau revealed brownish cryptotephra shards that have been assigned to the G10ka series tephra on the basis of their morphology (pers. com. W. Dörfler). Most recently, Saksunarvatn

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tephra has also been discovered in a sediment sequence from Lake Poggensee (Zanon *et al.* 2019; Fig. 1).

The only known location at which the VA has been detected in Schleswig-Holstein is the site of Ahrenshöft. Here, the cryptotephra was found in two sediment profiles embedded in an archaeological context (Housley *et al.* 2012). Nevertheless, the tephra has not been found in the chronologically well-secured context of a lake sediment sequence. As the Nahe palaeolake is situated within the known fallout zone of the VA, as suggested by Bramham-Law *et al.* (2013), Davies *et al.* (2012) and Wulf *et al.* (2016), this ash was suspected to be preserved in sediments from there.

The most prominent Lateglacial volcanic eruption in central Europe was the eruption of the Laacher See Volcano in western Germany. Dated to $12\,880 \pm 40$ varve a BP (Brauer *et al.* 1999), ash was distributed over wide areas of central Europe. Laacher See Tephra has been documented at more than 400 sites, extending from the Alps and central France to Bornholm and Poland (Bronk Ramsey *et al.* 2015; Riede 2016; Riede *et al.* 2011; Turney *et al.* 2006; van den Bogaard and Schmincke 1984). The LST, however, has so far not been identified in Schleswig-Holstein, which is outside the known and documented visible fallout lobes.

The aims of this study were:

1. to detect cryptotephra horizons in NAH sediment cores based on their expected occurrence in pollen stratigraphy;
2. to geochemically fingerprint the tephra layers;
3. to gain additional chronological tie-points for the age–depth model of the NAH record;
4. to underline the potential of future research into NAH sediments regarding cryptotephra layer identification.

Study site

The NAH is located in Schleswig-Holstein about 30 km north of Hamburg (Germany). The basin of the former lake was part of a larger glacial lake system and is separated from further elongated incised lakes by two narrow sand ridges to the north-west and south-east (Smed 1998; Woldstedt 1935, 1954). To the south-east, Lake Itzstedt is the water-bearing remnant of the lake system.

The size of the palaeolake surface was about 16 ha during the Lateglacial (Fig. 1). The terrestrialisation process was completed in the course of the late Holocene. Today, the river *Rönne* flows in the centre of the still existing depression and thereby follows the course of the former lake in a north-westerly direction before turning southwards and draining off into the river *Alster*. The area is today used as pasture and partly forested by alder, birch and willow. The coring location is situated in the formerly deepest part of the incised lake ($53^{\circ} 48.711' \text{ N}$, $10^{\circ} 8.082' \text{ E}$).

At the coring location approximately 1.6 m of fen peat overlie a sequence of 12.2 m of predominantly detrital gyttja. The shift from the Lateglacial to Holocene is reflected in a gradual shift from clayish to calcareous and finally detrital gyttja. Lateglacial mainly organic depositions of 1.6 m thickness contain a 50 cm sequence of very fine annual lamination (Dreibrodt *et al.* 2020; Krüger *et al.* 2020). The sediment cores reached glacial sand at 15.8 m. The chronology is based on AMS radiocarbon dates, pollen events, varve counting and additionally on the identified tephra layers (Dreibrodt *et al.* 2020).

Methods

Field methods and sampling

The coring campaign in the dry centre of the Nahe palaeolake took place in October 2017. A modified Livingston piston corer (Mingram *et al.* 2007)—the so called *Usinger-corer*—was used to extract the sediment cores. Two overlapping sediment sequences with a diameter of 80 mm and 16 m in length have been reached by coring. Each 1 m segment was cut longitudinally and stored as well as processed at the Institute for Pre- and Protohistoric Archaeology in Kiel, Germany. In order to connect the core sequences, a series of distinct layers and stratigraphic marker horizons have been defined in the parallel cores. In this way, a composite core was constructed, providing a continuous record avoiding gaps (Dörfler *et al.* 2012).

The interdisciplinary approach of the study requires that the results of different methods must be easily correlated across depths. Therefore, a grid of 5 mm step size was created spanning the lower 5 m of the sequence. Each sample was

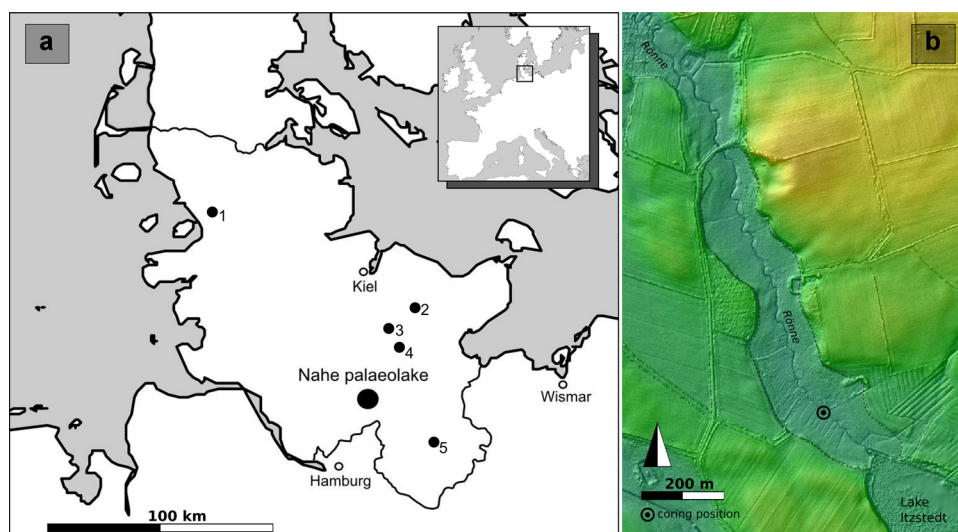


Figure 1. Location of the Nahe palaeolake (a) and coring location (b). DEM based on LVerGeoSH. 1–5 show sites as mentioned in the text. 1 – Ahrenshöft; 2 – Lake Plußsee; 3 – Lake Belau; 4 – Lake Muggesfeld; 5 – Lake Poggensee. [Color figure can be viewed at wileyonlinelibrary.com]

labelled according to consecutive numbers (953 potential samples in total, 11.10–15.86 m below the surface).

Pollen analysis

Samples for pollen preparation were mostly taken every centimetre but at least every fourth centimetre. Sample preparation was carried out according to standard techniques (Erdtman 1960; Fægri and Iversen 1989). Lycopodium spore tablets were added to enable the calculation of pollen concentrations (Stockmarr 1971). Pollen counting was performed at a total magnification of $\times 400$ for routine counting and $\times 1000$ for critical objects. A pollen sum of at least 550 TTP (total terrestrial pollen) per sample was achieved. Pollen identification followed mainly Beug (2004) as well as Moore *et al.* (1991). The reference collection at the Institute of Pre- and Protohistoric Archaeology in Kiel was further consulted. The results were visualised using the CountPol software (I. Feeser, Kiel University) as well as Inkscape (ver. 0.92.4). The general results of the pollen analysis of the complete section are presented by Krüger *et al.* (2020).

Tephra analysis and identification

On the basis of the preceding pollen analysis and a preliminary comparison of these results with investigations in northern central Europe (Krüger *et al.*, 2020), certain sequences were selected for a search for cryptotephra (Fig. 2). The selected depths were sampled in 2 cm steps (Lateglacial sequence) and 1 cm steps (Holocene sequence) resulting in sample weights

between 5 and 11 g. The chemical preparation included treatment with HCl to dissolve carbonates, concentrated H_2SO_4 and HNO_3 to remove the organic material from the samples and KOH (10%) to eliminate diatom silicates. Moreover, a density separation using sodium polytungstate was applied to separate heavy mineral particles of more than 2.7 g/cm^3 from the lighter particles (Turney 1998). The lighter fraction was mounted in glycerol-gelatine and subsequently analysed using a light microscope under bright field, $\times 250$ magnification. Cross-polarisation was additionally used to check critical particles. The identified cryptotephra horizons were labelled according to sample numbers. As one cryptotephra sample spans 2 cm (equalling four samples on the composite core) the bottom sample numbers according to the composite core were utilised for the tephra samples.

To gain material for electron-microprobe analyses (EMPA) the mounted material was re-dissolved and embedded in synthetic resin. Subsequently polished thin sections were prepared from these slides.

Electron-microprobe analyses

The major- and minor-element geochemistry of the glass shards was determined with the JEOL JXA 8200 electron microprobe equipped with five wavelength dispersive spectrometers at GEOMAR (Kiel, Germany). The analytical conditions were 15 kV accelerating voltage, 6 nA current and $5 \mu\text{m}$ electron beam size. For calibration, a set of natural reference materials from the Smithsonian collection was used, the quality of the calibration was tracked by running the Lipari

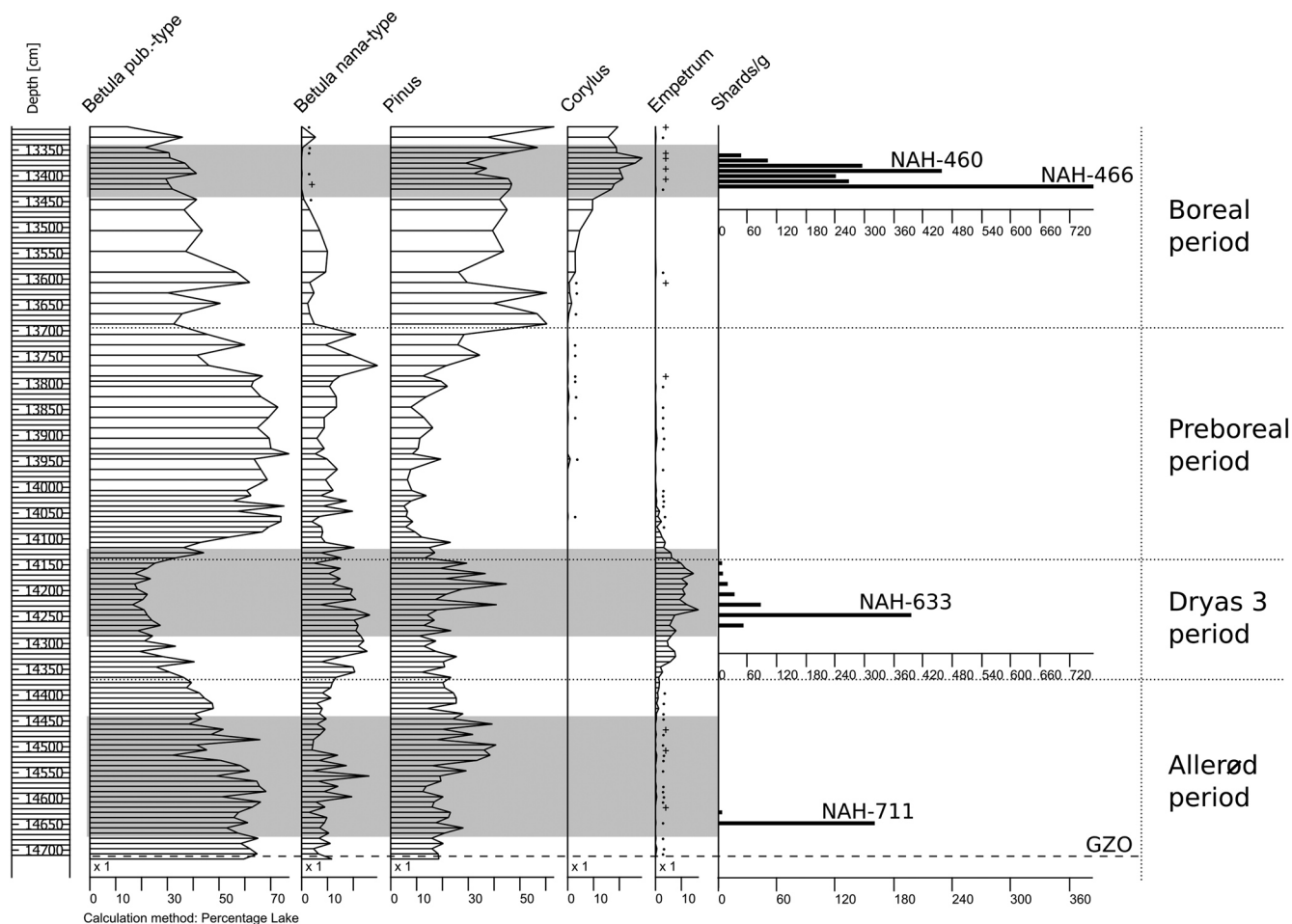


Figure 2. Overview of results of the targeted search. Sequences prepared for cryptotephra search are shaded in grey. The dashed line (labelled GZO) indicates the local palynologically identified end of the Gerzensee Oscillation.

obsidian standard as a secondary glass standard. The laboratory was part of the INTAV (International Quaternary Association's focus group on tephrochronology) comparison of tephrochronology laboratories, which confirmed the high quality of the major-element data produced by the instrument set-up (Kuehn *et al.* 2011). For further details on the analytical procedure see Dörfler *et al.* (2012) and Zanon *et al.* (2019). Analyses with totals <95% were discarded. All data are plotted normalised to 100% volatile free. Average analyses are shown in Tables 1–3.

Results and discussion

A total of 39 sediment samples have been subject to the search for cryptotephra. The targeted search resulted in three clear cryptotephra shard concentrations of more than 350 shards/g (or 150 shards/g at generally lower concentrations). The outcome of the targeted search is displayed in Fig. 2. Shard sizes differ between 15 and 75 μm (Fig. 3). Samples with peak shard concentrations were analysed for the geochemical composition of the shard population with EMPA.

Identification, characterisation and correlation of tephra layers

NAH-466

The Saksunarvatn eruption(s) can be assigned to the phase of rapidly increasing *Corylus* (Hazel) pollen values during the Boreal period in northern central Europe (Bramham-Law *et al.* 2013; Merkt *et al.* 1993). As this increase is strikingly and unequivocally reflected in the NAH record (Krüger *et al.* 2020), a rough determination of the position of the ash could easily be made.

Here, the targeted search for cryptotephra revealed a two-part maximum of shards (Fig. 2) in samples NAH-460 (13.390–13.400 m) as well as NAH-466 (13.420–13.430 m). Both peaks (NAH-460 and 466) correlate to the rapid increase and first *Corylus* pollen maximum of the (biostratigraphical) Boreal period.

Shard counts of sample NAH-460 yielded about 450 shards/g and NAH-466 about 770 shards/g. The shards in both peak occurrences are exclusively brown in colour (Fig. 3a–b). The morphology of the glass shards is blocky, angular with curved shards, similar to that described by Merkt *et al.* (1993). The size spectrum ranges from 15 to 40 μm . Single shards with more than 60 μm appeared rarely. Shards from sample NAH-466 were analysed for geochemical composition.

The glass shard population in the tephra horizon NAH-466 is geochemically homogeneous. The glass shards reveal a basaltic composition, with 49.6 ± 0.3 wt% SiO_2 , 3.1 ± 0.1 wt% TiO_2 , 14.5 ± 0.3 wt% FeO , 10.1 ± 0.2 wt% CaO (Fig. 4). The full geochemical analyses are given in Table 1.

The chemical composition is consistent with the SA that erupted from the Grímsvötn volcanic system on Iceland (Andrews *et al.* 2002; Bramham-Law *et al.* 2013). Tephra of this age, brownish glass shards and the same major- and minor-element composition, has been described at several terrestrial sites in Northern Europe, in marine cores in the North Atlantic and also in the GRIP ice core (Fig. 5a).

However, a recent review by Óladóttir *et al.* (2020) emphasised that the SA at different locations derives from various eruptive pulses of the Grímsvötn volcanic system. Tephra associated with the SA G10ka tephra series are of a very similar chemical composition (Fig. 5b–e).

Due to the size of the glass shards in the NAH tephra and the still-missing interlaboratory comparison tests for calibrating the analytical machines, we abstained from analysing trace-element compositions.

The recently published data on Saksunarvatn-type tephra from Havnardalsmyren on the Faroe Islands revealed up to five tephra from the Grímsvötn volcanic system, deposited within an interval of about 400 years. Major-element geochemistry shows that two older cryptotephra (Havn 3 and 4) can be separated by lower MgO than CaO content from a visible Saksunarvatn tephra and two younger ashes (Wastegård *et al.* 2018). The glass shards from NAH-466 fall into the field of high Mg-Saksunarvatn tephra (Fig. 5).

The targeted search for SA revealed two separate peaks in shard concentrations that correlate to the phase of rapidly

Table 1. Geochemical data on glass shards from NAH-466 determined by electron-microprobe analysis.

Volatile-free normalised values	SiO_2^	TiO_2^*	Al_2O_3^*	$\text{FeO}_{\text{tot}}^*$	MnO^*	MgO^*	CaO^*	Na_2O^*	K_2O^*	P_2O_5^*	F	SO_3	Cl	Analysed total	Comment
NAH-466	49.66	3.17	13.06	14.57	0.19	5.65	10.21	2.66	0.48	0.35	0.11	0.23	0.03	97.47	Saksunarvatn
>97%	49.29	3.12	13.18	14.94	0.25	5.65	9.94	2.78	0.47	0.37	0.00	0.26	0.04	97.67	Saksunarvatn
	48.97	2.69	13.52	14.27	0.22	6.25	10.71	2.66	0.39	0.32	0.10	0.15	0.04	98.42	Saksunarvatn
	49.88	2.89	13.10	14.30	0.26	5.81	10.26	2.78	0.41	0.32	0.00	0.26	0.04	98.97	Saksunarvatn
	49.80	3.15	13.08	14.82	0.23	5.38	9.99	2.78	0.46	0.30	0.03	0.15	0.03	99.40	Saksunarvatn
	49.44	3.11	13.10	14.80	0.25	5.50	10.16	2.88	0.46	0.29	0.09	0.18	0.03	98.23	Saksunarvatn
	49.45	3.00	13.10	14.42	0.23	5.93	10.12	2.95	0.46	0.35	0.00	0.25	0.06	97.63	Saksunarvatn
	49.75	3.11	12.97	14.68	0.24	5.65	10.02	2.78	0.45	0.35	0.00	0.31	0.04	99.61	Saksunarvatn
	50.01	3.20	13.10	14.28	0.25	5.54	10.14	2.70	0.49	0.30	0.00	0.19	0.03	97.40	Saksunarvatn
	49.84	3.14	13.23	14.68	0.23	5.30	9.87	2.93	0.46	0.31	0.14	0.20	0.04	99.29	Saksunarvatn
	49.71	3.14	13.13	14.60	0.27	5.56	10.07	2.76	0.46	0.30	0.05	0.23	0.04	98.60	Saksunarvatn
	49.86	3.23	12.97	14.37	0.28	5.50	10.01	2.96	0.48	0.34	0.03	0.21	0.04	97.90	Saksunarvatn
	49.40	2.90	13.54	14.24	0.22	5.89	10.30	2.78	0.44	0.27	0.05	0.24	0.05	97.29	Saksunarvatn
	49.65	3.24	13.21	14.28	0.29	5.41	10.24	2.88	0.47	0.33	0.00	0.22	0.04	97.62	Saksunarvatn
	49.76	3.16	13.06	14.70	0.18	5.49	9.98	2.91	0.49	0.27	0.06	0.23	0.04	97.68	Saksunarvatn
	49.79	3.20	12.93	14.67	0.22	5.64	10.02	2.76	0.47	0.31	0.06	0.23	0.04	97.35	Saksunarvatn
	49.29	3.17	13.04	14.86	0.21	5.60	9.95	3.07	0.47	0.34	0.00	0.21	0.04	98.01	Saksunarvatn
	50.09	2.92	13.20	13.84	0.22	6.02	10.49	2.53	0.40	0.29	0.08	0.17	0.04	97.98	Saksunarvatn
avg.	49.65	3.09	13.14	14.52	0.24	5.65	10.14	2.81	0.46	0.32	0.04	0.22	0.04	97.94	
$\pm 1\sigma$	0.29	0.15	0.17	0.29	0.03	0.24	0.21	0.13	0.03	0.03	0.04	0.04	0.01	0.75	

Table 2. Geochemical data on glass shards from NAH-633 determined by electron-microprobe analysis.

*Volatile-free normalised values	SiO ₂ *	TiO ₂ *	Al ₂ O ₃ *	FeO _{tot} *	MnO*	MgO*	CaO*	Na ₂ O*	K ₂ O*	P ₂ O ₅ *	F	SO ₃	Cl	Analysed total	Comment
NAH-633	71.24	0.27	14.04	4.01	0.18	0.18	1.45	4.94	3.66	0.03	0.13	0.03	0.17	96.83	Vedde Ash
>95%	70.60	0.34	13.98	4.31	0.10	0.50	2.01	4.82	3.30	0.05	0.15	0.02	0.17	98.09	Vedde Ash
	71.77	0.28	13.73	4.00	0.16	0.17	1.42	4.76	3.66	0.04	0.11	0.02	0.17	97.51	Vedde Ash
	71.30	0.33	13.60	4.19	0.13	0.22	1.41	5.21	3.55	0.06	0.33	0.03	0.17	99.42	Vedde Ash
	71.64	0.31	13.89	3.82	0.13	0.27	1.41	4.95	3.55	0.03	0.27	0.04	0.18	98.28	Vedde Ash
	71.17	0.30	14.02	3.93	0.21	0.19	1.38	5.17	3.62	0.00	0.15	0.01	0.19	97.47	Vedde Ash
	71.35	0.29	13.77	3.97	0.09	0.26	1.38	5.36	3.50	0.05	0.16	0.00	0.18	95.00	Vedde Ash
	71.59	0.30	13.66	3.83	0.14	0.17	1.44	5.27	3.56	0.03	0.08	0.03	0.19	96.84	Vedde Ash
	71.43	0.28	13.88	3.78	0.17	0.19	1.39	5.25	3.61	0.03	0.30	0.02	0.18	97.42	Vedde Ash
	71.28	0.30	13.98	3.88	0.18	0.22	1.42	5.14	3.56	0.04	0.16	0.02	0.17	97.17	Vedde Ash
	71.61	0.32	13.74	3.79	0.14	0.23	1.45	5.21	3.51	0.01	0.23	0.02	0.18	97.63	Vedde Ash
	71.02	0.30	14.15	3.93	0.19	0.19	1.46	5.17	3.51	0.08	0.10	0.04	0.17	95.01	Vedde Ash
	71.59	0.32	13.62	3.73	0.13	0.20	1.48	5.35	3.52	0.05	0.22	0.02	0.18	94.97	Vedde Ash
	71.47	0.29	13.74	3.91	0.11	0.18	1.34	5.38	3.54	0.04	0.06	0.04	0.18	97.12	Vedde Ash
	71.13	0.31	13.54	3.95	0.15	0.23	1.49	5.54	3.64	0.02	0.14	0.04	0.18	95.68	Vedde Ash
	71.11	0.30	13.79	3.97	0.17	0.20	1.40	5.45	3.61	0.00	0.17	0.04	0.18	95.95	Vedde Ash
	71.08	0.27	13.99	3.76	0.19	0.17	1.53	5.32	3.64	0.06	0.20	0.09	0.19	94.88	Vedde Ash
avg.	71.30	0.30	13.79	3.93	0.15	0.20	1.42	5.21	3.56	0.04	0.16	0.03	0.18	97.12	
±1 s	0.29	0.02	0.18	0.15	0.03	0.08	0.15	0.22	0.09	0.02	0.08	0.02	0.01	1.33	

increasing values of *Corylus* pollen in the NAH record. A 9 cm sediment sequence was sampled in 1 cm steps, equivalent to a rather narrow scope of investigation. As large-scale turbations have been excluded for the whole NAH sequence this result either reflects: (i) potentially two very closely spaced eruptions;

or (ii) small-scale rearrangement, bioturbation or secondary inwash of shards.

(i) At Potremser Moor—an in-filled lake about 230 km east of NAH—Bramham-Law *et al.* (2013) recorded two close and significant peaks in tephra shard concentration that correlate to

Table 3. Geochemical data on glass shards from NAH-711 determined by electron-microprobe analysis.

*Volatile-free normalised values	SiO ₂ *	TiO ₂ *	Al ₂ O ₃ *	FeO _{tot} *	MnO*	MgO*	CaO*	Na ₂ O*	K ₂ O*	P ₂ O ₅ *	F	SO ₃	Cl	Analysed total	Comment
NAH-711	59.78	0.53	20.50	2.40	0.15	0.26	1.78	7.10	7.41	0.08	0.17	0.10	0.31	97.07	LST
>96%	60.61	0.49	20.72	1.90	0.05	0.20	2.31	6.29	7.35	0.08	0.08	0.06	0.26	97.85	LST
	60.94	0.52	20.43	2.12	0.16	0.19	1.94	6.17	7.49	0.03	0.10	0.06	0.34	96.53	LST
	59.90	0.53	20.52	2.26	0.16	0.28	1.61	7.21	7.45	0.07	0.15	0.11	0.33	96.83	LST
	59.74	0.54	20.50	2.27	0.13	0.27	1.79	7.22	7.52	0.02	0.11	0.08	0.32	97.57	LST
	59.83	0.51	20.46	2.32	0.19	0.28	1.74	7.27	7.33	0.06	0.11	0.07	0.31	97.15	LST
	59.99	0.47	20.63	2.29	0.14	0.24	1.64	7.07	7.47	0.06	0.17	0.15	0.29	98.09	LST
	59.98	0.53	20.59	2.31	0.10	0.22	1.64	7.02	7.55	0.05	0.19	0.07	0.35	97.12	LST
	60.08	0.57	20.12	2.53	0.23	0.26	1.70	7.12	7.37	0.02	0.02	0.09	0.34	98.40	LST
	60.06	0.49	21.18	2.13	0.15	0.23	2.57	6.58	6.61	0.00	0.14	0.09	0.23	97.30	LST
	59.66	0.58	20.61	2.24	0.19	0.27	1.80	7.16	7.44	0.06	0.11	0.12	0.35	96.95	LST
	60.41	0.34	20.50	1.99	0.21	0.12	1.48	7.34	7.60	0.02	0.22	0.09	0.31	97.76	LST
	60.40	0.57	20.36	2.20	0.17	0.24	1.90	6.80	7.32	0.03	0.10	0.08	0.28	97.72	LST
	60.51	0.59	20.48	2.17	0.10	0.28	1.86	6.78	7.21	0.03	0.01	0.07	0.30	97.26	LST
	59.62	0.42	20.79	2.27	0.23	0.20	1.60	7.50	7.35	0.02	0.17	0.05	0.35	96.99	LST
	60.17	0.52	20.60	2.20	0.13	0.25	1.72	6.73	7.63	0.05	0.09	0.08	0.32	97.50	LST
	59.73	0.53	20.34	2.43	0.11	0.31	1.77	7.01	7.70	0.08	0.15	0.09	0.29	97.32	LST
	60.89	0.50	20.61	1.80	0.11	0.20	2.27	6.44	7.15	0.01	0.03	0.08	0.23	97.95	LST
	62.51	0.41	20.03	1.45	0.08	0.18	2.39	4.96	7.93	0.05	0.06	0.08	0.11	97.34	LST
	60.14	0.54	20.49	2.16	0.20	0.26	2.11	6.87	7.17	0.06	0.16	0.06	0.29	97.14	LST
	59.52	0.52	20.43	2.38	0.20	0.29	1.77	7.24	7.60	0.06	0.26	0.10	0.30	97.01	LST
	60.16	0.31	19.86	2.70	0.40	0.23	1.80	7.81	6.74	0.00	0.23	0.18	0.41	97.04	LST
	59.41	0.56	20.61	2.37	0.18	0.29	1.70	7.23	7.59	0.08	0.06	0.07	0.31	97.99	LST
	59.81	0.57	20.71	2.30	0.19	0.28	1.77	6.89	7.42	0.05	0.18	0.07	0.31	97.75	LST
	59.72	0.53	20.71	2.23	0.16	0.23	1.76	7.01	7.63	0.02	0.22	0.13	0.32	97.40	LST
	59.84	0.54	20.49	2.42	0.14	0.25	1.66	6.99	7.63	0.04	0.12	0.07	0.33	97.79	LST
	60.21	0.56	20.17	2.36	0.20	0.28	1.71	7.09	7.36	0.04	0.18	0.11	0.33	98.88	LST
	59.87	0.53	20.30	2.57	0.19	0.31	1.79	6.85	7.51	0.09	0.20	0.09	0.30	98.06	LST
	59.52	0.59	20.39	2.36	0.22	0.28	1.78	7.17	7.61	0.07	0.20	0.13	0.29	97.23	LST
	62.49	0.33	20.75	0.96	0.01	0.02	2.55	4.39	8.46	0.04	0.02	0.06	0.03	97.04	LST
	60.42	0.55	20.19	2.31	0.19	0.29	1.72	6.87	7.41	0.04	0.15	0.09	0.32	98.90	LST
avg.	60.22	0.51	20.47	2.20	0.17	0.24	1.88	6.82	7.45	0.04	0.13	0.09	0.29	97.51	
±1s	0.81	0.08	0.29	0.37	0.07	0.07	0.29	0.74	0.37	0.02	0.07	0.03	0.07	0.57	

LST: Laacher See Tephra.

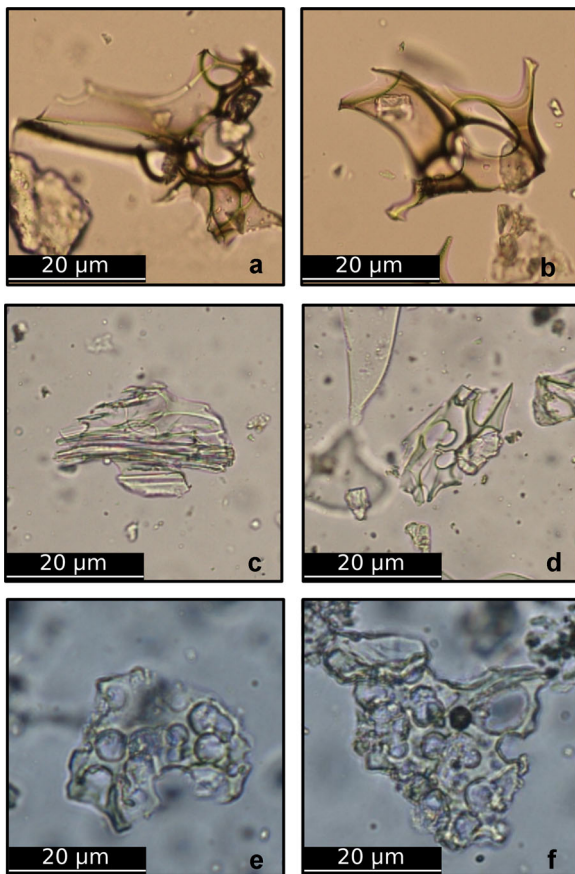


Figure 3. Images of cryptotephra shards from the Nahe palaeolake record; a–b Saksunarvatn Ash, c–d Vedde Ash, e–f Laacher See Tephra. [Color figure can be viewed at wileyonlinelibrary.com]

the main expansion of *Corylus*. Here, shard morphology has been utilised to distinguish between the two peaks. The lower peak contained brown platy and curvilinear shards, whereas the upper mainly comprised colourless shards with occasionally closed vesicles but mainly irregular morphologies. The lower and more distinct has been geochemically identified as a SA (Bramham-Law *et al.* 2013).

However, the double peak observed in the NAH record does not contain separate peaks of morphologically different shards. The geochemical composition of the lower and more pronounced peak clearly reflects a known SA fingerprint. Here, one explanation could be two temporally close successive eruptions of the same volcanic system or two separate basaltic volcanic systems.

There is more than one known eruption from the Grímsvötn volcanic system that is linked to SA (Bramham-Law *et al.* 2013; Davies *et al.* 2012; Jóhannesdóttir *et al.* 2006; Wastegård *et al.* 2018; Wulf *et al.* 2016). Recent studies by Harning *et al.* (2018) and Wastegård *et al.* (2018) as well as the review by Óladóttir *et al.* (2020) demonstrated that there were at least three, potentially even seven, eruptions from the Grímsvötn volcanic system.

One ash plume was distributed towards the north-west of the system and was recorded in the Greenland ice cores (Rasmussen *et al.* 2006). At least one other dispersal envelope was directed towards the south-east, and has been identified at a variety of sites in continental Europe (Bramham-Law *et al.* 2013; Jones *et al.* 2018; Lohne *et al.* 2013; Merkt *et al.* 1993; Wulf *et al.* 2016). The SA recorded in the NAH is most likely related to this south-east dispersal fan.

In this respect, only single cryptotephra horizons associated with the SA have been recorded in annually laminated sequences in northern Germany (Dörfler *et al.* 2012; Jones

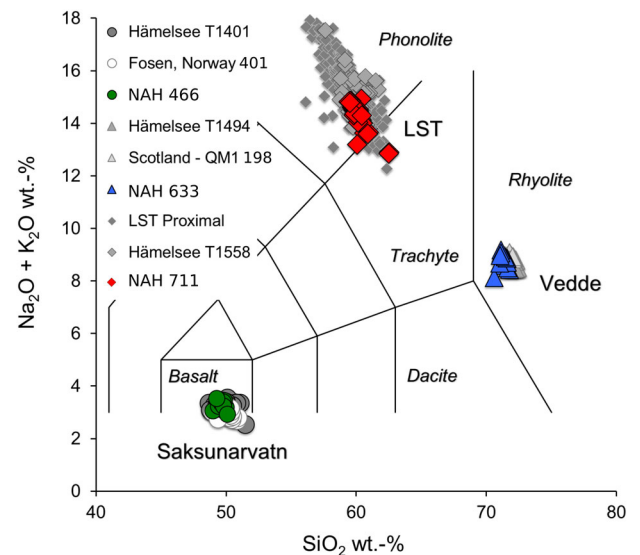


Figure 4. Classification diagram for volcanic glass shards from NAH-466, NAH-633 and NAH-711. Total-alkali-silica classification diagram according to Le Bas *et al.* (1986). The geochemical composition of single glass shards of selected sites are given for comparison. For Saksunarvatn Ash the composition in nearby Hämeelsee (Jones *et al.*, 2018) and from Grønlia on the Fosen peninsula, Norway (Lind *et al.* 2013). For the rhyolitic part of the Vedde Ash the composition in Hämeelsee (Jones *et al.* 2018) and Scotland (Timms *et al.* 2017) is displayed. Data on the Laacher See Tephra (LST) are taken from microprobe glass analyses from proximal LST Ash (van den Bogaard and Schmincke, 1985; unpublished data) and LST in Hämeelsee (Jones *et al.*, 2018). All data plotted are normalised to a volatile-free base. [Color figure can be viewed at wileyonlinelibrary.com]

et al. 2018; Merkt *et al.* 1993). One of those sequences derives even from Lake Poggensee (Zanon *et al.* 2019)—a lake less than 30 km east of the Nahe palaeolake.

(ii) The palaeo-environmental record of NAH revealed the presence of increasing amounts of undefined shells and shell fragments in the depth that corresponds to the SA. They can potentially be associated with small-scale lake-level fluctuations within the Nahe palaeolake. This assumption is in line with indicators of small-scale rearrangement. Therefore, it is probable that the two separate peaks can be explained by the redeposition of material or a secondary inwash of shards, respectively. Consequently, redeposition could be considered as a determining factor for the observed distribution pattern of cryptotephra in the sediment sequence (NAH-460 and NAH-466).

The SA is intended to provide an additional time span to the age–depth model of the NAH sequence. Therefore, the depth needs to be clarified to which the tephra is to be assigned. In this respect, the NAH record could be correlated to the pollen sequence from close by Lake Poggensee (POG; M. Zanon pers. com.). Here, the SA is embedded as a single visible layer in annually laminated sediments.

The results of the palynological analysis revealed that the curves of *Corylus* pollen ratios of NAH and POG match closely (pers. com. M. Zanon). This is not surprising as the distance is less than 30 km and the size as well as the catchment of the two lakes would be approximately equal. Palynologically, the SA was detected in the sediments of Lake Poggensee, exactly where the lower SA peak was detected in the NAH record. Considering this, the event horizon is assigned to the depth of the lower shard peak (NAH-466).

NAH-633

The pollen stratigraphic location of the VA is challenging. The fallout date of the VA has been placed in the

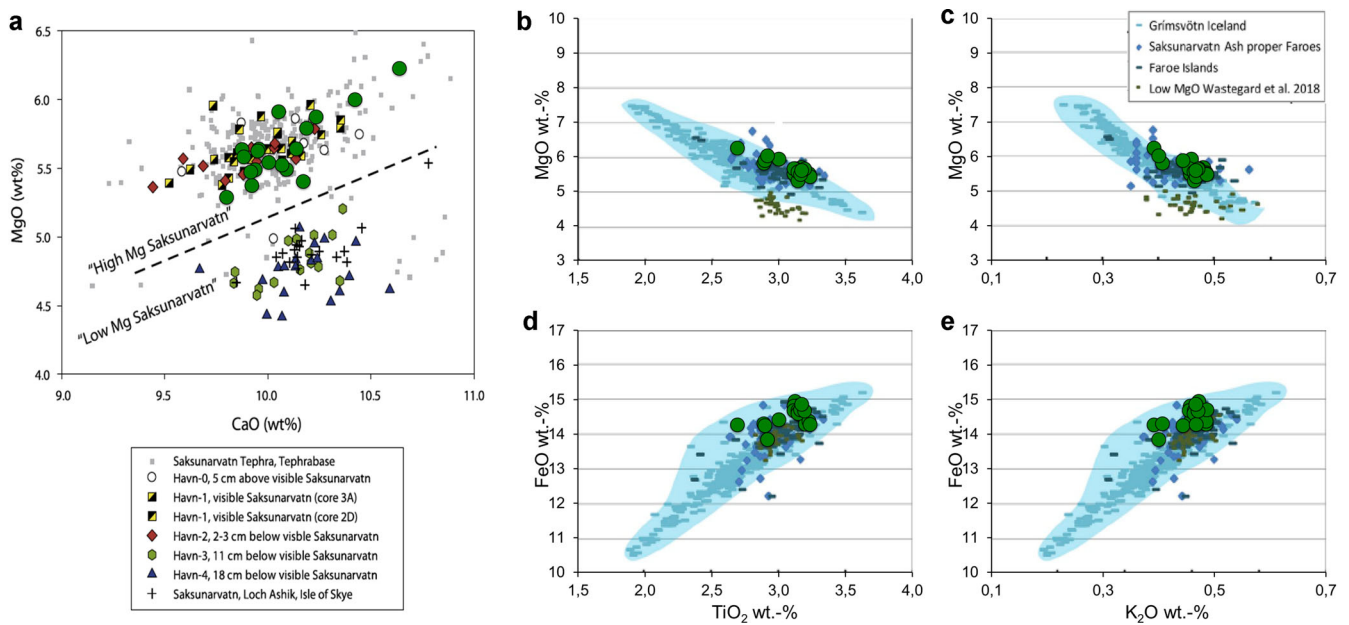


Figure 5. (a) NAH-466 glass shard composition (dark green dots) in the Saksunarvatn Ash discrimination diagram shown in Fig. 13 in Wastegård *et al.* 2018. Up to five ash horizons were described in one section on the Faroe Islands. (b)–(e) Selected bi-plots showing tephra glass shard major-element compositions of G10ka series previously correlated to Saksunarvatn Ash proper at various selected sites around the North Atlantic adapted from Fig. 6 in Óladóttir *et al.* 2020. [Color figure can be viewed at wileyonlinelibrary.com]

mid-Younger Dryas period and was determined to represent a distinct marker horizon that separates the early and the later phase of the Younger Dryas period (Bakke *et al.* 2009; Hafliðason *et al.* 2018; Lane *et al.* 2012a, 2013; Mangerud *et al.* 1984). The VA has been associated with pollen stratigraphy from Scotland (Lowe and Turney 1997), Sweden (Björck and Wastegård 1999) and Russia (Wastegård *et al.* 2000). For a pollen stratigraphic comparison with the present study, however, these are too remote to be used for comparison with the NAH record in northern Germany.

In north and north-western Germany, the second half of the (biostratigraphical) Dryas 3 period (terminology following Krüger *et al.* 2020) is linked to the spread of *Empetrum* sp. (*cf. E. nigrum*) in different degrees, reflecting climatic alterations towards increased oceanicity (Krüger *et al.* 2020; Merkt and Müller 1999; Overbeck 1975). As an increase in *Empetrum*-type pollen has also been seen during the Dryas 3 period in the NAH record, a search for VA cryptotephra has been carried out in corresponding depths.

Here, the targeted search revealed one clear maximum concentration of shards in sample NAH-633 (14.245–14.265 m). The depth of the sample position corresponds pollen-stratigraphically directly to a rapid increase in *Empetrum*-type pollen values as observed midway through the Dryas 3 period (Fig. 2; Krüger *et al.*, 2020).

Shard counts yielded about 395 shards/g. The shards are exclusively colourless (Fig. 3(c)–(d)). Morphologically, they appear platy to highly vesicular, and a few have tubular properties. The size spectrum ranges from 20 to 50 μm .

The tephra has a homogeneous geochemical composition. In the total-alkali-silica (TAS) classification diagram it falls into the field of rhyolite composition with 71.3 ± 0.3 wt% SiO_2 , 5.2 ± 0.2 wt% Na_2O and 3.6 ± 0.1 wt% K_2O (Fig. 4). The full geochemical analyses are given in Table 2.

The general characteristics of geochemical composition (Fig. 6), age and morphology of shards are in line with the description of shards of the rhyolitic phase found at sites across Northern Europe (among others: Davies *et al.* 2005; Mangerud *et al.* 1984; Timms *et al.* 2017; Jones *et al.* 2018).

NAH-711

The Laacher See Eruption occurred after the palynologically defined termination of the Gerzensee Oscillation and around 200 years before the Dryas 3 period became fully established (Litt *et al.* 2003; Litt and Stebich 1999; Merkt and Müller 1999; von Grafenstein *et al.* 1994). In a number of pollen diagrams from north-eastern Germany a significant decrease of *Pinus* pollen values in the last third of the Allerød period is seen around the LST horizon (Jahns 2000; Theuerkauf 2003). This trend, albeit not strikingly pronounced, is observable in the pollen concentration values of the NAH record.

Here, the targeted search revealed one clear maximum concentration of glass shards at the 14.635–14.655 m core depth (NAH-711).

With respect to pollen stratigraphy, the sample depth corresponds to the last third of the Allerød period (Fig. 2). The high resolution of the pollen record allowed a clear distinction between the termination of the (palynologically defined) Gerzensee Oscillation and the timing of cryptotephra deposition (Dreibrodt *et al.* 2020; Krüger *et al.* 2020). It correlates to decreasing *Pinus* pollen values as well as increasing concentration values of pollen from grasses and herbaceous plants towards the end of the Allerød period.

Glass shard counts yielded about 160 shards/g. The tephra horizon consists of colourless vesicle-rich pumiceous shards with spherical vesicles, and pipe-like elongated bubbles (Fig. 3e–f). The external shape of these shards is determined by densely packed, open (burst) vesicle cavities. Single brownish shards occur. The size spectrum ranges from 20 to 75 μm .

Geochemical analysis was done on 31 shards (analyses that resulted in major-element weight percentage totals <96 wt% were discarded). The tephra has a phonolitic composition with 60.2 ± 0.8 wt% SiO_2 , a range of 7.8 to 4.3 wt% Na_2O , a range of 8.4 to 6.6 wt% K_2O and 2.6–1.5 wt% CaO . The full geochemical analyses are given in Table 3.

The geochemical fingerprinting of the NAH-711 glass shards confirms an identification with tephra from the Laacher See Eruption (Fig. 4). The glass shards of NAH-711 show the geochemical and morphological characteristics of the glass

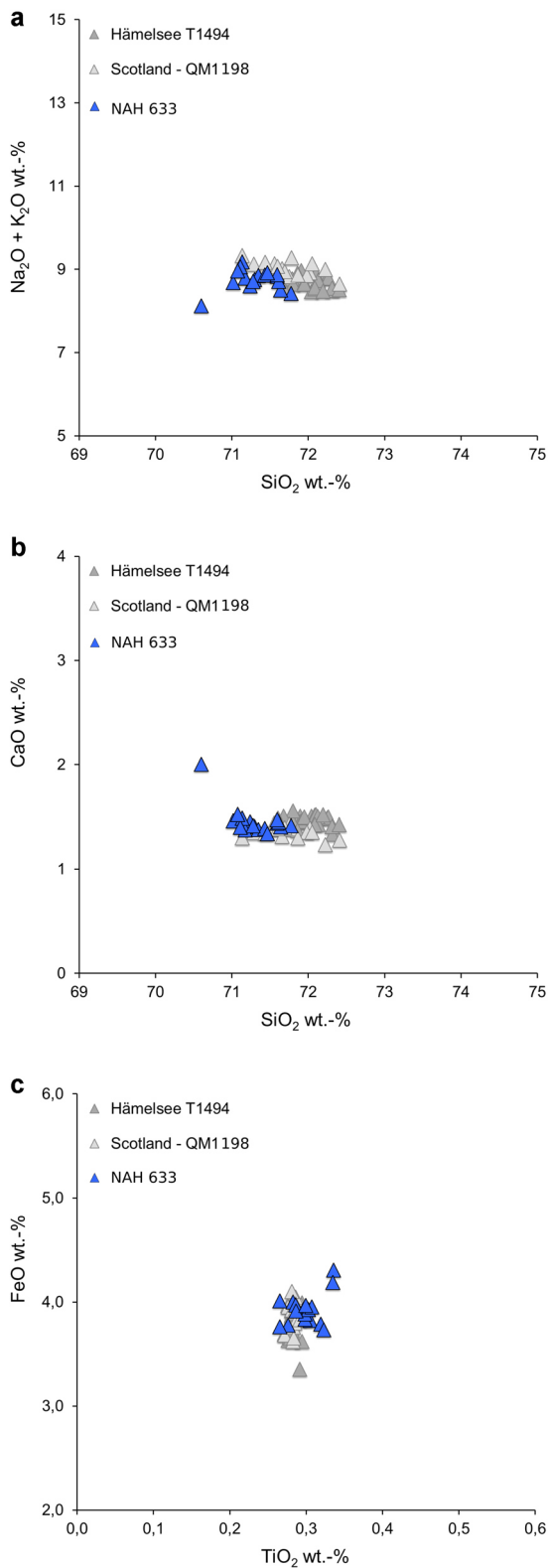


Figure 6. Geochemical composition of Tephra NAH-633 compared with the composition of the rhyolitic Vedde Ash at Hämelsee (Jones *et al.* 2018) and from Quoyloo Meadow, Orkney (Timms *et al.* 2017) in (a) SiO₂ versus alkali, (b) SiO₂ versus CaO and (c) TiO₂ versus FeO. [Color figure can be viewed at wileyonlinelibrary.com]

shards described from the proximal Plinian eruption phases (Fig. 3e–f), following the comparison with data from LST from the proximal type sites (van den Bogaard and Schmincke 1985; C. van den Bogaard, unpublished data).

The published data from distal sites in the north-western fallout (Housley *et al.* 2012; Jones *et al.* 2018; Lane *et al.* 2015;

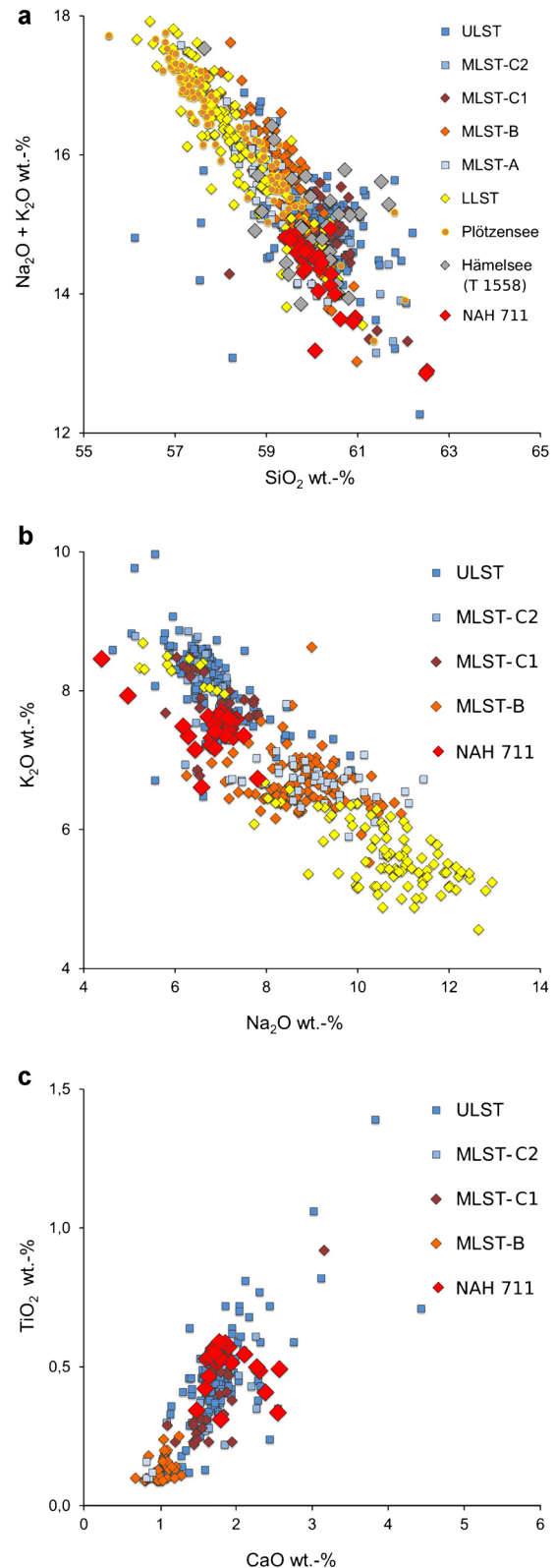


Figure 7. Tephra NAH-711 compared with glass shard composition of proximal Laacher See Tephra (LST) from the different eruption phases: LLST, MLST A, B, C1, C2 and ULST (after van den Bogaard and Schmincke, 1984; unpublished data). (a) silica versus alkalis, glass shard composition from Plötzensee Berlin (unpublished data) represent the LLST fallout, (b) bi-plot Na₂O versus K₂O (c) and CaO versus TiO₂. [Color figure can be viewed at wileyonlinelibrary.com]

Larsson and Wastegård 2018; Procházka *et al.* 2018; Riede *et al.* 2011; Turney *et al.* 2006; van den Bogaard and Schmincke 1984, 1985; Wulf *et al.* 2013) are in line with this interpretation. The chemistry suggests a fallout from the

eruption phases MLST C1 (Fig. 7). This is also supported by the morphology of NAH-711 glass shards: the glass shards are highly vesicular and colourless. This is indicative of shards described from the LST eruptive phase that resulted from Plinian eruptions. Vesicle-rich pumiceous clasts with pipe-like elongated vesicles, are typical for LLST, MLST B and MLST C1 deposits, pumiceous clasts with spherical bubbles are described throughout the eruption sequence, but especially from LLST to the base of ULST. Glass shards from the phreatomagmatic phases of the eruption MLST A, MLST C2 and ULST are mostly angular and blocky with few vesicles (Jones *et al.* 2018; van den Bogaard and Schmincke 1985).

Targeted cryptotephra search based on palynology

It has been shown before that palynological records can be useful tools when intending to find cryptotephra layers (Dörfler *et al.* 2012). Preceding pollen analyses inherit the strength to narrow down the extent of the sediment sequence to be subsampled for tephra analysis.

In the present study, three cryptotephra layers out of three suspected were detected. The scope of the respective search sequence was in each case comparatively narrow (7–16 cm) due to the high resolution of the pollen record. Regarding all cryptotephra layers, the targeted search has been directly successful. Consequently, it must be questioned whether the detection of tephra in narrow sequences of very homogeneous sediments (here in the case of sediments deposited during the Dryas 3 and Boreal periods) means that cryptotephra is generally present throughout the sediment due to different depositional processes or turbations.

Nevertheless, with regard to the representation of shards per sample and depth of the VA and LST, large-scale rearrangement becomes very unlikely. In both cases a clear maximum of shards is recorded, considered to reflect the timing of the volcanic eruption and ash fallout. The presence of shards below the main peak can be explained by minor bioturbation (Anderson *et al.* 1984). As suggested by Davies *et al.* (2012), the concentration of shards per depth can decrease above the concentration peak, indicating the mobilisation of shards in the catchment. In this respect, the NAH cryptotephra record mainly contains expectable minor redepositions of shards resulting in a common *tail-off* pattern.

In order to exclude the possibility that shards are not generally present in every sample, specific sequences of transitional sediments were analysed. In addition, sequences were also considered in which no tephra layer would be expectable—this again on the basis of pollen stratigraphy and the current state of knowledge of tephra-producing events. Therefore, a sequence of 24 cm was selected spanning a transition from laminated to gradually more homogeneous sediments. According to pollen stratigraphy, this sequence was deposited during the last third of the Allerød period as well as during the transition from the Allerød to the Dryas 3 period. In the samples from the bottom of this sequence, the LST shows a clear peak. All samples above this maximum contained at most two shards, but predominantly no cryptotephra shards at all (*cf.* grey shaded areas shown in Fig. 2).

Consequently, two conclusions can be drawn. Firstly, only minor and expectable rearrangements of shards can be observed. This is in line with previous results from other approaches (Dreibrodt *et al.* 2020; Krüger *et al.* 2020). Therefore, large-scale rearrangements can be excluded.

Secondly, it becomes apparent that pollen stratigraphy is a very valuable instrument as a basis for a targeted search for cryptotephra horizons. However, this of course requires a high resolution of the palynological record as well as a profound

knowledge of pollen stratigraphic positioning of the cryptotephra layers in compared regional diagrams.

Tephrochronological discussion

The detected cryptotephra layers could successfully be correlated by comparing their geochemical compositions with known volcanic eruptions of the Lateglacial and Early Holocene. NAH-466 correlates to a SA/G10ka series tephra, NAH-633 to the VA and NAH-711 to the LST. Hence, we here present the first geochemically confirmed find of LST in Schleswig-Holstein—placed outside the known dispersal envelope of visible LST (Fig. 8) (Riede *et al.* 2011; van den Bogaard and Schmincke 1984).

These results provide three independent age estimates for the age–depth model of the NAH record. As only a segmental sequence of the sediment is laminated, we here refrain from estimating our own age model of the eruptions. Therefore, it is crucial to discuss which available chronological tie-points should be used for the individual events (Table 4).

For the LST, reference is made to Bronk Ramsey *et al.* (2015) who compiled and improved age estimates for Late Quaternary European tephra horizons. The age estimate for the LST is based on tree-ring data from Friedrich *et al.* (1999), as well as age estimates from Holzmaar, Soppensee and Rotsee. The resulting $12\,937 \pm 23$ ($\mu \pm \sigma$; IntCal13), is in good agreement with estimates by Brauer *et al.* (1999) and dating by van den Bogaard (1995).

The record from Lake Holzmaar (HZM; Zolitschka 1998; Zolitschka *et al.* 1995) provides lamination until recent times, inheriting the opportunity to easily correlate further sequences. One of these sequences is the Meerfelder Maar (MFM) sequence that is correlated to the HZM record by using the Ulmener Maar tephra as chronological anchor (Brauer *et al.* 1999). The MFM record in turn provided varves throughout the Younger Dryas and the mid-Allerød period resulting in a very accurate estimate of $12\,880 \pm 40$ varve years BP for the LST.

Based on 118 AMS ^{14}C dates from a sequence of Lake Kråkenes, Lohne *et al.* (2013 – IntCal09; 2014 – IntCal13) provided the most accurate dating of the VA to date. The age estimate of $12\,066 \pm 42$ cal BP is in line with further estimates from lake sediments in Europe (Birks *et al.*, 1996; Wastegård

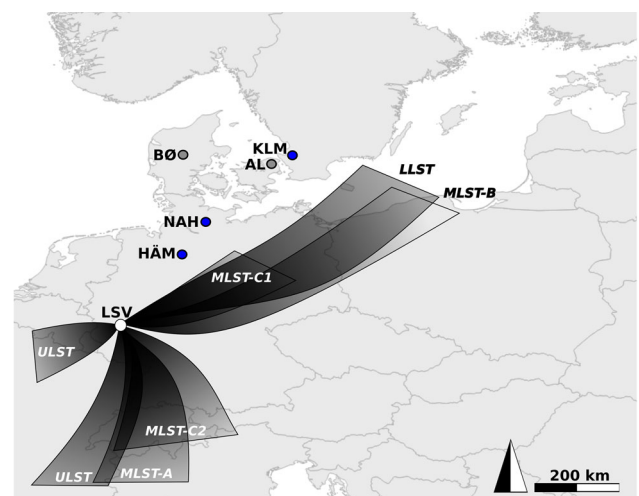


Figure 8. Estimated fallout of the Laacher See Tephra (LST) by van den Bogaard and Schmincke (1985) and modified by Housley *et al.* (2013), with the locations of the Nahe palaeolake (NAH), Körslättamossen (KLM; Larsson/Wastegård 2018), Lake Hämelsee (HÄM; Jones *et al.*, 2018), the Allerød-type locality (AL; Hartz/Milthers 1901) and the Bølling-type locality (BØ; Iversen 1942). [Color figure can be viewed at wileyonlinelibrary.com]

Table 4. Overview of recent dating of the respective cryptotephra horizons found in the Nahe palaeolake record.

Sample	Correlation	Age estimate	Reference
NAH-466	Saksunarvatn Ash	10 210 ± 35 cal. a BP	(Lohne <i>et al.</i> 2013)
NAH-633	Vedde Ash	12 064 ± 48 cal. a BP	(Lohne <i>et al.</i> 2014)
		12 023 ± 43 cal. a BP	(Bronk Ramsey <i>et al.</i> 2015)
		12 140 ± 43 varve a BP	(Lane <i>et al.</i> 2015)
NAH-711	Laacher See Tephra	12 937 ± 23 cal. a BP	(Bronk Ramsey <i>et al.</i> 2015)
		12880 ± 40 varve a BP	(Brauer <i>et al.</i> 1999)

et al., 1998; Matthews *et al.*, 2011) but provides a considerably smaller uncertainty.

The combined age model by Bronk Ramsey *et al.* (2015) to estimate the age of the VA is based on data from Lake Kråkenes, Abernethy, Soppensee, Rotsee and Bled. The resulting estimate of 12 023 ± 43 ($\mu \pm \sigma$; IntCal13) is in good agreement with the GICC05 date by Rasmussen *et al.* (2006).

In their analysis on the synchronicity of high-precision ^{14}C ages and the Greenland Ice Core Chronology, Lohne *et al.* (2013) further provided an age estimate for the SA of 10 210 ± 35 ($\mu \pm \sigma$; IntCal09). Based on the review by Óladóttir *et al.* (2020) it cannot be clarified with certainty to which of the G10ka series tephra the shards of the NAH record would correlate. Nevertheless, it has been shown that the pollen stratigraphical position of the lower shard peak from the NAH record correlates to the position of the SA layer in the pollen stratigraphy from Lake Poggensee (Zanon *et al.* 2019). At the near Lake Poggensee as well as Lake Woserin (Zanon *et al.* 2019; I. Feeser, pers. com.) only one ash layer has been identified in a laminated sequence. Both have been assigned to a SA (Zanon *et al.* 2019). As their individual dating falls well within the given age estimate by Lohne *et al.* (2013) this age has been utilised for the NAH age–depth model.

Resulting tephrostratigraphical framework, regional implications and future work

The identification of the volcanic eruptions allow for a direct correlation between the NAH sediment sequence and European key sites for palaeo-environmental research such as Meerfelder Maar (Brauer *et al.* 1999; Litt and Stebich 1999), Lake Hämelsee (Jones *et al.* 2018; Merkt and Müller 1999), Endinger Bruch (De Klerk 2002; Lane *et al.* 2012b), Lake Kråkenes (Lohne *et al.* 2013; Mangerud *et al.* 1984), Lake Tiefer See (Wulf *et al.* 2016) and Lake Soppensee (Lane *et al.* 2011; Lotter 2001). This highlights the relevance of the NAH location in correlating important key sites in northern and central Europe.

In combination with finds of LST at Lake Hämelsee (Jones *et al.* 2018) as well as Körslättamossen fen (Larsson and Wastegård 2018) the results of the present study demonstrate that the dispersal envelope of the Laacher See Eruption can be shifted further to the north-west.

In this respect it might even be possible to detect non-visible ash beds of the LST in Denmark (apart from Bornholm where it had already been identified—Turney *et al.* 2006) which would imply that biozonal-type localities such as Bølling (Krüger and Damrath 2019; Iversen 1942) or especially Allerød (Hartz and Milthers 1901) could finally be correlated to modern palaeo-environmental investigations by event stratigraphy (Fig. 8).

The targeted search for cryptotephra comprised 18% of the total analysed NAH Lateglacial to Early Holocene sequence. Considering the extensive sections without a search for cryptotephra, it is evident that the sediment cores inherit the possibility of containing even more non-visible ash beds. The sequence already analysed palynologically covers spatially as well as temporally the eruptions and (predominantly) fallout

zones of, e.g. Borrobol-type tephra, as well as Askja-S tephra, or Håsseldalen tephra (Davies *et al.* 2003; 2012; Pyne-O'Donnell *et al.* 2008; Turney *et al.* 1997; Wastegård *et al.* 2018; Wulf *et al.* 2016). Hence, we here emphasise the considerable potential of future investigations.

Conclusion

Three cryptotephra layers have been discovered and geochemically confirmed as G10ka series tephra (SA), VA and LST in sediments from the NAH. Consequently, we here present the first finding of LST in Schleswig-Holstein—located outside the ash plume that was reconstructed on the basis of visible ash layers. The combination of published LST findings from Lake Hämelsee (Jones *et al.* 2018) as well as Körslättamossen fen (Larsson and Wastegård 2018) reveals that the dispersal fan reached further to the north-west than previously assumed (Litt *et al.* 2003; Riede *et al.* 2011; Schmincke *et al.* 1999; Theuerkauf 2003; van den Bogaard and Schmincke 1985). Hence, the detection of LST in Jutland or the Danish Islands (adding to the finds on Bornholm) comes within reach, inheriting the potential to correlate important Lateglacial-type localities with recent palaeo-environmental investigations.

Furthermore, these results add three independent ages to the age–depth model for the NAH sequence (Dreibrodt *et al.* 2020), thereby emphasising the considerable potential for further investigations into both the site itself and general further tephrochronological studies in Northern Europe.

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Data availability statement

All data generated or analysed during this study are included in this published article. Palynological data are available from the corresponding author on reasonable request.

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Appendix III

Limnological response to the Laacher See eruption (LSE) in an annually laminated Allerød sediment sequence from the Nahe palaeolake, northern Germany

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BOREAS



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This paper presents evidence for a limnological response to the Laacher See eruption (LSE) as detected in lake sediments from Nahe, northern Germany. The sediment section of the Allerød period dating to between 13 422 and 12 708 cal. a BP is preserved in annual laminations. Within this section, the LSE was identified as a cryptotephra layer (12 944±44 cal. a BP). Microfacies analysis, continuous high-resolution geochemical measurements and pollen analyses enabled a high-resolution reconstruction of environmental change. The older part of the Allerød (c. 13 422 to 12 943 cal. a BP) was characterized by relatively stable sedimentation conditions. Evidence for windier conditions dating to c. 13 160 to 13 080 cal. a BP probably reflects the Gerzensee oscillation. Pronounced changes of the lake sedimentation followed the LSE. Four unusually thick varves with increased amounts of allochthonous material indicate serious disturbance of the local environment immediately after the LSE, related to increased storminess and/or the occurrence of high intensity rainfall events. A pronounced reduction of biogenic silica accumulation for c. 60 years after the LSE could reflect a period of acidification. Indications of a simultaneous lake level increase until c. 60 years after the LSE are in line with the supposed reduced evapotranspiration associated with cooler conditions. About 120 years after the LSE, increased oxygen access at the lake bottom, allochthonous input and Cl fluxes point to an onset of increasingly stronger westerly winds, probably as a long-term response to the LSE. This supports the idea of a southward shift of the mid-latitude westerlies wind system within the interval between the LSE and the beginning of the Younger Dryas. The pace of the southwards shift of this wind system decreased from 10 km a⁻¹ in the initial phase (40–120 years after LSE) to 6 km a⁻¹ in the later phase (120–200 years after LSE).

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The consequences of the Laacher See eruption (LSE) for central European environments and groups of humans have been discussed for more than three decades by palaeoenvironmentalists (e.g. Merkt 1971; Lotter & Birks 1993; Brauer *et al.* 1999; Merkt & Müller 1999; Theuerkauf 2003; Baldini *et al.* 2018), volcanologists (e.g. van den Bogaard & Schmincke 1985; Schmincke *et al.* 1999) and archaeologists (Riede 2014). Baldini *et al.* (2018) even discuss the LSE as a possible trigger for the onset of the Younger Dryas (YD).

The LSE is dated to 12 880±40 varve years BP based on the tephra deposition in Lake Meerfelder Maar (Brauer *et al.* 1999; Lane *et al.* 2013; Wulf *et al.* 2013; Bronk Ramsey *et al.* 2015). This is consistent with radiocarbon ages of 12 934±165 cal. a BP (Baales *et al.* 2002) or ⁴⁰Ar/³⁹Ar dates of 12 900±500 years BP (van den Bogaard 1995). The eruption was one of the largest during the late Quaternary in central Europe (e.g. van den Bogaard & Schmincke 1985; Baales *et al.* 2002) and is considered to have been particularly rich in sulphur (Harms & Schmincke 2000).

Several consequences have been considered for the impact of the LSE on contemporary regional environments and people, including ash deposition (Baales *et al.* 2002), acid rain (De Klerk *et al.* 2008), wildfires

(De Klerk *et al.* 2008; Engels *et al.* 2015, 2016), increased precipitation (Schmincke *et al.* 1999; De Klerk *et al.* 2008), and cooling (Merkt & Müller 1999; Rach *et al.* 2014; Baldini *et al.* 2018).

A variety of partly contradicting palaeoenvironmental scenarios have been reconstructed regarding the impact of the LSE on central European landscapes. At some sites, the occurrence of severe storms and heavy precipitation events immediately after the LSE was deduced from the sediment records (Merkt & Müller 1999; Schmincke *et al.* 1999). A serious impact of acid aerosols on large parts of central European landscapes has been considered as well (Schmincke *et al.* 1999; De Klerk 2008). Cooling due to the LSE was assumed by Merkt & Müller (1999) and has also been reconstructed based on biomarker analysis (Rach *et al.* 2014). In contrast, De Klerk (2008) found palynological indications of a warming after the end of the Gerzensee oscillation, considered to have occurred simultaneously with the LSE. At a number of sites, a water level increase was reconstructed after the LSE (Theuerkauf 2003). A strong change in the north-Atlantic wind system has been reconstructed to have followed the LSE (Brauer *et al.* 2008). The LSE has recently been considered as the trigger of this changing wind system and consequently

Table 1. Overview of radiocarbon dates and additional age estimates for the Nahe palaeolake sequence. * = the original age estimates given by Litt *et al.* (2007) have been corrected by 110 years to the older considering a hiatus according to Brauer *et al.* (2001); ** = age estimates used in present age-depth modelling.

Radiocarbon dates Lab. no.	Material dated	¹⁴ C age (a BP) ± 1σ	Master scale (cm)	δ ¹³ C (‰ PDB)	Treated as outlier
GrM-17885	Leaf (Poaceae)	15 230±60	1538.95	-17.71±0.2	x
KIA-53569	Branch (undiff.)	11 520±45	1475.7	-29.10±0.2	x
GrM-17289	Branch (undiff.)	10 640±40	1438.8	27.77±0.15	
KIA-53568	Branch (undiff.)	10 445±45	1427.8	-26.60±0.4	
GrM-17841	Branch (undiff.)	10 450±55	1425.3	-27.05±0.2	
KIA-53567	Leaf (<i>Salix</i>)	10 450±65	1424.8	-29.70±0.3	
GrM-17288	Fibrillose stem	11 055±40	1424.3	-20.20±0.15	x
GrM-17423	Wood (<i>Populus</i>)	11 635±45	1422.3	-27.82±0.15	x
KIA-53566	Wood (<i>Populus</i>)	11 650±45	True replicate	-26.40±0.2	x
KIA-53570	Periderm (Pinus)	9650±40	1380.8	-26.00±0.2	
GrM-17242	Root bark	9220±35	1332.8	-24.78±0.15	x
KIA-53565	Root bark	9235±35	True replicate	-24.00±0.2	x
Tephra layers					
Tephra layer	Master scale (cm)	Age estimate (μ + σ cal. a BP)	Reference		
Laacher See Tephra	1465.0	12 937±23	(Bronk Ramsey <i>et al.</i> 2015)		
Vedde Ash	1425.0	12 040±35	(Bronk Ramsey <i>et al.</i> 2015)		
Saksunarvatn Ash	342.5	10 264±47	(Zanon <i>et al.</i> 2019)		
Chronostratigraphical events					
Boundary	Master scale (cm)	Age estimate	Reference		
Pleniglacial/ Meindorf	1552.0	4560 varve years BP	Corr. after Litt <i>et al.</i> (2007)		
Meindorf/Dryas 1	1524.0	13 910 varve years BP	Corr. after Litt <i>et al.</i> (2007)		
Dryas 1/Allerød	1518.0	13 780 varve years BP	Corr. after Litt <i>et al.</i> (2007)		
Allerød/Dryas 3	1437.0	12 680 varve years BP	(Litt <i>et al.</i> 2007)		
Dryas 3/Preboreal	414.0	1560 varve years BP	(Merkt & Müller 1999)		

has even been assumed as a possible trigger of the onset of the YD cold period (Baldini *et al.* 2018).

An environmental impact is obvious in the areas of the previously known ash fall-out close to the eruptive centre. The Nahe palaeolake, as a very distal site (485 km north of Laacher See), sets a new point on the distribution map of the LSE envelope (Krüger & van den Bogaard 2020). This raises the question whether there is evidence for short-term and direct, i.e. by atmospheric eruptive material, and/or long-term and indirect, i.e. by larger scale climatic responses, impacts on the local environment of distal sites. The presence of the LSE cryptotephra layer within an annually laminated lake sediment sequence at Nahe palaeolake hereby offers the possibility to answer this question with high temporal confidence.

Material and methods

Site

The Nahe palaeolake is located in Schleswig-Holstein (northern Germany) about 30 km north of Hamburg. The former lake basin was part of a larger glacial lake system and is separated from further elongated incision lakes by two narrow sand ridges to the northwest and southeast (Wild 2017). To the southeast, Lake Itzstedt is the water-bearing remnant of the lake system. The geology of the catchment area is composed of glacial

deposits (tills, fluvial sands and lacustrine deposits) of the Weichselian glaciation, mainly composed of sediments rich in quartz, with accessory feldspars, mica and clay minerals.

The palaeolake's surface was about 16 ha in size during the Lateglacial. Today, the river Rönne flows in the centre of the still existing depression and thereby follows the course of the former lake towards the northwest and then turning southwards and draining off into the river Alster (Fig. 1). Nowadays, the area is used as pasture and partly forested by alder, birch and willow. The coring location is situated in the formerly deepest part of the lake incision (latitude 53°49'N, longitude 10°08'E). From test corings conducted by Hartmut Usinger in 2003/04 it was clear that the depositional environment of this palaeolake met numerous conditions that are unique in Schleswig-Holstein to date. This includes the facts that (i) the sediments were deposited undisturbed during the entire Lateglacial and Early Holocene, (ii) that they contain an annually laminated section, and (iii) that a Lateglacial cryptotephra was geochemically identified in the sequence Fig. 1 (Krüger & van den Bogaard 2020; Krüger *et al.* 2020).

Fieldwork and sediment sequence

A coring campaign in the centre of the Nahe palaeolake (latitude 53°49'N, longitude 10°08'E) was carried out in



Fig. 1. Microphotograph of the Laacher See cryptotephra detected in the sequences at a depth of 1465.0 cm.

October 2017. A modified Livingston piston-corer (Mingram *et al.* 2007) – the so-called Usinger-corer – was used to extract sequences of 1-m-long sediment cores. Two overlapping sediment sequences with a diameter of 80 mm and a total length of 16 m were recovered. Each 1-m-segment was cut longitudinally and stored in PVC-liners. In order to connect the core sequences, a series of distinct layers and stratigraphical marker horizons were defined in the parallel cores. This way, a composite master sediment record was constructed, representing a continuous sequence avoiding gaps between the individual core segments. As a next step, a subsampling grid of 5-mm step size was created spanning the lower 5 m of the total sequence.

Dating and age-depth modelling

The master sediment record was intensively searched for datable organic material during the subsampling process for pollen and geochemical analysis. A total of 12 botanical macrofossils for AMS ^{14}C dating (including two true replicates) were sent to laboratories in Groningen (GrM) and Kiel (KIA). Additionally, the identification of three cryptotephra layers (Laacher See, Vedde and Saksunarvatn eruptions) in the sediment sequence of Nahe (Fig. 2; Krüger & van den Bogaard 2020) provides three age estimates based on published ages for these chronological event horizons (Bronk Ramsey *et al.* 2015; Zanon *et al.* 2019). Further age estimates are based on the identification of chronostratigraphical palynological events regarded to relate to distinct rapid climatic fluctuations during the Lateglacial period in northern Germany (Table 1).

For the section between 14.93 and 14.45 m, annual laminations allowed the establishment of a floating varve chronology. Varve counting was carried out on thin sections during the microfacies analyses (see below).

An overview of the age information used for the construction of the age-depth model is presented in Table 2. Age-depth modelling was carried out using OxCAL v4.3 (Bronk Ramsey 2009) and the IntCal13 calibration curve (Reimer *et al.* 2013). P-sequences (cf. Bronk Ramsey 2008) were used for the unlaminated sections between 1566.5 and 1493.0 cm (lower part) and 1440.0 to 1274.5 cm (upper part), respectively. For the varved section between 1493.0 and 1444.9 cm, a V-sequence was used to anchor the floating varve chronology in terms of the absolute time scale. In order to include information on short-term changes of the sedimentation rate based on the varve chronology in the OxCAL model, the Date() function was used to define a date at least every 25 varve years with an associated uncertainty in the gaps of 1. For the additional age estimates based on chronostratigraphical pollen features uncertainties of ± 100 years were assigned. Additionally, boundaries were defined in the OxCAL model for points at which the sediment composition changes abruptly to allow for associated abrupt changes in the modelled sedimentation rate.

Varve counting and microfacies analyses

Overlapping series of large-scale petrographic thin-sections were prepared for the varved section according to Merkt (1971). Microfacies analysis was carried out using a LEITZ Aristoplan polarization microscope at $25\times$ to $800\times$ magnification under various light and optical conditions. The varves were counted, their thicknesses measured, and the structure of the sub-annual layers (spring, summer–autumn, winter) recorded in accordance with previous microfacies studies on annually laminated lake sediments (e.g. Baier *et al.* 2004; Brauer 2004; Zahrer *et al.* 2013). For the interval c. 12 960 to 12 707 cal. a BP, additional sediment components were recorded in detail. The concentration of calcareous shells of *Phacotus lenticularis* (Ehrenberg, Diesing 1866), a species regarded to be sensitive to summer wind conditions, was estimated in semi-quantitative concentration classes ranging from 0 (absent) to 0.75 (blooms, 10% by volume of the sediment) and related to the thickness of the respective layer for the sake of comparability between varves of different thicknesses. The abundance of the green algae *Phacotus lenticularis* is related to water conditions with CaCO_3 super saturation and $\text{pH} > 8.1$ (Schlegel *et al.* 1998, 2000; Gruenert & Raeder 2014). Such conditions are common in the littoral zones of temperate hardwater lakes during intensive vegetation growth phases. Planktonic blooms of *Phacotus lenticularis* are restricted to the summer months in field observations in northern Germany (Schlegel *et al.*

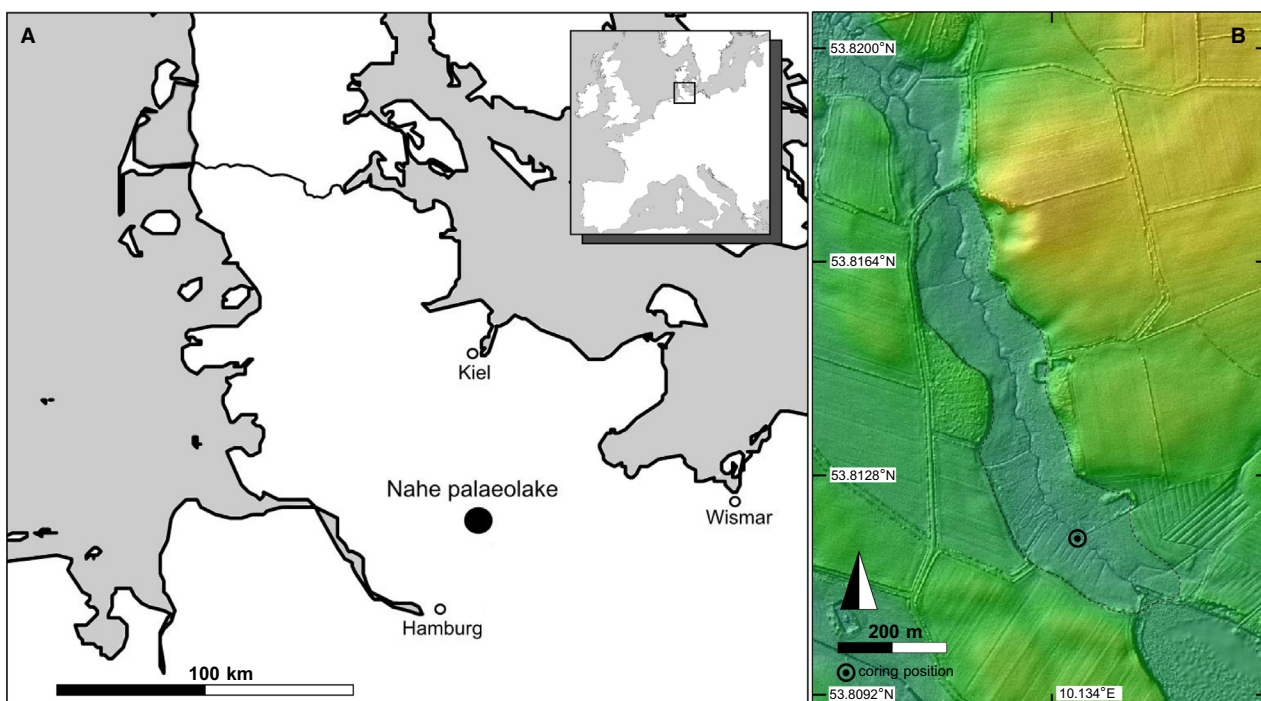


Fig. 2. Geographical location of the Nahe palaeolake in northwest Germany (A) and in Europe (inset) and topographical map (B).

2000). Additionally, the occurrence of hypidiomorphic calcite precipitation layers (spring, summer) was documented.

Varve preservation was recorded using an index ranging from 1 (excellently preserved varve, seasonal sedimentation processes precisely to reconstruct) to 5 (not well-preserved varve, not well developed or disturbed). Statistical analyses (e.g. REDFIT time series analysis) on varve thickness data were carried out using PAST software (version 2.06, Hammer *et al.* 2001).

Water content, bulk density, total elemental contents

Water content (WC) and dry density (DD) of the sediment deposited during the Allerød and YD were determined gravimetrically after drying volumetrically continuous 0.5-cm increment samples in a vacuum dryer. Following homogenization, the total and minor elemental contents were determined using a p-ed-XRF device (Niton XL3t900). The measurements were carried out with He-flotation in the measurement chamber of this device using the 'mining, Cu/Zn' settings for 300 s. All elements measured with an error of >10% according to the device were discarded from further analysis. Correction factors published in Dreibrodt *et al.* (2017) were used to convert the semi-quantitative % values as displayed by the device into % by weight values.

Total carbon (TC), total nitrogen (TN) and total inorganic carbon contents (TIC) were measured for the varved sediment section following the LSE on a Euro

EA-CHNSO Element Analyzer. Total organic carbon (TOC) contents were calculated by subtracting TIC from TC.

Based on the chronology and dry density of the sediments, the sediment accumulation rate (SAR) was calculated ($\text{g cm}^{-2} \text{a}^{-1}$). Elemental contents were converted into fluxes according to that SAR.

Pollen analysis

Pollen sampling, preparation and counting techniques follow standard protocols (Erdtman 1960; Fægri & Iversen 1989; Beug 2004) and are described in detail in Krüger *et al.* (2020). Reported influx values (pollen accumulation rates) were calculated based on the sedimentation rate (cm a^{-1}) as derived from varve counting.

Results and interpretation

Chronology

The results of the age-depth modelling are presented in Fig. 2. Seven of the available 12 radiocarbon dates revealed too old ages in the context of other available age estimates, i.e. anticipated ages for the known volcanic eruptions and 'pollen-stratigraphical' features. Accordingly, these radiocarbon dates were interpreted as outliers, probably relating to reworked secondary material. The dating of the lower non-laminated part (NAH P_Sequence lower part in Fig. 2) therefore relies only on

Table 2. Comparison and definition of chronostratigraphical palynological features of the Nahe palaeolake sequence with biochronological events for northern Germany.

Terminology NAH	Terminology MFM (Litt <i>et al.</i> 2007)	Age estimate	Features of NAH PAZ boundaries
Preboreal	Preboreal		<i>Betula pub.</i> -type ↑, <i>Filipendula</i> , <i>Typha lat.</i> -type ↗, Poaceae, <i>Artemisia</i> , <i>Empetrum</i> , other NAP-types ↘
Dryas 3	Younger Dryas	(11 560 varve a BP)** (Merkt & Müller 1999)	<i>Betula pub.</i> -type ↘, <i>B. nana</i> -type, Poaceae, <i>Artemisia</i> , other NAP-types ↗
Allerød 3	Allerød/	(12 680 varve a BP)** (Litt <i>et al.</i> 2007)	<i>Betula pub.</i> -type ↗, <i>Juniperus</i> , Poaceae, other NAP types ↘
Allerød 2/ Dryas 2	Older Dryas	(13 350 varve a BP) (Litt <i>et al.</i> 2007)	<i>Betula pub.</i> -type ↘, <i>Juniperus</i> , Poaceae ↗
Allerød 1	Bølling	(13 650 varve a BP) (Litt <i>et al.</i> 2007*)	<i>Betula pub.</i> -type ↑, <i>Hippophaë</i> ↗ Poaceae, <i>Helianthemum</i> ↘
Dryas 1	Oldest Dryas	(13 780 varve a BP)** (Litt <i>et al.</i> 2007*)	<i>Hippophaë</i> , AP ↘, Poaceae, <i>Helianthemum</i> , <i>Rumex acet.</i> -type ↗
Meiendorf	Meiendorf	(13 910 varve a BP)** (Litt <i>et al.</i> 2007*)	<i>Pinus</i> ↘, <i>Betula pub.</i> -type, <i>B. nana</i> -type, <i>Artemisia</i> , <i>Hippophaë</i> ↗
Pleniglacial	Pleniglacial	(14 560 varve a BP)** (Litt <i>et al.</i> 2007*)	

‘pollen-stratigraphical’ synchronization. The upper non-laminated part (NAH P_Sequence upper part), however, is constrained by four radiocarbon dates, the dating of the Saksunarvatn tephra event as dated by Zanon *et al.* (2019) and two ‘pollen-stratigraphical’ features representing the end of the Allerød and the Younger Dryas periods, respectively. The chronology of the varved section (NAH V_Sequence) mainly relies on the floating varve chronology fixed by the dating of the Laacher See eruption according to Bronk Ramsey *et al.* (2015). According to the model the varved sequence spans the younger part of the Allerød period starting at 13 421 cal. a BP (2 sigma range 13 464–13 378±43 cal. a BP) and ending at 12 708 cal. a BP (2 sigma range 12 751–12 665±43 cal. a BP). In the following, all ages relating to the Nahe sediment sequence refer to the modelled median ages of the presented age-depth model.

Geophysical and geochemical sediment analyses

Water content (WC) and dry density (DD) curves are given in Fig. 3. The diagrams span the interval from the Dryas 1 period to the Preboreal period. In general, the cool climatic periods are characterized by lower WC and higher DD values. The Allerød section contains a generally higher water content and a lower dry density compared to the remaining sediment sequence. This reflects changes of the sediment composition between warmer and cooler climatic periods. In both curves, there is a trend towards maximum values of WC and minimum values of DD between 13 200 and 12 900 cal. a BP.

Following the LSE, a trend towards lower WC and higher DD values is visible. A pronounced step with lower WC and higher DD values characterizes the transition to the YD.

Sediment accumulation rates (SARs) were calculated for the varved part of the sediment sequence (Fig. 3). A general trend of increasing values is visible throughout the Allerød period. Between 13 180 and 13 090 cal. a BP a secondary maximum of SAR is visible.

Varve analyses

Varve preservation. – The preservation of varves is displayed in Figs 5 and 9. The varve preservation throughout the Allerød is varying. Most varves are preserved in a moderate condition. The variability of the varve preservation is different in the pre- and post-LSE sections of the Allerød period.

Varves of the pre-LSE section are generally preserved in a moderate condition (varve preservation index generally between 3–4) except between c. 13 160–13 120 cal. a BP and after c. 13 040 cal. a BP, where there is generally better preservation (varve preservation index generally between 2–3). After the LSE, between c. 12 930 and 12 840 cal. a BP a high variability and generally lower level of varve preservation prevail including three small non-varved sections. Microscopical inspection gave no indications of an extraordinary input event or lake internal slump of sediments. Instead, a faint layering of the main components (carbonates, organic detritus) is present.

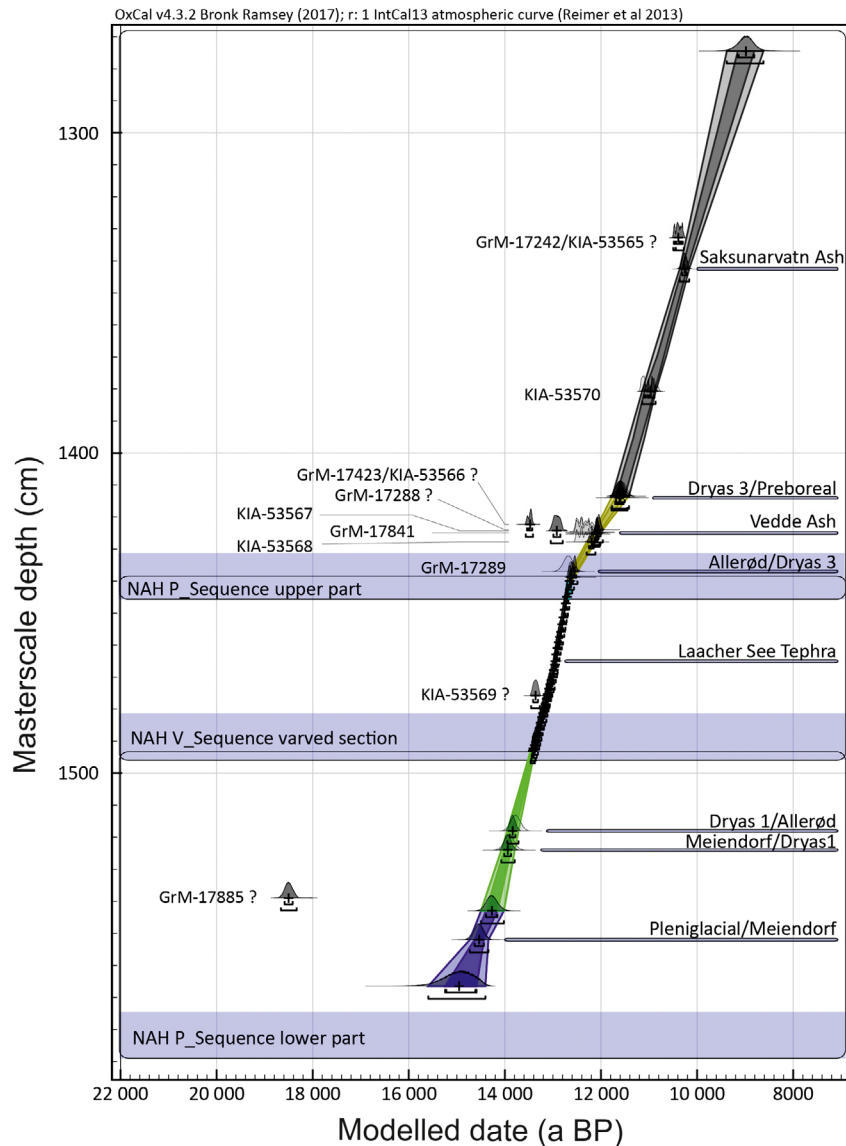


Fig. 3. Age-depth model of the Nahe palaeolake sediment sequence. Labels of radiocarbon dates are given to the left of the age-depth curve. Dates treated as outliers are marked with question marks. Level and names of additionally used age estimates, i.e. volcanic eruptions and ‘pollen-stratigraphical’ events, are indicated on the right side of the age-depth curve. Different coloured sections represent differentiated stratigraphical units separated by the Boundary () function in the OxCal model (Bronk Ramsey 2009).

Therefore, the mean thicknesses of the foregoing and following five varves were used to interpolate the sedimentation of the non-varved sections. The remaining varved section (*c.* 12 840–12 707 cal. a BP) shows medium to good varve preservation that ends abruptly towards the YD transition.

Varve counting. – Varve counting of the 205-cm-thick laminated interval yielded a duration of 716 years, including three short sections without varve preservation. These non-varved sections date to the late Allerød period after the LSE and have thicknesses of ~6, 9 and 2 mm. The microscopical analysis revealed no indication of strong disturbance (slump), but instead a faint

layering. Thus, the sedimentation rates were extrapolated based on the average of the five foregoing and following varves to reflect deposition periods of 7, 12 and 4 years respectively. These interpolated 23 years make up less than 4% of the total varve number and thickness of the sequence and are thus not considered to change the chronology significantly.

Varve thickness. – Varve thickness is displayed in Fig. 3. The average and median varve thicknesses measure 0.64 and 0.57 mm, respectively, with a minimum of 0.20 mm and a maximum of 4.35 mm. While showing some variability there is a long-term trend of growing varve thicknesses throughout the Allerød (Fig. 3).

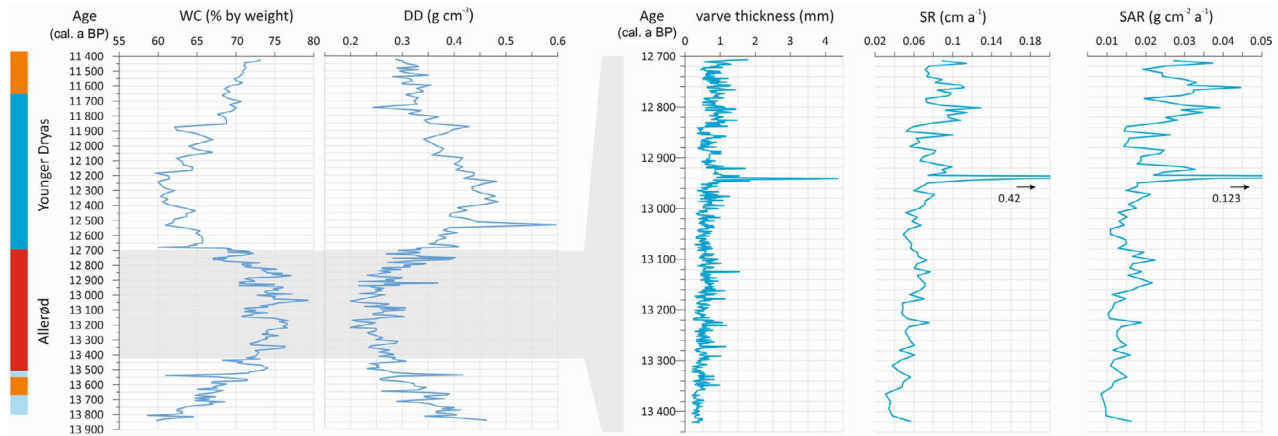


Fig. 4. Allerød and Younger Dryas section of the Nahe palaeolake sediment sequence. Left: water content (WC) and dry density (DD); right: varve thickness, sedimentation rate (SR) and sediment accumulation rate (SAR).

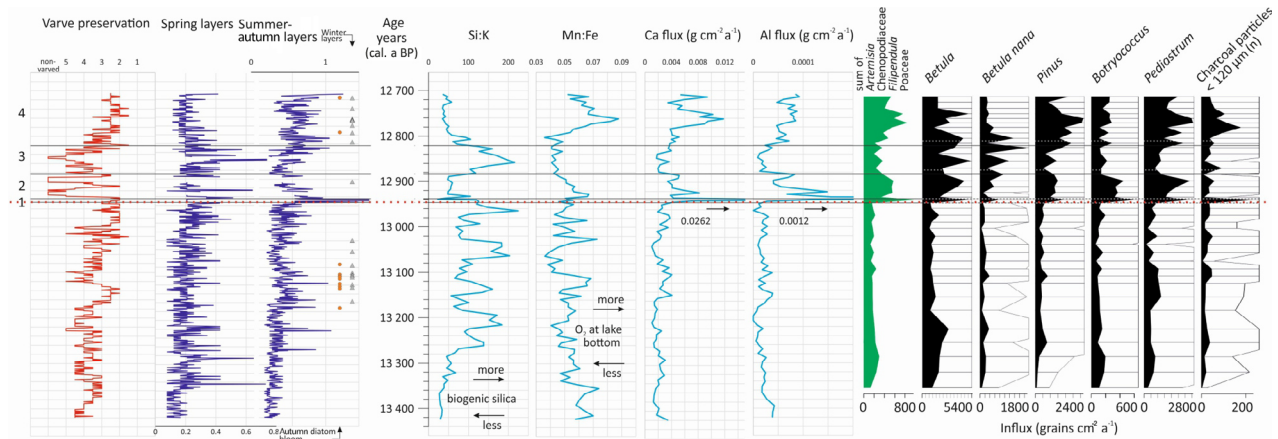


Fig. 5. Selected results of microfacies analysis, geochemical measurements and influx rates of pollen and spores from the annually laminated Allerød sequence of the Nahe palaeolake sediment sequence: varve preservation from 1 (excellent) to 5 (non-varved), varve thickness in mm of spring and summer–autumn layers in mm, Si:K ratio, Mn:Fe ratio, Ca- and Al-flux ($\text{g cm}^{-2} \text{a}^{-1}$); influx rates of selected pollen and algal types, number of micro-charcoal particles per sample ($<120 \mu\text{m}$).

Within the subsampling range of the identified Laacher See cryptotephra (1463.5–1465.5 m) a series of extraordinarily thick varves were recorded (1465.0–1462.9 m, mean 1.8 mm, median 1.3 mm). Particularly the lowermost varves exhibit thicknesses considerably greater than usual (1.67, 3.46, 4.31 and 2.52 mm). According to the age-depth model, they date to the years 12 943–12 940 cal. a BP and are therefore interpreted to reflect the years directly after the LSE. A pronounced minimum of varve thickness is present between 12 854 and 12 839 cal. a BP. Subsequently varve thickness shows generally higher values (mean 0.86 mm) compared to the mean Allerød values.

A REDFIT time series analysis was applied to the varve thickness data (Schulz & Mudelsee 2002). Because of the presence of poor and non-varved parts after LSE, the analysis was restricted to the pre-LSE part of the Allerød sequence (from 13 371 to 12 894 cal. a BP).

Figure S1 displays short cycles (2–3, 8 and 62 years), which could reflect a response of the lake system to the North Atlantic climate variability (NAO and AMO). Longer cycles (93.2 and 99.2 years) could reflect the impact of solar activity on the lake system (Gleissberg cycle, e.g. Peristykh & Damon 2003). The identification of cycles reflecting known climatic variability supports the quality of the established chronology and the sensitivity of the sequence to external triggers.

Varve composition. – The varves show a general structure similar to Holocene calcareous biogeochemical varves of hardwater lakes (e.g. Zahrer *et al.* 2013). These consist of a spring biogenic silica layer followed by a carbonate layer assumedly reflecting summer to early autumn epilimnic carbonate precipitation. This merges with the autumn deposition containing resuspended littoral material and organic matter (cf. Fig. 6). In some

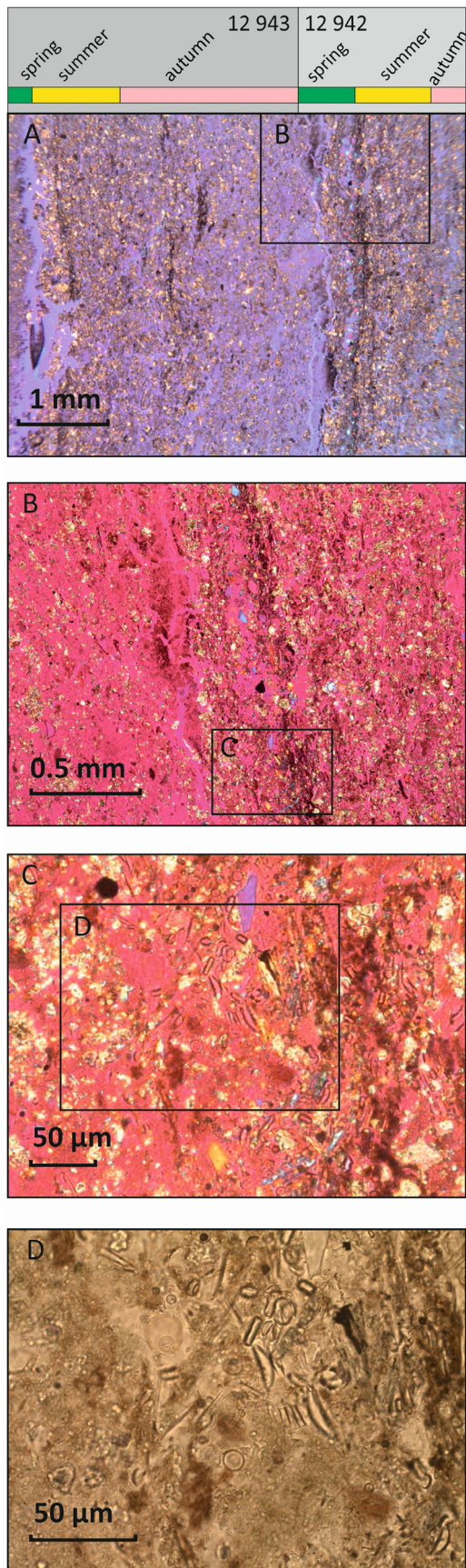


Fig. 6. Microphotographs of the varves dating to 12 943 and 12 942 cal. a BP. A–C. Crossed Nichols, lambda red filter; D. Non-polarized light. A. Overview showing the annual sequence of year 12 943 on the left: spring (clear blue, one large littoral bio-remain), summer (rich in calcite), autumn (resuspended mixture including organic remains) followed by spring, summer, and the initial part of the autumn layer of year 12 943. B. The autumn of year 12 943, spring, summer and initial part of autumn of year 12 942; note the layer of detrital input (quartz grains) in the late spring layer. C. Spring of the year 12 942; note calcite precipitation, detrital grains (quartz) and diatoms, followed by organic detritus and carbonate minerals of the summer layer. D. Diatom frustules preserved in the spring layer of year 12942 (*Stephanodiscus* spec., *Cymbella* spec., *Fragilaria* spec.).

varves, autumn diatom blooms have resulted in the deposition of a biogenic silica layer. Very rarely, thin fine detritus-rich layers reflect the preservation of winter layers. The varve sub-annual composition is given in Figs 5 and 9. The spring layer thickness exhibits considerable variability. From *c.* 13 340 to 12 780 cal. a BP, the spring layers are thicker in general. Maxima of phases coincide with high Si:K ratios of the sediment. The most pronounced variability in spring layer thickness occurs after the LSE. The variability in summer–autumn layer thickness is most pronounced after the LSE. Despite this long-term trend, a phase of increased summer–autumn layer thickness is recorded between *c.* 13 160 and 13 080 cal. a BP. After the LSE, the most pronounced variability in summer–autumn layer thickness is visible. Occurrences of autumn diatom blooms are limited to the intervals between 13 185–13 080 cal. a BP and after the LSE (orange circles in Figs 5 and 9). Winter layers are preserved between *c.* 13 180–13 040 cal. a BP and after the LSE (grey triangles in Figs 5 and 9).

Except for a very few years, no intact diatom frustules are preserved in the varves. Instead, a layer of silica gel is preserved, similar to that described by Merkt & Müller (1999). Poor diatom preservation is a well-known feature of Lateglacial to Early Holocene sediments (e.g. Smol & Boucherle 1985; Newberry & Schelske 1986). It is considered to reflect diatom frustule dissolution in higher lake-water pH at the time of carbonate deposition. The presence of the silica gel layer in the microstratigraphical position below the carbonate rich layers throughout the sequence indicates that diatom frustule dissolution was a seasonal phenomenon followed by re-precipitation of the opal at the lake bottom. The stratigraphical position of the silica gel layer further indicates a regular deposition following the spring planktonic diatom blooms during the early part of the summer stratification. The development of anoxic conditions at the beginning of summer stratification probably resulted in the annual re-precipitation of the silica gel at the lake bottom by promoting lower pH conditions.

In the four extraordinarily thick varves deposited immediately after the LSE, however, diatom valves are preserved (Fig. 6). The valves are embedded in a matrix rich in silicate minerals that originated from allochtho-

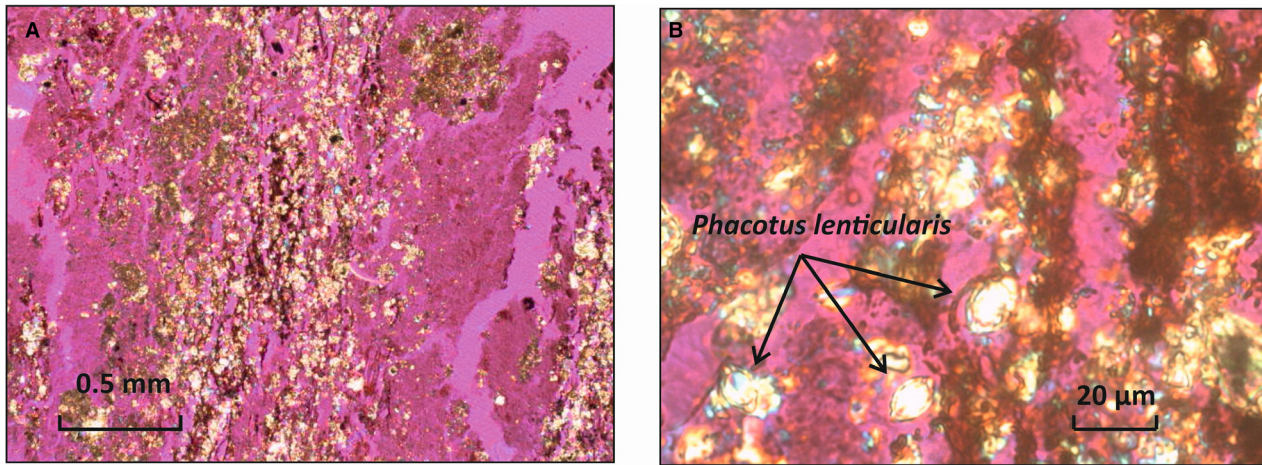


Fig. 7. Calcareous shells of the green algae *Phacotus lenticularis* in varve year 12 911 cal. a BP; crossed Nichols, lambda red filter. A. Overview of year 12 911, spring layer (amorphous silica gel), summer layer (carbonate precipitation, micritic/detrital mixture), late summer/early autumn layer (organic detritus/carbonate mixture), autumn layer (resuspended mixture, including some striatal grains), followed by the spring layer (amorphous silica gel) of year 12 912. B. Shells of *Phacotus lenticularis* embedded in the mixture of organic detritus and carbonates of the late summer/early spring layer.

nous input into the lake. A higher amount of allochthonous detrital minerogenic input is visible in the autumn layers as also described by Merkt & Müller (1999). Therefore, the preservation of frustules in the four varves after the LSE was probably favoured by a higher amount of silica solute in the lake's water body. In the second varve year after the LSE an increased input of quartz grains is visible in the spring season, perhaps reflecting soil erosion due to a high-energy rainfall event in the catchment area. The preserved diatom assemblage deposited on top of this allochthonous input layer contains a large amount of planktic diatoms, thus reflecting remains of a spring plankton bloom.

The abundance of the green algae *Phacotus lenticularis* (Fig. 7) is related to water conditions with CaCO_3 super saturation and $\text{pH} > 8.1$ (Schlegel *et al.* 1998, 2000; Gruenert & Raeder 2014). Such conditions are common in the littoral zones of temperate hardwater lakes during intensive vegetation growth phases. Since planktonic blooms of *Phacotus lenticularis* are restricted to the summer months in field observations (Schlegel *et al.* 2000) and their shells are made up of calcite, blooms are probably also related to wind conditions during the summer time. Windier summer seasons with higher turbidity should allow the relatively heavy shells to stay longer in the epilimnion than less windy summer seasons.

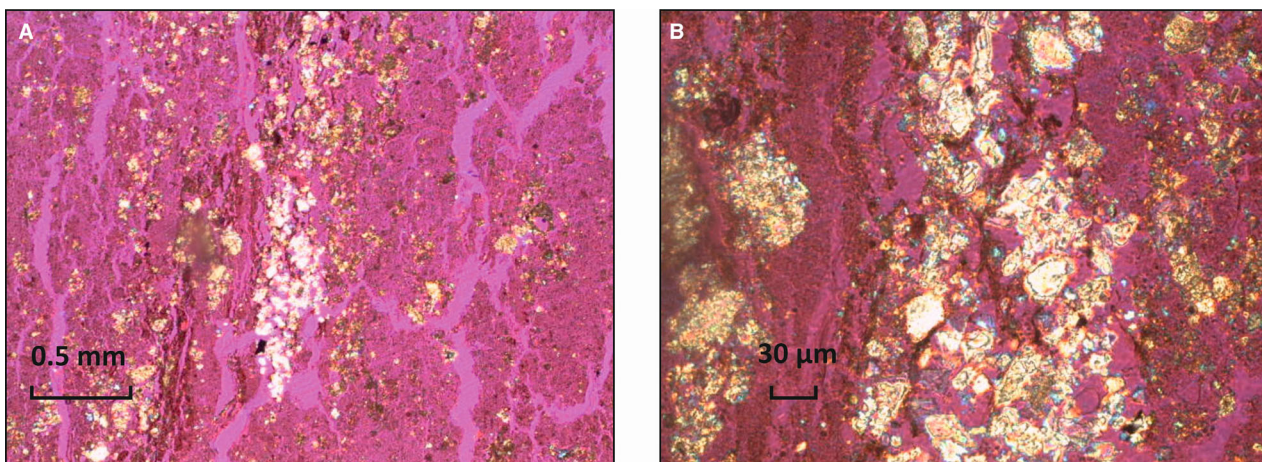


Fig. 8. Hypidiomorphic spring calcite crystals of varve year 12 854 cal. a BP; crossed Nichols, lambda red filter. A. Overview of year 12 953, autumn layer (mixture of calcite, detritic organic matter), and 12 954 spring layer 1 (amorphous silica gel), spring 2/early summer layer (hypidiomorphic carbonate precipitation), late summer/early autumn layer (micritic carbonate/detrital mixture), autumn layer (organic detritus/carbonate mixture). B. Hypidiomorphic calcite crystals of a diameter between <10 and $30 \mu\text{m}$ in the late spring/early summer layer.

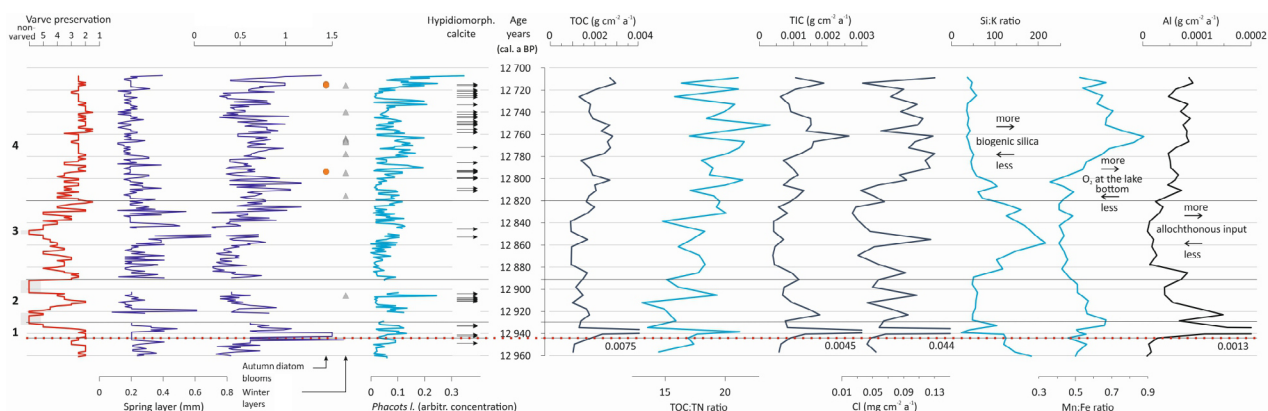


Fig. 9. Selected results of microfacies analysis and geochemical measurements from the annually laminated sediments deposited after the LSE. Varve preservation from 1 (excellent) to 5 (non-varved), concentration of shells of *Phacotus lenticularis* (arbitrary concentration units related to layer thickness), occurrence of hypidiomorphous calcite crystals in the spring/early summer layers; accumulation rates of TOC, TIC, Cl and Al, ratios of TOC:TN (allochthonous vs. autochthonous organic matter), Si:K (biogenic silica) and Mn:Fe (aeration of the lake bottom).

The concentration of shells of *Phacotus lenticularis* shows an increasing trend in the post-LSE period although with considerable variability (Fig. 9). Increased concentrations hereby coincide with higher TIC, Cl, and the occurrence of larger hypidiomorphous calcite precipitation in the sediment.

The occurrence of coarse-grained hypidiomorphous calcite crystals (Fig. 8 and indicated by lateral arrows in Fig. 9) precipitated in the epilimnion is considered to reflect enduring turbulent water conditions during crystal growth (e.g. Kelts & Hsü 1978; Prasad *et al.* 2007; Czymzik *et al.* 2016). Large hypidiomorphous calcite crystals occur immediately after the LSE and in the following interval more regularly from 12 812 varve years BP to the end of the preserved varved sequence. The hypidiomorphous crystals co-occur with higher fluxes of Cl, Al and *Phacotus lenticularis* into the sediment as well as a higher Mn:Fe ratio.

Geochemical sediment analyses

The total elemental contents of the Allerød sediment sequence are given in Table S1. A correlation matrix is given in Table S2. The strongest positive correlation exists between Ca and Sr underlining their co-occurrence in carbonates in lake sediments. The strongest negative correlations are observed between Fe and Ca and Fe and Sr, respectively. This might indicate a relationship between bioproductivity and precipitation of carbonates in the lake system. Hereby, a high level of bioproductivity could have induced oxygen consumption at the lake bottom during the decomposition process of organic matter, in turn causing more reducing conditions at the lake bottom unfavourable for Fe immobilization. The correlations of Si with Al, K and Zr are rather weak, indicating that a certain amount of the Si is not bound to allochthonous mineralogenic particles but of biogenic origin. The positive correlation of Si with Fe, and the negative correlations

between Si and Ca and Sr, indicate that amorphous silica re-precipitation is related to redox and alkalinity conditions at the lake bottom. An overview of indicative elemental ratios and flux rates is shown in Figs 5 and 9. Si content of lowland lake sediments is related to two main sources. These are catchment and shore erosion and biogenic silica (mainly diatoms). Thus, the content of excess Si (biogenic silica) is often evaluated using ratios between Si and other elements abundant in catchment minerals but not in diatom valves, e.g. Si:Ti (e.g. Kylander *et al.* 2011). Since the Ti values are below detection limits in our sequence, we could not use the Si:Ti ratio as a proxy for biogenic silica here. Instead, the Si:K ratio (Figs 5, 9) is considered to reflect the variability of Si unbound in minerals and thus is a proxy for the biogenic silica content of the sediment. K is considered here as a rather conservative element that mainly reached the lake with allochthonous input (muscovite, illite, feldspars). The pattern of the Si:K ratio of the sequence shows high similarity to the Si:Al and Si:Zr ratios (Table S1), which both are also likely to reflect mainly the variability of excess Si (biogenic silica). Whereas the biogenic silica content of the sediment is in general higher during the interval from c. 13 000 to 12 800 cal. a BP than before and after, considerable variability is visible in the record. The curve displays a quasi-cyclicity with alternating minima and maxima of biogenic silica deposition with cycle lengths of 50–80 years, typical for the Atlantic Multidecadal Oscillation (AMO, e.g. Kerr 2000). Immediately after the LSE, there is a drop to low Si:K levels. Subsequently, about 60 to 120 years after the LSE, high Si:K values reflect higher amounts of biogenic silica deposition again, before biogenic silica deposition decreases and remains low until the end of varve preservation.

The Mn:Fe ratio (Figs 5, 9) reflects the oxygen conditions at the lake bottom (e.g. Wersin *et al.* 1991; Naeher *et al.* 2013). In general, the Mn:Fe ratio shows lower values during the interval from c. 13 000 to

12 800 cal. a BP compared to the previous and subsequent phases. This probably reflects a higher content of organic components in the Allerød sediment sequence. The decomposition of the organic matter would explain more intensive oxygen consumption at the lake bottom. The LSE is followed by a short increase in the Mn:Fe ratio, before a trend to lower values is visible for about *c.* 120 years. This is followed by a steep increase in the Mn:Fe ratio culminating in a maximum at *c.* 12 760 cal. a BP. Towards the end of varve preservation a slight decrease to moderately high values can be observed.

The Ca flux rate (Fig. 5), interpreted to represent the accumulation of CaCO₃, shows only little variability during the Allerød period before the LSE. Increased Ca and Al accumulation between *c.* 13 160–13 080 cal. a BP coincides with a maximum in Si:K between 13 140–13 120 cal. a BP followed by a maximum of Mn:Fe ratios as well as with poorer preservation of thinner varves until *c.* 13 100 cal. a BP. This sedimentation pattern could indicate higher wind speed conditions leading to increased carbonate precipitation (e.g. Czymzik *et al.* 2016). Statistical analysis of weather and surface wave data from Lake Woserin, northern Germany, spanning the past 70 years indicates this effect was probably related to higher numbers of seed crystals and a longer growth time of calcite particles in more turbulent surface water, additionally to increased in-wash of Ca. The time after the LSE is characterized by distinctly increased variability of the Ca flux rate reflecting rapidly changing sedimentation dynamics. A pronounced maximum of Ca accumulation is reached immediately after the LSE, followed by a stepwise decrease. A distinct minimum is observed between 12 880 and 12 840 cal. a BP. Afterwards moderate Ca accumulation rates (12 840–12 780 cal. a BP) are visible, followed by a steep increase to a secondary maximum of Ca accumulation between 12 780 and 12 740 cal. a BP.

Similarly to the Ca flux rate, the Al flux rate (Figs 5, 9), interpreted to reflect allochthonous minerogenic input, shows rather little variability over large parts of the Allerød before the LSE. Although there is some increase of Al accumulation between *c.* 13 160 and 13 080 cal. a BP, this is clearly exceeded by maximum values that occurred after the LSE.

The Cl flux curve (Fig. 9) may reflect the deposition of chlorine from different sources. They might be of marine (aerosols) or geological origin. Whereas salt diapirs (Zechstein) are known to exist as extended subsurface geological structures in northern Germany, in very few cases the Zechstein rocks reach the surface. One is located close to the city of Elmshorn, 40 km west of the investigated palaeolake (e.g. Schneider & Gebhardt 1995). Thus, the Cl accumulation observed in the NAH sequence is probably associated with the strength of westerly winds, either reflecting the input of aerosols

from the Atlantic-maritime air masses or from the small known exposure of Zechstein rocks.

Pollen accumulation rates

The influx curves for selected pollen, algal remains and charcoal particles are given in Fig. 5. A sum curve of selected non-arboreal pollen (NAP) includes pollen types identified as *Artemisia* sp., *Filipendula* sp., Chenopodiaceae and Poaceae. There is some noticeable variability in the influx rates of terrestrial plant pollen and algae in the displayed part of the pre-LSE Allerød. Higher influx values of *Betula* occurred between 13 360 and 13 200 cal. a BP. Afterwards, until the LSE, the influx values of *Betula* are lower. *Pinus* appears with a moderate influx value at *c.* 13 260 cal. a BP and remains at a low level with little variability. The influx of the green algae *Pediastrum* sp. shows higher values between 13 160 and 13 080 cal. a BP, paralleling the trends in Ca and Al accumulation. Some peaks of charcoal input occurred between 13 120 and 13 080 cal. a BP and 13 040 to 13 000 cal. a BP. Compared to this pre-LSE variability, however, an overall significant shift towards higher influx values is apparent immediately after the LSE.

Discussion

Palaeolimnological and -environmental changes before the LSE

Varve microfacies analysis and geochemical data of the Allerød sequence from the Nahe palaeolake imply rather continuous lake sedimentation processes in a dynamic equilibrium with the interstadial conditions prior to the LSE.

The shift in the sediment composition between *c.* 13 160 and 13 080 cal. a BP, increased Ca and Al accumulation (Fig. 5) and lower WC and higher DD (Fig. 3), are regarded to reflect a local response to cooling and increased average wind speed related to the Gerzensee oscillation (e.g. Lowe *et al.* 2008; von Raden *et al.* 2013). The observed increase in carbonate precipitation and input of Al coincides with the occurrences of autumn diatom blooms and winter layers and probably is the result of increased in-wash and/or shore erosion (cf. Czymzik *et al.* 2016). The parallel increase of the *Pediastrum* curve (Fig. 5) therefore most likely indicates enhanced nutrient availability. The observed pattern is in good agreement with the assumption of a phase with cooler than usual winters and windier than usual conditions during the vegetation growth period. The recurrence of prior sedimentation conditions and the persistence of reflected Atlantic patterns within the record (cf. results for biogenic silica in Geochemical sediment analyses section) imply a response of the lake system to climate variability that does not distinctly cross the thresholds of the system's vulnerability.

In comparison, limnological changes after the LSE are much more pronounced. Changes in the sediment record, including short interruptions of varve preservation, imply a serious disturbance of the lake system triggered by the LSE.

Palaeolimnological and -environmental changes after the LSE

As this paper focusses on the local palaeolimnological and -environmental changes after the LSE the developments between 12 944 and 12 707 cal. a BP as recorded in the Nahe record are in the following described and discussed in four phases. These phases have been defined based on coinciding distinct changes in multiple proxies and therefore are regarded to represent phases of different palaeoenvironmental conditions.

Phase 1 (12 944–12 930 cal. a BP). – This phase is characterized by the onset of a series of extraordinarily thick varves (12 943–12 940 cal. a BP), mainly due to increased thickness of the summer–autumn layers (mean 1.60 mm, max. 4.35 mm, min. 0.81 mm). High accumulation values of Al and a discrete layer rich in quartz grains in the second year after the LSE point to a serious storm or erosion event within the catchment area. This might indicate stormy seasons and/or local heavy precipitation events that immediately followed the LSE (e.g. Merkt & Müller 1999; Schmincke *et al.* 1999). The immediate and synchronous rise in PAR and in particular charcoal influx probably reflects changed pollen introduction into the lake and could likewise be explained by extreme weather events that plausibly mobilized material in the shore area and catchment of the lake.

To conclude, the results indicate serious disturbance of the local environment immediately after the LSE.

Phase 2 (12 929–12 893 cal. a BP). – The sediment record of Phase 2 consists of two non-laminated sections between 12 929–12 913 and 12 902–12 893 cal. a BP with a laminated part in between, indicating variable sedimentation conditions. It is characterized by low Si:K and high PAR values. A distinctly increased minerogenic content is furthermore indicated by a lull in the water content (WC) and high dry density (DD) values (Fig. 3). Compared to pre-LSE conditions the Al and Ca accumulation rates remain at an elevated level, although a trend towards lower values is recorded. A similar trend is observed for the Mn:Fe ratio. Indicators of aquatic biogenic productivity such as TOC and the Si:K ratio have low values (Fig. 9), whereas the accumulation rates for green algae (*Botryococcus* sp., *Pediastrum* sp.) are increased, in a context of generally high PAR values (Fig. 5). The TOC:TN ratio of the deposited organic components shows a clear drop with the beginning of Phase 2 and low values prevail until c. 12 905 cal. a BP.

Afterwards TOC:TN increases sharply. This increase seems to be associated with more undisturbed sedimentation processes in the middle of Phase 2, i.e. represented by the section with preserved varves between 12 922–12 903 cal. a BP. This section is further characterized by local minima of the Al and Ca accumulation rates and regular records of hypidiomorphic carbonate crystals.

The low biogenic silica deposition, as reflected in low Si:K values coinciding with low TOC accumulation and low TOC:TN ratios, could reflect an acidification of the lake water during Phase 2. This seems reasonable because the LSE is known to have been a sulphur rich eruption (Harms & Schmincke 2000) and acidification effects on lakes have been described for other strong volcanic eruptions as well (e.g. Grattan & Charman 1994). The drop in biogenic silica, as expressed in the Si:K ratio, and the thinner varves are interpreted to reflect decreased diatom productivity. Diatoms are pH sensitive and have been intensively used as proxies for lake water acidification (Battarbee *et al.* 1984, 1999). The assumed acidity related drop of diatom productivity could partly explain the occurrence of the two small non-laminated sections, since the biogenic silica layer constitutes a main component of the varves. The low TOC:TN ratio before 12 905 cal. a BP is thus not interpreted to indicate eutrophication (e.g. Meyers 1994; Meyers & Ishiwatari 1995) but might rather reflect that mainly acid tolerant algae groups of phytoplankton contributed to the aquatic bioproductivity. The higher influx values of the green algae *Botryococcus* sp. and *Pediastrum* sp. that parallel the low amount of biogenic silica partly reflect the shift in dominant algal groups following an acidic input (Weckström *et al.* 2010).

The recorded short-term response of the Nahe palaeolake system to the LSE is in accordance with acid rain fall-out and events of intense precipitation reported from other sites in northwestern Europe (Schmincke *et al.* 1999; De Klerk 2008). Since lake acidification changes the aquatic food web to a major extent, including shifts of fish species and their abundances, relevant to early fisherman, might be considered (e.g. Hogsden *et al.* 2009).

The sinking Mn:Fe ratio indicates decreasing oxygen concentration to the lake bottom. Less oxygen at the lake bottom could result from eutrophication, lowering in wind speed, and lake level increases. The former two can be excluded considering the indications of lower aquatic bioproductivity and allochthonous input into the lake. The high pollen influx rates during Phase 2 point towards the same direction. They probably result from increased in-wash or increased sediment focussing in the deeper part of the lake, due to increased redeposition of littoral sediments (Davis 1968, 1973; Davis & Ford 1982). A lake level rise would explain the declining Mn:Fe ratio in the context of increased accumulation rates for Al, palynological microfossils and terrigenous organic matter (TOC:TN) in the deeper part of the lake basin associated with shore erosion and/or redeposition of littoral sediments.

The geomorphic setup of glacial lakes in the northern European plain allows a lake level rise only (i) until a certain threshold is reached (outflow barrier), and (ii) if the lake level was below that threshold before. The chemical composition of Lateglacial sediments, which is often found to be enriched in readily soluble elements (e.g. sulphur) and alkaline minerals (e.g. siderite), points towards the presence of closed lake systems during the Lateglacial period (Smol & Boucherle 1985; Newberry & Schelske 1986; Merkt & Müller 1999). The contents of S and P in the studied sediment sequence (particularly the pre-LSE sediment) are much higher than those observed in sediments of Holocene open lake systems with inflow and outflow (Table S1). Thus, it is very possible that the Nahe palaeolake had no outlet during large parts of the Allerød, and a lake level increase up to the geomorphological barrier of the basin occurred after the LSE. Water level increases are reported from wetland areas in northeastern Germany following the LSE (e.g. Lange *et al.* 1986; Peterss *et al.* 2002; Theuerkauf 2003). Evidence for a decrease in temperature as assumed by Merkt & Müller (1999) and observed by Rach *et al.* (2014) could have favoured lake level increases by decreased evapotranspiration in the lake catchment.

Phase 3 (12 892–12 820 cal. a BP). – This phase is characterized by high Si:K and low Mn:Fe ratio values. Additionally the flux values for Al and most palynological taxa are distinctly reduced.

The Si:K ratio increases at the beginning of Phase 3 and reflects the recovery of more alkaline conditions in the lake system *c.* 50 years after the LSE. A reorganization of the aquatic life is also indicated by further changes in the sediment record. The stable Mn:Fe ratio and low Al input in this phase, coinciding with lower pollen influx rates of many taxa, are regarded to indicate that no further lake level change occurred. A re-rise in varve thickness and diatom productivity indicates that aquatic bioproductivity returned to a moderate level. The latter is indicated by relatively high TOC:TN ratios. A maximum in spring layer thickness and Si:K ratio that coincides with a Cl accumulation peak and some hypidiomorphic carbonate precipitation between *c.* 12 860–12 840 cal. a BP indicates that this re-increase was driven by intensive circulation of the lake water. That there is no simultaneous peak in the Mn:Fe ratio can be interpreted as an additional indicator of the high lake level inferred for this interval. The reason for the short interruption of varve preservation at *c.* 12 850 cal. a BP remains unclear.

Phase 4 (12 820–12 707 cal. a BP). – The beginning of Phase 4 is characterized by the onset of frequent occurrences of winter layers and a more regular appearance of hypidiomorphic calcite crystals. This is associated with low and decreasing Si:K values, high values of Al and Cl fluxes and generally higher values for most palynological taxa. The Mn:Fe ratio increases distinctly

at the beginning of this zone, reaching a maximum at *c.* 12 760 cal. a BP. At the same time accumulation rates for NAP, *Pinus* and *Pediastrum* show maximum values.

These changes indicate that Phase 4 signals another shift in depositional conditions. The decrease in biogenic silica (Si:K), coinciding with higher TOC:TN ratios, points to a decrease in aquatic bioproductivity. The winter layer record indicates a general cooling, whereas the occurrences of autumn diatom blooms and in particular repeated occurrences of hypidiomorphic carbonate precipitation point to turbulent conditions in the summer half of the year. Higher TOC:TN ratios and Cl and Al accumulation is interpreted to reflect stronger westerly winds that resulted in more intensive shore erosion (Baldini *et al.* 2018). The maximum of the Mn:Fe ratio associated with high PARs for most taxa is in line with stronger winds leading to increased bottom water oxygenation. Less pronounced anoxic conditions during a weakened or absent stable summer stratification of the lake water could provide an additional reason for the decreasing Si:K ratio. This would result from the decrease in aquatic bioproductivity and the deeper and more complete mixing due to the onset of stronger winds that led to a limited re-precipitation of biogenic silica during the summer (see Results and interpretation section, varve composition) and a more continuous recycling of biogenic silica. Thus, whereas more intensive mixing possibly fostered diatom spring blooms, the biogenic silica did not find its way into the sediment because of a change in the syn- and postdepositional conditions at the lake bottom. To summarize, the observed sediment record is best explained by the onset of increased wind speeds during the summer half of the year starting at *c.* 12 809 cal. a BP under generally cooling climate conditions at the NAH site.

The return of the influx values of *Betula nana*-type pollen to low pre-LSE influx levels and a simultaneous pronounced minimum of the influx curve of *Betula pubescens*-type pollen at around 12 790 cal. a BP is explained by a local fire event, as reflected in a coinciding maximum of micro-charcoal particles (Krüger *et al.* 2020). This local fire event falls into an interval of Europe-wide repeated fire events that led to the deposition of the so-called Usselo (charcoal) layer especially towards the end of the Allerød period (van Geel *et al.* 1984; van der Hammen & van Geel 2008; Kaiser *et al.* 2009). Often, these soil surfaces are found buried by aeolian redeposition of sands in northern Europe. The assumed increased windiness could partly explain these Allerød period phenomena as it would have induced drier climatic conditions. This could have led to higher frequency of wildfires in particular in coniferous woods, as also assumed for parts of the Early Holocene (Dreibrodt *et al.* 2010; Crombé 2016). The windy conditions would have favoured a return to aeolian activity in sandy landscapes stripped of woods by the wildfires (e.g. Hilgers 2007).

A southwards shift of westerly winds from the north Atlantic preceding the onset of the YD and subsequent to the LSE has already been proposed for *c.* 200 years after the LSE at Lake Meerfelder Maar (Brauer *et al.* 1999) and *c.* 40 years after the LSE at Lake Kråkenes (Lane *et al.* 2013; Baldini *et al.* 2018).

Regarding the geographical position of the Nahe palaeolake and the detected increase in average storminess 135 years after the LSE, our record provides additional evidence for the southward shift of the westerlies prior to the onset of YD conditions. Whereas the southward movement between Lake Kråkenes (62°N) and the Nahe palaeolake (53.5°N) occurred at an average pace of $\sim 10 \text{ km a}^{-1}$, from the Nahe site towards the Meerfelder Maar (50°N) the pace of shifting lowered to $\sim 6 \text{ km a}^{-1}$. Thus, the present study supports the idea of a time-transgressive shift of the north Atlantic climate system, similar to the observations by Lane *et al.* (2013). Since the applied indicators in the studied lakes all imply an abrupt shift towards windier conditions, this change might reflect a long-term response to the LSE, as proposed by Baldini *et al.* (2018).

The results of the high-resolution reconstruction of limnological responses to the LSE from the NAH palaeolake sequence presented here add to arguments for a link between the LSE and the onset of the YD as suggested by Baldini *et al.* (2018). How this compares with the other hypotheses about the YD onset, such as the meltwater pulse (e.g. Johnson & McClure 1976; Berger 1990; Alley 2000; Broecker *et al.* 2010; Schenk *et al.* 2018) or the bolide-impact hypothesis (e.g. Firestone *et al.* 2007; Kennett *et al.* 2009), remains a matter of ongoing research.

Conclusions

The multi-proxy investigation of the annually laminated sediment record from the palaeolake Nahe, northern Germany, allowed the identification of local limnological and environmental changes during the Allerød and in particular responses to the Laacher See eruption (LSE) as follows.

- Little variability characterizes the varve microfacies and geochemical composition prior to the LSE. With respect to the Gerzensee oscillation a weak signal, potentially indicating cooler and windier conditions, has been recorded at the site.
- Regarding the LSE, direct short-term local and probably long-term regional climatic responses can be inferred from the sediment record.
- A serious disturbance of the local environment immediately after the LSE (4 years) resulted from erosion at the shore or in the lake catchment area due to increased storminess and perhaps including heavy precipitation events.

- An acidification of the lake system, probably due to acidic aerosols that originated from the eruption, lasted for about 50 years (12 944–12 890 cal. a BP), a period during which biogenic silica deposition (diatoms) declined and then recovered.
- A lake-level increase between 12 930 and 12 878 cal. a BP is inferred, probably resulting from a change of the water balance as a response to cooling.
- 120 years after the LSE (12 830 cal. a BP) the onset of strong westerly winds is reconstructed and is considered to reflect long-term regional response to the LSE. This intensification of westerly winds has been determined to occur at an earlier stage in Norway (40 years after the LSE) and at a later stage in southwest Germany (200 years after the LSE). The observed delay probably reflects a latitudinal, time-transgressive response of the north Atlantic climate system to the LSE as has been proposed recently.
- A comparison of the timing between the sites implies a changing pace of the southward shift of the westerlies subsequent to the LSE: 40–120 years after the LSE (62°N to 53.5°N) $\sim 10 \text{ km a}^{-1}$, 120–200 years (53.5°N to 50°N) $\sim 6 \text{ km a}^{-1}$.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at <http://www.boreas.dk>.

Fig. S1. REDFIT analysis of the pre-LSE varve thicknesses (478 years, tau- 0.66871, bandwidth- 0.005063, oversample- 2, segments- 3, window- rectangle), green line- indication chi square level of 95%; note the

occurrence of cycles of 2–3 and 8 years considered to reflect NAO variability, 54 to 62 years probably reflecting AMO cycles, and 93 years perhaps reflecting sun activity (Gleissberg).

Table S1. Total elemental contents of samples of the varved Allerød sequence from the Nahe palaeolake.

Table S2. Correlation matrix of the total elemental content data from Table 1.

Appendix IV



Sequence completed – palynological investigations on Lateglacial/Early Holocene environmental changes recorded in sequentially laminated lacustrine sediments of the Nahe palaeolake in Schleswig-Holstein, Germany

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ABSTRACT

The exploration of Lateglacial vegetation history in Schleswig-Holstein is elaborate and comprehensive. Despite being one of the most studied areas, regarding to the Lateglacial, no biostratigraphy covering the complete Lateglacial and Early Holocene periods without hiatus have so far been recovered. In this paper we present a biostratigraphy of the Nahe paleolake, therewith intending to deal with this desideratum.

The special strength of the presented sequence is expressed in the fact that these are the only palynologically investigated sequentially annual laminated limnic sediments of the Lateglacial in Schleswig-Holstein. These laminated sediments, as well as radiocarbon dating of botanical macrofossils and three geochemically confirmed cryptotephra layers (Laacher See Tephra, Vedde Ash and Saksunarvatn Ash), provide excellent chronological control and allow for a Europe-wide correlation. Particularly important is a complete discussion of the vegetation history and the spatial proximity to Late Paleolithic sites, which renders it possible to evaluate potential human-environment-interaction long before classical palynological human indicators occur.

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1. Introduction

During the Lateglacial, the area of modern Schleswig-Holstein (Germany) constituted part of a corridor directed towards Scandinavia, thus assuming an essential function in the north-facing colonization processes by flora, fauna and humans. As a result, the interest into paleo-environmental research was continuously growing since the 1930s. This was further amplified by the excellent preservation conditions of several Paleolithic sites, which from early days paved the way for close interlinking of vegetation history and archeological research (Aletsee, 1959; Averdick et al., 1972; Bokelmann et al., 1983; Hallik and Grube, 1954; Schüttrumpf, 1935, 1936, 1943, 1958; Tidelski, 1960; Usinger, 1975, 1978b, 1981a, 1981b, 1981c, 1985, 1998, 2004; Usinger and Wolf, 1982).

A comprehensive study of the hitherto presented pollen profiles, however, reveals that various obstacles arose which could hardly be overcome. One of those still is that the pollen-analytical investigations of different time periods are bound to the geological tripartition of

Schleswig-Holstein. This implies that suitable palynological archives for the Lateglacial are mainly located within the younger moraine area in the east (Fig 1). Here, the basins and depressions of the lakes and bogs mainly originate from dead ice and subglacial meltwater streams (Woldstedt, 1954).

Melting of buried dead ice often resulted in turbations and rearrangement of Lateglacial sediments from important Holocene key sites in Schleswig-Holstein such as Lake Belau and Lake Poggensee (pers. com. I. Feeser). Unfortunately, this deprives the often even annually laminated Lateglacial depositions of their usefulness for an investigation.

In addition, a widespread hiatus in sediment sequences especially in the transition between the late Allerød and Dryas 3 periods are demonstrated at many localities. Usinger (1981a) was able to explain this by climatically caused lake level fluctuations and erosion processes.

Since many of the sites were studied during the early days of pollen analysis it is worth mentioning the recent methodological progress within palynology. The pioneering nature of the research has often prevented difficult pollen types such as *Juniperus* (juniper) and *Populus* (poplar) from being recognized. Also the separation of birch pollen types – which is crucial for the reconstruction of the Lateglacial

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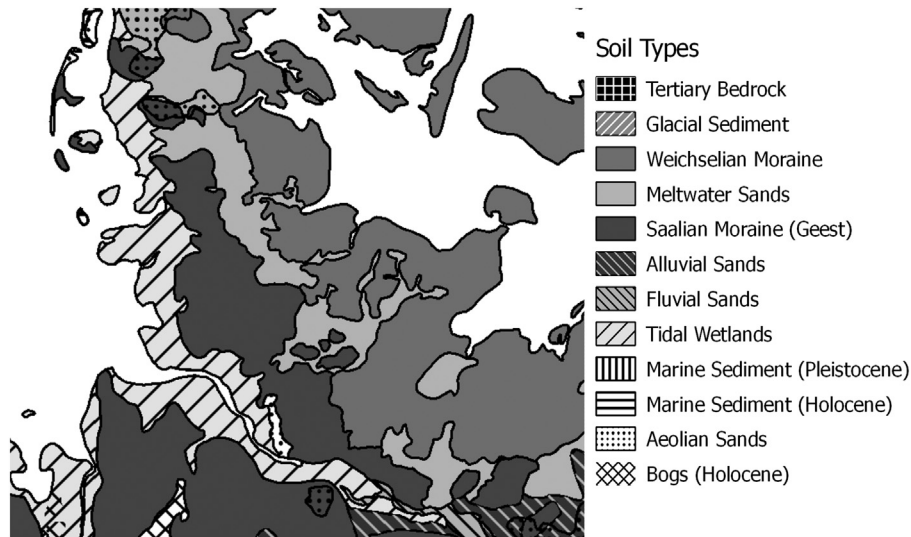


Fig. 1. Map of soil types in the area of Schleswig-Holstein.

vegetation history – only became a standard in Schleswig-Holstein with investigations by Hartmut Usinger (Usinger, 1975, 1981b, 1981c; Usinger and Wolf, 1982).

Another challenge is the ambiguity in biostratigraphical terminology on a geographically large scale that are only gradually being overcome (De Klerk, 2004a; Donner, 1995; Hoek, 1997, 2009; Krüger and Damrath, 2019; Litt et al., 2007; Mangerud et al., 1974; Menke, 1968; Usinger, 1985). The comprehensive research results from Schleswig-Holstein could just marginally contribute to the discussion of terminology, as radiocarbon dates were rarely used to ensure a reliable chronological frame. Also a contribution to the Lateglacial tephrochronological framework is missing. Hence, there is a lack of pollen profiles that can be directly correlated with the existing event stratigraphy (Björck et al., 1998; Blockley et al., 2014; Jones et al., 2018; Rasmussen et al., 2006).

Despite all these obstacles, the previous work has substantially contributed to the understanding of Lateglacial vegetation history.

The same applies also to the interlinking of Lateglacial archeology and palynology in Schleswig-Holstein. This interlinking has so far been based exclusively on a stratigraphic correlation. Schürumpf (1936) reports that archeological finds from the Meiendorf site were embedded in sapropel. By determining the pollen spectrum of the corresponding layer, archeological cultures were related to the development of vegetation in order to achieve a chronological classification of finds. The same methodology was applied to other sites in the Ahrensburg tunnel valley (Schürumpf, 1935, 1943, 1958).

Even recent sites in Schleswig-Holstein were dated by pollen stratigraphy (Usinger, 1998) presenting a direct stratigraphic link between vegetation history and archeology. However, the focus has never been on investigating human influence on the surrounding environment by way of applying palynology on- or near-site, likely because the classical human indicators in pollen records are associated with the Neolithic (Behre, 1981, 1986; Firbas, 1937; Iversen, 1941). Nevertheless, there are several studies that discuss both Early Holocene and Lateglacial human indicators (Bos and Janssen, 1996; Bos and Urz, 2003; Bos et al., 2005; Edwards, 1990; Kaplan et al., 2016; Mortensen et al., 2014b; Selsing, 2018).

Consequently, there is a research desideratum with regard to a Lateglacial archeological site that has been palynologically investigated. It still remains unclear how Late Paleolithic and Early Mesolithic human activity is reflected in the palynological record.

After several years of collecting surface finds, the Archaeological State Department Schleswig-Holstein conducted excavations in Nahe

(Kr. Segeberg/ Germany). Here, on the former shore of a Lateglacial incision lake (Nahe paleolake, NAH), faunal remains including more than 80% reindeer (*Rangifer tarandus*) were found dating to the Dryas 3 period. In combination with the lithic artifacts the finds can be assigned to the Ahrensburgian. The excavated area is interpreted as a refuse zone of a nearby camp site, which is assumed to lay on a slight elevation (Wild, 2017). The investigation was accompanied by numerous drillings that were carried out by Hartmut Usinger. The examination of 68 sediment sequences revealed laminated sediments in the deeper part of the basin – approximately 100 m from the assumed refuse zone. Here, another coring campaign was conducted in October 2017. The analysis yielded a complete Lateglacial to Early Holocene sediment sequence with partial lamination and extraordinary preservation conditions for botanical macrofossils and pollen including the opportunity of integration into the archeological context (Dreibrodt et al., 2020). A targeted search for cryptotephra revealed three layers of non-visible ash beds allowing for direct correlation with European key sites via event stratigraphy (Dreibrodt et al., 2020; Krüger and van den Bogaard, 2020). Consequently, we here present the results of the palynological and macro-botanical investigations of the sediment sequence from the Nahe paleolake.

Aims:

1. To present and discuss the first complete Lateglacial/Early Holocene pollen profile from Schleswig-Holstein (supported by macrofossil data).
2. To investigate the temporal scale of phases of environmental transformations.
3. To compare biostratigraphic transformations (Dryas 1-Allerød/Dryas 3-Preboreal).
4. To correlate the site with further European key sites.
5. To consider different causes for the recorded charcoal particle concentrations.

2. Study site

The Nahe paleolake is located in Schleswig-Holstein about 30 km north of Hamburg (Germany). The basin of the former lake was part of a larger glacial lake system and is separated from further elongated incision lakes by two narrow sand ridges to the northwest and southeast (Smed, 1998; Woldstedt, 1935, 1954). To the southeast, Lake Itzstedt is the water-bearing remnant of the lake system.

The size of the paleolake surface was about 16 ha during the Lateglacial. The terrestrialization process was completed in the course

of the late Holocene. Today, the river *Rönne* flows in the center of the still existing depression and thereby follows the course of the former lake in north western direction before turning southwards and draining off into the river *Alster* (Fig. 2). The area is used as pasture and partly forested by alder, birch and willow today. The coring location is situated in the formerly deepest part of the incision lake (53°48,711'N, 10°8,082'E). The position was selected on the basis of preceding extensive survey corings in 2003 and 2004 by Hartmut Usinger.

The Nahe paleolake is embedded in a well-known archeological find area. In this respect, the southeastern shore of the former lake on the narrow ridge to Lake Itzstedt and the associated flat moraine are of interest for this study. Here, the top of the moraine was intensely surveyed by Thomas Poelmann for the last 30 years. These surveys yielded more than 12,000 lithics that have predominantly been assigned to the Ahrensburgian as well as Hamburgian techno-complexes (Weber et al., 2011).

Three separate concentrations at an elevated position suggest the location of former camp sites. Succeeding excavations in the paleo-shoreline were carried out by Ingo Clausen of the Archaeological State Department Schleswig-Holstein. These investigations revealed further stone artefacts as well as faunal remains (Weber et al., 2011; Wild, 2017).

Faunal remains have been investigated by Wild (2017) and radiocarbon ages of bones and antler suggest a temporal classification into the Dryas 3 period and partly into the early Preboreal period. For that time, a ford situation can be reconstructed at the south-eastern end of the lake in the form of a shallow water area above a sand ridge, situated at the foot of the morain. The composition of the finds, antler technology as well as the topographical situation reflect a comparable situation as reconstructed for the Ahrensburg tunnel valley, located only 18 km to the south (Rust, 1943; Rust and Gripp, 1937).

3. Materials and methods

3.1. Field methods and sampling

The coring took place in October 2017. A modified Livingston piston corer (Mingram et al., 2007) – the so called *Usinger-corer* – was used to

extract the sediment cores. Two overlapping sediment sequences with a diameter of 80 mm and a length of 16 m have been reached by drilling. Each 1-m-segment was cut longitudinally, stored in PVC-liners and processed at the Institute for Pre- and Protohistoric Archaeology in Kiel, Germany. In order to connect the core sequences a series of distinct layers and stratigraphic marker horizons have been defined in the parallel cores. In this way, a composite core was constructed, representing a continuous record avoiding gaps (Dörfler et al., 2012).

The interdisciplinary approach of the study required that the results of different methods could be correlated across depths. Therefore, a grid of 5 mm step size was created spanning the lower 5 m of the sequence. Each sample has been labelled according to consecutive numbers (953 potential samples in total, 11.10–15.89 m below the surface). A preliminary examination with 16 pollen samples determined the focus sequence for the analyses. The scope of the analyses is set on the sequence between sample 330 (12.745–12.750 m, ~10,030 cal yr BP) and 907 (15.605–15.610 m, ~14,780 cal yr BP).

3.2. Stratigraphy and loss on ignition

Subsequent to glacial gravel and sand at 15.78 m below the surface banded clay has been deposited up to 15.42 m with inserted layers of sand. This is overlaid by a sequence of clayey gyttja up to 15.1 m, fine varved gyttja up to 14.48 m and sandy gyttja up to 14.19 m. The transition from Lateglacial to Holocene sediments is reflected in an increasing organic sediment content that corresponds to an increasingly darker coloring of the detrital gyttja up to 13.8 m below the surface. Detrital gyttja interspersed by calcareous gyttja layers has been deposited up to 1.6 m, where fen peat overlays the sequence. The visual sediment transitions are exclusively gradual. Apart from sand layers at the bottom of the sequence no sharp boundaries have been observed.

Loss on ignition (LOI) was determined at 550° and 950 °C using a thermogravimetric analyzer (*ELTRA TGA Thermostep*). Therein, sample sizes of 2 cm³ sediment were proceeded following Heiri et al. (2001).

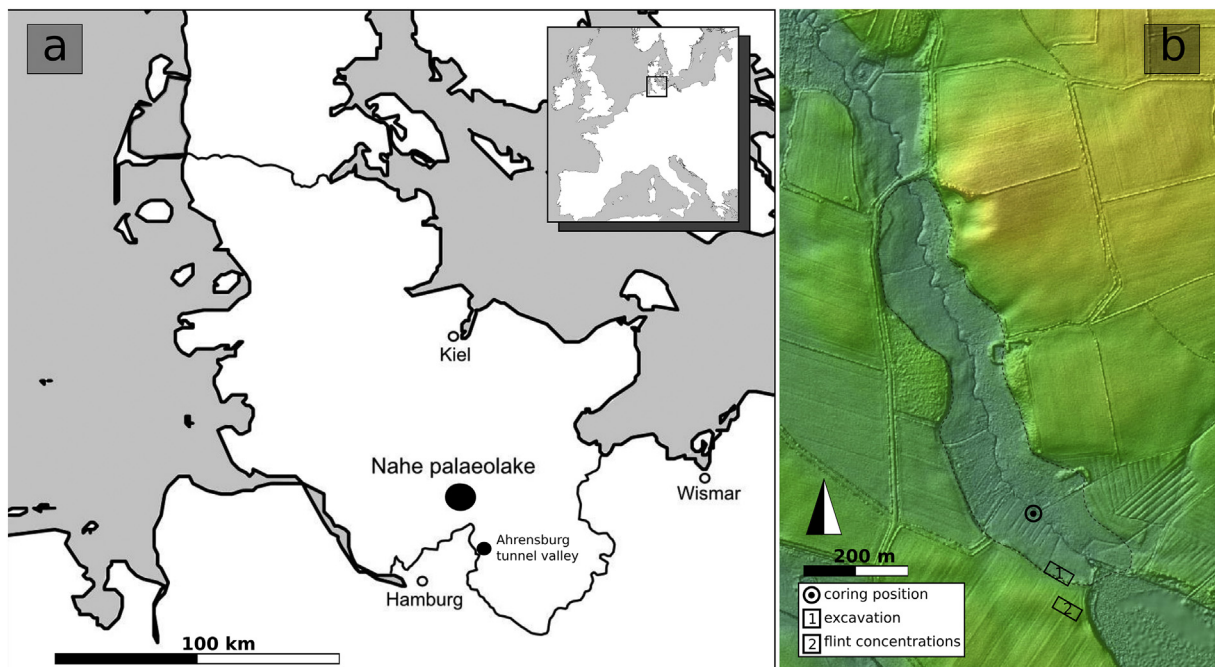


Fig. 2. Location of the Nahe paleolake (a) and coring location and archeological site (b). DEM based on LVerMGeoSH.

3.3. Pollen analysis

Pollen sampling was continuously carried out in 5 mm steps throughout the determined focus sequence. Samples for pollen analysis were chosen for every centimeter (i.e., every second subsample taken) through most of the studied sequence. In some levels samples of every fourth centimeter were analyzed. The halves of the core stored in the PVC-liners were cut into 5 mm slices. The resulting quarters were sampled using sterile prepared disposable syringes. The volume of the individual samples is between 1 and 1.9 cm³ sediment. Sample preparation was carried out according to standard techniques (Erdtman, 1960; Fægri and Iversen, 1989) including HF (60%) treatment of samples with high clay and silt contents. *Lycopodium spore* tablets were added to enable the calculation of pollen concentrations (Stockmarr, 1971). Pollen counting was performed at a total magnification of x400 for routine counting and x1000 for critical objects using a *Nikon Eclipse 50i* microscope. A pollen sum of at least 550 TTP (total terrestrial pollen) per sample was achieved. A total of 191 samples were counted. Cyperaceae were excluded from the TTP sum due to the high amount of locally produced pollen.

Pollen identification mainly followed Beug (2004) as well as Moore et al. (1991). The reference collection at the Institute of Pre- and Protohistoric Archaeology in Kiel was consulted. As supplement to the macrofossil data *Betula* pollen were measured in order to differentiate between a *Betula nana*-type and a *B. pubescens*-type (Beug, 2004). Therefore, a fixed threshold of 21.5 µm was applied following Birks (1968), Karlsdóttir et al. (2007), Kolstrup (1982), Krüger and Damrath (2019), Mortensen et al. (2011) and Usinger (1975, 1978a, 1981b, 1982). Pollen of termophilous taxa such as *Alnus*, *Quercus*, *Ulmus*, *Tilia*, *Carpinus*, *Corylus*, *Fagus*, *Hedera* and *Ilex aquifolium* are regarded as rebedded if appearing in a Lateglacial context.

Infrequent appearing pollen clumps where counted as one pollen of the respective type.

Further, regularly occurring non-pollen palynomorphs (NPPs) were recorded following Van Geel (1976). Charcoal identification was made based on morphological characteristics such as sharp breaking edges (including a halo effect at phase contrast setting around these), angular, opaque usually planar and often asymmetric shape and a deep black color (Krüger et al., 2017; Patterson et al., 1987; Tipping, 1996). The recording also included a classification of three size classes (10–50 µm, 50–100 µm, >100 µm).

Zone boundaries were set according to substantial changes in taxa representation following Hedberg (1976) and additionally on loss on ignition. A cluster analysis (CONISS, broken stick model) using the *Tilia* software (Grimm, 2000, vers. 1.7.16) was applied to cross-check general major boundaries. Subzones were defined by visual assessment. The results of pollen ratios and concentration were visualized using the *CountPol* software (I. Feeser, Kiel University) as well as *Inkscape* (vers. 0.92.4) where zone boundaries have been drawn and minor changes have been made.

The terminology used is described further below (cf. Section 4.1).

3.4. Macrofossil analysis

The standard processing of fossil pollen samples includes the extraction of botanical macrofossils from the sediment samples in preparation. After removing humic acids and a deflocculation with 5–10% KOH, a sieve with 200 µm mesh size was used to remove coarse particles (Fægri and Iversen, 1989). In this way, macrofossils were extracted from each pollen sample resulting in 191 samples. The comparatively small volume of the individual samples of between 1 and 1.9 cm³ sediment results in only a few macrofossils being obtained. As they occur only sporadically, raw counts are given in the results.

Macrofossils were identified and counted at 10–40x magnification using an *Olympus SZ51* binocular. Standard identification guides (Bejerinck, 1976; Cappers and Bekker, 2013) and the reference

collection at the Institute of Pre- and Protohistoric Archaeology at Kiel University were consulted.

3.5. ¹⁴C dating and age–depth model

The sediment sequence has been subject to an intense search for datable organic material during the subsampling process for pollen analysis. Twelve levels containing terrestrial plant macrofossils were AMS ¹⁴C dated (further including two true replicates) at the laboratories in Groningen (GrM) and Kiel (KIA; supplementary material 3). Additionally, a targeted search for cryptotephra revealed three event horizons that have been used as further dates (Dreibrodt et al., 2020; Krüger and van den Bogaard, 2020). The sediment sequence between 14.93 and 14.45 m appeared laminated and has hence been subject to varve counting. As the only datable macrofossil from the lower section of the sequence gave a much too old result, additional pollen analytical features were used as chronological markers. The compiled data contributes to the age–depth model used here that has been described by Dreibrodt et al. (2020).

4. Results and discussion

The scope of the analyses is set on the sequence between sample 330 (12.745–12.750 m/~8,980 cal yr BP) and 920 (15.665–15.670 m/~14,950 cal yr BP) covering lacustrine sediments deposited between the end of the Pleniglacial and the Early Holocene. The diagram was divided into seven pollen assemblage zones (PAZ; NAH-1 to NAH-7), which further included 18 subzones. The general development in the pollen record is described in supplementary material 1. The pollen diagram showing percentage values calculated on TTP excluding Cyperaceae are shown in Fig. 3 including the results of LOI. A simplified concentration diagram is given in Fig. 4 and b.

The spectrum of recorded macrofossils is limited by the small sample volume and different sedimentation conditions. The results are given in supplementary material 2 and included in the discussion below.

4.1. Biostratigraphical terminology and zonation of the Lateglacial

Zonation and setting of biostratigraphical boundaries (or transitions) are dependent on multiple factors and are time transgressive across different landscapes. However, they represent significant biostratigraphic equivalents that can be used as marker horizons (Firbas, 1954; Menke, 1968). With regard to biostratigraphic correlation Schleswig-Holstein forms a bridge between central European and Scandinavian pollen records (Litt and Stebich, 1999). Nevertheless, in these areas biostratigraphic designations were used in different ways. Considering the bridging function of the presented record, it is crucial to briefly discuss the terms in use, without temporal contextualization or absolute chronological analogy.

For the first phase of the Lateglacial the local term *Meiendorf* was introduced by Menke (in Bock et al., 1985; Menke, 1968) in Schleswig-Holstein, which is also applied in the present study. The separation from the Pleniglacial is linked to a significant increase in *Artemisia* values as well as characteristic species as *Hippophaë*, *Helianthemum*, *Selaginella selaginoides* and an increase in overall AP (arboreal pollen) percentages (De Klerk, 2008b; Hoek, 1997; Iversen, 1954; Menke, 1968; Van der Hammen, 1951; Van Geel et al., 1989). Following the results of Krüger and Damrath (2019) *Meiendorf* as biostratigraphic expression equals the term *Bølling* (Iversen, 1942) in classical Danish research context. Therefore, and to further avoid confusion of terms, we refrain from using the term *Bølling/Bølling* as designation for the first phase of the later following Allerød period (Usinger, 1981c, 1985).

The differentiation between the previous *Meiendorf* period and the successive *Dryas-1* period is determined by an increase in NAP. Regarding terminology, Arabic numbers have proven to be useful in order to

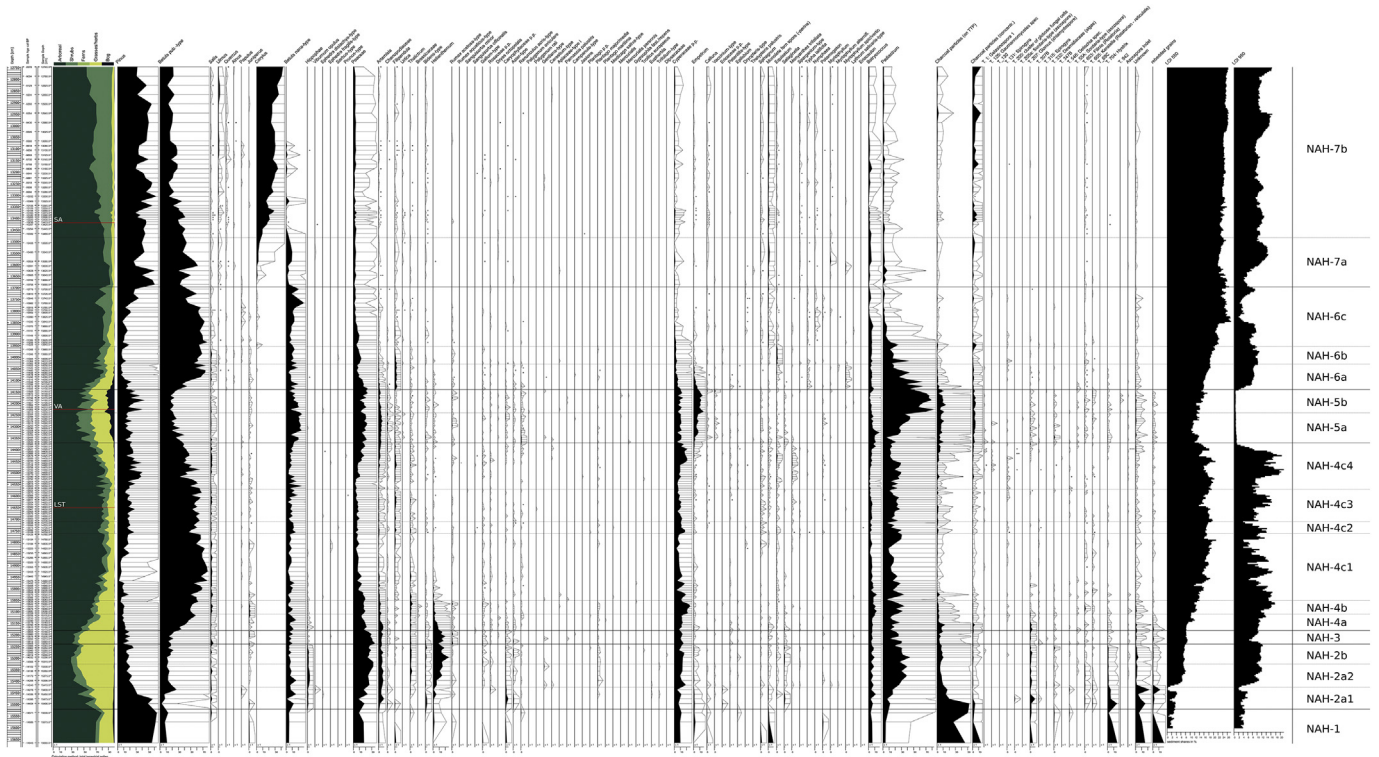


Fig. 3. Pollen diagram from the NAH sequence including loss on ignition data (LOI 550; LOI 950). Red bars in the composition column indicate positions of cryptotephra layers (SA - Saksunarvatn Ash; VA - Vedde Ash; LST - Laacher See Tephra).

avoid confusion with terms as Oldest, Older or Younger. The term *Dryas-1* has been introduced by Nilsson (1960) and originally designated the *Oldest Dryas* sensu Iversen (1942) or the *Earliest Dryas* sensu Kolstrup (1982) – terms for the onset of the Lateglacial in Danish and Swedish research context prior to the work by Mortensen et al. (2011). *Dryas-1* in the present study equals *Älteste Tundrenzeit* sensu Menke (1968) including indicative pollen types as *Helianthemum* sp., *Selaginella selaginoides* or *Thalictrum* sp., strong decrease in *Hippophaë* sp. and an increase in general NAP (non-arboreal pollen) percentages, separating the *Meiendorf* period from the successive *Allerød* period.

The term *Allerød* period is applied here in the classical connotation. The decisive factor in this respect is the spread of birch trees (Hartz and Milthers, 1901). As this can never be linked to a rapid increase in *Betula pubescens*-type pollen percentages alone the presence of macrofossils is fundamental (Birks and Birks, 2000; Schürtrumpf, 1943).

Benefitting from the high resolution of the record, the *Allerød* period is divided into multiple sub-periods. These further include two separate phases of recurrent *Betula pubescens*-type pollen percentages and increasing NAP percentages. The first of these declining phases succeeds the rapid spread of birch trees at the onset of the *Allerød* period, which was formerly referred to as *Bölling* in German research context (Litt and Stebich, 1999; Usinger, 1985). The short-term increase in pollen of heliophilous species – the same that had a considerable proportion of the *Dryas-1* pollen-flora – led to the designation *Dryas-2* period for this first intra *Allerød* oscillation.

The second of these internal *Allerød* declining phases precedes the Laacher See Tephra. The stratigraphical context in combination with palynological characteristics leads to the designation *Gerzensee-Oscillation* (Andersen et al., 2000; Björck et al., 1998; Lotter et al., 2000; Mortensen et al., 2011). Even if this is often referred to as *intra-Allerød-cold-period* (IACP), this might be a misleading term here with regard to the *Dryas-2* that would hence be another IACP.

The stadial-period separating the *Allerød* period from the onset of the Holocene is widely known as *Younger Dryas* period. This is in accordance

with the majority of palynological records across central and northern Europe and is characterized by an increase in *Betula nana*-type pollen percentages and NAP percentages as well as a decrease in AP percentages (Birks and Birks, 2008; Hoek, 1997; Iversen, 1942, 1954; Jahns, 2000; Litt et al., 2007; Litt and Stebich, 1999; Mangerud et al., 1984; Merkt and Müller, 1999; Mortensen et al., 2011, 2014b; Neugebauer et al., 2012; Overbeck, 1975; Wulff et al., 2013). Nevertheless, in order to maintain the line of reasoning, the term *Dryas-3* is used here following Nilsson (1960) and Usinger (1978a).

4.2. Environmental synthesis

The environmental synthesis comprises the discussion of palynological, macrofossil and sedimentological data based on the division according to pollen assemblage zones (PAZs). The brackets following the PAZ designation contain an assignment of the PAZ to biostratigraphy as defined above, followed by the depth below the ground surface and calibrated ages BP. In this context, it should be emphasized that the given ages do not represent absolute dates of the biostratigraphic units, but represent temporal estimates of the respective depths.

NAH-1: (cf. Pleniglacial, 15.695–15.550 m) 14,950–14,510 cal yr BP.

During the termination of the Pleniglacial, the surroundings of the basin were subject to extensive erosional processes. Based on the position relative to the former ice margin and push moraines it can be discerned that besides permafrost, solifluction and aeolian activity also extensive glacio-fluvial and meltwater activity affected the area.

These activities are reflected in, e.g., sand layers of different thickness that can be regarded as event horizons intermitting varved clay in the lowermost section of the sediment sequence. These layers consist of homogeneous medium to coarse grained sand bands and are reflected as distinct and synchronous minima in organic and CaCO₃ sediment content. They can be associated with clasts that were probably introduced into the channel-like basin by collapsing banks that in turn remained extremely unstable due to very sparse or a lack of vegetation

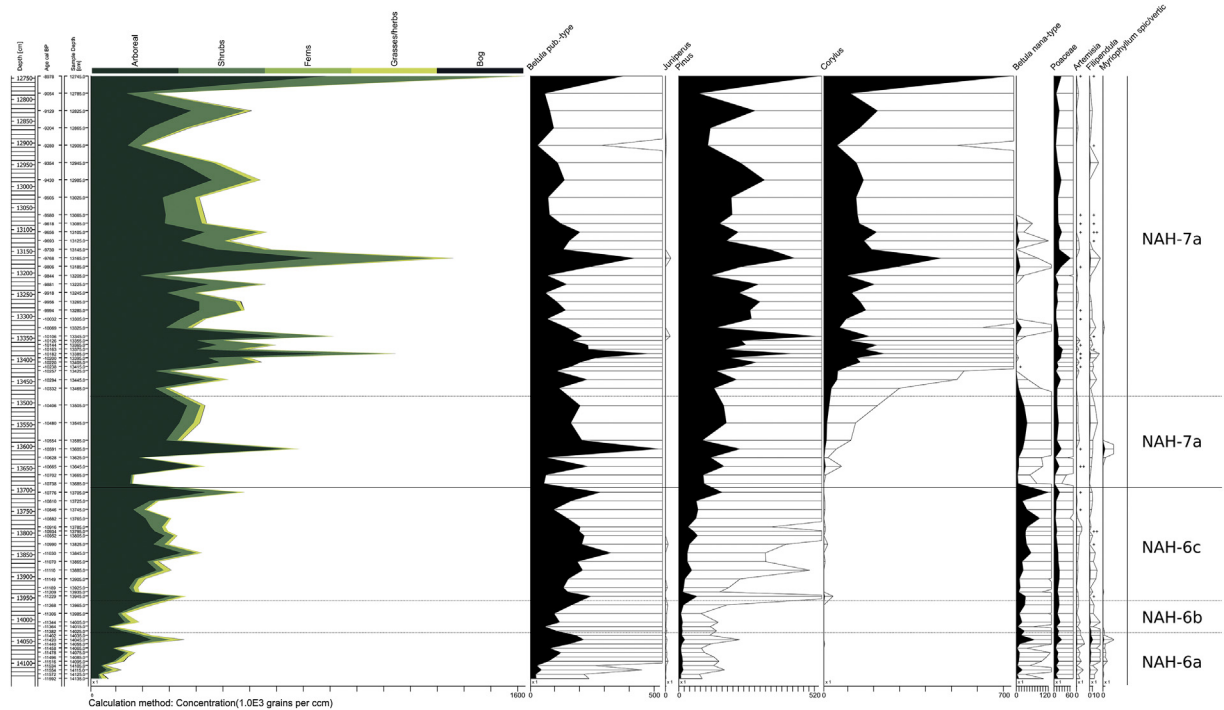
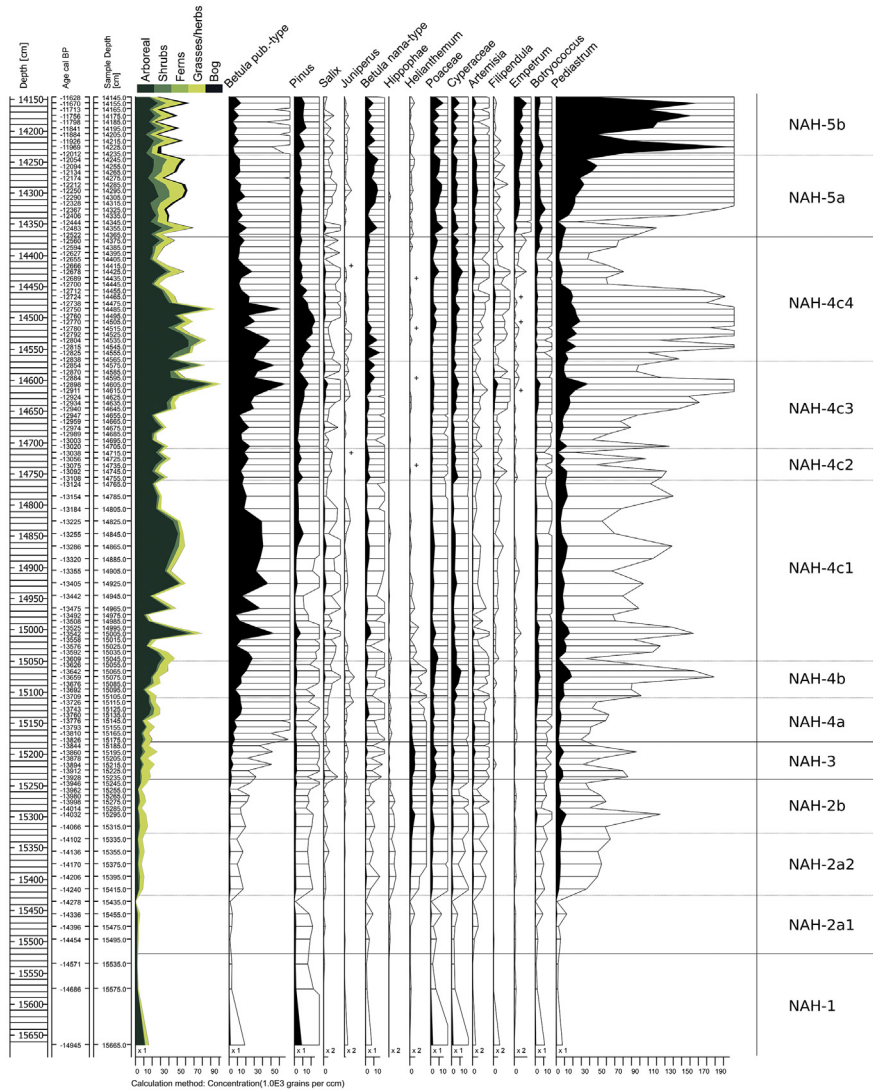


Fig. 4. Concentration diagram of selected taxa for the Lateglacial part of the record. (b) Concentration diagram of selected taxa for the Holocene part of the record.

cover (Birks and Birks, 2008; Shaw, 1975). This is concordant with a generally low concentration of predominantly less than 1000 pollen and spores per cm³ sediment and high proportions of corroded pollen grains.

Indications of various erosional processes are also documented by dinoflagellate cysts (HdV-704), the *Glomus*-type (cf. *G. fasciculatum*; HdV-207), high charcoal particle concentrations and high amounts of corroded pollen grains as well as rebedded pollen grains of thermophilous taxa. Here, especially dinoflagellate cysts are a sign of persistent melt water activity and secondary deposition as they are originally part of the marine fauna (Bakker and van Smeerdijk, 1982; Lotter, 1999).

However, *Pinus* pollen is the predominant pollen type of the assemblage zone with values partially significantly above 50%. These high quantities can probably be attributed to increased aeolian activity and thus long-distance transport. Proportions of these high counts could also be redeposited as the abundance of thermophilous taxa suggests (Hoek et al., 1999). This assumption would be consistent with the high number of almost exclusively recorded single aerial sacks/sacci (Odgaard, 1994).

With regard to the size also *Betula pubescens*-type pollen are recorded in increased abundances that cannot be ignored. In the absence of macrofossils and lacking evidence of the tree birch north of the Bavarian Prealps and northwest of Hungary during the terminating High Glacial period (Bennett et al., 1991; Tzedakis et al., 2013; Willis et al., 2000), presence of tree-sized *Betula* seems rather unlikely. Redeposition and long-distance flight are again plausible sources (Hjelmroos, 1991; Hjelmroos, 1992; Wallin et al., 1991).

Minor quantities of *Betula nana*-type pollen, *Salix* sp. and *Juniperus* sp. may be reflections of the vegetation on dry raw soils of the surrounding area. However, it is rather probable that these dwarf shrubs – if actually present – were scattered and did not form comprehensive populations.

The pollen spectrum of NAH-1 further includes light-demanding families and species of open partially humid habitats as Poaceae, Caryophyllaceae, Cyperaceae, Polypodiaceae and *Helianthemum* sp. In general, it can therefore be assumed that a sparse and rather barren local vegetation predominated, with low grasses, herbs and dwarf shrubs. It is also plausible that raw soils were part of the landscape – exposed to the energy of various erosion processes.

However, the pollen composition of NAH-1 is characteristic for records of mineroclastic infills from lakes of various origin, where the pollen signal is masked by turbations and redeposition (Leroy et al., 2000; Litt and Stebich, 1999). It cannot be excluded that all material originated from a pure secondary pollen record, impairing the interpretation (Iversen, 1942).

NAH-2a1: (cf. Meiendorf period, 15.550–15.455 m) 14,510–14,260 cal yr BP.

The continuous erosional activities during NAH-2a1 are displayed in various proxies. Still, major erosional processes occurred resulting in the deposition of homogeneous medium to coarse grained sand bands, presumably reflecting further clastic input into the lake basin (e.g., spring melting). They are again correlated with distinct synchronous minima in organic and CaCO₃ sediment content. A pollen sample taken from a sand layer (15.465) reveals an intermittent interruption of various pollen curves. A recorded peak in *Corylus* values and several finds of thermophilous *Ilex aquifolium* pollen unveil that the spectrum must be considered out of sequence. This strengthens the assumption that the sand layers are to be classified as pure redeposited event layers.

However, increased meltwater activity during NAH-2a1 is indicated by different thermophilous taxa (regarded as secondarily deposited), high numbers of corroded pollen grains and especially maximum values of dinoflagellate cysts (HdV-704) (Bakker and van Smeerdijk, 1982; Lotter, 1999). This is in line with the general strengthened ablation of glaciers due to the temperature rise of the temporally corresponding

GI-1e, to which the onset of the Lateglacial is ascribed (Björck et al., 1998; Hoek, 2008; Weaver et al., 2003).

Within the assemblage zone, a succession of colony-forming green algae can be observed. A first maximum of *Botryococcus* values precedes an increase of *Pediastrum* values. Some of the associated species are considered to be lacustrine pioneers because of their ability to bind nitrogen in initially nitrogen-poor waters and thus create the basis for other aquatic organisms (Van Geel et al., 1984). The gradual increase in the degree of eutrophication is also expressed in the presence of *Filinia longiseta*-type rotifers (HdV-603), indicative for clear water conditions (pers. com. M. Wieckowska-Lüth). Clearly, their continuous presence would imply a climatic amelioration that would be in line with the rapid warming of the Meiendorf period (Koste, 1980; Litt and Stebich, 1999; Ruttner-Kolisko, 1980). Aquatic species react more directly to climatic events having a very short reproduction cycle (Iversen, 1954; Lotter, 2001; Wright, 1984). Here, the spread and diversification of aquatic organisms is clearly associated with the onset of the Lateglacial.

The minor increase in overall pollen concentration is linked to the spread of heliophilous herbs and grasses within the assemblage zone. Still, *Pinus* pollen is the dominant pollen type showing a rapid decrease from 50 to 20%. However, this is not reflected in the pollen concentration where values remain stable. The preservation conditions towards the end of the assemblage zone are rapidly improving, resulting in a much higher TTP sum including a diversification of recorded pollen types. This is accompanied by an increase in *Betula pubescens*-type and *B. nana*-type pollen. It can be assumed that the overall input in *Pinus* pollen presumably remained stable – prevailing a mixture of long-distance flight and redeposition – and resulting in stable concentrations, whereas the percentage diagram here depicts a calculation effect.

The synchronous rise in percentages of heliophilous grasses and herbs (*Artemisia* sp., *Hippophaë* sp., *Bidens*-type, *Selaginella selaginoides*, Chenopodiaceae, Caryophyllaceae, Asteraceae) at the beginning of NAH-2a1 is concordant with the biostratigraphical characteristics of the onset of the Lateglacial throughout northern central Europe (De Klerk, 2002; De Klerk et al., 2008a; Hoek, 1997; Iversen, 1954; Menke, 1968; Merkt and Müller, 1999; Usinger, 1985; Van der Hammen, 1951; Van Geel et al., 1989).

It is likely that an increase in summer temperatures or longer summer periods led to the spread of various aquatic, telmatic and terrestrial species (De Klerk, 2008a). Thereby, insufficient soil formation is a potential limiting factor for the spread of the upland vegetation. The upland vegetation in turn was dominated by heliophilous grasses and herbs. At favorable probably sheltered stands, dwarf shrubs as *Betula nana* and *Juniperus* sp. flourished but the general appearance of the vegetation remained rather barren. *Salix polaris* is represented in the macrofossil record and was therefore certainly part of the first vascular plants colonizing raw formerly glaciated soils in the surrounding area. The light seeds are distributed very easily by wind and thus, as well as by the low habitat requirements, the plant has an advantage in the opening up of habitats released by the glaciers (Bennike and Jensen, 1995).

Biostratigraphical characteristics of the Lateglacial were met before the termination of main erosion events (sand layers) in the area. This is consistent insofar as the upland vegetation was probably able to consolidate the surrounding slopes and the soil only by the end of the PAZ. *Hippophaë* sp., with its widely branched root system, presumably made an essential contribution to the soil stabilization (Heinisch, 1952; Skogen, 1972). Whether there were still exposed unvegetated areas in the landscape cannot be clarified but remains likely.

NAH-2a2 (cf. Meiendorf period, 15.455–15.335 m) 14,260–14,080 cal yr BP.

A change to a clayey gyttja as a potential mixture of glacial outflow material and metabolic products of aquatic organisms as well as external organic input prove continuous meltwater activity during NAH-2a2. Nevertheless, the absence of massive mineroclastic layers reveal calmer conditions within and around the incision lake. This is consistent

with continued detection but marked decreases in values of dinoflagellate cysts (HdV-704), pollen of thermophilous taxa and charcoal concentration. Although erosion continued to play a role, the increasing coverage of soils by tundra vegetation is certainly responsible for a weakening of rearrangement and in particular solifluction, resulting in a decrease of all erosion indicators.

Organic and CaCO₃ sediment contents double within the assemblage zone. It is likely that rising temperatures stimulated the growth of algae (especially *Pediastrum* sp.) to a degree that resulted in increased precipitation of CaCO₃ (Chrobok, 1986). Algae growth was further amplified by the clear water conditions in the basin, as potentially indicated by the presence of the *Filinia longiseta*-type (HdV-603).

The pollen concentration rises from about 500 to more than 1000 grains per cm³ sediment. This is a result of a slight increase in AP and a strong increase in NAP, of which Poaceae and *Helianthemum* sp. have significant shares.

Concentrations of extra-local allochthonous elements such as *Pinus* sp. and *Betula pubescens*-type pollen (Janssen, 1972) remain rather stable. Still, a local presence of *Pinus* sp. and *Betula pubescens* is rather unlikely, but especially the geographical range of *Betula pubescens* shifted northwards to western Pomerania (De Klerk, 2004b; De Klerk et al., 2001) or mid Germany and the southern Netherlands (Hoek et al., 1999; Merkt and Müller, 1999) in the course of the early Lateglacial.

The values of *Hippophaë* sp. (cf. *rhamnoides*) pollen reach their maximum (~4%) within this assemblage zone. As the species is insect pollinated and a low pollen producer comprehensive local stands can be assumed by even low percentage values (De Klerk et al., 2008a; Firbas, 1934, 1949; Overbeck, 1975; Søgaard et al., 2018). Local presence of *Hippophaë* sp. had been assumed at different sites in northern central Europe at comparable values: Stellmoor 2.1% – Usinger unpubl.; Glüsing ~1% – Menke (1968); Slotseng ~2% – Mortensen et al. (2011); Hämelsee ~1% – Merkt and Müller (1999); Reinberg basin ~6% – De Klerk et al. (2008a) (Fig. 5). *Hippophaë* sp. presumably grew on the sandy slopes close to the lake together with *Betula nana*, *Juniperus* and *Salix* sp.

Marked increases in Poaceae, *Helianthemum* sp. and a maximum in *Artemisia* pollen values within this assemblage zone are apparent. The spread of further heliophilous and unpretentious herbs such as Caryophyllaceae, Rosaceae, Asteraceae, *Galium* sp., *Gentiana* sp., *Plantago major/media* and especially *Thalictrum* sp. allude to a diversification of the riparian/telmatic and tundra vegetation. Their high demand for light and comparable low habitus indicate that the landscape continued to be dominated by an open tundra-like vegetation. The characteristics of the assemblage zone are in line with those of the *Hippophaë*-*Betula nana*-PAZ as defined by Usinger (1985) for the area of investigation.

NAH-2b (cf. Meiendorf period, 15.335–15.270 m) 14,080–13,940 cal yr BP.

The lithological characteristics of the previous assemblage zone are met in NAH-2b as well. Very homogeneous clayey gyttja without visible stratification features stable or partly stagnating organic and CaCO₃ sediment contents. Again, a dependence on the development of the green algae population (especially *Pediastrum* sp.) seems plausible, as it also shows stagnating or decreasing values.

Erosion indicators (HdV-704, pollen of thermophilous taxa and charcoal concentration values) display marginally higher values and *Pinus* sp. pollen values are increasing towards the end of the assemblage zone, the latter suggesting that an increased allochthonous input may be responsible.

Two distinct minima in the overall pollen concentration are mainly caused by minima in Poaceae concentrations. This is in line with decreasing Poaceae percentage values mainly in favor of *Helianthemum* sp., *Bidens* sp. and AP values.

A comparison of the percentage values of *Helianthemum* sp. with other locations in northern central Europe reveals exceptionally high percentages (max. >25%, ø 14%) for the investigated area: Stellmoor 3.4% – Usinger unpubl.; Glüsing ~5% – Menke (1968); Kubitzbergmoor



Fig. 5. Map of southern Scandinavia and northern Germany with locations of the Nahe paleolake (NAH) and pollen profiles as mentioned in the text. 1 – Allerød (Hartz and Mülthers, 1901); 2 – Bølling Sø (Iversen, 1942; Krüger and Damrath, 2019); 3 – Slotseng (Mortensen et al., 2011); 4 – Scharnhager Moor (Usinger, 1981b); 5 – Kubitzbergmoor (Usinger and Wolf, 1982); 6 – Glüsing (Menke, 1968); 7 – Liether Moor (Bokelmann et al., 1983; Usinger, 1981c); 8 – Stellmoor (Usinger unpubl.; Schürumpf, 1943); 9 – Reinberg basin (De Klerk et al., 2008a); 10 – Westrhauderfehn (Behre, 1966); 11 – Hämelsee (Merkt and Müller, 1999).

~5% – Usinger and Wolf (1982); Slotseng ~8% – Mortensen et al. (2011); Hämelsee ~5% – Merkt and Müller (1999); Reinberg basin 1–3% – De Klerk et al. (2001).

A pollen-morphological distinction between a *Helianthemum oelandicum*-type and a *H. nummularium*-type (Beug, 2004) was not possible and has yet been carried out at only few locations in Lateglacial context (Mortensen et al., 2011, 2014b). However, this is relevant for an interpretation, as associated species are either insect or wind pollinated (Lack, 1982; Widén, 2018).

Unfortunately, macrofossil evidence on *Helianthemum* sp. from Lateglacial contexts in northern central Europe is lacking so far.

In order to approach this problem, an indication is given by the record of Slotseng, in which both pollen types with clear dominance of the *H. oelandicum*-type were reported on (Mortensen et al., 2011). As with *Hippophaë* sp., the insect pollinated *H. nummularium*-type also implies local presence, assuming that both pollen types were included in a mixed ratio. This is concordant with the observations by Iversen (1944, 1947), Van der Hammen (1951) and Menke (1968).

Consequently, the high values suggest that *Helianthemum* sp. was present throughout the surrounding of the incision lake. Comprehensive and even exposed stands must be inferred. On the well-drained substrata of the vicinities different species of *Helianthemum* presumably formed a major part of the barren tundra or grassland and are indicative for calcareous and alkaline conditions in the area (Hoek, 1997; Lang, 1994; Rothmaler, 2017; Widén, 2018). This assumption is in line with

the record of further heliophilous and partly thermophilous weed and steppe elements such as *Galium* sp., *Plantago major/media*, *Selaginella selaginoides*, Asteraceae and Chenopodiaceae.

The values of *Helianthemum* sp. appear significantly higher in a supra-regional comparison. A potential explanation would be the orientation of the Nahe paleolake. The basin is aligned east-west, bordered by shallow slopes. This implies that an elongated shore area is oriented to the south and thus locally optimal site conditions for rockrose (*Helianthemum* sp.) prevailed.

Presumably *Juniperus* sp. and *Salix* sp. as well as *Betula nana* and *Hippophaë* sp. continued to be present in the more sheltered locations and banks of the depression. A clump of *Betula nana*-type pollen potentially indicates local presence (De Klerk, 2002; Janssen, 1984) for the first time in the area. For *Hippophaë* sp., a second, albeit weakly pronounced maximum can be observed which can be compared to other sites in Schleswig-Holstein (Usinger, 1985, 1998) as well as Denmark (Krüger and Damrath, 2019; Mortensen et al., 2011) and suggests, that sea buckthorn was prevalent among the shrub vegetation. The characteristics of the assemblage zone are mainly in line with those of the *Hippophaë-Betula nana*-PAZ as well as partly with the *Helianthemum-Betula nana*-PAZ as defined by Usinger (1985).

With regard to the Meindorf period as a biostratigraphical unit, it should be noted that it cannot be clarified beyond doubt whether it has been recorded completely or only in part. Nevertheless, considering geographically close pollen profiles, the twofold maximum of *Hippophaë* sp. found within NAH-2 suggests a complete record of the Meindorf period.

NAH-3 (cf. Dryas 1 period, 15.270–15.210 m) 13,940–13,830 cal yr BP.

A minor change within the sediments is visible under consideration of the loss on ignition values within the assemblage zone. While the organic sediment content remains relatively stable, a strong decrease of the CaCO₃ content is observed. Here, short-term water level fluctuations or a change in the duration of the vegetation period are plausible triggers for the synchronous decrease of *Pediastrum* sp. (Turner et al., 2014). Nevertheless, both are not to be seen here in direct dependence. The trigger for a decrease are probably the clearly lowered temperatures or/and increased dryness, that would correspond to the climate event GI-1d. Even if the given time ranges for the regional Dryas 1 period and the GI-1d do not overlap temporally, their offset is well within the given deviation of more than 150 years (Björck et al., 1998; Lowe et al., 2008; Mortensen et al., 2014b; Usinger, 1985), or assumed uncertainty (± 100) in the lower part of the age-depth model of the NAH record (Dreibrodt et al., 2020).

A significant increase in pollen concentration is mainly due to an increase in Poaceae and *Helianthemum* concentrations within NAH-3. This can be attributed to the comprehensive distribution of the respective species in the area and the associated higher input of pollen.

Unpretentious, low-growing species such as *Artemisia* sp., *Rumex* sp., *Potentilla* sp., *Galium* sp., Caryophyllaceae, Rosaceae and Chenopodiaceae are part of a now dryer steppe and grassland vegetation dominated by Poaceae and *Helianthemum* sp. Also the eponymous *Dryas octopetala* occurred. All these species successively occupied vacant areas abandoned by the retreating dwarf shrubs of *Betula nana*, *Salix* sp. and *Juniperus* sp., but in particular by *Hippophaë* sp.

Yet, a clump of *Salix*-type pollen still proves local presence. However, a distinction of pollen morphology is not possible on species level (Beug, 2004). Although, local and regional finds of macrofossils suggest that *Salix polaris*, *S. reticulata* and probably most common *S. herbaceae* are amongst the present species (Bennike et al., 2004; Brandt, 1954; Firbas, 1949; Nathorst, 1891; Schüttrumpf, 1937; Tralau, 1963; Usinger, 1985; Usinger and Wolf, 1982).

De Klerk et al. (2008a) assumed that partly disappearing *Hippophaë* sp. could favor soil erosion. Nevertheless, an expected increase in various erosion indicators, here especially the *Glomus*-type (cf. *G. fasciculatum*; HdV-207), is not observed. On the contrary, these as

well as dinoflagellate cysts, redeposited and corroded pollen grains gradually decrease. It can be deduced that the degree of soil erosion was either just insignificant, or the steppe and grassland vegetation already covered the majority of raw soils preventing them from being eroded.

Further, one should consider that a slight increase in *Juniperus* sp. values in the second half of the PAZ could be seen as a precursor to the subsequent spread of tree birches (Usinger and Wolf, 1982). The same applies to the observations of Merkt et al. (1993), who interpret the repeated spread of *Helianthemum* sp. as a sign of an increase in temperature.

The characteristics of the assemblage zone are mainly in line with those of the *Helianthemum-Betula nana*-PAZ as defined by Usinger (1985) and indicate grass and herb dominated dry steppe in the surroundings of the lake.

NAH-4a (cf. Allerød 1 period 15.210–15.110 m) 13,830–13,710 cal yr BP.

A slightly pronounced alteration in the sediment is visible within the frame of the assemblage zone. This alteration – the increase of the organic sediment content – can be explained by increased allochthonous input. This is in line with the increasing pollen concentration within the sediment. Values rise from about 1500 to partly more than 4000 grains per cm³ sediment. Here, tripling *Betula pubescens*-type pollen concentrations are mainly responsible, but *Betula nana*-type pollen also contribute. The concentrations of grasses and herbs decrease only slightly. This is mainly due to a decrease in *Helianthemum* sp., while Poaceae maintain the concentration values.

With regard to the AP/NAP-ratio it becomes clear that a rapid transformation of the vegetation occurred. In this respect the rapid increase in *Betula pubescens*-type pollen, here from around 25% to more than 58%, is typical for the onset of the Allerød period. The increase in pollen productivity was a response to rapidly increasing warmer climatic conditions of the GI-1c₃ (Björck et al., 1998; De Klerk, 2002; Fredskild, 1975; Hoek, 1997; Hoek et al., 1999; Litt and Stebich, 1999; Usinger, 1985, 1998).

According to the biozonal characteristics at the type locality described by Hartz and Milthers (1901), the presence of tree sized birches is inevitable for an association with the Allerød period. In this respect it is important to note that a fruit scale of *Betula pubescens* has been identified (15.145 m), coinciding with the peak values of *Betula pubescens*-type pollen in NAH-4a. Further, the assumption of local presence is supported by a *Betula pubescens*-type pollen clump. The finds are in line with early macrofossil evidence of tree sizes birches in the area by Schüttrumpf (1943).

The percentage values suggest that the spread of tree birches primarily occurred at the expense of *Helianthemum* sp., *Artemisia* sp., *Hippophaë* sp. and *Juniperus* sp. Taking the concentration values into consideration, however, it becomes clear that only *Helianthemum* sp. suffered a significant decline. For the high percentages of *Betula pubescens*-type pollen and the associated first spread of trees in the Lateglacial, it can therefore be stated that (i) such a high record of pollen can also be explained by the clearly superior pollen productivity compared to other species (Broström et al., 2008; Theuerkauf et al., 2012), which could also be explained by a few individuals and not necessarily by the development of a dense woodland, (ii) hybrid forms of *Betula nana* and *Betula pubescens* could equally have an unrecognized percentage share (Karlsdóttir et al., 2007), (iii) on the basis of the unchanged Poaceae concentrations a spread of birch trees certainly did not comprehensively cover the area, but took place selectively at favorable locations.

Light has always been a decisive factor in the competitive behavior (Caldwell, 1987; Horn, 1971; Overbeck, 1975). In this respect, migrating individuals of *Betula pubescens* would have been advantageous, but the first tree birches were far below their potential growth height presumably due to substrate conditions (Mortensen et al., 2014a). In addition, even at favorable locations, the populations were not particularly dense. This could explain why many grasses and herbs, as well as dwarf shrubs, were only partially prevented from spreading.

As reflected by the concentration values, *Hippophaë* sp. and *Juniperus* sp. spread at the beginning of the assemblage zone before being displaced again in some locations. However, Usinger (1975, 1981b, 1998); Usinger and Wolf, 1982) was able to prove for several locations in Schleswig-Holstein that the concentration values of *Hippophaë* sp. in early Allerød (and in NAH-4a) are approximately as high as the maximum values during the Meiendorf period (NAH-2a2). Based on these observations and under consideration of the present record, it can be assumed that *Hippophaë* sp. may have spread almost to a similar extent within the early NAH-4a assemblage zone.

Moreover, considering numerous heliophilous species such as *Potentilla* sp., *Artemisia* sp., *Bidens* sp., *Galium* sp. (including a clump of pollen), Asteraceae, Caryophyllaceae, Chenopodiaceae and Rosaceae as well as the stable concentrations of Poaceae, it becomes clear that the vegetation cannot be characterized as forested (Bennett, 2001; Chazdon et al., 2016). The appearance of vegetation in the landscape towards the middle of the assemblage zone can certainly be considered as groups of *Betula pubescens* individuals that are far from forming closed canopies. It seems plausible that stands of tree birches were mainly located in the sheltered riparian zone of, e.g., incision lakes. Here, plausibly at, e.g., the south-facing bank of the paleolake. The population density was high enough to gradually displace shrubs (especially *Hippophaë* sp. and *Juniperus* sp.) through dominance in the competition for light.

The percentages of *Pinus* reached a first minimum within this assemblage zone. The former high percentages have so far been interpreted as an extra-local input into the basin, although evidence on regional *Pinus* sp. presence in Schleswig-Holstein is not absent (Schütrumpf, 1958; Usinger, 1998). If we assume that the percentage representation of long-distance pollen depends on local pollen production (Birks et al., 2005), it can be deduced that (i) the local vegetation forms a closed cover, thus (ii) the low percentages of *Pinus* can be explained, and (iii) the general extra-local input is potentially lowered.

Further, it is worth considering the concentrations of charcoal particles. As within the previous assemblage zones, the erosion indicators within this PAZ continue to decrease. This was previously associated with decreasing meltwater input into the lake basin. As meltwater transport has been interpreted as the main input path of charcoal, it is reasonable to assume that charcoal concentrations have equally declined so far. An explanation for the noticeable short-term increase at the transition from NAH3 to NAH-4a could be that fires in the catchment area of the lake are by now the source for the input. However, a response of the vegetation to a hypothetical fire event cannot be observed within the assemblage zone. Another explanation could be charcoal input by regional fires.

As general remark, it can be said that there is a transition within this assemblage from an open grasses- and herb-dominated dry steppe to a very open, sparse and mosaic like woodland (Bennett, 2001), reflecting an important step within the primary succession.

NAH-4b (cf. Allerød 2 period/Dryas 2 period, 15.110–15.050 m) 13,710–13,610 cal yr BP.

The previously observed stratification of the clayey gyttja is not recorded further within the boundaries of this assemblage zone. The strongly fluctuating values of CaCO₃ can partly be explained by reflections of recorded mollusc fragments within the sediment. These in turn need to be considered in terms of potential lake level fluctuations. At the transition from the previous assemblage zone stronger alterations in the aquatic ecosystem can be observed. *Pediastrum* sp. and *Botryococcus* sp. display synchronous maxima and minima and also *Spirogyra* sp. (HdV-130) coincides with the changes at the transition. Later, the *Filinia-longisetata*-type reaches a maximum. In combination with the molluscs it needs to be assumed that water levels were presumably lowered at least seasonally during the assemblage zone (Van Geel et al., 1989).

The overall concentration values likewise display a decrease at the transition towards NAH-4b. This is mainly due to a strong decrease in

Betula pubescens-type and *Betula nana*-type pollen, which, however, is much less manifested in pollen percentages.

In the percentage composition a spread of grasses and herbs is reflected. It is noticeable that in addition to *Artemisia* sp., *Galium* sp., *Rumex* sp., *Dryas octopetala* and Poaceae also Brassicaceae are added to the previously referenced Dryas flora, whereas records of *Selaginella selaginoides* gradually decrease and disappear. Locally, in more humid areas – which may also become available due to lake level fluctuations – *Thalictrum* sp. and especially Cyperaceae spread rapidly.

In this assemblage zone, local stands of *Betula pubescens* on well drained predominantly sandy locations are displaced because of their low tolerance to drought of the corresponding GI-1c₂ (Mortensen et al., 2014a). Drought is further indicated as a reason for displacement by the fact that the abandoned areas are occupied partly by grasses and herbs, but predominantly by *Juniperus* sp. These have comparable temperature requirements as, e.g., *Betula pubescens* (Bos, 1998), but are much more tolerant to aridity (Miller and Wigand, 1994; Willson et al., 2008). Previous macrofossil finds, however, suggest that a likely representative of *Juniperus* was *J. communis* (Fischer et al., 2013; Hartz and Milthers, 1901; Mortensen et al., 2011). Thereby the species acted as further soil preparer and did not grow above shrub height (Iversen, 1973). According to Usinger and Wolf (1982), it is plausible that *Juniperus* sp. was promoted by light and temperature until trees (*Betula pubescens*) in the following PAZ restricted growth again by shading. The characteristics of such a pre-woodland-phase or *Vorwaldphase* (Usinger, 1998) can be seen in several diagrams in northern Germany: Stellmoor – Usinger unpubl.; Hämelsee – Merkt et al. (1993); Esinger Moor – Usinger (1981c); Kubitzbergmoor – Usinger (1981b); Glüsing – Menke (1968); Reinberg C – De Klerk (2008a).

The palynological characteristics meet mainly those of the *Juniperus*–*Betula pubescens*–PAZ as defined by Usinger (1985). The landscape of the area is again characterized by a grass and herb dominated shrub steppe with a higher contribution of *Juniperus* sp., where tree sized birches were presumably only present at isolated locations.

NAH-4c1 (cf. Allerød 3a period/mid Allerød period, 15.050–14.760 m) 13,610–13,120 cal yr BP.

A very fine annual lamination can be observed in the sediment soon after the beginning of the assemblage zone (14.975). Presumably, this phase of fine stratification mainly is a result of decreased wind exposure due to increased tree and woodland cover of the surroundings (Lotter, 1999). Furthermore, this corresponds to minor values and partly absence of erosion indicators (HdV-704, HdV-207, and rebedded pollen grains).

The strongly fluctuating values of CaCO₃ are attributed to the presence of fragmented molluscs in the sediment. The generally decreasing tendency is contrary to the organic sediment content, which is in turn a mirror of increased external organic input due to woodland cover of the surroundings.

The general concentration values tend to increase, with the shares of AP more than doubling. The initial strong fluctuations are due to *Betula pubescens*-type pollen and can partly be explained by changes in the sediment. A short-term drop in the organic sediment content and the initiation of fine lamination (14.975 m) indicate an altered sedimentation rate, which explains the changes in pollen concentrations. The lower lying minimum (15.025 m) occurs within a sediment sequence of very homogenous material. On the one hand a non-detectable change in the sedimentation rate would be plausible, on the other hand, such alterations were attributed to a variable local tree birch spread as stated by Schütrumpf (1943).

Considering the pollen percentage diagram, the dominance of *Betula pubescens*-type pollen is evident. In this assemblage zone, the tree birches reach their maximum Lateglacial distribution of > 77%. Therefore, it is not surprising that *Betula pubescens* is represented in the macrofossil record with fruit scales, benefitting from the temperature rise of the GI-1c₁. In this context, the decrease and partly the termination of the curves of heliophilous species (*Artemisia* sp., *Bidens* sp., *Helianthemum*

sp., *Rumex* sp., *Hippophaë* sp.) points to the formation of a birch woodland. However, *Betula pubescens*, even in more comprehensive populations, is not capable of shading the ground effectively (Dörfler, 2017).

The density of the woodland cover is mirrored in the well-established presence of faunal remains of various forest animals (*canis lupus*, *cervus elaphus*, etc.) found in north-eastern Germany and southern Scandinavia during the Allerød period (Bratlund, 1996; Wygal and Heidenreich, 2014). Synchronously, the presence of large herbivores with antler spans of 2 m to more than 3.5 m (*alces alces*, *megaloceros giganteus*) indicates that the tree population (at least in major parts) may not have been dense (Bokelmann et al., 1983; Bratlund, 1993; Riede et al., 2010; Terberger et al., 2004). This in turn would be consistent with the continuous values of *Betula nana*-type pollen and Poaceae.

As far as those are concerned, the concentrations remain approximately constant, which plausibly reflects the still rather open character of the woodland. This is also indicated by the percentage and concentration increase of *Betula nana*, that is low tolerant to shade but still could thrive in such an open birch tree woodland (de Groot et al., 1997; Ellenberg et al., 2001).

Whether *Pinus* sp. was already a part of this open woodland or still remains an expression of allochthonous input cannot be clarified with certainty. However, it is noticeable that the concentration of *Pinus* pollen is increasing towards the end of NAH-4c1 and that *Filipendula* and *Populus* pollen, albeit with few examples, have also been detected. According to Usinger and Wolf (1982), the distribution of pine in Schleswig-Holstein is accompanied by the occurrence of *Filipendula* sp. and *Populus* (cf. *tremula*), which in turn is the only broad-leaved tree species during the Allerød period apart from *Betula pubescens* (De Klerk et al., 2008a; Theuerkauf and Joosten, 2009).

However, Schütrumpf (1943) reports on macrofossils of *Pinus sylvestris* during the mid Allerød period in the area. Further also Overbeck and Schneider (1938) mention several finds of *Pinus sylvestris* needles from Lower Saxony from the same time period. Even if the presence of pine in this assemblage zone cannot be proven locally, it is very likely and would be in accordance with the results of Firbas (1949) and Schütrumpf (1937, 1958).

In this respect it cannot be ignored, that Usinger (1998) reported on much older charred wood fragments from the archeological site Ahrenshöft that could without doubt be identified as *Pinus sylvestris*. According to biostratigraphy, its presence would fall within the maximum expansion of *Hippophaë* sp. and would hence imply a migration of *Pinus sylvestris* already during the Meiendorf period. However, as suggested by Usinger (1998) it is more likely that these charred fragments are the remains of potentially broken arrows or artefacts that are made of imported wood and not locally collected fuel (Caruso Fermé, 2019). Further, also driftwood collected nearby at far reaching streams such as the Elbe river would be plausible (Mortensen et al., 2011).

Concerning NAH-4c1 special attention should be given to records of *Ephedra dystachia*-type and *E. fragilis*-type pollen. In northern central Europe there are several studies recording at least one of these types especially during the Allerød period. Nevertheless, some authors just record it without comment (Bos and Urz, 2003; De Klerk et al., 2008a; Jahns, 2000; Kolstrup, 1982; Litt and Stebich, 1999), some mention it and suggest long distance flight as source of origin (Fredskild, 1975; Krog, 1954), but some also infer presence without proof (Bos et al., 2018; Iversen, 1973). It is possible that it was more widely spread across northern central Europe during colder periods of the Lateglacial as species of *Ephedra* are drought and cold tolerant. Nevertheless, there is still no macro botanical evidence on Lateglacial presence in northern central Europe (Lang, 1994). Based on this lack of macrofossils, (ii) the very discontinuous *Ephedra* pollen record within the present study without clear pattern and (iii) with regard to species requirements of *Ephedra* sp. concerning light-demand and the fact that an open woodland spread locally, we clearly propose to attribute these pollen finds to the allochthonous input into the lake basin.

In the telmatic zone of the incision lake, *Filipendula* sp. (cf. *ulmaria*) sprouted on nutrient rich soils. In previous assemblage zones *Thalictrum* sp. and *Bidens* sp. had been able to spread here on the potentially periodically flooded banks.

The palynological characteristics of the assemblage zone meet mainly those of the *Empetrum*-*Betula pubescens*-PAZ as defined by Usinger (1985) with one constraint. This is the spread of *Empetrum* sp. that is not recorded in NAH and is attributed here to different local developments. Generally, a major transformation of the vegetation occurred as a result of the developing open woodland. In this woodland, *Betula pubescens* (on clayey soils) dominated but it is plausible that also *Pinus sylvestris* (on sandy grounds and river valleys) and *Populus* sp. contributed to the present tree species (Theuerkauf and Joosten, 2009).

NAH-4c2 (cf. Allerød 3b period/Gerzensee-Oscillation/IACP, 14.760–14.710 m) 13,120–13,030 cal yr BP.

Still, fine laminated sequences reflect constant and stable sedimentation conditions. Although, a short-termed change in the sediment is observable in the CaCO₃ content. The values decrease from 14% to 4%. An equal and synchronous drop is depicted in *Pediastrum* sp. values. This decrease in algae population as well as the drop in CaCO₃ content might be caused by the colder climate of the corresponding Gerzensee-Oscillation (Björck et al., 1998; Lotter et al., 2000).

The palynological characteristics of the Gerzensee-Oscillation are defined by Andersen et al. (2000) for Denmark and resumed by De Klerk (2002), De Klerk et al. (2008a), Krüger and Damrath (2019), Mortensen et al. (2011, 2014b), and they are observable in NAH-4c2 as well. Pollen concentrations for *Betula pubescens*-type pollen are lowered whereas *Pinus* pollen concentrations increase – a development that is equally reflected in the percentage diagram. Here, slight increases in heliophilous species such as *Artemisia* sp., *Plantago major/media* and *Filipendula* sp. could indicate short-term and small scale openings of the already open woodland. Contrary to the more northerly areas, however, there is only a minor spread of grasses and herbs in total, but presumably a rather accelerated spread of *Betula nana*.

At the same time, a reduction in *Betula pubescens*-type pollen could be explained by reduced pollen production in consequence of reduced temperatures of the GI-1b (Mortensen et al., 2011), which in turn could result in the higher concentrations and percentages of *Pinus* pollen. With regard to the presence of *Pinus* sp. it should be mentioned that a massive cluster of *Pinus* pollen has been recorded within this assemblage zone. Consequently, it is inferred that *Pinus* sp. (cf. *sylvestris*) was probably part of the local woodland.

Further, the local vegetation reflects a spread of species of wetter habitats. Cyperaceae, *Equisetum* sp. and *Thalictrum* sp. increase and the continuous record of *Empetrum* sp. could allude to more oceanic conditions and/or to a gradual leaching of carbonates (Bennike et al., 2004; Overbeck, 1975). The coincidence of *Sparganium* sp., *Sphagnum* sp. and Cyperaceae indicate the formation of a local marsh zone and is an expression of the ongoing terrestrialization.

In general, it is likely that only a slight change in vegetation can be expected during this assemblage zone. No significant further opening of the already open woodland can be inferred.

In conjunction with very different resolutions it becomes clear why relatively short oscillations are not reflected in the pollen profiles from Schleswig-Holstein so far. At low sample resolution, the Gerzensee-Oscillation (that is reflected in the NAH record for less than 100 years) might only be recorded in one or two samples and would hence potentially be neglected during zonation.

NAH 4c3 (cf. Allerød 3c period/late Allerød period, 14.710–14.570 m) 13,030–12,840 cal yr BP.

Alterations of the sedimentation rate within this assemblage zone are related to the influence of the Laacher See Tephra (LST), which is further used as an important isochronous time marker here (Brauer et al., 1999; Bronk Ramsey et al., 2015; Schmincke et al., 1999). The

varve thickness is quadrupled temporarily, but the lamination continued (Dreibrodt et al., 2020). This thickening of varves further explains the rapid but short-termed drop in organic sediment content. Here, the input of silicates in particular favored the preservation of diatoms for about 20 years (Dreibrodt et al., 2020). Congruently, a time range of 20–25 years is given by Merkt and Müller (1999) for the Hämelsee sequence and by Litt and Stebich (1999) for the Meerfelder Maar sequence until the sedimentological conditions returned to their state prior to the Laacher See eruption (LSE).

The LSE is one of the most powerful eruptions of the late Quaternary (Schmincke et al., 1999). Therefore it is not surprising that cryptotephra was found in the sediments of the Nahe paleolake (Krüger and van den Bogaard, 2020), even if the position was previously considered to be located outside the known ash fallout zone (Riede et al., 2011; van den Bogaard and Schmincke, 1984). Hence, the question arises to what extent the LSE had a detectable effect on the local and regional environment.

Sediment analyses of the respective NAH record section revealed that the introduction of different material from the LSE conditioned a slight acidification of the lake system. Generally, an aquatic ecosystem reacts directly to alterations. In this respect the strong and immediate rise in *Pediastrum* sp. and *Botryococcus* sp. values subsequent to the LSE can be linked to altered competition conditions favoring different green algae species (Dreibrodt et al., 2020; Weckström et al., 2010).

The concentration values reveal that various telmatic and upland species report an increase around the LST. However, in contrast to green algae values, they do not rise synchronously and occur before (*Pinus* sp., *Betula pubescens*-type, *Artemisia* sp., Poaceae, Cyperaceae), at (*Salix* sp., *Filipendula* sp., *Rumex acetosa*-type) and after the cryptotephra layer (*Juniperus* sp., *Menyanthes* sp., Chenopodiaceae). Following De Klerk et al. (2008b) it is plausible that these increases in concentration are linked to temperature rises succeeding the Gerzensee-Oscillation rather than being connected to an eutrophication of the environment by nutrient input through the LSE. Equal degrees of delay in pollen concentration increase can be explained by amplified varve thickness.

General small-scale changes in the palynological spectrum could also be related to increased allochthonous input by stronger erosional processes through storms and extreme weather events following the LSE (De Klerk et al., 2008b; Schmincke et al., 1999). These led to short-term discontinuations of the annual stratification of the NAH sediment record that coincide with synchronous drops in various concentration curves (Dreibrodt et al., 2020).

Coinciding maximum values of *Filipendula* sp., *Salix* sp. and Cyperaceae are apparent. A spread can be related to an increase in the water level that in turn was controlled by heavy rainfall following the LSE (Dreibrodt et al., 2020; Theuerkauf, 2003).

In this context the decline of the bank vegetation can also be seen. Here, decreasing or fluctuating values of *Sphagnum* sp., *Menyanthes* sp., *Sparganium* sp. and *Equisetum* sp. can be observed, relating to unstable water tables.

Consequently, considering the environmental impact of the LSE to the surrounding of the Nahe paleolake we might assume that a change within the aquatic ecosystem occurred abruptly, whereas the upland vegetation does not seem to be effected.

Up to the following assemblage zone, the concentration and percentage values of *Betula nana*-type pollen show a classical sawtooth pattern without an obvious tendency. Differences in the sample preparation are not given and even unlikely, because only *Betula nana*-type pollen are affected.

A spread of *Betula nana* after a drop of the water level and a drought is not to be assumed, because *Betula nana* is especially sensitive to dryness (Ellenberg et al., 2001). Also the parallelization with corresponding high-resolution regional diagrams (Stellmoor - Usinger unpubl.) shows no further spread of dwarf birches.

Fluctuations (although independent of *B. nana*) can also be observed in *B. pubescens*. Both could potentially be related to different pollen productivity in different flowering years (Sugita et al., 2010).

NAH-4c4 (cf. Allerød 3d period/late Allerød period, 14.570–14.370 m) 12,840–12,540 cal yr BP.

The palynological assemblage and the geochemistry of NAH-4c4 are controlled by two important factors. The first is a profound fire event that occurred around 14.525 m/~12,790 cal yr BP to which a reaction of the vegetation is observable. The second, however, is a fast but gradual alteration around 14.448 m/~12,700 cal yr BP from annually laminated to very homogenous sediments. These factors and the resulting effects need to be considered separately, although, with regard to biostratigraphy, they belong to the same unit – describing the transition from a dense woodland to a shrub tundra. This overarching transition is clearly visible in (i) the AP/NAP ratio, which changes from 90/10 to 70/30, here mainly to the decrease of *Betula pubescens*-type pollen, (ii) in an overall decrease in pollen concentration from about 6000 to about 3500 pollen per cm³ sediment and (iii) the corresponding decreasing tendencies in organic sediment content and CaCO₃ content.

With regard to the peak in charcoal particle concentration and in coincidence with increased occurrences of larger particles (charcoal size classes > 50 µm), a fire of unknown size is inferred.

Rearrangement or secondary deposition of the charcoal particles can be excluded, as for the first time these do not display similar trends as erosional indicators. Here, single high values of charcoal coincide with absence of HdV-704 and HdV-207. This is further supported by the fact that continued stable conditions in and around the basin are indicated by the persisting annual lamination of the sediment. Finally, a reaction of the vegetation (natural succession) is observable succeeding the charcoal peak.

A drop in the organic sediment content can be observed as a direct result of the fire event and its impact on the environment. It is possible that the produced black carbon and ash was introduced into the lake system and caused a slight eutrophication (*Pediastrum* sp. and *Botryococcus* sp.) (Odhiambo and Routh, 2016).

A strong decrease of *Betula pubescens*-type pollen visible in concentration and percentage values as well as less-pronounced decreases of *Juniperus* sp. and *Betula nana*-type pollen are the direct consequence of the fire. In contrast, *Pinus* sp. does not appear to have been adversely affected as an increase is indicated directly subsequent to the fire.

This opens up two possibilities for an interpretation. On the one hand it is possible that the immediate higher input of *Pinus* sp. pollen can be interpreted as an increased allochthonous component, in direct consequence of reduced woodland cover. However, this seems unlikely, as the sediments, which are continuously annually laminated, display practically no variation in layer thickness.

On the other hand, it could be assumed that the fire was not a crown fire but a surface fire. This would explain why shrubs such as *Juniperus* sp. and *Betula nana* are particularly affected. *Betula pubescens* could also be affected, as leaves and bark can easily burn in periods of extreme drought. *Pinus* sp., in turn, is at least partially protected against ground fire by the growth of a bark (Fernandes et al., 2008; Pausas, 2015).

The second explanation seems plausible, as here the woodland cover would only partially decrease and continue to contribute to a certain protection against wind, which would firstly favor the formation of varves in the lake and would secondly explain the rapidly increasing *Pinus* concentration and percentage values.

Clearly grasses and herbs would have been burned and effected as well, but as one sample covers several years (here about 5) a decline would only be visible on an annual resolution level. Therefore, the record shows that grasses and herbs directly benefitted during the following growing seasons from the brightening up of the ground and the partly reduced shading. This explains the synchronous spread of *Artemisia* sp., *Filipendula* sp., *Galium* sp., *Salix* sp. (cf. *herbaceae*), *Menyanthes* sp., Chenopodiaceae, Rosaceae and Poaceae. Especially the continuous record of *Helianthemum* sp. indicates the reduced degree of shading.

Further, this is in line with evidence on the heliophilous and entomophilous *Epilobium* sp. (cf. *angustifolium*) that initially colonized burned areas (Keeley and Keeley, 1987; Tinner et al., 2008).

Regarding the cause of the fire, a phenomenon seems plausible that is reflected at the transition from Allerød period to Dryas 3 period at multiple sites and records in northern central Europe. Due to extreme drought, temporally undefined wildfires occurred here, which subsequently led to the formation of the *Usselo* and *Finow* horizons at terrestrial sites (Crombé, 2016; Hoek, 1997; Kaiser, 2003; Kaiser et al., 2009; Tolksdorf et al., 2014; Van der Hammen and Van Geel, 2008). In limnic archives of Jutland and Schleswig-Holstein at the transition from the Allerød period to the Dryas 3 period often hiatuses can be observed (Krüger and Damrath, 2019; Iversen, 1942; Usinger, 1981a; Usinger and Wolf, 1982). Here, these hiatuses are mainly the result of the mentioned droughts that in turn are responsible for lake level fluctuations and extensive redeposition processes (Kasse, 1997; Usinger, 1981a). As the presented sediment sequence derives from the center of the former incision lake these fluctuations only had a minor effect, explaining a continuous record and the reflection of a fire event.

After the fire the new spread of the tree birches began until about 20–23 years later the conditions prior to the fire event existed again. However, once these conditions are reached, a gradual opening of the woodland occurred, which is indicated by strong increases of *Artemisia* sp. and *Filipendula* sp. towards the upper boundary of the assemblage zone.

The gradual opening is particularly reflected in the concentration values of *Betula pubescens*-type pollen that now fall to levels equal to stadial periods. *Pinus* sp. declines to an equal extend. The inferred loss of woodland cover resulted in pronounced exposure to wind and further erosional processes and explains the termination of yearly laminae in the sediment (Lotter, 1999; Usinger, 1981a).

The altered sedimentation conditions caused strong fluctuations in organic sediment content and CaCO₃ content. The latter decreases extremely towards the upper boundary and thus compares Europe-wide records of the beginning Dryas 3 period (Hoek et al., 1999; Mortensen et al., 2011; Van Asch et al., 2012).

Immediately coinciding with the sediment change, erosion indicators reappear (HdV-704, HdV-207, and rebedded pollen grains). The concentration of charcoal particles rises equally, without any visible reaction of the vegetation. Therefore, these now suggests rearrangement or secondary deposition rather than further fires, although this cannot be excluded with absolute certainty.

The gradual transformation of a dense woodland into a shrub tundra is manifested in the increase of pollen of heliophilous grasses and herbs (*Artemisia* sp., *Rumex acetosa*-type, *Ranunculus acris*-type, *Potentilla* sp., Caryophyllaceae, Asteraceae, Chenopodiaceae, Poaceae) and *Betula nana*-type pollen as well as the overall decrease in AP. The record of the heliophilous but also thermophilous *Filipendula* sp. revealed decreasing concentration and percentage values. This is explained by the decreasing temperatures, which is the limiting factor here.

Rising water levels or at least changed precipitation conditions ensure that *Equisetum* sp. and especially Cyperaceae spread among the local and riparian vegetation. In conjunction with an accelerated spread of *Menyanthes* sp. and the presence of *Sphagnum* sp. this is likely to reflect oligotrophication (Menke, 1968).

The quantitative and temporal contribution of *Betula* (cf. *pubescens*), *Pinus* (cf. *sylvestris*) and *Populus* (cf. *tremula*) deadwood in the landscape is difficult to estimate. It is likely that up to a certain point dead trees also contributed to the landscape at the end of the Allerød period. But apart from spores of *Gaeomannomyces hyphopodia* (HdV-126) and clusters of globose fungal cells (HdV-200) – both potential indicators of local stands of *Carex* sp. that fit well with the recorded Cyperaceae pollen (Kuhry, 1997; Van Geel et al., 1989) – there are no expectable indicators for wood decomposition in the record.

It can of course be argued that this last section of the assemblage zone (from 14,448 m/~12,700 cal yr BP onwards) can already be

ascribed to the Dryas 3 period. As the boundaries were set according to biostratigraphy, they do not necessarily coincide with lithological boundaries (Hedberg, 1976; Leroy et al., 2000). Therefore, the biostratigraphic unit Dryas 3 in this profile comprises exclusively that section which reflects fully developed stadial conditions. Assemblage zone NAH-4c4 apparently reflects the transformation of the vegetation from a dense woodland to a shrub tundra and is hence categorized as belonging to the Allerød period. Therewith, the (biostratigraphic) Allerød period extends far into the (climatically defined) GS-1, highlighting once again that biostratigraphic terms and climatic phases are not to be used as synonyms.

NAH-5a (cf. Dryas 3a period, 14.370–14.240 m) 12,540–12,030 cal yr BP.

The assemblage zone comprises very homogeneous clayey gyttja without recognizable stratification. It includes a significant portion of coarse-grained material that suggests rising degrees of different erosional processes – especially aeolian activity (Bakke et al., 2009; Brauer et al., 2008). In addition, the sediment sequence of NAH-5a encompasses the Vedde Ash (14.260 m/~12,110 cal yr BP), which is deposited just before the upper zone boundary. An environmental impact cannot be estimated as potential (if any) influences are masked or blurred by the degree of redeposition. This is apparent through the common tail-off pattern of the cryptotephra shards into the following assemblage zone as well as through bioturbation of fewer shards rearranged into slightly deeper levels (Krüger and van den Bogaard, 2020).

Lime precipitation had completely ceased by the end of the previous assemblage zone. According to Hoek et al. (1999) this is controlled by the deep seasonal frost, a major drop in July temperatures as well as permafrost formation in the area (Theuerkauf and Joosten, 2012). The organic content of the sediment decreases to levels comparable to the Meiendorf or Dryas 1 period. This can be explained by the significant loss in biomass around the incision lake and the strong reduction of aquatic productivity. However, the depth 14.310 m/~12,310 cal yr BP marks a turning point.

By that depth organic proportions of the sediment continuously rise. The only detectable change at this stage is an extreme increase in *Pediastrum* sp. concentrations and percentages. This was preceded by a spread of *Botryococcus* sp. Nevertheless, it is rather unlikely that these green algae are the reason for an upheaval in the organic sediment content. It is far more plausible that the previous reduced organic sediment content can to a certain point be explained by erosion of former bank sediments and their secondary deposition due to a lowered lake level. This in turn leads to the conclusion that the interpretation of the palynological record can only be done with caution, as it is also masked by rearrangement.

Rearrangement and redeposition of older sediments are further emphasized by the anewed closed curves of HdV-205 and HdV-704. At the same time the record of Desmidiaceae (HdV-332) reflects stadial conditions and is indicative for the Dryas 3 period throughout northern central Europe (Van Geel et al., 1989).

Tripled concentrations of charcoal particles can likewise be associated to some extent with increased erosion. A wildfire in the immediate vicinity of the basin is excluded, as unlike within NAH-4c4, no recognizable reaction of the vegetation is discernible. This is further referred to in 4.5 considering charcoal particles of the palynological record and in detail by Krüger 2020.

The general pollen concentration rate in the sediment displays only slightly lower values compared to the terminating Allerød period. However, the composition underwent a marked change. The proportion of AP drops to about 30%. Here, continuously long-distance flight is the undoubted explanation for unaltered 10% of *Pinus* pollen concentration throughout NAH-5a and 5b.

The further decreasing values of *Betula pubescens*-type pollen can likewise rather be explained to a certain extent by long-distance transport (Hjelmroos, 1991, 1992; Wallin et al., 1991). However, *Betula*

pubescens macrofossils are present in the NAH record. Certainly, these too may have been subject to rearrangement and could well originate from the previous Allerød period. Nevertheless, the high number of detected nutlets and fruit scales of *Betula pubescens* across the region highlight the presence of trees during the Dryas-3 at least in southern parts of Schleswig-Holstein (Firbas, 1949; Schütrumpf, 1943; Usinger, 1981b, 2004).

Betula nana-type pollen (supplemented by finds of macrofossils) reached their Lateglacial maximum values by the beginning of NAH-5a and likewise Poaceae values increase strongly, indicating a significant spread. This coincides with the incipient and continuous record of diverse heliophilous species such as *Artemisia* sp., *Selaginella selaginoides*, *Dryas octopetala*, *Ranunculus acris*-type, Caryophyllaceae, Asteraceae, Chenopodiaceae (also recorded as macrofossil) and *Helianthemum*-type pollen, reflecting a regime shift of the vegetation towards an open heathland/steppe like vegetation. Although, significantly lower values indicate less pronounced distributions than, for example, during the Meindorf and Dryas 1 period. As already suggested by Iversen (1954) *Empetrum* sp. (cf. *nigrum*) here supersedes *Helianthemum* sp., which can be interpreted as a clear sign for the leaching of carbonates from the soil (Bennike et al., 2004; Overbeck, 1975). This is in line with the continuous presence of the more acidophilous *Rumex acetosa*-type, *Calluna* sp. and *Vaccinium*-type pollen.

We might assume that low tree birches grew at favorable locations, such as the banks of the Nahe paleolake, and partly formed riparian woodlands, with the majority of the vegetation being dominated by a grass and shrub-heath tundra. Here *Betula nana* and *Empetrum* sp. (cf. *nigrum*) predominated the mosaic-like vegetation dispersal in the landscape that Usinger (2004) understandably refers to as *park-tundra*.

It has been assumed on several occasions to divide the Dryas 3 period into two phases. The first phase would here, on the one hand, be characterized by persisting dryness with very cold winters – due to sea ice formation in the North Atlantic – but still rather warm summers. In particular the latter could here be inferred from *Filipendula* sp. and *Urtica* sp. pollen, which are exclusively recorded during NAH-5a.

The second phase, however, would then be controlled by more oceanic conditions, i.e., rising humidity and on average colder summers, which is consistent with the palynological assemblage of the following NAH-5b (Bakke et al., 2009; Broecker, 2006; Denton et al., 2005; Isarin and Bohncke, 1999; Leroy et al., 2000; Merkt and Müller, 1999; Overbeck, 1975; Theuerkauf and Joosten, 2012; Usinger, 1981b).

NAH-5b (cf. Dryas 3a period/late Younger Dryas period, 14,240–14,140 m) 12,030–11,560 cal yr BP.

A homogeneous clayey gyttja including coarse-grained material further characterizes also the sediment sequence of NAH-5b. Whilst the CaCO₃ content remains unaltered low, the organic content continues to increase. Following De Klerk et al. (2008a) the higher organic content in comparison to the Dryas 1 period is controlled by less allochthonous input due to a denser vegetation cover of the park-tundra. However, redeposition, potentially of mobilized material from the shore, is unequivocally indicated by HdV-205, HdV-704 and *Cenococcum geophilum* sclerotia. This is in line with fragments of wood of *Populus tremula*. It was found at 14,220 m/~11,940 cal yr BP and has been dated twice (Dreibrodt et al., 2020). Both radiocarbon dates give equal results and fall well within the Allerød period, emphasizing persisting rearrangement of potentially Allerød sediments from shallower areas or the shore line.

The remarkably high concentration values of charcoal particles can equally be explained to a certain extent by redeposition. Thus, a wildfire near the incision lake cannot be assumed, as there is no reaction of the vegetation inferable from the record. It is remarkable that these high values coincide with the reconstruction of more humid conditions (see below). Therefore, and because of the archeological record in the vicinity (Wild, 2017), human–environment–interaction must be considered as an additional component of the total charcoal concentration.

This is further referred to in 4.5 considering charcoal particles of the palynological record and in detail by Krüger 2020.

Already in the previous assemblage zone, a strong increase in *Pediastrum* sp. values was recorded, which rise up to the clear Lateglacial maximum in NAH-5b. As *Pediastrum* sp. and *Botryococcus* sp. both include various taxa that differ in ecological requirements (Jankovská and Komárek, 2000; Komárek and Marvan, 1992), it is not clear what caused this rapid spread. However, this can hypothetically be linked to (i) further lake level alterations or, more plausible, to (ii) nutrient input via aeolian activity (Brauer et al., 2008).

The general pollen concentration in the sediment decreases marginally. However, increases of *Pinus* sp. and *Empetrum* sp. – which characterize this assemblage zone in the percentage diagram – are clearly visible, due to the fact that concentrations of other pollen types are decreasing considerably. These include *Betula pubescens*-type, *B. nana*-type and *Artemisia* sp. pollen. Consequently, a minor decline of these species is more likely than a significant expansion of *Pinus* sp.

There is again a distinct sawtooth pattern observable in the concentration values. Within NAH-5b this affects several pollen types simultaneously (Poaceae, Cyperaceae, *Artemisia* sp., *Betula pubescens*-type, *B. nana*-type) and could thus be associated with differences in sample preparation. Samples with lower concentrations were taken from a more recent series of subsampling and were treated temporally longer with acetolysis (Fægri and Iversen, 1989). Additionally, increasing humidity and colder summers could be another factor that adversely affected the general pollen production of different species during this assemblage zone resulting in an overall concentration decline (Overbeck, 1975; Usinger and Wolf, 1982).

The assumption concerning colder summers would be in line with the termination of evidence of *Urtica* sp. and a further decline of *Filipendula* sp. In contrast, the absence of *Pinus* sp. in the area is rather linked to permafrost formation (north of 53°N) during the Dryas 3 than to lower summer temperatures (Theuerkauf and Joosten, 2012).

During NAH-5b characteristic steppe elements (*Artemisia* sp., Poaceae, Chenopodiaceae) and especially elements of the shrub tundra (*Betula nana*, *Empetrum* sp., *Juniperus* sp.) were continuously dominant among the vegetation. *Betula pubescens* probably remained present in the most sheltered places. Indicators of stadial conditions (*Dryas octopetala*, *Selaginella selaginoides*) and numerous other heliophilous species (*Helianthemum* sp., *Ranunculus acris*-type, Rosaceae, Asteraceae, Caryophyllaceae) were common.

Within the mosaic-like vegetation in the landscape there was a shift in importance of *Betula nana* and *Empetrum* sp. (cf. *nigrum*). The latter is favored in certain regions by the increasing oceanicity and in others by the increased formation of dunes as a result of aeolian activity. Both is controlled by relatively warm and moist winds. The resulting accelerated expansion of *Empetrum* sp. (cf. *nigrum*) is shown in maximum distributions in a wide range along the coastal areas between the Netherlands, Northern Germany and Denmark (Bakke et al., 2009; Behre, 1966; De Klerk, 2008a; Hoek, 1997; Hoek et al., 1999; Iversen, 1954; Litt and Stebich, 1999; Merkt and Müller, 1999; Mortensen et al., 2014b; Müller and Kleinmann, 1998; Odgaard, 1994; Usinger and Wolf, 1982).

The appearance of vegetation in the landscape remained a mosaic of predominantly tundra and steppe elements, but possibly with groups of tree birches in the most sheltered and protected places, on southern slopes of low moraine ranges and the riparian zones of various wetlands areas and streams (Usinger, 2004).

NAH-6a (cf. Preboreal a/ early Preboreal/ Friesland Oscillation, 14,140–14,030 m) 11,560–11,390 cal yr BP.

NAH-6a covers a sediment sequence of very homogeneous gyttja with increasing organic content. Coarse-grained material is no longer found. This coincides with the termination of the curves of various erosion indicators (HdV-205, HdV-704, corroded and rebedded pollen grains), which in sum suggests a reduction of different erosional processes in and around the lake. Only the charcoal particle concentrations

display slower declining tendencies and temporarily remain at higher levels. This is again further referred to below and in detail by Krüger 2020.

The resumption of CaCO₃ precipitation is clearly controlled by the rapidly increasing temperatures that are generally responsible for the massive alterations in vegetation composition in this assemblage zone (Björck et al., 1998; Johnson et al., 1992).

The general pollen concentration in the sediment reveals partly a more than tenfold increase of the values. While *Pinus* sp. pollen concentrations marginally rise, its actual presence cannot be clarified. Here, *Betula pubescens*-type pollen constitute the dominant share, but also *Betula nana*-type pollen, *Salix* sp., *Filipendula* sp. and Poaceae proportions increase.

Concerning *Betula pubescens*-type pollen in particular, different factors interact here: The presence of tree birches during the preceding Dryas 3 period implies that a dispersal of birch trees can occur immediately succeeding the temperature rise, without possible time-lag. Furthermore, the temperature stimulated the pollen production, which in sum explains the substantial increase of the concentration values. Therefore, in southern Schleswig-Holstein, there is no pronounced *Juniperus* phase heralding the spread of woodland, as is known from Danish records (Krüger and Damrath, 2019; Mortensen et al., 2011). It is observable in the concentration values, that there is a rise in *Juniperus* sp. values in the early Preboreal period that might even be stronger pronounced than during the early Allerød period. However, a potential widespread distribution of *Juniperus* sp. is potentially masked by the strong pollen production of the tree birches. Also, and contrasting the early Allerød period, this rise coincides with the mass expansion of tree birches (*B. pubescens* and *pendula*).

Macrofossils have so far proven that *Betula pendula* was strongly expanding in Schleswig-Holstein by the beginning of the Preboreal period (Usinger and Wolf, 1982). Their distribution is bound to higher summer temperatures, a longer duration of the vegetation period and the melting of permafrost (Theuerkauf and Joosten, 2012) – all given in the course of the Preboreal period.

Consequently a further birch species is presumably present in the record that produce pollen of a size that lays statistically between *B. pubescens* and *B. nana* (Beug, 2004; Usinger and Wolf, 1982). This means that an application of the defined threshold of 21.5 µm can no longer be justified. Pollen of *B. pendula* and potential other hybrid forms explain the fluctuations of *B. nana*-type pollen values. These fluctuations of concentrations and percentages in the early Preboreal period are probably less related to the spread of *B. nana* than to the spread of *B. pendula*. Certainly, *B. nana* was still present at some sites, but the high pollen concentration of *B. pubescens*-type pollen suggests that tree birches (both, *B. pubescens* and *B. pendula*) formed closed stands. Usinger and Wolf (1982) suggested that *B. pendula* spreads on drier soils. This could explain the low values of *Pinus* sp. as its spread could presumably be partially prevented.

Large-scale shading of smaller growing plants is illustrated by strong declines or terminations of the values of heliophilous species (*Helianthemum* sp., *Artemisia* sp., *Rumex* sp., *Ranunculus acris*-type, *Bidens*-type, *Empetrum* sp., Chenopodiaceae, Caryophyllaceae, Asteraceae). However, also the increased pollen productivity of *Betula* species – potentially taking advantage of the warmer temperatures – could lead to an overall declining effect in other pollen types.

However, conversely the values of the Poaceae increased. Here *Phragmites* sp. is suspected to contribute to a certain extent, masking the actual decline of upland grasses (Averdieck, 1957; De Klerk, 2002; Overbeck, 1975; Usinger, 2004). *Phragmites* sp. possibly established as part of the bank vegetation, to which also *Equisetum* sp. and Cyperaceae belonged. The spread of bank vegetation with the beginning of the assemblage zone is in turn closely related to the rise in temperature. *Filipendula* sp. and especially *Typha latifolia* imply that the annual average temperature reached at least 13 °C (Bos, 1998).

The declining *Pediastrum* sp. values can presumably be explained by less erosional material that is introduced into the basin. Likewise, it could be connected with a spread of *Myriophyllum* sp. (cf. *spicatum*). Accordingly, there must have existed sufficient shallow water areas near the banks where it could thrive (Rothmaler, 2017). Whether the expansion of *Myriophyllum* sp. is controlled by an upheaval of the lake level – as suggested by Usinger (1981a) for lakes throughout Schleswig-Holstein in the early Preboreal period – cannot be deduced. However, apart from the presence of the *Myriophyllum spicatum*-type and the termination of the curve of *Spirogyra* (HdV-131) there are no further signs of altered lake levels here.

At the beginning of the Holocene, a primary succession started, that has been named *Friesland-Schwankung/Friesland-Oscillation* by Behre (1966) and was as further described by Iversen (1973), Overbeck (1975), Odgaard (1994), De Klerk (2002), Hoek (2001), Usinger (2004) or Nelle and Dörfler (2008) for northern central Europe. Concerning the surroundings of the Nahe paleolake, the park-tundra was replaced within a relatively short timeframe by a birch forest that extended over large parts of the landscape. The share of dwarf birches cannot be determined from pollen statistics by the beginning of the Holocene. Here, for the Nahe paleolake, current studies on lipid biomarkers may provide further information.

NAH 6b (cf. Preboreal b/ Preboreal Oscillation/Rammelbeek phase, 14,030–13,955 m) 11,390–11,250 cal yr BP.

NAH-6b spans a sediment sequence of homogeneous gyttja with rarely altering (increasing) organic content and CaCO₃ content. However, significant changes in pollen concentrations are apparent. The total pollen concentration declines by approximately one-half, whereby this is particularly at the expense of *Betula pubescens*-type pollen.

In case that the landscape becomes more open, one would expect the heliophilous *Betula nana* to expand at least temporarily. The concentration values of *Betula nana*-type pollen, however, are likewise declining. This can be explained by the assumption that *B. pendula* actually had large proportions of both birch pollen types since the beginning of the preceding assemblage zone. Their previous distribution was particularly limited by the low temperatures (Theuerkauf and Joosten, 2012). Decreasing annual mean temperatures are now again restrictive (Kromer and Becker, 1993; Lotter et al., 1992). However, it is most unlikely that an actual opening took place. It can rather be assumed that lower temperatures predominantly led to lower pollen production (Theuerkauf et al., 2014).

The absence of erosion indicators – here especially soil erosion (HdV-205 and *Cenococcum geophilum*) – would be an argument against an opening of the landscape. Further, also the absence of coarse grained material in the sediment suggests a closed vegetation cover – with regard to the pollen composition predominantly of forest character. Nevertheless, rising trends in Poaceae pollen concentrations and percentages are evident. In the previous assemblage zone it has already been assumed that *Phragmites* sp. contributed to this to a certain extent (Usinger, 2004). To assume an opening due to a general Poaceae increase is therefore not justified.

In case that this could be excluded, a slight spread of the Poaceae could, however, equally be related to the shadowing of *Empetrum* sp. and *Calluna* sp. due to the forest cover. Grasses, herbs and ferns (cf. *Polypodium* sp.) would thrive in the shady undergrowth of the denser birch forest (Overbeck, 1975). Nevertheless, apart from minor increases in *Rumex* sp., *Thalictrum* sp. and *Salix* sp. (cf. *herbaceae*) there are no further observable alterations in pollen values of low growing plants.

Whether *Pinus* sp. gradually became part of the forest remains uncertain. In contrast, macrofossils of *Populus tremula* are a clear indication for the presence of this tree during the early Preboreal period (Schütrumpf, 1937; Usinger, 2004), despite the fact that *Populus* sp. is generally represented with very low values: present study <1%; Slotseng <1% – Mortensen et al. (2011); Hämelsee ~1% – Merkt and Müller (1999); Westerhauderfehn ~1% – Behre (1966); Stellmoor ~8%

– Usinger unpubl.; Kubitzbergmoor 1–2% – Usinger (1981b); Scharnhagener Moor 1–2% – Usinger (1981b).

Changes of the vegetation within this assemblage zone are considered to be controlled by a short-termed climatic setback and hence are in line with multiple records across northern central Europe (Björck et al., 1997; Iversen, 1973; Lotter et al., 2000; Usinger, 2004; Van Geel et al., 1981). Here, this assumption is supported by the reaction of thermophilous species. While *Filipendula* sp. is significantly decreasing in concentration and percentage values, the curves of *Typha latifolia* and *Myriophyllum spicatum* terminate. As a result, the average July temperature has probably undershot the 13 °C limit (Bos, 1998). This lead to a shift in competition among different species potentially favoring *Equisetum* sp. that hence occupied habitats on the banks of the lake.

In this assemblage zone, an opening of the forest, if actually occurring, is only marginally. The observed decline of certain species depends in some cases on their low tolerance of lower average July temperatures. This leads on the one hand to a decline in the population (*Typha latifolia*, *Myriophyllum spicatum*, *Filipendula* sp.) and on the other hand to a reduction in pollen productivity (cf. *Betula pendula*).

NAH-6c (Preboreal c/ late Preboreal period, 13.955–13.695 m) 11,250–10,750 cal yr BP.

The abundant production of organic matter by the surrounding forest causes a further increase in the organic content of the gyttja. A change in sediment towards a reduced CaCO₃ content within this assemblage zone could at least partly be linked to the growth of *Nymphaea* sp. The expansive leaves of the water lily probably shade algae (*Botryococcus* sp., *Pediastrum* sp., HdV-603), which further decreased lime precipitation and explains the fluctuation of CaCO₃ content in the sediment (Hoek et al., 1999).

The beginning of NAH-6c coincides with a peak in charcoal particle concentrations. Nevertheless, only minor changes can be observed in the concentration values of several species (*Artemisia* sp. Poaceae, *Betula nana*-type, *Betula pubescens*-type, *Pinus* sp., *Equisetum* sp.), but they do not reveal any discernible correlation or succession as in NAH-4c4 (late Allerød period). A potential wildfire remains uncertain.

The assemblage zone is characterized by a general renewed increase of pollen concentrations in the sediment. In particular, AP have a strong proportion, with *Betula pubescens*-type pollen rising immediately, while *Pinus* sp. pollen values increase steadily and gradually. Strongly fluctuating but generally increasing proportions of *Betula nana*-type pollen are again bound to the influence of *B. pendula* pollen. A dense forest appears plausible and explains the lack of heliophilous herbs and shrubs. The undergrowth of the trees is composed of different species of the Poaceae family, as well as an increasing amount of ferns (*Dryopteris* sp., *Polypodium* indet.).

An increase in Poaceae is connected once again with an expansion of *Phragmites* sp. This is plausible in consideration of the development of a dense and tall growing bank vegetation of *Typha latifolia*, to which *Sparganium* sp. subsequently follows. Here, they replace *Filipendula* sp. and *Equisetum* sp. in particular.

A dense forest can be assumed for NAH-6c, in which *Pinus* sp. became progressively important. The proportion of *Betula nana* cannot be estimated, although it is plausible that it was gradually shadowed and could not thrive for long in the undergrowth of the Early Holocene forest.

Usinger (2004) suspected a second Preboreal oscillation (PBO2) that would fall within NAH-6c. This hypothetical oscillation, however, cannot be detected here. The visible changes in pollen composition are well within the expected natural range and do not reveal alterations where climatic causes must be considered. This is either because (i) a possible second oscillation is of such short duration that it is not pronounced within the sampling grid, (ii) it was not detected because its short duration in combination with a changed sedimentation rate led to its blurring in a mixed spectrum, (iii) a possible oscillation had no detectable influence in the region (as could be inferred from Table 1 compiled by Usinger in the same publication in 2004), or (iv) the inferred oscillation

Table 1

Overview on the lithology of the NAH sequence.

Depth masterscale (cm)	Lithology
160–surface	Fen peat
13.850–160	Detrital to calcareous gyttja
14.190–13.850	Detrital gyttja with decreasing clay component
14.415–14.190	Clayish detrital gyttja with medium to fine grained sand
14.449–14.415	Clayish detrital gyttja
14.930–14.449	Fine laminated gyttja
15.100–14.930	Gyttja with increasing organic components
15.411–15.100	Gyttja with silt and clay components
15.451–15.422	Layer of medium to fine grained sand
15.480–15.451	Very homogenous clay with fine grained sand components
15.496–15.480	Layer of medium to fine grained sand
15.551–15.496	Irregularly varved and partially homogenous clay
15.565–15.551	Layer of medium to fine grained sand
15.619–15.565	Irregularly varved and partially homogenous clay
15.670–15.619	Layer of medium to fine grained sand
15.778–15.670	Varved clay
15.890–15.778	Coarse grained glacial sand

at Kubitzbergmoor (Usinger, 2004) reflects a natural succession subsequent to a local fire. Unfortunately, the latter cannot be proven right or wrong as Usinger did not record (or show) charcoal particles in pollen profiles.

NAH-7a (Boreal a/early Boreal period, 13.695–13.485 m) 10,750–10,370 cal yr BP.

In the course of NAH-7a, stable values of the organic sediment content and the CaCO₃ sediment content are reached. While the reason for the strong initial fluctuation of CaCO₃ content remains unclear, a constant forest cover with a closed canopy requires stable and continuous input of organic material.

The general pollen concentration values increase strongly, but display a minimum of two samples revealing that all taxa are affected. The two samples belong to a preparation series in which the *acetolysis* was carried out over a prolonged time period (cf. NAH-5b). Therefore, this is unfortunately more an effect of preparation than an oscillation.

However, initially the AP/NAP ratio of 92/8 continues to indicate a very dense forest. Poaceae and ferns remain present in the undergrowth, while other herbs and heliophilous species have rarely been or not been recorded at all. The concentration values show a gradual shift in importance from *Betula* sp. (cf. *B. pendula* and *B. pubescens*) to *Pinus* sp. (cf. *sylvestris*), whereas the latter is increasingly dominant in the forest. *Quercus* sp. and *Ulmus* sp. now frequently appear within the pollen spectrum. Actual growth of these species in the area is likely (Nelle and Dörfler, 2008; Overbeck, 1975). In addition, *Corylus* sp. (cf. *avellana*) spreads gradually. The accelerated increase of the *Corylus* sp. curve towards the end of the assemblage zone indicates optimal growth conditions, even in the understory of the forest (Overbeck, 1975; Theuerkauf et al., 2014; Wiethold, 1997).

The forest in turn reached close to the banks of the lake. Here, *Sparganium* sp. grows in shallow water. Aquatic plants include various species of *Myriophyllum*.

NAH-7b (Boreal b/mid-late Boreal, 13.485–12.740 m) 10,370–8900 cal yr BP.

The assemblage zone encompasses the deposition of the Saksunarvatn Ash (Krüger and van den Bogaard, 2020). The diffuse distribution of the shards reveals that to a certain extent rearrangement probably masked also the palynological record. For this reason, a possible environmental impact of the Saksunarvatn ash cannot be considered (Zanon et al., 2019). However, it is striking that the reconstructed depth of the cryptotephra layer correlates with the main increase-phase of *Corylus* sp. Thus the tephra can be used as a stratigraphic time marker for a European comparison.

Concentration values rise again to an average of 3.3 x 10³ and partly even 13 x 10³ grains per cm³ sediment. Here, *Pinus* sp. is the dominant

tree species. *Quercus* sp. is considered a potential part of the forest in which *Ulmus* sp. continues to spread slowly. In combination with especially *Corylus* sp. *Betula* (cf. *pubescens* and *pendula*) is successively displaced. The maximum of *Corylus* sp. values reflects the characteristic Boreal hazel maximum (Averdieck, 1957; Firbas, 1949; Giesecke et al., 2011; Overbeck, 1975).

However, the spread of *Corylus* sp. is much less pronounced than in adjacent areas. Propagation may depend predominately on edaphic factors and less on a potential promotion by humans, as first stated by Firbas (1949) and recently shown by Theuerkauf et al. (2014) or Zanon in Groß et al. (2019).

Grasses and a few herbs, including *Urtica* sp. (cf. *dioica*) and ferns (*Polypodium* indet.) constituted the undergrowth of the pine, hazel and birch forest. In turn, *Empetrum* sp. and *Calluna* sp. are no plausible components here due to their considerable demand for light (Ellenberg et al., 2001). It is more likely that the continuous record of both pollen types suggests that (i) there may have been few open spots in the forest, or (ii) that together with, for example, Cyperaceae and *Sphagnum* sp. they were part of a bog vegetation at the terrestrialized former banks of a subsequent incision lake.

Still the forest reached close to the banks of the lake. Here, *Typha latifolia* and *Sparganium* sp. thrived. In deeper waters *Myriophyllum* sp. and *Nymphaea* sp. were present.

Disturbances in the forest are mainly caused by fires, as the record of micro charcoal particles documents. Fires occurred frequently, potentially controlled by drier climatic conditions and promoted by the high proportion of *Pinus* sp. in the forest (Rickert, 2003). However, a fire event in the immediate vicinity of the lake can be ruled out, as no opening or succession as a result of a fire is apparent in the course of NAH-7b.

4.3. Temporal scale of environmental transformations

The most fundamental environmental changes observable in the record is the transition from tundra to woodland. In fact this shift occurred twice within the record (during the Lateglacial and very Early Holocene).

A variety of pollen profiles from northern Europe, especially from Schleswig-Holstein, suggest that there are various similarities in the primary succession of the early Allerød period and the early Preboreal period. The palynological features of both transition phases (Dryas-1-early Allerød transition and Dryas-3-Preboreal transition) overlap considerably. This includes that pollen of the tree birch type (*Betula pubescens*-type) show rapid increases, which, especially in northern Schleswig-Holstein, is often preceded by a short phase of a pronounced *Juniperus* pollen abundance (Schüttrumpf, 1943; Schüttrumpf, 1958; Usinger, 1975, 1981b; Usinger and Wolf, 1982). The same is reflected in the present record.

Obviously, similarities between the early Allerød period and the Preboreal period do not mean that the actual alteration of the vegetation is identical. In fact, they differ significantly (compare, e.g., NAH-4a and NAH-6a). Furthermore, it is evident that similarities also depend on sedimentation rate, sampling strategy, preservation of archives as well as their size. However, changes are undeniable and the questions are, (i) can we delimitate the temporal dimension of these environmental transformations, and (ii) how can we evaluate the degree of alteration in order to compare these transformations?

A general difficulty with such a comparison is, that it contrasts two constantly progressing primary successions of different pace, which in turn are linked to different factors. These in particular include local conditions such as available soils and, above all, the presence of species or distances to refugial sites. However, if one addresses certain pollen analytical features which are compared to each other, it is possible to define the temporal scale to some extent (Table 2; Fig. 6a and b).

Both periods are preceded by a phase in which stadial vegetation prevailed and in which the pollen spectrum was dominated by NAP. The pre-woodland phase (Vorwaldphase) with increased, partly

Table 2

Overview on the chronological classification of pollen featured as mentioned in the text.

Palynological feature	Early Allerød period	Early Preboreal period
(a) Start of pre-woodland phase	~13,890 cal yr BP	~11,520 cal yr BP
(b) Start of steep <i>Betula</i> -rise	~13,850 cal yr BP	~11,550 cal yr BP
(c) End of steep <i>Betula</i> -rise	~13,740 cal yr BP	~11,450 cal yr BP
(d) Establishment of open woodland	~13,480 cal yr BP	(undefined)
(e) Establishment of dense woodland	~13,000 cal yr BP	(undefined)
(f) Establishment of forest		~11,250

maximum *Juniperus* values precedes the *Betula*-rise of the Allerød period and occurs around 13,890 cal yr BP. A few decades later, around 13,850 cal yr BP, *Betula* pollen values display steep increases.

In contrast to that, the pre-woodland phase, measured by the concentration values, was even more pronounced during the early Preboreal period, but it already coincided with the *Betula*-rise around 11,550 cal yr BP. This coincidence can in turn be explained by more favorable local conditions (prepared soils), as well as by the fact that populations of *Betula pubescens* survived the Dryas 3 period locally, whereas they first needed to migrate from southern stands during the early Allerød period.

The steep rise of *Betula pubescens*-type pollen values in both periods corresponds to a clearly decreasing percentage of NAP. This steep increase of the early Allerød period terminated around 13,740 cal yr BP. In the course of the Preboreal period it reached maximum values around 11,450 cal yr BP. Consequently, both phases have a strikingly correlating duration of about 100 years (11,550–11,450 cal yr BP) or 110 years (13,850–13,740 cal yr BP).

This temporal coincidence is deceptive. Within a similar time period the concentration values in early Allerød increase from 1,000 to 3,000 pollen/cm³ sediment. In clear contrast, during the early Preboreal period they rose from 2,000 to 29,000 pollen/cm³ sediment. It must be clear that this is in turn controlled by multiple further factors, however, this alone illustrates that an environmental change was potentially much more profound during the Early Holocene – judged by modern perception at least.

However, in both periods the actual change of the environment is not finished with the termination of the steep rise of *Betula pubescens*-type pollen. During the mid Allerød period (Allerød 3, around 13,480 cal yr BP), following the cooler period of Dryas 2, finally an open woodland developed.

In the Preboreal period a forest development – here probably attenuated by the PBO – is detected at about 11,250 cal yr BP. At this time, there are scarcely any pollen of shade-intolerant species left in the pollen spectrum.

Again, an approximatively temporal correlation of about 370 years (13,850–13,480 cal yr BP) to 300 years (11,550–11,250 cal yr BP) is apparent. And again, a coincidence is deceptive as the pace of actual vegetation change within this time frame is different.

The preboreal *Betula* rise can be compared in many pollen profiles with the rise of the early Allerød period. However, there are clear indications that trees formed much denser populations during the Early Holocene. There are no representative pollen types of the open park tundra detectable in the course of the Preboreal period and closed curves of *Artemisia* and *Empetrum* rapidly terminate – different to the mid Allerød period (Averdieck, 1957; Overbeck, 1975). When comparing these two developments, it must be clear that the pollen spectrum can appear almost equal, but at the same time they reflect very distinct levels of the primary succession – an open woodland for the mid Allerød period and a forest for the Preboreal period (for differentiation see Section 4.4).

This means that a comparison of apparently similar pollen features can be made on a temporal basis, but the actual speed of vegetation change is divergent. Initial points are in both cases pollen spectra that reflect tundra vegetation. But within a comparable temporal dimension

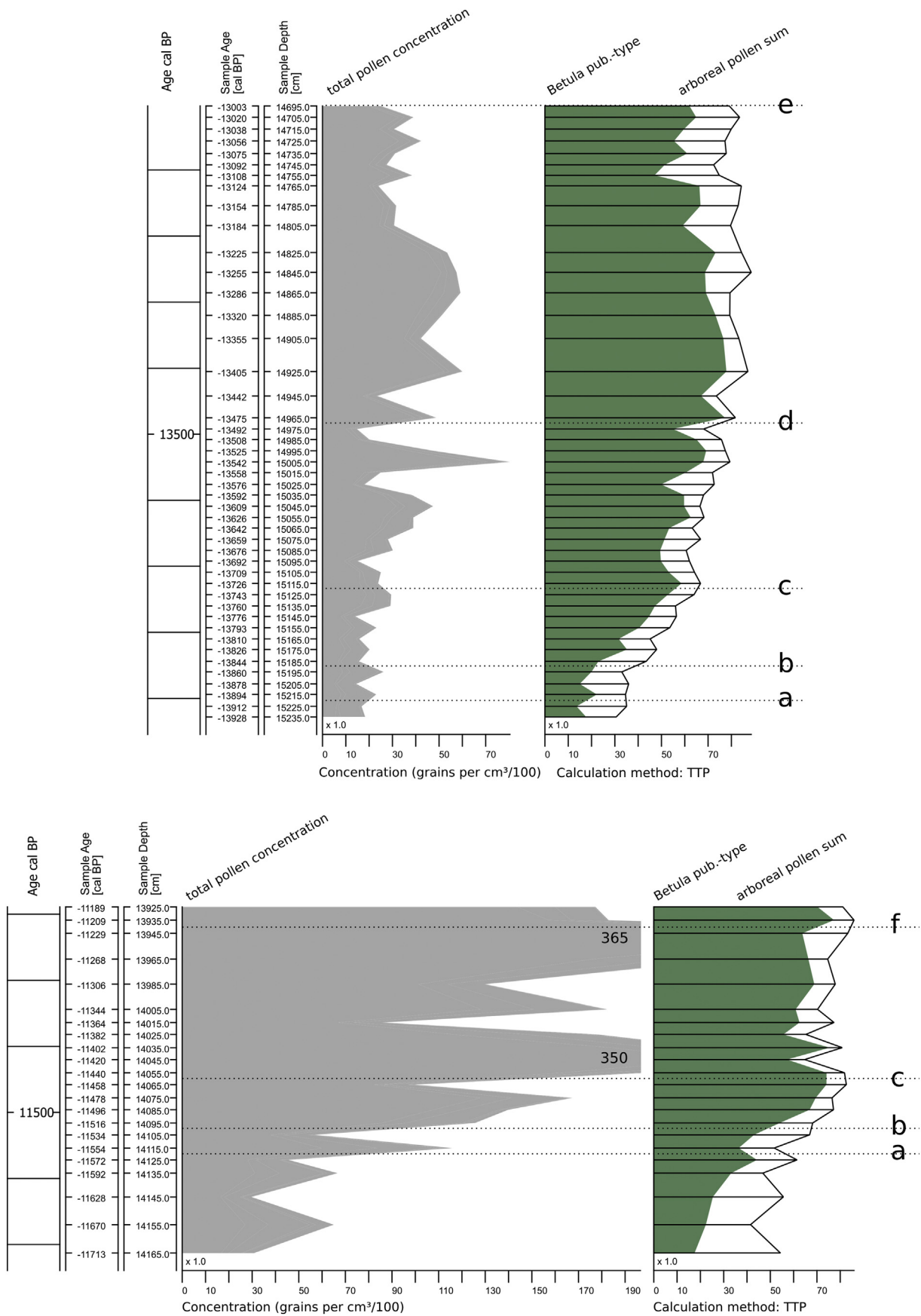


Fig. 6. (a) Diagram showing pollen concentration, percentage of arboreal pollen sum based on TTP and shares of *Betula pubescens*-type pollen during the early to mid Allerød period of the NAH record. Diagram plotted on age scale for better correlation. Designations a–e refer to Table 2. (b) Diagram showing pollen concentration, percentage of arboreal pollen sum based on TTP and shares of *Betula pubescens*-type pollen during the early to mid Preboreal period of the NAH record. Diagram plotted on age scale for better correlation. Designations a–f refer to Table 2.

no comparable actual development is reflected. This is particularly due to edaphic factors, the distance to refugial sites or the presence of species, as well as other factors that cannot be assessed, such as weather or exploitation by animals as well as people.

When intending to evaluate the degree of change it can be stated that in both cases the spread of trees must be regarded as fundamental. Here the question remains whether the appearance of the first trees should be considered as more profound, or the rapid rate at which birch trees (and of course others as *Pinus sylvestris*, *Betula pendula* or *Populus tremula*) spread during early Preboreal period.

4.4. Correlation to key sites – the bridging function

Following Litt and Stebich (1999) Schleswig-Holstein forms a bridge between central European and Scandinavian pollen records with regard to biostratigraphic correlation. This fact can be demonstrated on the basis of the first evidence of tree birches (in this case *Betula pubescens*) as well as the development of denser woodlands and forests along a transect across the North European Plain. For this purpose the records of Slotseng (SLO) (Mortensen et al., 2011) and lake Hämelsee (HÄM) (Merk and Müller, 1999) are selected for a comparison with the here presented record (Table 3; Fig. 7). All records contain high-resolution analyses of pollen as well as additionally botanical macrofossils and deal with Lateglacial limnic deposits. The distance between two locations is approximately equal (150–200 km; Fig. 5). Nevertheless, it should be noted that the result may be slightly biased, as the HÄM record does not differentiate between *Betula pubescens*-type and *B. nana*-type pollen.

The comparison is mainly based on biostratigraphy. However, a range of calibrated radiocarbon dates are additionally provided for the corresponding steps of vegetation development. Within these steps a differentiation is made between open woodland (*Betula pubescens*-type pollen/AP ~70%, grasses and herbs ≥20%, heliophilous grasses and herbs present, few or no shade tolerant species), dense woodland (*Betula pubescens*-type pollen/AP > 75%, grasses and herbs ≤ 15%, heliophilous grasses and herbs rare, few shade tolerant species) and forest (AP > 85%, grasses and herbs < 10%, heliophilous grasses and herbs absent, shade tolerant species present).

Within the most southern record (HÄM) first macrofossils of *Betula pubescens* already occur in sediments deposited during the Meiendorf period (here between 14,200 and 13,800 cal yr BP). However, as Merk and Müller (1999) mentioned redeposition of pollen in corresponding depths, this needs to be considered for *Betula pubescens* macrofossils as well.

From the early Allerød period (referred to as Bølling by Merk and Müller (1999)) the character of the vegetation can be described as an open woodland (here between 13,650 and 13,500 cal yr BP). Here, *Betula pubescens* fruits are abundant and hence represent a *terminus ante quem* concerning the migration of tree birches. In sediments deposited at about the same biostratigraphic period the first appearance of

Betula pubescens macrofossils (here around 13,770 cal yr BP) occur in the NAH record.

In turn, first macrofossils of *Betula pubescens* are recorded in SLO in the course of the mid Allerød period (here around 13,500 cal yr BP).

If the Gerzensee oscillation is taken as a time marker (13,120–12,880 cal yr BP following Andersen et al. (2000); HÄM: 13,100–12,950 cal yr BP; NAH: 13,115–13,030 cal yr BP; SLO: 13,150–12,950 cal yr BP), a forest is already reflected in the HÄM record prior to that, while an open woodland can be inferred from the NAH record during this phase of the Allerød period.

Until the late Allerød period a dense woodland is established in the area surrounding the Nahe paleolake (here between 13,000 and 12,750 cal yr BP). In SLO the environment of the late Allerød is described as a heterogeneous landscape with open areas and stands of open woodland.

In HÄM birches started to spread so rapidly during the early Preboreal period that they directly formed forests by about 11,600 cal yr BP. Also in NAH a forest developed early in the Preboreal period (here between 11,530 and 11,450 cal yr BP) due to the fact that tree birches survived the Dryas-3 period forming riparian woodlands in the area. This, however, is not the case for SLO. A development of a dense woodland and later of a forest was delayed at SLO during the Preboreal period because tree birches did not survive the Dryas-3 period locally (Mortensen et al., 2011).

This comparison, although simplistic, clearly demonstrates the value of the NAH record as being an important connection between Northern European and Central European pollen records. In addition, it emphasizes the fact that meaningful results can only be achieved if both biostratigraphic units and absolute dating is included. Nevertheless, it is essential that absolute dating does not concern the temporal delimitation of biostratigraphic units and their spatial comparison, but rather the temporal framework of specific phases or palynological features, which can be completely different in different geographical locations.

4.5. Considering charcoal particles of the palynological record

In this paper, the interpretation of a wildfire within the catchment area is based on the assumption that a successional cycle occurs subsequently to a fire event, which in turn is reflected in the palynological record at a sufficient resolution (Green, 1982). This applies to the charcoal peak (NAH-4c4) discussed above (see also supplementary material 3). In this case, the increased charcoal concentration cannot be reasonably explained by redeposition either, as no corresponding erosion indicators are recorded. In addition, a specific taxon that is common after fires (*Epilobium* cf. *angustifolium*) (Keeley and Keeley, 1987) is involved in the vegetative succession. For this reason, the characteristics can be compared with further suspected fires, even under the premise that potential fires of different vegetation types are confronted.

A further basic criterion for the identification of fire regimes adjacent to the investigated archive is the simultaneous occurrence of charcoal particles of different size classes (larger than 50 µm) that correlate with increased total charcoal concentration. The size and thus the weight of the particles determines the distance of transport (Clark, 1988) – even if they are generally distributed like pollen and local, regional and supra-regional components need to be considered (Fægri and Iversen, 1989; Patterson et al., 1987). Based on the record, this results in three phases for the last part of the Lateglacial and the Early Holocene transition that need a closer examination (NAH-5a [2], NAH-5b [3], NAH-6a [4]; for environmental contextualization see Section 4.2.). They are compared to the identified wildfire [1] recorded in NAH-4c4 in Table 4.

On the basis of this comparison, it can be concluded that multiple reasons could be responsible for the charcoal input [2] coincides with [1] in the period of increased dryness and extensive wildfires (Crombé, 2016; Hoek, 1997; Kaiser, 2003; Kaiser et al., 2009; Tolkdorf et al., 2014; Van der Hammen and Van Geel, 2008). It is

Table 3

Overview on phases of vegetation development classified after biostratigraphic terminology as used in the present study.

Period // location	HÄM	NAH	SLO
Meiendorf	First tree birches		
Dryas-1			
Allerød 1	Open woodland	First tree birches	
Dryas-2/ Allerød 2			
Allerød 3a	Forest	Open woodland	First tree birches
GZO/ Allerød 3b			
Allerød 3c-d	Forest	Dense woodland	Open woodland
Dryas 3			
Early Preboreal	Forest	Forest	

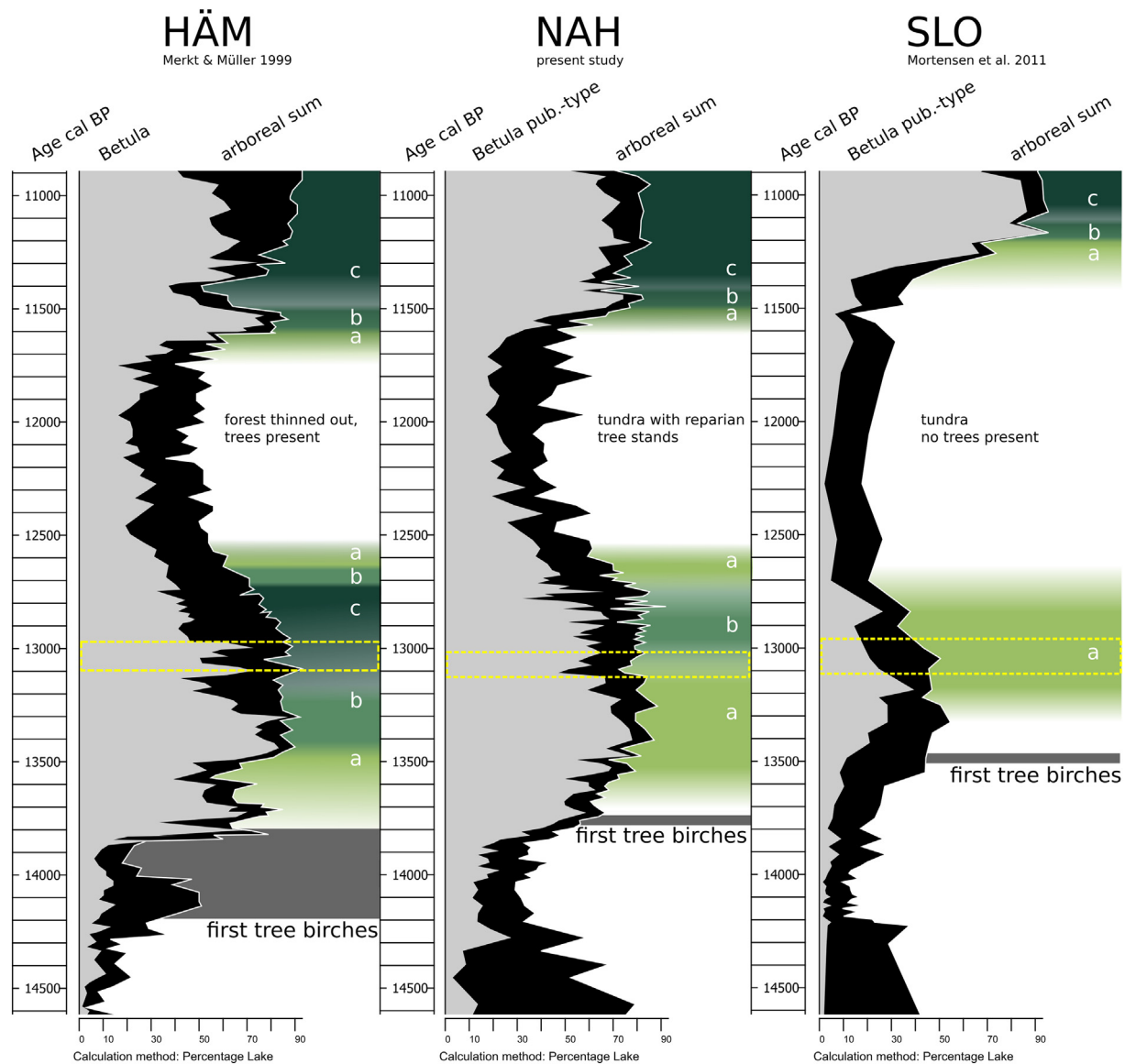


Fig. 7. Visual comparison of the Hämelsee record (HÄM - Merkt and Müller (1999)), the Slotseng record (SLO - Mortensen et al. (2011)) and the present study (NAH). All records are plotted on age scale for reasons of comparability. The black curve displays the arboreal pollen sum based on TTP, the gray curve displays shares of *Betula* pollen (HÄM, including *B. nana*-type pollen) or *Betula pubescens*-type pollen (NAH and SLO). Yellow dashed line indicates Gerzensee-Oscillation as given according to the authors. Dark gray bar marks time period of first occurrence of tree birch macrofossils in the records. Light green/a: open woodland; middle green/b: dense woodland; dark green/c: forest.

Table 4

Overview on proxy data for the defined four phases of charcoal events.

	[1]	[2]	[3]	[4]
Charcoal size class > 50 μm	x	x	x	x
Charcoal size class > 100 μm	x	x	x	x
Vegetation response	x			
Erosion indicator		x	x	
Synchr. Usselo horizons	x	x		
Arch. finds		x	x	x
Arch. ^{14}C dates			x	x

possible that they both reflect regional fires from the catchment (or further away), whereby a potential succession is masked by the input of pollen from the local and regional vegetation. It is equally plausible that long-distance input contributed to the total concentration in the sediment and the prolonged record is an effect of continuous rearrangement (Wolbach et al., 2018).

[3] Falls into a period of increased oceanicity and thus stronger humidity (Overbeck, 1975; Usinger and Wolf, 1982). Intensive forest fires over large areas of Europe are no longer proven and hence, increased charcoal input from long-distance flight is rather unlikely. Secondary deposition of earlier charcoal inputs is possible, as e.g., indicated by the persisting record of erosion and rearrangement indicators (Wolbach et al., 2018). Fire of anthropogenic origin is likewise probable, as human activity is archeologically (typologically and by ^{14}C data) documented near-site (Wild, 2017). The most plausible explanation is again a mixture of different sources. Nevertheless, human-environment-interaction must be considered as an additional and significant component of the total charcoal concentration.

Finally, [4] lies in a phase of strong environmental transformations with increased precipitation and the rapid spread of a birch forest in the area. However, rearrangement indicators are not well represented. The increasingly dense vegetation renders it rather unlikely that terrestrially deposited charcoal particles are washed into the lake (see

NAH-6a). Here, fires of anthropogenic origin are most probable as human activity is archeologically documented (Krüger, 2020; Wild, 2017).

These interpretations are of course simplistic. However, it is generally noticeable that charcoal input is at its highest (at [3] and [4]) when (i) no reaction of the vegetation is detectable, (ii) erosion indicators are present at rather low levels, (iii) the high humidity suggests that extensive wildfires are not impossible but rather implausible, and (iv) at the same time human presence is archeologically proven. Here, this can at least be considered as an emerging and interesting pattern.

5. Conclusion

This article presents the first complete pollen profile that covers the Lateglacial and Early Holocene in the area of Schleswig-Holstein, Germany. The particular strength lies in the fact that (i) the investigated sediments are not interrupted by the prominent hiatus at the Allerød-Dryas 3 transition (Usinger, 1981a), (ii) the record comprises the first Lateglacial annually laminated sediments of Schleswig-Holstein, which (iii) in combination with radiocarbon dated botanical macrofossils and three cryptotephra layers provide excellent age control (Dreibrodt et al., 2020; Krüger and van den Bogaard, 2020). Therefore, (iv) it is possible to integrate the record into the existing event stratigraphy and to compare it with important European key sites. Thus the record fills multiple previously existing desiderata.

Due to the good chronological resolution, emphasis is given to the temporal scale of environmental transformation. A comparison of apparently similar pollen features (here the *Betula pubescens*-type pollen curve at the Dryas 1-Allerød transition and at Dryas 3-Preboreal transition) can be made on a temporal basis, but the actual speed of vegetation change is divergent. Within a comparable temporal dimension different steps of the primary succession are reached that in turn are not as different when looking at the pollen spectrum and percentage diagram alone. This highlights how challenging and complex it is to compare seemingly resembling alterations of the vegetation and their characteristics even within one record.

Schütrumpf (1955) as well as Litt and Stebich (1999) already emphasized that palynological records of the Lateglacial from the area of present-day Schleswig-Holstein have an important bridging function. This is particularly evident in the comparison of Central and Northern European pollen profiles. A comparison with the records from Lake Hämelsee (Merkt and Müller, 1999) and Slotseng (Mortensen et al., 2011) further illustrates this assumption. As could be shown by the migration and dispersal of *Betula pubescens*, the data set of the Nahe paleolake fits perfectly into existing records and thus refines our understanding of the vegetation history on a spatial and temporal level.

In this respect, a locally occurring peculiarity is, e.g., unusually high *Helianthemum* sp. values during the Meiendorf and Dryas 1 periods respectively. Regarding general tendencies of the vegetation development the presented pollen profile is consistent with the majority of local and regional records (Bock et al., 1985; Bokelmann et al., 1983; Menke, 1968; Schütrumpf, 1935, 1936, 1937, 1943, 1958; Usinger, 1975, 1981b, 1981c, 1985, 1998; Usinger and Wolf, 1982).

Archeological and palynological research have always been closely interlinked, especially in northern Germany. This paper also keeps this tradition, as the coring location is very close to a Paleolithic site (Wild, 2017). Thus it is possible to discuss human action and its reflection in the palynological record long before classical human indicators occur. In this context, it could be demonstrated that high charcoal particle concentrations especially at the transition from the Pleistocene to the Holocene can be explained with high probability by human action. This is of particular interest, in the light of the find region of the Ahrensburg tunnel valley, which lies only 18 km to the south.

Declaration of Competing Interest

No potential conflict of interest was reported by the author.

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Appendix A. Supplementary data

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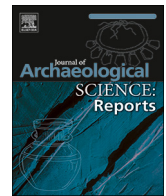
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Appendix V



Of birches, smoke and reindeer dung – Tracing human-environmental interactions palynologically in sediments from the Nahe palaeolake

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ABSTRACT

Sediments from the Nahe palaeolake in Schleswig-Holstein provided a continuous and high-resolution palynological record in the vicinity of a Lateglacial archaeological site in northern Germany. The principal objective of the study was to investigate potential reflections of Palaeolithic human-environmental interaction, which is generally regarded as challenging. Charcoal particle frequencies in different size classes and coinciding fungal spores reveal a remarkable pattern at the transition from the Dryas 3 to the Preboreal period that corresponds to the chronological attribution of parts of the archaeological record. The applied indicators of human action render it possible to define a temporally limited phase of generally elevated large charcoal particle inputs, reflecting potentially anthropogenic activity. The interpretation of the palynological record leads to the hypothesis that the climatically driven rapid change of the vegetation at the Pleistocene-Holocene transition caused temporally increased hunting activities by Late Palaeolithic hunter-gatherers. The excellent age control of the record allowed to date this phase between 11,650 and 11,520 cal yr BP.

1. Introduction

Mobility is one key adaptation to the environment (Gamble, 1985; Kelly, 1983). This applies to the annual cycles of the widespread megafauna of the Lateglacial as well as to humans (Binford, 1980; Binford, 1984; Burch, 1972; Parker, 1972). Resulting from this high degree of mobility, it is not surprising that Late Palaeolithic hunter-gatherers are generally considered to leave ephemeral traces in the archaeological record. In this respect, the close-to-nature way of life or seasonal residence and also the very local and unweighty character of their environmental impact determine them to be difficult to record, not only in archaeology but also in palynology.

The investigation of a potential environmental impact requires a suitable environmental archive and the application of e.g. palynological methods. In turn, the evaluation of a palynological record concerning potential human-environmental interactions during the Lateglacial requires the fulfillment of certain preconditions. As expectable traces are only detected locally, a close vicinity of an archaeological site to the sampled archive would be imperative (Bos and Janssen, 1996; Bos and Urz, 2003; Kuneš et al., 2008; Ledger, 2018). Furthermore, a potential environmental impact caused by human action is conditioned by the duration of seasonal residence, group size, activities, etc. Therefore, also a high resolution sampling grid needs to be applied, to at least preserve the possibility to detect these short termed impacts. Finally,

and most importantly we need to raise the question for actual expectable indicators.

There have been investigations on large scale Early Holocene fires and their interpretation as potential Mesolithic landscape management (Edwards, 1990; Selsing, 2016; Tipping, 1996). However, most researcher would agree with Iversen (1941) that apart from these fires there was generally no discernable large scale influence of prehistoric people on the composition of the vegetation prior to the Neolithic period.

Therefore there have been attempts to find changes in the composition of non-arboreal pollen (NAP) types and the reduction of arboreal pollen (AP) on a local scale (Bos and Janssen, 1996; Hicks 1993). Nevertheless, those studies investigated human influence on a primarily forested landscape, which does not correspond to the vegetation of large parts of the Lateglacial in northern central Europe (Bos et al., 2018; De Klerk, 2002; Hoek, 1997; Krüger et al., 2020; Merkt and Müller, 1999; Mortensen et al., 2011; Usinger, 1978; 1981b; 1985; 1998; Usinger and Wolf, 1982). In addition, the pollen indicators in question (classified as secondary anthropogenic indicators; cf. Chenopodiaceae) are likewise part of the natural vegetation, which further complicates an interpretation and a general application.

In contrast to that, there seems to be a large consensus on the high indicative value of increased charcoal particle inputs. Charcoal particles have been used in previous studies as a marker of anthropogenic

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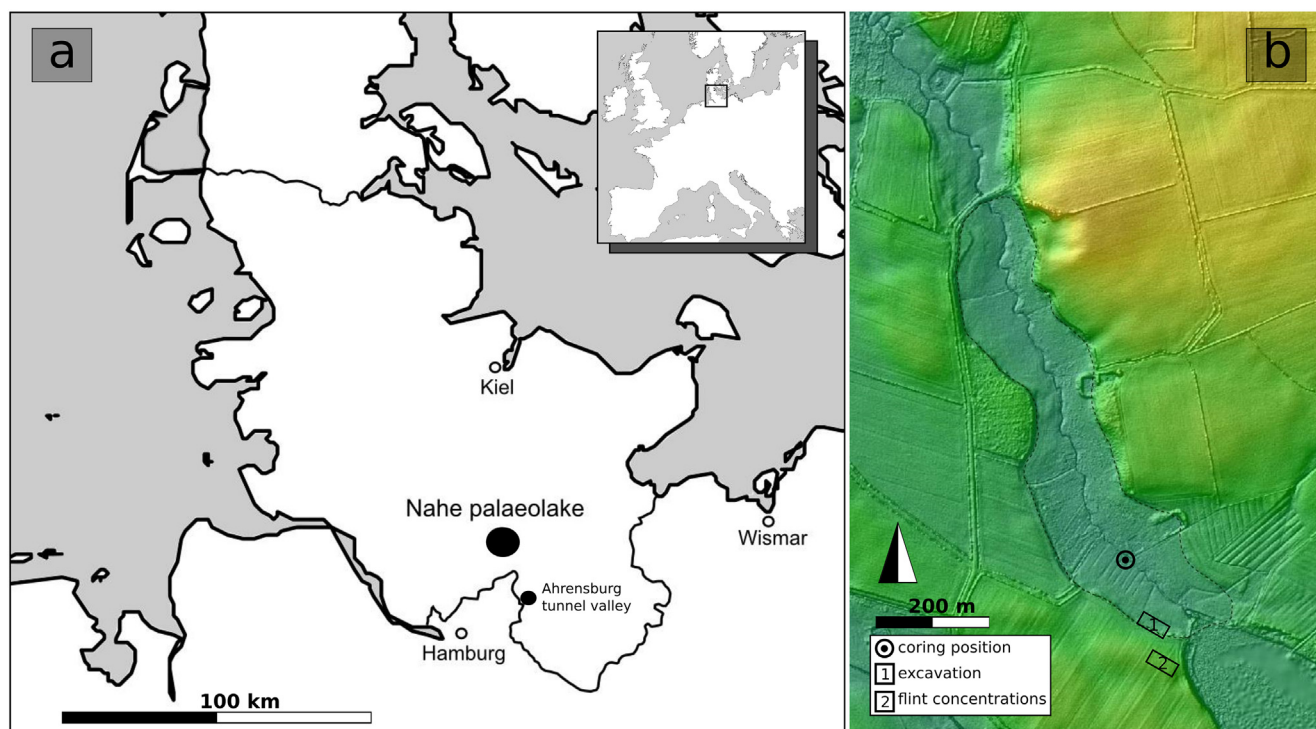


Fig. 1. Location of the Nahe palaeolake (a) and coring location and archaeological site (b). DEM based on LVerGeoSH.

activity in both forested and tundra landscapes in a Lateglacial-Early Holocene context (Bos and Urz, 2003; Crombé, 2019b; Day, 1996; Day and Mellars, 1994; Edwards, 1990; Edwards, 2004; Edwards et al., 2000; Fischer et al., 2013b; Høeg, 1995; Innes et al., 2013; Krüger et al., 2017; Kuneš et al., 2008; Mortensen et al., 2014a; Overton and Taylor, 2018; Patterson et al., 1987; Selsing, 2016; 2018; Simmons, 1979; Timpany et al., 2017; Tipping, 1996).

However, the lack of standardised identification protocols of particles results in a challenge to compare different sites. Previous studies furthermore revealed that the evaluation of different ways of charcoal ratio calculation (on pollen sum, concentration or influx) can lead to misleading assumptions (Selsing, 2018). An interpretation of the recorded charcoal particles must therefore examine other possible ways of introduction and their alterations as well as taphonomic issues before considering anthropogenic fires as origin.

Recent studies on non-pollen palynomorphs (NPP) – especially on coprophilous fungal spore types – have further emphasized their significance for palaeo-ecological research (Baker et al., 2013; Baker et al., 2016; Bos et al., 2005; Crombé, 2019a; Kamerling et al., 2016; Perrotti and van Asperen, 2018; Räsänen et al., 2007; Timpany et al., 2017). Ledger (2018) has proven how the combination of charcoal particles, fungal spores and archaeological information can document the presence of highly mobile Inuit groups in the sub-arctic tundra of south-western Alaska. This demonstrates that the combination of archaeological information and palynological proxies is able to trace human activity even in unforested environments. In order to apply this multi-proxy approach to the context of Lateglacial foragers, the above mentioned preconditions – very high resolution, coring site close to a former camp site – are required.

The applicability of the preconditions is in turn bound to respective archaeological sites featuring a lake or bog in the immediate vicinity suitable for palynological investigations. Currently, there are only few excavated Lateglacial-Early Holocene sites in northern central Europe featuring organic preservation that have additionally been investigated with on- or near-site palynological analyses

(Hasselø – Mortensen et al. (2014a); Krogsbølle – Riede et al. (2019); Lundby Mose – Jessen et al. (2015); Nørre Lyngby – e.g. Iversen

(1942) and Fischer et al. (2013a); Slotseng – Mortensen et al. (2011); Trollesgave – Fischer et al. (2013b); Star Carr – e.g. Day and Mellars (1994); Lubrza – Sobkowiak-Tabaka et al. (2017); Milheeze – Bos and Janssen (1996); Zutphen – Bos et al. (2005); Endinger Bruch – De Klerk (2002); Ahrensburg tunnel valley – e.g. Schüttrumpf (1937); Schüttrumpf (1943); Nahe palaeolake – Krüger et al. (2020)).

A comparison of the sites reveals that apart from the Nahe palaeolake (NAH) there is no other investigated sediment sequence so far that features partly annually laminated depositions and at the same time allows a classification into the existing event stratigraphical framework via cryptotephra layers close to an archaeological site (Krüger and van den Bogaard, 2020). Therefore, as well as due to its proximity to the Ahrensburg tunnel valley, the NAH sequence is predestined for the assessment of a potential human-environmental interaction. This issue is discussed in the present paper addressing the following main questions:

1. Is human-environmental interaction reflected in the palynological and palaeoecological record of the Pleistocene-Holocene transition in the NAH record?
2. In which way is it reflected and what are plausible causes?
3. What do these results imply for our understanding of Palaeolithic human actions?
4. Is it possible to narrow down the temporal dimension of phases of local human presence by using palynology and palaeoecology?

2. Site and background

2.1. The Nahe palaeolake

The Nahe palaeolake is located in Schleswig-Holstein about 30 km north of Hamburg (Germany). The basin of the former lake was part of a larger glacial lake system and is separated from further elongated incision lakes by two narrow sand ridges to the northwest and southeast (Smed, 1998; Woldstedt, 1935; Woldstedt, 1954). To the southeast, Lake Itzstedt is the water-bearing remnant of the lake system.

The size of the palaeolake surface was about 16 ha during the

Lateglacial. The silting-up process was completed in the course of the late Holocene. Today, the river *Rönne* flows in the centre of the still existing depression and thereby follows the course of the former lake in north western direction before turning southwards and draining off into the river *Alster* (Fig. 1). The area is used as pasture and partly forested by alder, birch and willow. The coring location is situated in the formerly deepest part of the incision lake (53°48,711'N, 10°8,082'E). The position was selected on the basis of preceding extensive survey corings in 2003 and 2004 by Hartmut Usinger.

2.2. Vegetation development

At the end of the biostratigraphic Allerød period (here between 12,700 and 12,540 cal yrs BP) a shift from a dense woodland to a shrub dominated tundra can be reconstructed from the NAH record (Krüger et al., 2020). However, the large scale die back did not lead to a complete decline of trees in the area. Based on macrofossils of *Betula pubescens* (Firbas 1949; Krüger et al., 2020; Schüttrumpf, 1943; Usinger, 1981b; 2004) it can be inferred that low growing birch trees thrived at favourable sheltered sites, such as riparian zones or sunny slopes.

The vegetation of the biostratigraphic Dryas 3 period cannot be characterized as homogenous. Here *Betula nana* and *Empetrum* sp. predominated the mosaic-like vegetation dispersal of tundra and steppe elements including groups of low growing tree birches in the most protected places.

The presence of *Betula pubescens* throughout the Dryas 3 period is decisive for the very early expansion of trees in the area at the onset of the Holocene. However, the rapidly closing woodlands (further also including *Pinus sylvestris*, *Betula pendula* or *Populus tremula*) of the Preboreal period did not immediately and completely shade the ground. The presence of heliophilous species indicates a still open character of the vegetation until about 11,250 cal yrs BP, just after the Preboreal Oscillation (Krüger et al., 2020).

2.3. The archaeological background

The Nahe palaeolake is embedded in a well-known archaeological find area. The southwestern shore of the former lake on the narrow ridge to Lake Itzstedt and the associated flat moraine are of interest for this study. Here, the top of the moraine was intensely surveyed by Thomas Poelmann for the last 30 years. These collections yielded > 12,000 lithics that were mostly attributed to the Ahrensburgian but also to the Hamburgian (Wild, 2017).

Three separated flint concentrations suggest the location of former camp sites at an elevated position on top of the moraine. From here, the archaeological find area extends down to the former shoreline where excavations were carried out by the Archaeological State Department Schleswig-Holstein, headed by Ingo Clausen, in 2003 and 2004. These revealed further lithic artefacts as well as faunal remains.

The faunal assemblage has been investigated by Wild (2017). Altogether 154 bones and antler fragments originate to 86% from reindeer (*Rangifer tarandus*). Apart from that seven terrestrial mammal species and six fish species have been identified. According to Wild (2017) these can be regarded as background fauna as the species are mainly represented by single bones.

In contrast to that, the reindeer assemblage contains all parts of a complete skeleton, which in combination with butchery marks refer to an interpretation as butchery refuse. Unfortunately, stratigraphic contexts could not be reconstructed. The finds were mainly unearthed by a mechanical digger due to difficult excavation conditions in the former shore line area. Therefore stratigraphic contextualization of the bones and lithics could not be made (pers. com. I. Clausen). However, radiocarbon ages of three bones and a piece of antler suggested a rough temporal classification into the Dryas 3 period (cf. Younger Dryas period; Fig. 7; Weber et al., 2011).

For that time, a ford situation can be reconstructed at the

southeastern end of the lake in the form of a shallow water area above the ridge, situated at the foot of the moraine. The composition of the finds, antler technology as well as the topographical situation suggest a comparison with the Ahrensburg tunnel valley (Rust, 1943; Rust and Gripp, 1937), located only 18 km to the south (Wild, 2017). However, it is not only the archaeological but also the palynological results from Stellmoor that are most suitable for a comparison. In this respect, the original dataset on coring location Stellmoor-B as given by Schüttrumpf (1943) is reconsidered in the present paper.

3. Materials and methods

Field methods, material and pollen preparation is described in Krüger et al. (2020). The coring campaign in the dry centre of the Nahe palaeolake took place in October 2017. A modified Livingston piston corer (Mingram et al., 2007) – the so called *Usinger-corer* – was used to extract the sediment cores, each of 16 m length, in 1 m segments. The cores cover a continuous sequence of sediments deposited between the onset of the Lateglacial and the Early to Mid-Holocene.

Pollen sample preparation was conducted according to standard techniques (Erdtman, 1960; Fægri and Iversen, 1989) including the addition of *Lycopodium spore* tablets (Stockmarr, 1971) to enable the calculation of microfossil concentrations e.g. per gram of sediment.

Apart from counting the pollen – where nomenclature mainly follows Beug (2004) – also regularly occurring non-pollen palynomorphs (NPPs) were recorded following Van Geel (1976). Charcoal identification was made based on morphological characteristics (Figs. 2a-b) such as sharp breaking edges (including a halo effect at phase contrast setting around these), angular, opaque usually planar and often asymmetric shape and a deep black colour (Krüger et al., 2017; Patterson et al., 1987; Tipping, 1996). The recording also included a classification of three size classes (10–50 µm, 50–100 µm, 100–200 µm) modifying suggestions of Mehringer et al. (1977) or Patterson et al. (1987). Further, charcoal particles were recorded featuring bordered pits (Figs. 3a-b).

As a principle anatomical characteristic that survives the carbonization process, these can be diagnostic for the distinction of charcoal particles originating from Coniferales (Jensen et al., 2007; Schweingruber, 1990).

Part of the pollen preparation protocol is to filter the samples through a sieve with a mesh size of 200 µm. In this way botanical macrofossils but also larger charcoal particles are extracted. The latter were identified and counted at 10–40x magnification using an *Olympus SZ51* binocular. The results are depicted as *charcoal* > 200 µm in Fig. 5.

In addition, further sediment samples were examined for even larger pieces of charcoal. The sampling was carried out according to a matrix, which allows an easy correlation to the pollen profile (Krüger et al., 2020). For this subsequent sampling, a sequence was selected which comprises the late Allerød period, the entire Dryas 3 period and the early Preboreal period, according to biostratigraphy. This was also done to rule out the possibility that the palynologically recorded charcoal was not a recent artefact of processing (stirring), but an actual former increased input of particles. Therefore, samples of 10–15 g sediment were taken in complete intervals of 2 cm without a gap. The sediment was filtered through a 350 µm sieve using H₂O. The extracted material was treated with 39% H₂O₂ (hydrogen peroxide) for 24 h to bleach organic materials, following mainly Rhodes (1998). Also these samples were counted at 10–40x magnification using an *Olympus SZ51* binocular.

Parts of the original palynological data set from Stellmoor/Ahrensburg tunnel valley have been published by Schüttrumpf (1943). In order to relate the respective results to the present study, the original data has been digitalised and calculated based standards in Lateglacial research following Iversen (1942), Janssen and Ijzermans-Lutgerhorst (1973) as well as De Klerk (2002). A reconsideration of parts of the

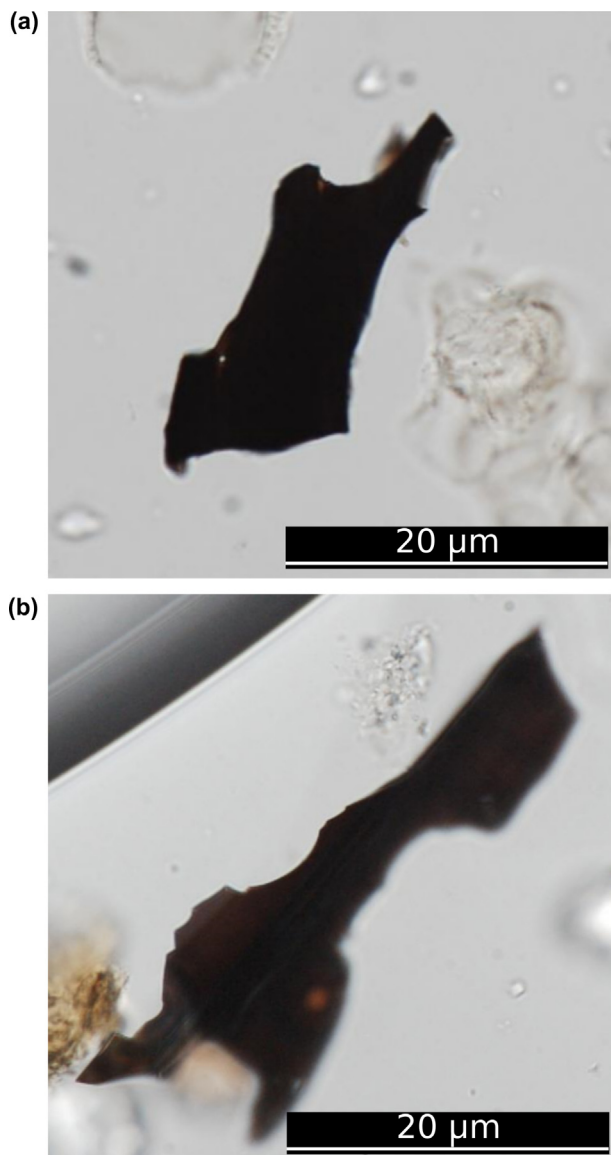


Fig. 2. a-b: Both pictures show microscopic charcoal particles with characteristic sharp breaking edges and black colour under bright field view.

Stellmoor-B data set is given further below (5.4).

4. Results

The results are given in Fig. 5. For better biostratigraphic correlation, indicative pollen types and pollen assemblage zones (PAZ) as well as a biostratigraphic assignment have been included as given in the complete diagram in Krüger et al. (2020). The results are briefly summarized below.

4.1. Abundances of NPPs

HdV-1 (*Gelasinospora* sp. cf. *Neurospora*; Kuhry (1997), Van Geel et al. (1981) and Van Geel and Aptroot (2006)) occurs without any recognizable accumulation or pattern and only sporadically.

HdV-332 (Desmidiaceae; Van Geel et al. (1981)) occurs exclusively within the defined biostratigraphic boundaries of the Dryas 3 period. Within these limits the record of HdV-332 palynomorphs remains continuous.

HdV-207 (*Glomus* cf. *fasciculatum*; Van Geel et al. (1989)) and **HdV-704** (Dinoflagellate cysts, *Hystrix*; Bakker and van Smeerdijk (1982))

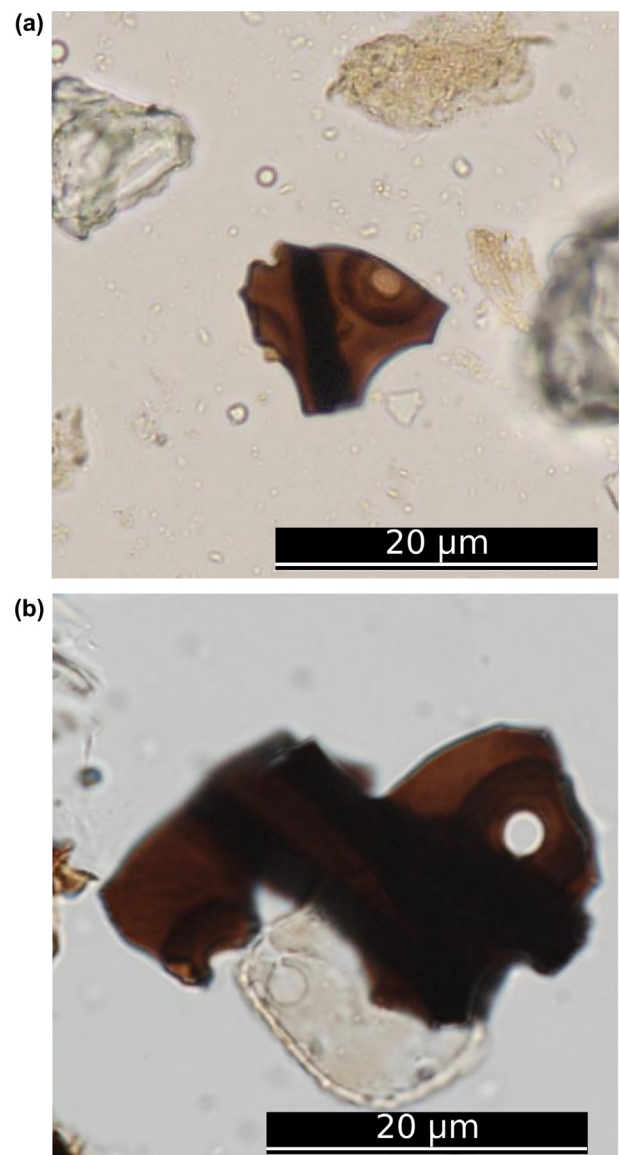


Fig. 3. a-b: characteristic charcoal particles with bordered pits (circular feature) under bright field view.

occur in the entire diagram. It is striking that both palynomorphs show clearly elevated values within the limits of the Dryas 3 period, but decline towards the transition to the Preboreal period and are sporadically represented in upper layers.

HdV-55A (*Sordaria*-type (Fig. 4); Van Geel (1978), Van Geel et al. (1981), Kuhry (1997) and Van Geel et al. (2003)) occurs sporadically, but in a remarkable pattern (cf. below; Fig. 5). Continuous evidence can be seen in a phase at the Dryas 3- Preboreal transition, which clearly correlate with the particles of the charcoal size class > 350 µm.

4.2. Charcoal particle quantities

The evaluation of charcoal size classes resulted in two clearly distinguishable phases, whereby phase two can further be subdivided (Fig. 5). Within the biostratigraphically defined limits of the Dryas 3 period, the charcoal particle concentrations show a threefold increase (from 1 to 1.5 to partially > 4.5×10^3 particles per cm^3 sediment). Contrarily, the charcoal influx fluctuates strongly without recognizable pattern throughout the Lateglacial part of the diagram and across the Pleistocene-Holocene boundary. Yet, based only on charcoal particle concentrations and influx values a division is not clear.

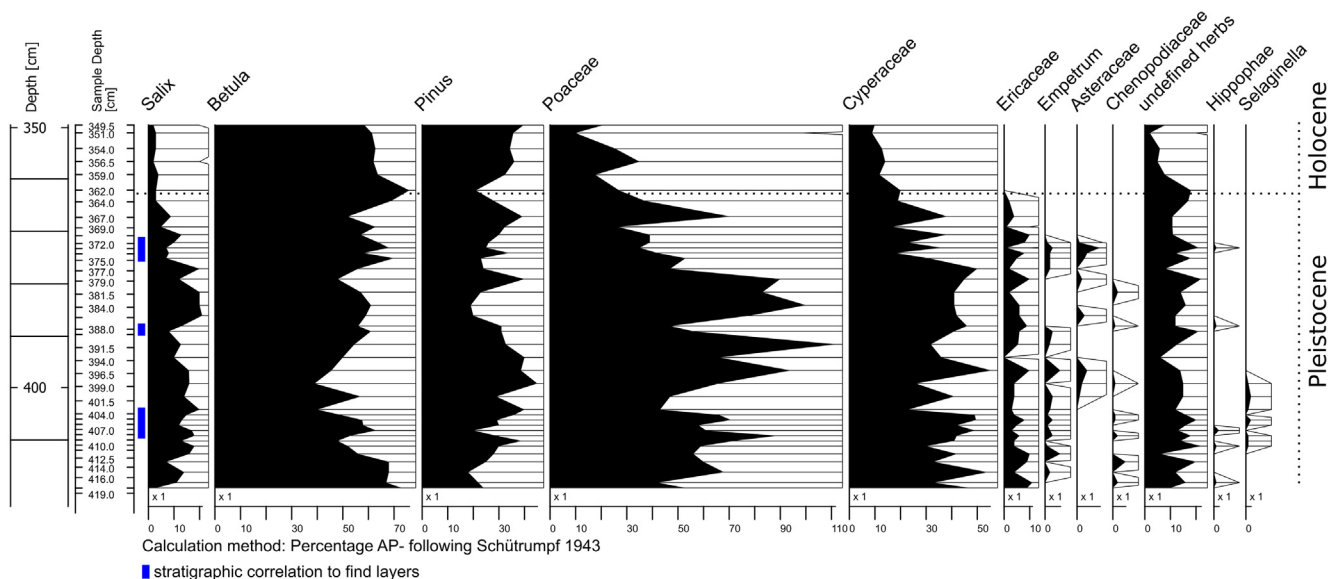


Fig. 6a. Extract of the Stellmoor-B dataset by Schütrumpf 1943 spanning the depths of Ahrensburgian find layers (marked in blue). Pollen percentages are calculated based on AP. The differentiation between Pleistocene and Holocene is given according to the original publication.

represent recorded spores in accumulation rates and not on pollen ratios. Here it must be clear that a change in the quantity of spores is only visible with an appropriately high total pollen sum. In addition, the size and catchment area of the Nahe palaeolake implies that an increased entry is also potentially masked - this explains the comparatively low influx values.

Ascospores of the *Sordaria*-type are suggested as being predominantly indicative for dung of large herbivores (Baker et al., 2013; Nyberg and Persson, 2002; Van Geel, 1978; Van Geel and Aptroot,

2006; Woelders et al., 2016). However, it has likewise been proven that these ascospores do occur in the context of plant decomposition (Etienne et al., 2013; Mighall et al., 2006; Perrotti and van Asperen, 2018). This is not surprising, as dung mainly consists of macerated and undigested remains of plants (López-Saéz and López-Merino, 2007; Richardson, 2001). Therefore, its indicative value is discussed in the following.

The final Allerød period is included in the diagram extract from the profile of the Nahe palaeolake (Fig. 5). As trees (*Betula pubescens*, *Pinus*

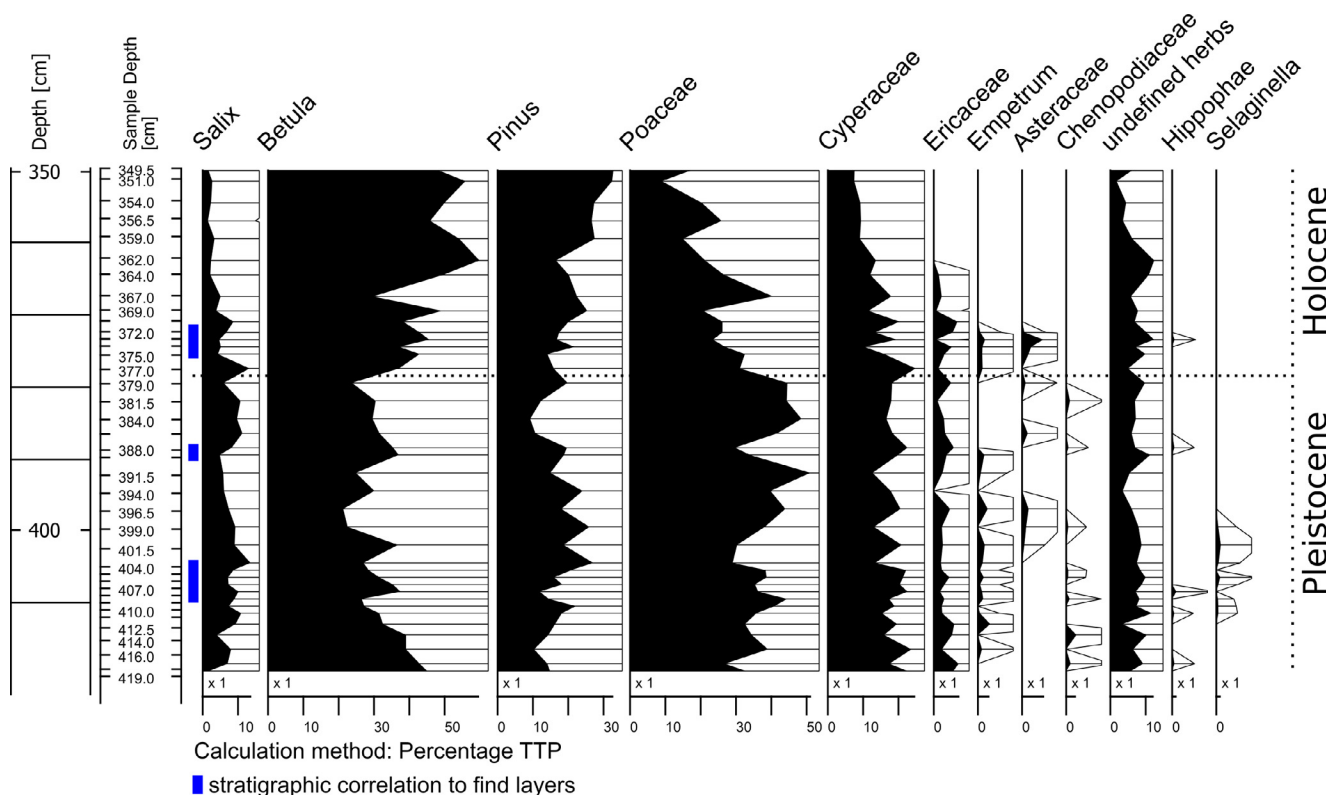


Fig. 6b. Extract of the Stellmoor-B dataset by Schütrumpf 1943 spanning the depths of Ahrensburgian find layers (marked in blue). Pollen percentages are calculated based on TTP. The differentiation between Pleistocene and Holocene is given according to a new classification (4.5.1).

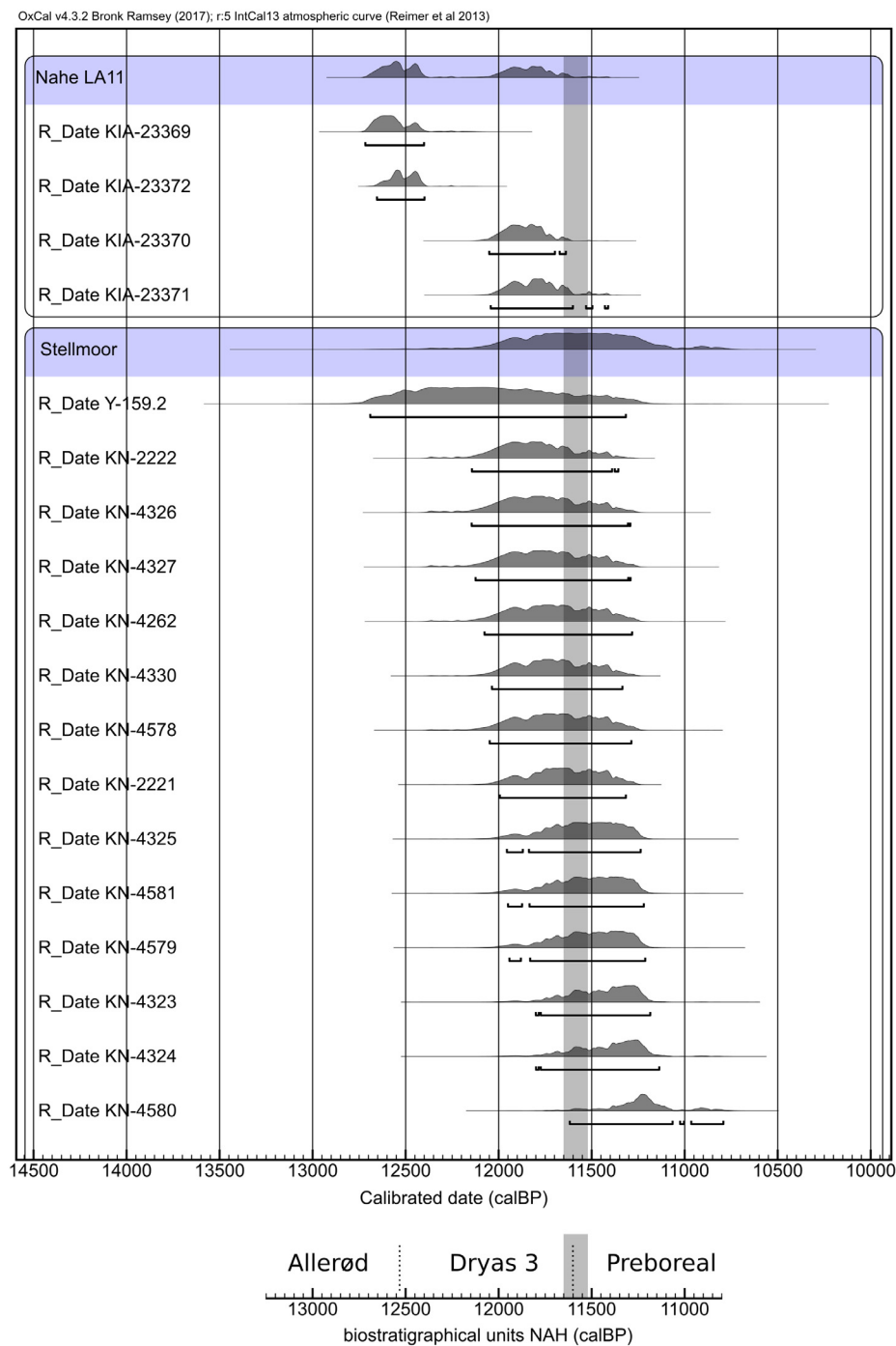


Fig. 7. Compilation of ^{14}C -dates from Nahe LA and Stellmoor after Weber et al. (2011). Top calibration for each site shows sum calibration. Grey bar indicates time span of the transformation phase. Bottom figure shows temporal classification of local biostratigraphic periods (Krüger et al., 2020).

sylvestris and *Populus tremula*) had provably established already in the study area at this time (Schütrumpf, 1943; Usinger and Wolf, 1982), higher quantities of biomass can be expected in the landscape, compared to e.g. the Dryas 1, Dryas 3 or even the very early Preboreal period.

In the transition phase from the Allerød to the Dryas 3 period, a large number of trees are expected to die off, as it is inferred from different central and northern European pollen and macrofossil records (Merkel and Müller, 1999; Mortensen et al., 2014b; Schütrumpf, 1943; Usinger and Wolf, 1982). This time range of about 200 years, until fully stadial conditions had established regionally (Dreibrodt et al., in prep.), is the temporal frame in which an increased spore input could be

expected because large areas of dead-wood-colonizing fungi could be assumed.

However, this is not the case for the Nahe palaeolake especially regarding HdV-55A. The input of this NPP-type based on influx values is only continuous as well as mostly pronounced at the biostratigraphic transition to the Preboreal period – a period of reforestation, not die-back.

It cannot be ignored, that more humid conditions at the beginning of the Preboreal period could have promoted fungal growth (Usinger, 1981a; 2004). Here, the question remains whether a comparable amount of dead biomass can be assumed, such as at the end of the Allerød period. However, this appears not very likely.

Therefore, one explanation for the record of HdV-55A could be that a different culture media was present at the Pleistocene-Holocene transition. More dung in the catchment area of the lake could be a very plausible suggestion. This assumption is further supported by the contemporary proven presence of large herbivores (cf. below).

The synopsis of the selected NPP types reveals a distinct pattern. During the Dryas 3 period, whose biostratigraphic boundaries are further clarified by HdV-332, higher values of erosion and rearrangement indicators occur as could be expected (HdV-207 and HdV-704). These decrease at the transition to the Preboreal period. At this transition a temporary continuous input of HdV-55A occurs.

5.2. Charcoal particles

5.2.1. Charcoal particles in palynological spectra

Incomplete combustion or incineration of plant material or organic matter results in amorphous, inorganic carbon compounds of different sizes and shapes. The smallest fraction occurring in this process – micro charcoal or charcoal dust – is transported by convection and wind and distributed like pollen (Fægri and Iversen, 1989). Through atmospheric circulation and finally rain, charcoal particles of this size are transported into bogs, rivers and lakes where they are deposited as part of the sediment (Edwards, 1990; Fægri and Iversen, 1989; Patterson et al., 1987). As charcoal is resistant to biological decomposition, it is preserved in various sediments and therefore also finds its way into the pollen samples.

The amount of charcoal that accumulates is dependent on the properties of the fire source as pointed out by Whitlock and Larsen (2003). The size and intensity of the fire mainly determine charcoal production and its transport. The transport in turn also depends on the size of the particles that are generated in a wide variety.

As suggested by Clark (1988) the major fraction of particles in pollen samples are 5–10 µm in size. They are not evenly deposited before one kilometer from the fire and can easily be lifted into heights over 1000 m. In this height they can travel several hundred kilometers – a consideration of long distance flight must hence be obligatory in charcoal studies (Patterson et al., 1987; Tinner et al., 2005; Whitlock and Larsen, 2003).

Particles of > 1000 µm in size are distributed near the fire source whereas those of < 100 µm spread well over distances beyond 100 m (Clark and Patterson, 1997). Studies by Whitlock and Millspaugh (1996) following modern fires suggest that particle sizes > 125 µm are found in a distance smaller than 7 km to the fire source. In contrast to that, Pisaric (2002), Tinner et al. (2006) or Conedera et al. (2009) have shown that severe convections of large scale wildfires can distribute even centimeter-sized charcoal across kilometres. Nevertheless, in case of such a fire it is justified to assume that an impact on the pollen composition must be recognizable.

However, corresponding to the aforementioned observations it is reasonable to record charcoal particles in different size classes. Generally, it can be deduced from different field experiments that the closer the fire occurred in relation to the archive under investigation, the higher the input of larger particles (Clark et al., 1998; Long et al., 1998; Walsh et al., 2010; Whitlock and Millspaugh, 1996).

In this regard, it has often been stated that fractionation occurs during the treatment process (stirring) (Fægri and Iversen, 1989; Selsing, 2018; Whitlock and Larsen, 2003). Nevertheless, an increased input of larger particles would be statistically reflected. This would also mean that the input of larger charcoal particles would not necessarily result in or be reflected in an increase in overall charcoal concentration.

It is conspicuous that charcoal influx values and concentrations of the present record do not correlate with the charcoal maximum of size class > 350 µm and > 200 µm. This means that a hypothetical effect of the amplification of charcoal particle quantities during the stirring process can actually be neglected.

However, the deposition of microscopic charcoal in lakes, bogs or

rivers may not take place immediately at or after burning. Depositional processes are depending on involved plant material, geomorphological setting, season, combustion and even weather (Conedera et al., 2009).

The fall-out and in-wash of charcoal consists of regional, extra-local and local particles forming the primary charcoal component. When interpreting the charcoal particles within a sediment it is crucial to consider also secondary charcoal resulting from redeposition processes caused by e.g. water level variation or erosion (Conedera et al., 2009; Whitlock and Larsen, 2003). In this way higher particle abundances especially during Lateglacial stadial periods (e.g. during spring melting) can occur.

5.2.2. Sources of origin and charcoal particle introduction into the lake system

Regarding the existence of charred material in the presented record a background component also needs to be considered. The background component is controlled by erosion and processes of redeposition, as well as dependent on alterations in fuel availability, e.g. at changes in the characteristics of the vegetation (Patterson et al., 1987).

Adding to the background component there are several other factors that influence the accumulation of charcoal particles in the lake. The type of the surrounding vegetation further controls the introduction of particles by constituting a filter for particle input. With harsher conditions and low growing vegetation, the input from erosion and in wash increased (Edwards et al., 2000; Mortensen et al., 2014b). In this respect, a general increase of charcoal concentration and influx especially during the Dryas 3 period needs to be attributed to the background component and increased input by long-distance flight.

Large local or regional fires are generally reflected as emerging peaks in the record (Carcaillet, 2007). This holds true for the NAH record and had already been proven for the Allerød period, including a recognizable reaction of the vegetation (Krüger et al., 2020). However, the patchiness of the vegetation requires that not all recorded fires are necessarily reflected in the pollen composition (Whitlock and Larsen, 2003). Further, fires of low intensity – such as domestic fires – do not produce large quantities of charred material. Consequently, one needs to question whether a small scale hearth fire can be reflected in a palynological record from large lakes.

Charcoal particle quantification from pollen samples (< 200 µm) and additional sieving (> 200 µm) does not result in comparable outcomes. On the one hand, Carcaillet (2007) points out that sieving material (and hence the larger particle fraction < 200 µm) represents the local fire history, whereas charcoal particles (smaller particle fraction > 200 µm) in pollen samples reflect regional burning activity.

On the other hand, Bennett et al. (1990) suggested that small scale fires (1 m² in size) would not result in plumes of higher than 18 m. Consequently, even the smallest fraction of particles would potentially be deposited relatively close to the fire source (Bellomo, 1993; Goldberg et al., 2017; Laasch et al., 2010).

As a consequence, it is challenging to deduce anthropogenic fires from the record. The incorporation of the NPP-types, charcoal size classes and, in particular, the archaeological background information provides assistance in interpretation of the here defined charcoal phases.

5.2.2.1. Charcoal-phase 1. The first defined phase spans across the biostratigraphical transition from the Allerød to the Dryas 3 period (14,425–14,265 m; 12,670–12,130 cal yrs BP). Coinciding with the biostratigraphic boundary, the concentration of charcoal particles in the pollen record triples (Fig. 5). A change in the pollen composition as a result of a local fire is not recognizable. Therefore, one might be tempted to assume that redeposition and long-distance flight can be responsible, as at the same time an increased input of medium sand into the sediment is detectable. Synchronously, values of indicators of different erosion processes increase (HdV-207 and HdV-704), supporting the interpretation. However, the charcoal influx continues

to fluctuate around the same level. Consequently, an actually increased input cannot be inferred. But with regard to alterations in size classes a shift in the composition of the input is observable.

The clear occurrence in abundance of charcoal particles of larger size ($> 50 \mu\text{m}$ and $> 100 \mu\text{m}$) limits the 1st phase. It is possible that they reflect regional fires from the catchment (or further away), whereby a potential succession of the local vegetation is masked by the input of pollen from the regional vegetation. However, it is noticeable that the largest recorded particles ($> 200 \mu\text{m}$ and $> 350 \mu\text{m}$) are low in quantity. Consequently, assuming fire regimes directly around the basin would not be justified.

At the same time, charcoal particles with bordered pits can exclusively be identified within charcoal-phase 1. These originate from individuals of Coniferales due to their clearly identified morphological characteristics (Jensen et al., 2007; Schweingruber, 1990). In northern central Europe, already widely distributed species of this order are exclusively *Pinus* (cf. *sylvestris*) and *Juniperus* (cf. *communis*) at the transition Allerød - Dryas 3 period (Firbas, 1949; Huntley and Birks, 1983; Lang, 1994).

Several records suggest that this is a period of extreme drought and intense wildfires (Crombé, 2016; Hoek, 1997; Kaiser, 2003; Kaiser et al., 2009; Tolksdorf et al., 2014; Van der Hammen and Van Geel, 2008; van Hoesel et al., 2012). As already reported by Van der Hammen (1951), wildfires benefit largely and are fueled by widespread pine forests that had established by the end of the Allerød period in parts of central Europe. Thus, it is plausible to assign the occurrence of the medium-sized particles in combination with particles with bordered pits to wildfires from central Europe that entered the lake via aeolian input.

Further, it is justified to assume that the prolonged record that resulted in the definition of a first phase is an effect of continued redeposition that succeeded the actually occurring fire regimes of the Allerød period in the course of the Dryas 3 period (Wolbach et al., 2018).

Nevertheless, the total input of charcoal particles cannot be explained solely by rearrangements and long-distance flight. Considerable further aspects are human activity and small scale wildfires, whereby the latter can theoretically be excluded already. Two ^{14}C dates of reindeer (humerus and antler) from the nearby littoral zone resulted in a time span that correlate to the biostratigraphic transition Allerød - Dryas 3 period in the area (12,650–12,420 cal yrs BP, after Wild (2017)). Therefore, it seems reasonable to assume anthropogenic activity, and hence domestic fires, as further minor source for charcoal particles.

The charcoal record of phase 1 thus consists of multiple possible components. Aside from the background component, allochthonous input from intensive wildfires is highly plausible. Whether and to what extent human activity had additional influence cannot be clarified with certainty, but remains possible. Further it is likely that redeposition processes masked potential single events.

5.2.2.2. Charcoal-phase 2. A gap in the record of small values of larger particles ($> 350 \mu\text{m}$) describes the transition between Charcoal phase 1 and 2, from the early to the late Dryas 3 period.

The second defined phase contains the late Dryas 3 period and spans across the biostratigraphic transition from the Lateglacial to the Holocene (14,225–14,060 m; 11,970–11,450 cal yrs BP). Coinciding with the biostratigraphic boundary, the concentration of charcoal particles in the pollen record decreases. The decrease correlates to a strong change in pollen composition as a rapid spread of birch trees is recorded (Krüger et al., 2020). Here the question remains as to when the thermophilic vegetation and the incipient development of a dense woodland or forest will act as a filter for allochthonous input (Edwards et al., 2000). This, however, seems to be the case not before the Preboreal-Oscillation (PBO) and hence after the end of charcoal-phase 2. The values of the charcoal influx fluctuate at higher levels until the PBO and

decrease successively.

Similar to charcoal-phase 1, no higher input of charcoal particles can be inferred from concentrations or influx for charcoal-phase 2. With regard to alterations in particle size classes a shift in the composition of the input is observable.

The definition of the second phase is again based on the different size classes. Within this phase, particles $> 50 \mu\text{m}$ and $> 100 \mu\text{m}$ form a first section, $> 200 \mu\text{m}$ and $> 350 \mu\text{m}$ a second, whereby both sections overlap exactly at the Dryas 3 - Preboreal transition. This overlap phase is referred to as *transformation phase* (14.150–14.100 m) further below.

Up to the biostratigraphic boundary Dryas 3 - Preboreal period, constant redeposition processes can be expected, as the input of HdV-207 and HdV-704 remains approximately the same. The background component caused by redistribution must therefore potentially be regarded as elevated before erosion indicators decrease.

In addition, there is a long-distance component, although it is unclear from what large scale fires these particles originate. Regarding an evaluation of long-distance flight, there are on the one hand neither local nor regional diagrams available, which included the recording of charcoal particles, and thus would be available for comparison.

On the other hand, the weather conditions have changed in comparison to the previous first half of the Dryas 3 period. As shown by Bakke et al. (2009) shifting weather systems resulted in more oceanic conditions in the second half of the Dryas 3 period. Consequently, these more humid conditions are reflected in a number of pollen records (cf. *Empetrum* sp.) across the Netherlands, northern Germany and Denmark (Behre, 1966; De Klerk, 2008; Hoek, 1997; Hoek et al., 1999; Iversen, 1954; Mortensen et al., 2014a; Müller and Kleinmann, 1998; Odgaard, 1994; Usinger and Wolf, 1982).

As a result, distant large scale fires are not suspected to be the cause of the input. Humidity increased and the amount of available biomasses is reduced compared to the Allerød-Dryas 3 transition. Local or regional large scale fires are not reflected in the record as no tundra clearance or succession can be derived from the pollen record that would deviate from the generally observable primary succession of the Early Holocene in the area (Averdieck, 1957; Overbeck, 1975; Schütrumpf, 1958a; Usinger, 1981b; Usinger, 2004). Particles with bordered pits were not found. However, a certain (low) input of distant travelled particles cannot completely be excluded.

The most plausible explanation for charcoal input within the first section of charcoal phase 2 is again a mixture of different sources. Nevertheless, human-environmental interaction must be considered as an emerging additional and significant component of the total charcoal input. The assignment of the find spectrum from the nearby site to the Ahrensburgian suggests general human activity during the Dryas 3 period. Here, Wild (2017) speculated whether there were several phases of human presence or even a palimpsest. Consistently, two additional ^{14}C dates from reindeer bones (two lumbar vertebrae) span the entire charcoal phase 2 (12,020–11,420 cal yrs BP) and cannot resolve this question. However, these support the assumption of anthropogenic fires in the area.

Special attention should be given to the transformation phase (or section 2, of charcoal phase 2).

The transformation phase coincides precisely with the rapid increase in the values of the *Betula pubescens*-type pollen. This phase includes a distinct peak of particles $> 350 \mu\text{m}$, which correlates to the phase of the highest input of particles of $> 200 \mu\text{m}$. Furthermore there are also particles recorded belonging to size classes $> 50 \mu\text{m}$ and $> 100 \mu\text{m}$.

Sediment changes are exclusively gradual and there is only a minimal increase in the sedimentation rate at the Pleistocene-Holocene transition. Therefore, redeposition as a reason for this comparatively strong record of larger particles is rather unlikely.

The beginning of the Preboreal period is biostratigraphically characterized by the distribution of birch trees (mainly *Betula pubescens*) and

Filipendula sp. At this location, this is predominantly *F. ulmaria* – a plant of the riparian and wetland area. According to Usinger (1981a; 2004) as well as Hoek and Bohncke (2002), the distribution of both species (*Betula pubescens* and *Filipendula ulmaria*) is not only a consequence of an increase in temperature, but also of a rise in lake levels throughout the North European Plain. This may likewise apply to the Nahe palaeolake (Krüger et al., 2020). It is possible that the narrow ridge to the east was submerged and thereby connected the Nahe palaeolake with Lake Itzstedt, which still exists today. However, as in turn Lake Itzstedt has no independent inflow, massive changes in charcoal particle size classes cannot be explained by this comparably minor enlargement of the catchment area. Furthermore, as the small river *Röñne* originates from underwater springs in Lake Itzstedt in the direct vicinity of the narrow ridge, no massive input of secondary charcoal is possible in this way.

Following Clark (1988), Whitlock and Millspaugh (1996) or Carcaillet (2007), larger charcoal particles are clear indications of local fires. If local large scale natural or even anthropogenic induced wildfires can be excluded due to the pollen record – which is the case here –, anthropogenic fires such as hearth or domestic fires remain plausible. This seems particularly justified considering the proximity of the respective archaeological site to the coring location.

Particle size classes $> 200 \mu\text{m}$ and $> 350 \mu\text{m}$ are not represented in concentration or influx values, as these have not been recorded during pollen counting but in a separate analysis. Further, the inferred potential local fires are not observable in concentration or influx calculations because either the convection of the fires could prevent the local deposition of the smaller particles (Clark, 1988; Conedera et al., 2009), or the input of the small particles is masked by the overall dominant regional input, and hence prevent the applicability of assumptions by Bennett et al. (1990) – local deposition of smallest charcoal fractions as a result of domestic fires with low intensity convections.

In line with the above mentioned ^{14}C dates and the archaeological record, the most probable explanation for the recorded charcoal particles of larger size ($> 200 \mu\text{m}$ and $> 350 \mu\text{m}$) is anthropogenic fires in the immediate vicinity to the lake. The phase of higher charcoal particle frequencies coincides with the Pleistocene-Holocene transition and thus exactly with a phase of rapidly changing vegetation and landscape.

If human action as origin is the most plausible explanation, the question remains why this is expressed in such a prominent way and in such a short period of time? Can these high values ($> 350 \mu\text{m}$) be linked to more or prolonged local seasonal presence of people? Does the change in the composition of the vegetation directly affect the annual cycle of hunter-gatherer groups? If so, is this palynologically reflected?

It is remarkable that high and continuous influx values of coprophilous fungal spores (HdV-55A) overlap the temporal span of charcoal-phase 2, section 2 or the transformation phase respectively. Therefore, it now needs to be discussed whether, and in which plausible context a correlation of large charcoal particles and coprophilous fungal spores exists.

5.3. Reindeer – Potential behavior of the main game animal

The reindeer (*Rangifer tarandus* L.) was the main game of the Dryas 3 period and thus an essential part of the nutrition during the annual cycle of Ahrensburgian hunters (Aaris-Sørensen et al., 2007; Baales, 1996; Bratlund, 1990; Bratlund, 1996; Eriksen, 1996; Grønnow, 1987; Kollau, 1943; Weber et al., 2011). Accordingly, large quantities of reindeer bones were found at the archaeological site on the banks of the Nahe palaeolake (Wild, 2017). The signs of slaughter on bones of complete carcasses as well as the local geomorphological situation are clear evidence that the site was situated along a reindeer path. This does not seem surprising, especially considering the geographical proximity to the Ahrensburg tunnel valley. Clearly, remains of other animal species were also found at Stellmoor (Bratlund, 1999; Kollau,

1943), but it is apparent from the archaeological record that the focus generally concentrated on reindeer exploitation.

Reindeer are almost constantly on the move. Movements can occur on smaller geographical scales (Aaris-Sørensen et al., 2007; Fontana, 2017) but also as large-scale migratory movements (Burch, 1972). However, migrations are not always unidirectional and sometimes include several passages through the same region. Regarding larger quantities of animals, this is generally associated with a catching up of the main concentration of moving ungulates (Parker, 1972; Seton, 1912). The migrations usually do not occur in a single clustered movement, but in bands, which in turn form an almost continuous stream of animals through an area (Munsterhjelm, 1974; Seton, 1912).

While moving, these Cervidae do not strictly follow the same trails each year. Timing, direction and length of migration of different herds can change. Nevertheless, two clear seasonal movements can be observed in most populations (Burch, 1972; Grønnow et al., 1983; Kellsall, 1968; LeResche and Linderman, 1975; Parker, 1972; Spiess, 1979). On both these migrations reindeers were hunted during the Dryas 3 period, but especially during the autumn as the archaeological finds of the region clearly demonstrate (Baales, 1996; Bratlund, 1990; Bratlund, 1996; Grønnow, 1987; Rust, 1943; Weber et al., 2011; Wild, 2017).

For the present study, longer migratory movements of reindeer are assumed to roughly follow the glacial meltwater valley of the Elbe river (Elbe-Urstromtal) (Price et al., 2017; Wild, 2017). The hypothesis is that large quantities of reindeer moved into the vast grasslands of the present North Sea basin, or Doggerland, east of the Elbe-Urstromtal during the summer months (Baales, 1996; Coles, 1998; Weber et al., 2011) and in smaller bands benefited from the nutritional potential of the pine dominated forests in the region around present-day Berlin/Brandenburg during the winter months of the Dryas 3 period (Kobe et al., 2019).

Reindeer react very rapidly to any alterations in order to optimize forage intakes (Lent and Klein, 1988). Certainly, also avoidance of predation is important, but above all, food supply stimulates and controls seasonal movement (Forbes and Kumpula, 2009; Rettie and Messier, 2000). Regarding forage intakes, the preferences of reindeer are wide, depending on the available forage. According to Spiess (1979), Cairns and Moen (2004) as well as Räsänen et al. (2007), reindeers mainly prefer to feed on willows and birch shoots as well as lichens, further also on grasses, sedges, and fungi depending on season and availability (Aronsson, 1991; Bjune, 2000; Grønnow et al., 1983; Horstkotte and Moen, 2019; Joly et al., 2007; Kellsall, 1968; Kumpula, 2006; Kurkela, 1976; Lent and Klein, 1988; Petersson, 1993; Staaland et al., 1993).

If we consider the transition of the Dryas 3 period to the Preboreal period, a fundamental shift in the vegetation and thus also in the available forage for reindeer can be concluded from the NAH record. In particular, the availability of young birch shoots (*Betula pubescens*, *B. pendula*) sharply increased regionally on a relatively short temporal scale (Krüger et al., 2020). This transformation phase from shrub tundra to developing forest correlates, as described, with a short-term increase in the introduction of coprophilous fungal spores.

The considered ascospores (HdV-55A) are of course not indicative for a certain species of large herbivores (Stivirns et al., 2019). On the contrary, in the context of reindeer, different spore-types have been identified until today (*Sporormiella*-type (HdV-113) – Kamerling et al. (2016); *Podospora*-type (HdV-368) – Räsänen et al. (2007); *Sordaria*-type (HdV-55A) – Anderson et al. (2014)). However, all three have been used as unambiguous indicator for large herbivores, either in sum or alone (Bakker et al., 2016; Raper and Bush, 2009).

Nevertheless, the sum of archaeological finds, ^{14}C data and analogies to the tunnel valley renders it possible that the ascospore input can be explained by fungi growing on reindeer dung. Comparatively more animal dung could be explained by a periodically prolonged seasonal stay due to changed food supply.

Another explanation could be the suspected strategy of drive-hunts

(Bokelmann, 1991; Bratlund, 1990; Eriksen, 1996) that would lead to an increased agglomeration of potential culture media for coprophilous fungi (dung). But clearly, also a mixture of both causes is possible.

Accordingly, the reason for increased fungi growth and the introduction of fungal spores into the lake – which in turn is conditioned by multiple factors – can only be speculative. However, the input correlates directly with the environmental change of the Early Holocene. Consequently, it is justified to assume that the given HdV-55A record reflects the immediate adaptation to an altered food supply and thus a potentially prolonged seasonal presence of reindeer in the area, which would correspond to the behaviour of present-day animals (Forbes and Kumpula, 2009; Räsänen et al., 2007).

This is further supported by recent studies by Tveraa et al. (2013) and Paoli et al. (2019) who suggest that a shift towards warmer climate and hence alterations in available spring forage positively affect reindeer. Thereby the early-year quantity of forage has been identified to be decisive. Now considering the transformation phase, both quantity and quality of available forage is improved, resulting in a potential positive effect on the respective reindeer population.

The maximum input of recorded HdV-55A ascospores coincides with the highest input of large charcoal particles during the transformation phase. Here, it has already been excluded that a large scale wildfire occurred. However, it should be mentioned that especially reindeer avoid clear cuts which were mainly caused by fires in the past (Klein, 1982; Lent and Klein, 1988; Rettie and Messier, 2000; Scherjon et al., 2015) – due to missing lichen availability. At least the core area of the fire is avoided by reindeer in a large distance (Joly et al., 2007). According to Spiess (1979) as well as Horstkotte and Moen (2019) arboreal and terrestrial lichens need at least 5–10 years, even up to 120 years after a wildfire, until they have reached their previous productivity and distribution. Thus, contrary to the assumptions of Selsing (2018) for example, large scale fires would even rule out the presence of reindeer.

If we assume that altered forage availability triggered prolonged stays of reindeer in the area that in turn are reflected in the palynological record, further questions arise: Does this causal chain lead to a short-term change in the hunting behaviour and the suspected short-termed increase of human action in the area that in turn could explain the increased input of large charcoal particles? If so, could this hypothesis be further supported by the archaeological record? Were there regional Ahrensburgian hunter-gatherer groups during the Preboreal period?

5.4. Revisiting Stellmoor data – The regional archaeological context

5.4.1. Biostratigraphical context of archaeological finds

The archaeological excavations in the Ahrensburg tunnel valley were accompanied by pollen analyses (Schütrumpf, 1935; 1936; 1937; 1943, 1958a, 1958b). Main objectives at that time were direct stratigraphic connections of find layers with the phases of vegetation development in order to achieve a chronological classification. Such biozonal and thus relative chronological classifications are beneficial even today, because they provide access to link archaeological layers also to other, well dated pollen profiles of the region such as the NAH record (Krüger et al., 2020).

The investigations in the tunnel valley were unquestionably fundamentally important pioneering work. This concerns both the combination of methods and the individual disciplines themselves. The accuracy of the publication renders it possible that the raw dataset collected by Schütrumpf (1943) (Stellmoor-B) is in parts directly available. Nevertheless, the character of the pioneering work also requires that the obtained results must later be viewed in the light of progress in methodology and advances of knowledge. For this reason, it is worth to partially revise and rethink the pollen profile from Stellmoor.

At the Stellmoor site, the pollen profile Stellmoor-A (partly sampled from the northern excavation profile, partly from a sediment core) was

taken from approximately the deepest part of the lake. As the find layer in the resulting pollen profile could only be connected to a section of five pollen spectra, further samples were taken from the southern excavation profile – Stellmoor-B – in order to achieve a more precise classification. Here, the sampling location was situated directly at the former shore line of a lake during the Dryas 3 period. The results showed that the Dryas 3 period in particular could be recorded at a significantly higher resolution including the full dimension of the upper find layer (Rust, 1943; Schütrumpf, 1943).

Nevertheless, the location relative to the former shoreline implies that considerable disturbances cannot be excluded and are even to be assumed. This is potentially also shown by the mentioning of four find layers by Schütrumpf (1943), which have been discussed by Rust (1943) as one unit covering about 50 cm.

Schütrumpf's interpretations and conclusions were drawn referring to a pollen profile that has been calculated on the basis of the arboreal pollen sum. The zonation of the original Stellmoor-B diagram follows the classifications of Gross (1937) which has direct consequences for the biozonal determination of the Lateglacial and hence, for the classification of cultural layers by Schütrumpf (1943) (Fig. 6a). The identification of the Pleistocene-Holocene transition is based on (i) the strong decrease of the non-arboreal pollen (NAP) values, (ii) the final increase of the pollen density, (iii) the final decrease of *Salix* values, and (iv) the decrease of minerogenic sediment components.

Schütrumpf assumed a decrease in woodland density, but clearly not an absence of trees in the area during the Dryas 3 period from the Stellmoor-B profile. His conclusions were supported by the archaeozoological record, especially of beavers, which were supposed to belong to the Ahrensburgian find layer (cf. below). Following all these criteria, his conclusions are absolutely justified.

Most of these conclusions could not withstand the expansion of knowledge of the past 80 years (the original manuscript was submitted in November 1939). As a result, several of the evaluations need to be reconsidered.

Since the early 1940s, the majority of Lateglacial pollen profiles has been calculated on the basis of the total terrestrial pollen (TTP) sum following Iversen (1942). In addition, Cyperaceae were excluded due to their dominant local pollen production around the investigated archives (De Klerk, 2002; Janssen and Ijzermans-Lutgerhorst, 1973). This represents the standard to date and is applied to the Stellmoor-B dataset in Fig. 6b.

The aforementioned criteria (i-iv) given by Schütrumpf can now be applied to this diagram again, but these also need reconsideration. Pollen density was more a subjective estimation than an objective calculation at the time of the investigation by Schütrumpf. His data regarding pollen density refers to pollen grains per slide and thus unfortunately lack any evaluability today. An objective method becomes possible only decades later with the work of Stockmarr (1971). Therefore, the detection of the actual increase in pollen density was beyond the contemporary possibilities.

Sedimentologically, Schütrumpf refers to a decreasing minerogenic sediment content. As this has not been quantified or somehow described in the text the criterion cannot be applied objectively either. In contrast to that, the pollen analytical characteristics are valid markers for biostratigraphic differentiation and can be applied here as well.

Finally, it should be mentioned that Bratlund (1996) stated that the finds of bones from forest animals among the Ahrensburgian assemblage potentially also require reinterpretation. They probably belong to a younger Mesolithic layer, which remained undetected during the excavations (Bratlund, 1999). Thus, another argument of Schütrumpf would no longer be justifiable.

Based on these reconsiderations the Stellmoor-B pollen profile calculated on TTP needs to be evaluated. From the comparison of the differently calculated diagrams (fig. 6a and b) the following conclusions can be drawn.

The partly strong fluctuations of the curves can be attributed to the

intended pollen sum of 100 arboreal pollen (AP) per sample. Nevertheless, they are absolutely sufficient for a well-founded estimation here.

The pollen morphological or statistical distinction between a *Betula pubescens*-type and a *B. nana*-type has not been made. Thus an estimation of the Pleistocene-Holocene transition is essentially only possible by referring to the decrease of the NAP values. As assumed by Schüttrumpf, the decrease of the *Salix* values can support this estimation.

The significant decrease of the NAP values – clearly dominated by Poaceae – occurs at around 378 cm. The strong decrease of the *Salix* values can be observed at about 376 cm. Considering that willow macrofossils are present as *Salix herbaceae* leaves and that other representatives of the genus were generally not present in the form of trees but rather as shrubs, a decrease of *Salix* values due to shadowing is likely. Above the depth of 376 cm, this is clearly caused by tree sized birches, as the rapidly increasing *Betula* values suggest. Generally, at this depth (376–372 cm) pollen analytical characteristics of the Friesland Oscillation can be observed (Behre, 1966).

This assumption is further confirmed by a subsequent short-term reversal of tendencies. The NAP values describe a recurrent maximum and at the same time *Betula* values are declining. The Rammelbeek phase or Preboreal Oscillation (PBO) is to be assumed here with some caution (Usinger, 2004; Van Geel et al., 1981). Characteristics of the developed Preboreal period follow further upwards.

After the PBO – which is also reflected in the diagram published in 1943 but not identified – Schüttrumpf suspected the actual onset of the Preboreal period and bases his assumption on subjectively determined lower mineral proportions of the detrital gyttja. In fact, the closing of the forest cover is reflected here, as can be inferred from the NAH record.

From these observations it can clearly be concluded that the biostratigraphic transition from the Pleistocene to the Holocene at Stellmoor occurred at about 378/376 cm (Fig. 6b) and not, as assumed by Schüttrumpf, at about 364 cm (Fig. 6a). However, it should be mentioned that Schüttrumpf already suspected that pollen assemblage zone VI-d (fully assigned to the Dryas 3 period in the original Stellmoor-B diagram) possibly contains parts of a pre-woodland phase, but did not further discuss it.

The partially reinterpretation of the Stellmoor-biostratigraphy has direct effects on the relative chronological classification of the find layers. Thus the uppermost archaeological layer associated with the Ahrensburgian (375–375 cm) now biostratigraphically corresponds to the early Preboreal period. This means that there is relative archaeological correlation with the previously established hypotheses on the transformation phase in the NAH record.

5.4.2. Absolute dating of reindeer and regional Ahrensburgian sites

Weber et al. (2011) provided an inventory of all radiocarbon dates of Ahrensburgian context from central European northern lowlands published so far. These substantiate previous assumptions (Benecke, 2004; Bratlund, 1999; Fischer and Tauber, 1987) that the majority of dates fall into the late phase of the Lateglacial stadial (cf. Younger Dryas). Recent datings of finds from the excavations of the 1930s–40s further confirm their validity (Grimm et al., in press; Rival et al., in press). In this paper, reference is made to Dryas 3 as a regional biozone, which is combined with absolute ages.

The time range covered by the transformation phase lies between 11,650 and 11,520 cal BP (Fig. 7). Considering regional biostratigraphic boundaries, this corresponds to the early Preboreal period. Also parts of the given Stellmoor dates fall into the early Preboreal period, whereby a plateau in the radiocarbon curve (Benecke, 2004; Jöris and Weninger, 2000) as well as a larger standard deviation lead to the fact that some data extend over about 900 years and thus provide only a vague result.

Most of the Stellmoor dates have been achieved by dating reindeer

antlers. None of them contain cut marks or traces of processing but some of them were still attached to the cranium, indicating that they represent hunting prey (Weber et al., 2011). Further, Benecke (2004) also demonstrated that reindeer were present in the region well into the Preboreal chronozone. These results are in line with investigations by Herre and Requate (1958). They reported reindeer bones from the Poggenwisch site in the Ahrensburg tunnel valley to be stratigraphically assigned to the Preboreal period as they were deposited in Early Holocene peat.

If one refers to the biozonal transition (Dryas 3-Preboreal period), the time range is clearly covered by dated archaeological finds. Thus, even after absolute dating, it would be justified to assume that humans were regionally present during the early Preboreal period – in biozonal terms – who are potentially associated with the Ahrensburgian (Grimm et al., in press).

Widening the scope, there are further European sites where the archaeological inventory is attributed to the Ahrensburgian and at the same time to the early Preboreal period (Barton, 1985; Mithen et al., 2015; Niekus, 2019; Niekus et al., 2019; Terberger, 2004) even without considering the Ahrensburgian-alike Fosna-Hensbacka inventories from southern Scandinavia (Fuglestad, 2007; Schmitt 1994; 2015a; 2015b; Schmitt and Svedhage, 2015).

5.5. Combining the dots – Adaptation to a changing world

Based on charcoal size classes, a transformation phase has been defined. In the present study, it was demonstrated that the largest recorded charcoal particle size class suggests that these particles most probably originate from local domestic fires (Carcaillet, 2007; Clark, 1988; Whitlock and Millspaugh, 1996). The corresponding maximum input of HdV-55A ascospores has been interpreted as indicative of animal dung (Baker et al., 2013; Nyberg and Persson, 2002; Van Geel, 1978; Van Geel and Aptroot, 2006; Woelders et al., 2016). In conjunction with the archaeological record (Wild, 2017), it is likely that culture media for fungi growth was reindeer faeces. The simultaneously occurring maxima of charcoal particles and ascospores coincide with the biozonal transition Pleistocene-Holocene and date the transformation phase between 11,650 to 11,520 cal yr BP.

The Pleistocene-Holocene transition is characterized by a rapid reorganisation of the vegetation in the catchment area of the Nahe palaeolake. In particular, the major alteration of the landscape caused by the rapid spread of trees is of fundamental importance (Krüger et al., 2020).

From this the following conceptual model can be proposed:

The rapid climatic change at the Pleistocene-Holocene transition resulted in a rapid expansion of woodland dominated by birch trees (*Betula pubescens* and *B. pendula*) locally and regionally (in southern Schleswig-Holstein). As a consequence, the food supply for reindeer herds and bands roaming the area twice a year changed significantly in terms of quantity and quality. It is possible that this altered food supply resulted in a seasonally prolonged stay of these animals, which is reflected in higher dung quantities and thus explains the increased input of coprophilous fungal spores. This rapid change of forage behaviour would be consistent with recent observations by Räsänen et al. (2007).

Highly mobile hunter-gatherers incorporated reindeer migrations into their annual cycle. Regional mass hunting during the Dryas 3 period is evident (Bratlund, 1990; Bratlund, 1996; Bratlund, 1999; Grønnow, 1987; Kollau, 1943). A prolonged stay of the reindeer and thus longer availability of the main game would therefore plausibly also lead to an adapted hunting behaviour and potentially to longer seasonal human presence or an intensification of hunting, which could explain the high quantities of the largest charcoal particles in the record. The resolution (about 7–8 years per sample) requires an almost simultaneity of the proxies in the record.

Following this causal chain, the break-off of both proxies can be explained by the advancing forest development of the Preboreal period

in the region (Krüger et al., 2020). The local extinction or potential migration of the reindeer herds to the North due to changed vegetation cover and density as well as a more temperate climate (Sommer et al., 2011; Stivrins et al., 2016) conditioned that these seasonally extended or intensified hunting activities terminated around 11,520 cal yr BP – leaving hunter-gatherer groups to adapt again. In any case, potential foraging groups, if locally present, by then pursued subsistence strategies that are either not reflected in the same way in the palynological record, or masked by altered pollen input and generally increased pollen productivity during the Early Holocene.

6. Conclusion and outlook

The present study examines a section of the palynological record from the Nahe palaeolake (Krüger et al., 2020) with special regard to Lateglacial-Early Holocene human-environmental interactions. Answers to the main questions raised at the beginning can be summarized as follows:

Human-environmental interaction is reflected in the palynological record at the Pleistocene-Holocene transition. Here, concurrent maxima of specific proxies (charcoal particles > 200 µm and 350 µm as well as ascospores of HdV-55A) correspond to strong environmental changes of the Pleistocene-Holocene transition. With respect to the direct environment these changes mainly concern the rapid spread of birch trees (predominantly *Betula pubescens*) and the formation of woodland and successively of a forest.

The phase of coincidence of proxies as well as strong alterations in the pollen composition is referred to as transformation phase. The temporal scale of this transformation phase covers the time between 11,650 and 11,520 cal yr BP. In conjunction with the regional and local archaeological record, an anthropogenic interpretation is evident. The results imply that under specific circumstances aspects of the annual cycle of hunter-gatherers and changes therein can be traced when combining the archaeological and palynological record.

The detection of the transformation phase is bound to adaptation processes that assumingly resulted in a temporal amplification of recorded proxies. People might have roamed the area throughout the Dryas 3 period but the reflection of their comparably lower environmental impact was potentially masked by the regional palynological input.

Hence, it is not possible to narrow down the general temporal dimension of local phases of occupation. A possible palimpsest – as mentioned by Wild (2017) – during the entire Dryas 3 period can therefore not be ruled out for the close archaeological site Nahe LA11. However, it is likely that a significant phase of increased human activity occurred at the transition to the Early Holocene that in turn depended on seasonally prolonged stays of reindeer in the area.

One general obstacle to overcome is that the presented investigation including pollen, NPPs and charcoal particles still remains an exception. A local or at least regional comparison is unfortunately not (yet) possible. A confirmation or rejection of parts of the proposed hypothesis could be provided by future examinations of sediments from the Ahrensburg tunnel valley.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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