jungstein ITE Journal of Neolithic Archaeology

6 December 2019
doi 10.12766/jna.2019.8

Land-use and environmental history at the Middle Neolithic settlement site Oldenburg-Dannau LA 77

Ingo Feeser and Walter Dörfler

Abstract

The 'Oldenburger Graben' is an extended wetland area in Northern Germany with a rich archaeological heritage. Several settlements from Late Mesolithic to Late Neolithic were found along the former shore in elevations under the recent sea level. Environmental reconstructions based on palynological investigations around the Middle Neolithic settlement site Oldenburg-Dannau LA 77 enabled a detailed reconstruction of the sea level development and the according environmental transformations. The general increase from values of -4 m a.s.l. at around 5500 cal BC to -2.5 m a.s.l. at around 3000 cal BC is described as a process of stagnation and transgression with strong influence on living conditions in the lowland area. A lake- and peat-landscape was drowned by the rising sea level and underwent a transformation into a marine environment. By the time the coastal erosion resulted in a damming of the former bay and a brackish lagoon lake developed that formed into a freshwater system. The Middle Neolithic settlement of Oldenburg-Dannau LA 77 can be linked to a brackish-marine transgression phase. From c. 3500 until 2900 cal BC the results indicate local settlement activities including cereal cultivation with a short phase of reduced activities at around c. 3200 cal BC. During this time of occupation, the sandy elevation was still connected to the mainland. After c. 2900 cal BC the site became an island, the time when the local inhabitation ceased.

The comparison with other investigated sites in the Oldenburger Graben region shows a stepwise Neolithisation process with indications for single domestic animals occurring already in the Late Mesolithic and a transition to animal husbandry around 4100 cal BC, the beginning of the Early Neolithic (EN) Ia. Single cereal-type pollen grains also occur already during the Ertebølle-time but arable farming did not contribute substantially to the nutrition before c. 3800 cal BC, i.e. the EN Ib. Thus, the transformation of the subsistence economy was a stepwise process what supports the idea of an autochthonous Neolithisation process.

Introduction

The Oldenburger Graben is a low lying (c. 0 to -2 m a.s.l.) wetland area in the young moraine area of Schleswig-Holstein. Its origin goes back to the last glaciation as melt water and tunnel valley. During the Holocene the hydrology and sedimentology of the area was strongly influenced by the post-glacial sea level rise, which favoured the widespread deposition of aquatic sediments and peat growth especially from mid-Holocene times onwards. This favoured water-

Article history:
Received 5 November 2019
Reviewed 12 November 2019
Published 6 December 2019

Keywords: Neolithic, Northern Germany, pollen analyses, palaeohydrology, palaeoecology, Neolithisation

Cite as: *Ingo Feeser, Walter Dörfler: Land-use and environmental history at the Middle Neolithic settlement site Oldenburg-Dannau LA 77 JNA 21, 2019, 157–208 [doi 10.12766/jna.2019.8]*

Authors' address:
Ingo Feeser
Institute of Pre- and Protohistoric Archaeology
Kiel University, D-24098 Kiel
ifeeser@ufg.uni-kiel.de

Walter Dörfler
Institute of Pre- and Protohistoric Archaeology
Kiel University, D-24098 Kiel
wdoerfler@ufg.uni-kiel.de

Acknowledgments
We thank C. Floors and S. Ibens for assistance during field work and laboratory analyses. J. Barabach carried out preliminary analyses on DAN 1–3. The research was financially supported by the German Research Foundation (DFG) in frame of the Priority Program 1400 and the Collaborative Research Centre 1266 (project number 2901391021 – SFB 1266).

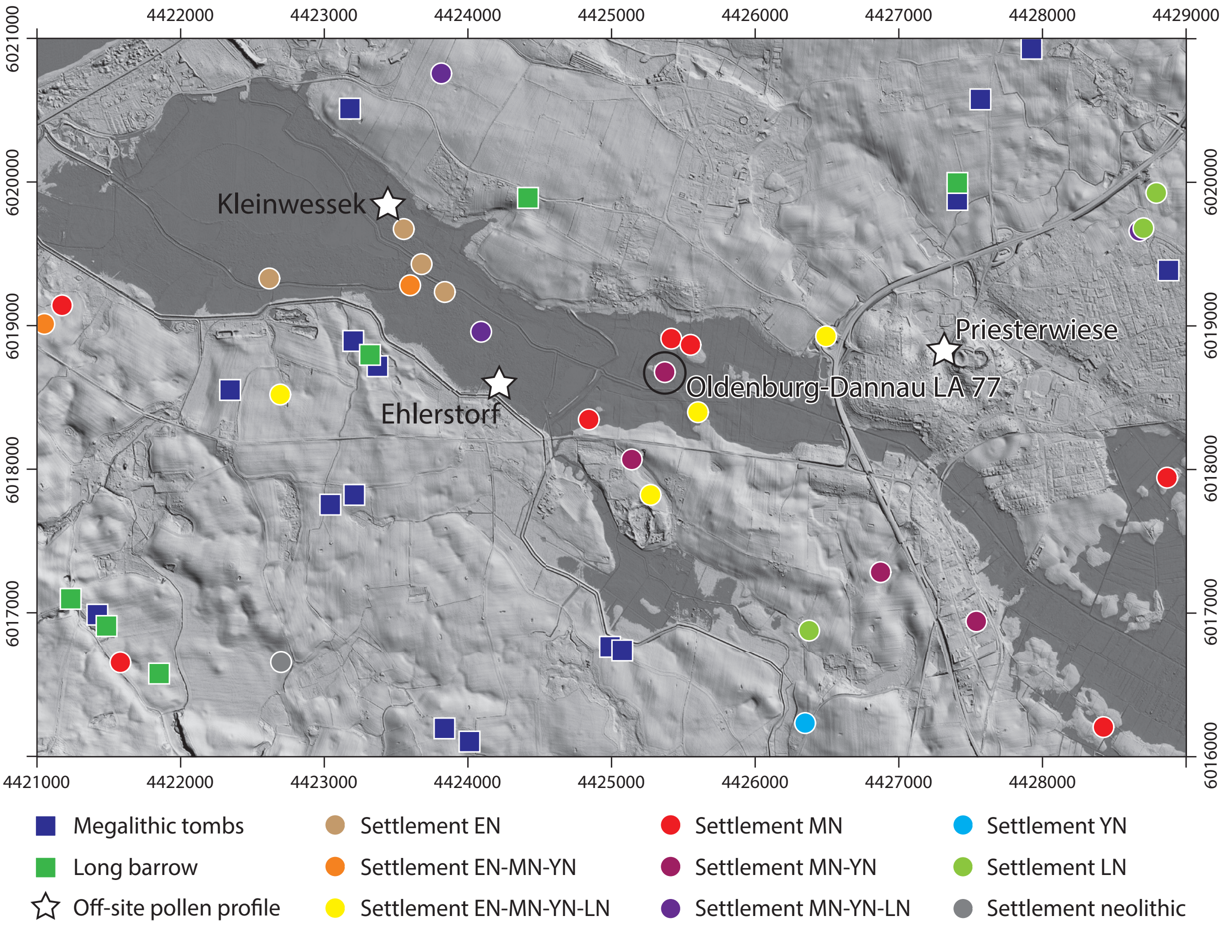


Fig. 1. Overview of the study area "Western Oldenburger Graben" with position of the investigated site Oldenburg-Dannau LA 77. Additional Neolithic sites and the location of off-site pollen profiles used in the present study are indicated. Areas below present day sea level are marked in dark grey, DEM ©LVermGeo SH (after Brozio 2016). EN: Early Neolithic (4100–3300 cal BC); MN: Middle Neolithic (3300–2800 cal BC); YN: Younger Neolithic (2800–2200 cal BC); LN: Late Neolithic (2200–1800 cal BC) (Chronology after Müller et al. 2012).

logged preservation of archaeological sites in connection with suitable archives for palaeoecological near-site studies.

The area has a rich archaeological heritage, including numerous Mesolithic and Neolithic settlement sites (Fig. 1). This exceptional situation is due to a damming of the eastern and western estuaries in the second half of the 19th century and the subsequent drainage of the areas up to -3 m above sea level (Kannenberg 1958; Graf von Platen 1963 as cited in König 1987). These circumstances are crucial for the discovery of settlement layers under the recent sea level. Without drainage and agronomic use many sites would probably still be undetected. Archaeological excavations were carried out from the 1970s onwards by Hermann Schwabedissen, Jürgen Hoika, and Jutta Meurers-Balke, summarized by Brozio (2016, 179 ff.).

First extensive pollen analyses were carried out by Venus (2004) as part of a geological mapping by Seifert (1963) in the early 1960s. Accompanying the archaeological excavations paleoecological investigations focussed on sites of the late Mesolithic and early Neolithic, namely Wangels LA 505, Grube-Rosenhof LA 58, Siggeneben Süd (Meurers-Balke 1983; Kalis/Meurers-Balke 2005; Hartz et al. 2011). But also research in context of Middle Neolithic sites, e.g. Oldenburg-Dannau LA 191 and Heringsdorf Süssau (König 1987; Schütrumpf 1987), was carried out. In the context of excavations at the slavic site of Oldenburg/Starigard Averdieck (2004) provided further pollen records from the area. Because of its special scientific importance, the Oldenburger Graben was intensively geomorphologically examined at the beginning of the 2000s by O. Jakobsen. He reconstructed the Holocene hydrological and morphogenetic landscape development (Jakobsen 2004) including a local sea level curve (Jakobsen et al. 2004).

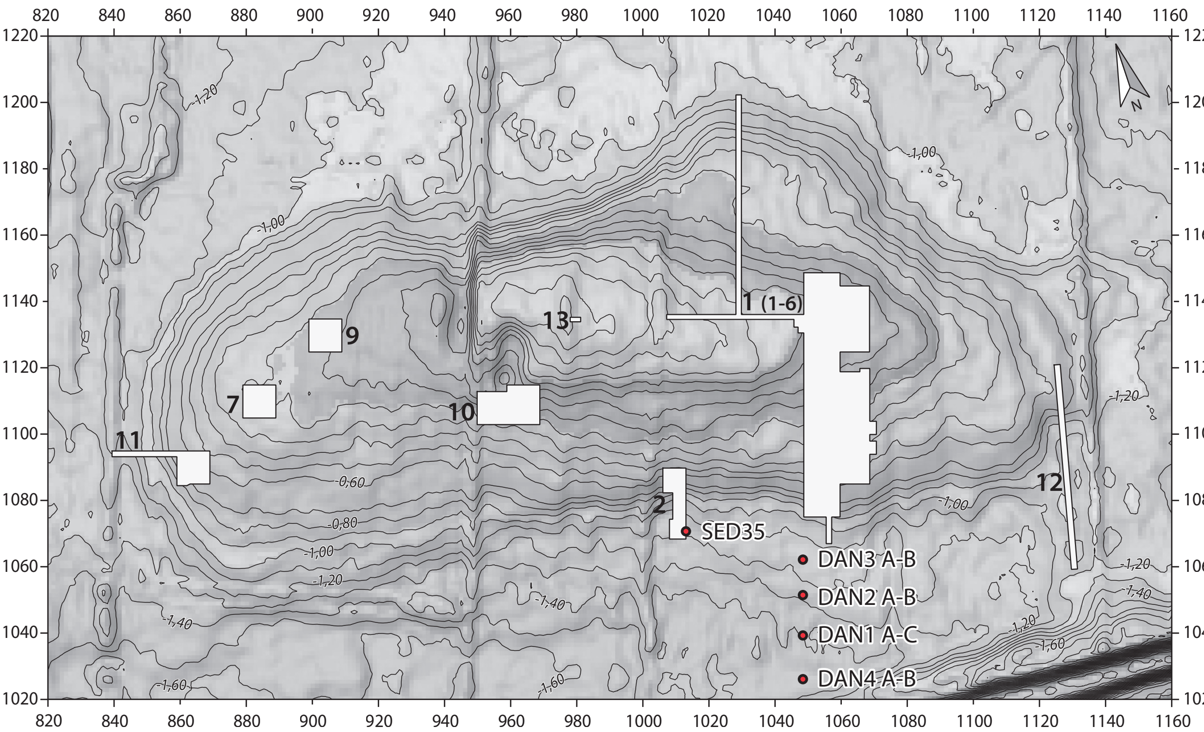


Fig. 2. Digital elevation model of the site Oldenburg-Dannau LA77 with areas excavated between 2009 and 2012 (white) and the location of the pollenanalytically investigated profiles (red). DEM ©LVermGeo SH (after Brozio 2016).

This paper presents the result of palaeoecological investigations carried out in context of archaeological investigations at the Middle Neolithic[1] settlement site Oldenburg-Dannau LA 77 in the western Oldenburger Graben, Northern Germany (Brozio 2016). These comprised near-site pollen analyses in order to reconstruct the local environmental development of the archaeological site. Suitable geoarchives for near-site analyses are undisturbed aquatic or semi-terrestrial sediments, e.g. peat or lake sediments, in the immediate vicinity of an archaeological site. These archives have to be far enough away from a settlement to be undisturbed by human activity but close enough to reflect the local development. Although the pollen input of such site has a strong local and extra-local component (i.e. deriving from an area a few hundred metres around the coring location, cf. Jacobson/Bradshaw 1981) the interpretation benefits from a comparison with the regional pollen component as reflected in off-site pollen diagrams. Therefore, existing off-site pollen profiles from the region were chronologically re-evaluated by pollenstratigraphic correlation using up-to-date age estimations from neighbouring regions (e.g. Dörfler et al. 2012).

Near-site analyses at the archaeological site Oldenburg-Dannau LA 77

The archaeological site Oldenburg-Dannau LA 77 is situated on a sandy morainic elevation of c. 3 ha size (Fig. 1–2). Archaeological investigations revealed several houses and domestic features, including well structures (Brozio et al. 2014), dating to the Middle Neolithic period, i.e. c. 3300 to 2900 cal BC. The present palaeoecological investigations aimed at reconstructing the environmental and land-use history in relation to this settlement. Therefore near-site archives, i.e. deposits with natural sedimentation in the ultimate vicinity of the archaeological site and thus strongly reflecting local to extra-local developments (cf. Jacobson/Bradshaw 1981), were chosen for sedimentological and palynological investigations. In order to identify potential deposits for detailed analyses a transect of corings (DAN 1

1 The usage of Neolithic archaeological periods and chronology follow Müller et al. 2012.

to 4) was used to explore the overall stratigraphy of the sediments in the south-eastern part of the elevation, i. e. downhill from the main excavation area (Fig. 2: excavation area 1) in direction of the former shore line. Preliminary pollen analyses were used for pollenstratigraphical dating. The point revealing the longest Holocene sediment sequence (DAN 1) was chosen for analyses. In course of the analyses, radiocarbon dating, however, revealed that the sediment sequence DAN 1 has a hiatus spanning c. 4300 to 2700 cal BC. Therefore, a second sediment sequence (SED35) spanning c. 3800 to 2500 cal BC from an archaeological excavation area c. 50 m north-west of DAN 1 (Fig. 2: excavation area 2) was additionally analysed in order to fill the gap.

Preliminary analyses in context of the coring transect

South of the main excavation area (Fig. 2: excavation area 1), four sediment sequences were taken using an Usinger corer, i.e. a modified piston corer (cf. Mingram et al. 2007). These consisted of at least two overlapping parallel corings (A and B) of drives of 1 meter length and 80 mm diameter at each coring point (Fig. 3). Coring started at the supposed deepest point south of the excavation area and north of the drainage ditch (DAN 1). Subsequently, the corings DAN 2 and 3 were placed further uphill from DAN 1. The last coring (DAN 4), however, was carried out south of DAN 1.

The stratigraphy at each point was recorded and pollen samples for preliminary pollenstatigraphical dating were taken at distinct changes in the lithology. The aim hereby was to identify undisturbed sediments of Subboreal or Neolithic age, respectively, as close as possible to the Middle Neolithic settlement. The results are summarised in the following.

DAN 1

At this point the thickest Holocene deposits were recorded. They consist of 3.22 m of aquatic to semi-terrestrial deposits on top of fluvial minerogenic glacial deposits (Tab. 1). Seven pollen samples were analysed from 170 to 300 cm below the surface (Fig. 4).

Table 1. Description of sediment stratigraphy at coring point DAN 1, Oldenburg-Dannau LA 77.

Depth below sediment surface (cm)	Depth above sea level (m NN)	Description
0–27	-1.41 – -1.68	Dark brown, sandy, peaty top soil
–49	– -1.90	Grey-brown calcareous gyttja with mollusc remains in the lower 3 cm
–103	– -2.44	Dark brown, strongly decomposed fen peat
–110	– -2.51	Dark grey-brown fine detrital gyttja with fine peaty layers
–125	– -2.66	Grey-brown calcareous fine detrital gyttja with peaty inclusions
–126	– -2.67	Bright grey-brown silty sediment
–140	– -2.81	Dark brown fine detrital gyttja
–140	– -2.81	Thin bright grey sand layer
–171	– -3.12	Dark brown moderately decomposed peat
–178	– -3.19	Dark red-brown, strongly decomposed peat
–190	– -3.31	Dark brown, moderately decomposed peat with wood remains up to 8 cm diameter
–237	– -3.78	Dark brown, moderately decomposed peat
–262	– -4.03	Dark brown, strongly decomposed peat
–264	– -4.05	Grey sand
–303	– -4.44	Brown sandy silty gyttja
–322	– -4.63	Dark brown moderately to strongly decomposed peat
–396	– -5.36	Bright grey sand

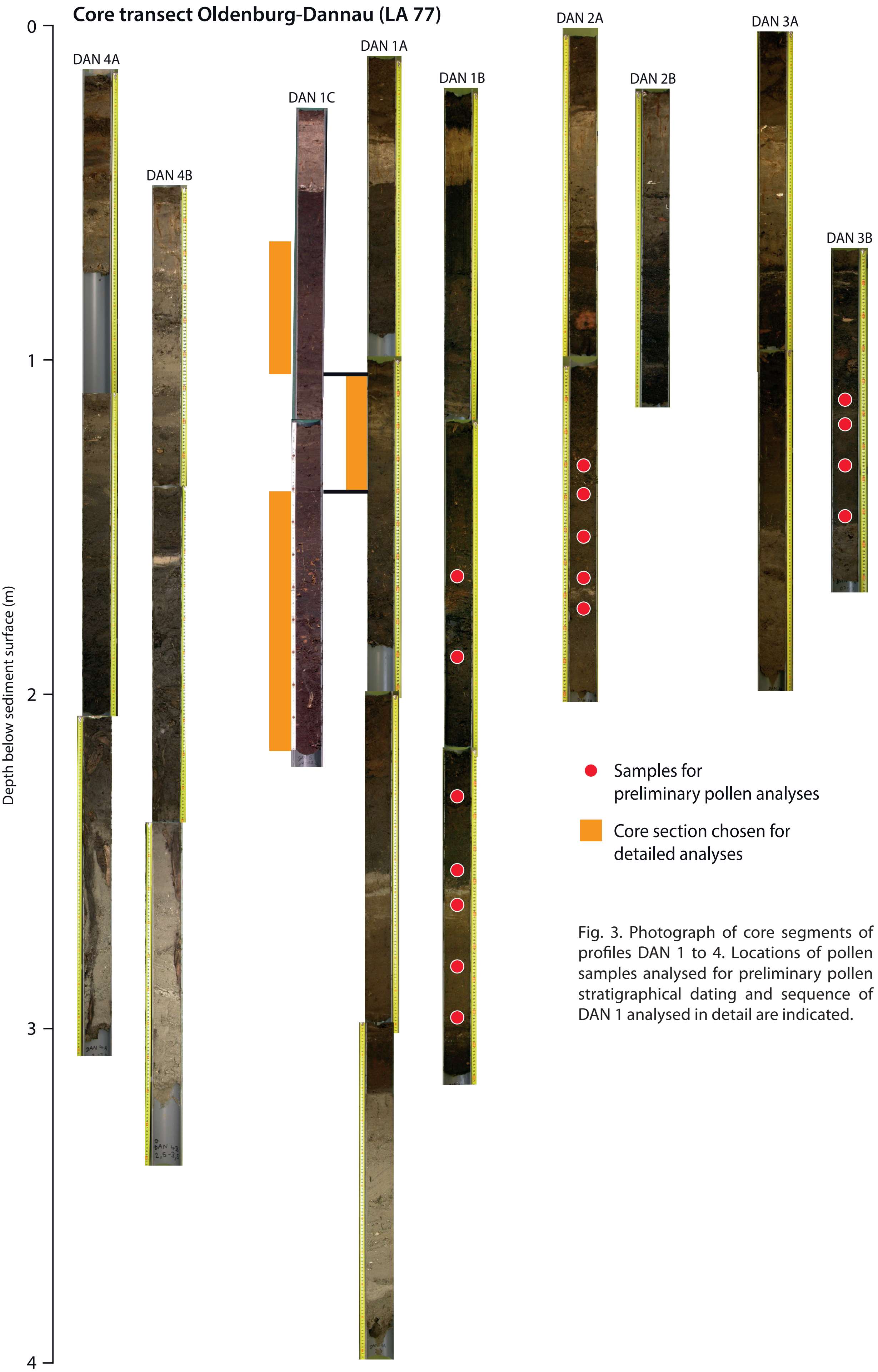


Fig. 3. Photograph of core segments of profiles DAN 1 to 4. Locations of pollen samples analysed for preliminary pollen stratigraphical dating and sequence of DAN 1 analysed in detail are indicated.

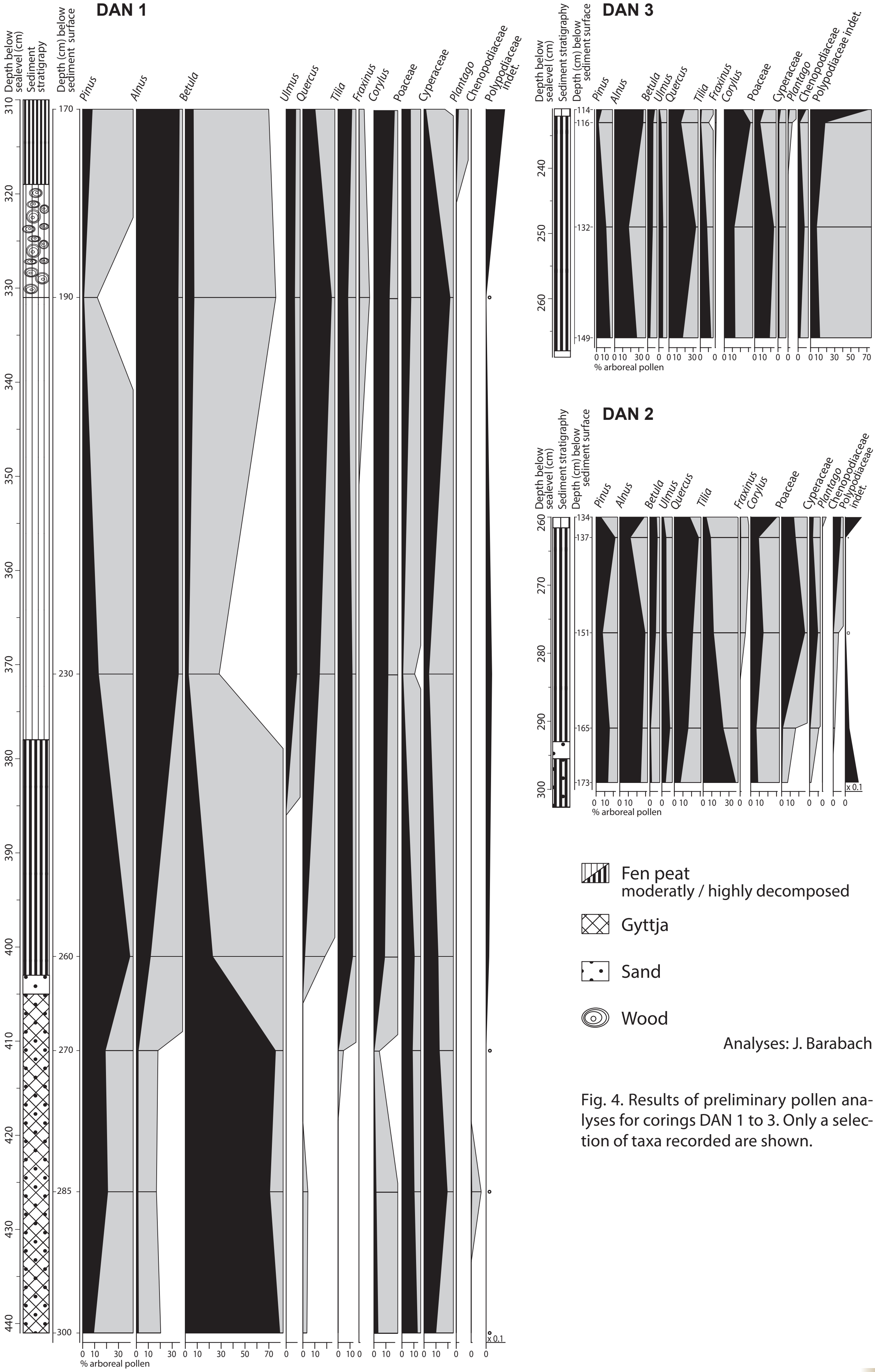


Fig. 4. Results of preliminary pollen analyses for corings DAN 1 to 3. Only a selection of taxa recorded are shown.

In the samples below 264 cm *Betula* is dominating the pollen spectrum and *Pinus* is well represented. Further common taxa not shown in Figure 4 include *Artemisia*, *Empetrum* and *Helianthemum*. This suggests a deposition during the Younger Dryas for the sandy gyttja between 264 and 303 cm. The underlying peat (303–322 cm below sediment surface), therefore, probably formed during the Allerød (~11400–10730 cal BC). Peat growth from 262 cm onwards re-commenced during the early Atlantic period (~7500 cal BC) as indicated by the presence of *Alnus* and increasing importance of mixed oak forest taxa. The sand band at the bottom of the Atlantic peat indicates unfavourable sedimentation conditions during the Early Holocene and/or a hiatus spanning the Preboreal and Boreal period. Anthropogenic indicators, e.g. *Plantago lanceolata*-type, were only recorded in the uppermost sample and were regarded to indicate a Subboreal age for the sediments above 170 cm.

DAN 2

The sediment stratigraphy at point DAN 2 is given in Table 2. The upper 2 meter consist mainly of peat with a c. 40 cm thick insertion of limnic sediments in the upper part of the profile. Below sandy sediments prevail. In total five pollen samples were analysed from the lower peat section (Fig. 4).

Table 2. Description of sediment stratigraphy at coring point DAN 2, Oldenburg-Dannau LA 77.

Depth below sediment surface (cm)	Depth above sea level (m NN)	Description
0 – 20.5	-1.260 – -14.500	Dark brown, sandy, peaty top soil
– 6.0	– -1.880	Grey-brown calcareous gyttka with increasing organic content towards the bottom (incl. wood remains up to 2 cm diameter)
– 131.0	– -2.570	Dark brown coarse detrital gyttja/alluvial peat rich in seeds, fruits and wood remains
– 135.5	– -2.615	Dark brown, sandy weakly decomposed peat with mollusc remains (sharp transition at the bottom)
– 167.0	– -2.930	Dark brown, strongly decomposed peat with rhizomes of *Phragmites*
– 169.5	– -2.955	Grey sand layer
– 178.0	– -3.040	Dark brown strongly decomposed peat with increasing sand content towards the bottom
– 200.0	– -3.260	Dark grey sand with decreasing organic content towards the bottom

In all samples mixed oak forest taxa, e.g. *Quercus*, *Ulmus* and *Tilia*, are well represented and indicate the beginning of peat growth during the first half of the Atlantic, probably after c. 7000 cal BC. High values for *Tilia*, especially in the lowermost samples, probably indicate lime dominated woodlands. From sample 151 cm onwards wild grass-type and Cyperaceae pollen increase and suggest the spread of reed communities. At the same time *Tilia* declines in favour of *Quercus*, maybe indicating a change in woodland composition due to rising ground water levels. The subsequent increase of Chenopodiaceae can be explained by increasing marine influence and the spread of nitrophile shore-line vegetation. The abrupt lithological change from highly to weakly decomposed peat at 135.5 cm is regarded to indicate a hiatus. It is in the pollen spectra above that first indicators of human activity, e.g. *Plantago lanceolata*-type, were found.

Table 3. Description of sediment stratigraphy at coring point DAN 3, Oldenburg-Dannau LA 77.

Depth below sediment surface (cm)	Depth above sea level (m NN)	Description
0–28.5	-1.170–-145.500	Dark brown, sandy, peaty top soil
–71.0	–-1.880	Grey-brown calcareous gyttja
–73.5	–-1.905	Dark brown alluvial peat
–74.0	–-1.910	Grey sand layer
–78.0	–-1.950	Dark brown sandy peat
–115.0	–-2.320	Dark brown moderately decomposed peat with wodd remains (sharp transiton at bottom)
–151.0	–-2.680	Brown strongly decomposed peat with rhizomes of *Phragmites*
–200.0	–-3.170	Dark brown organic rich sand

DAN 3

At this point a sediment sequence of two metres was recovered (Tab. 3). This comprised of c. 1.5 m of semi-terrestrial and aquatic deposits on top of sand deposits of glacial origin. The high organic content in the upper part of the sand suggest the presence of a paleosol. Similar to DAN 2 the sediments above the basal sand mainly consist of peat with a section of aquatic deposits near the top of the profile. In total four pollen samples were analysed focussing on the lowermost c. 50 cm of the peat deposits.

The high representation of mixed oak forest taxa in the lowermost pollen spectrum suggest the beginning of peat formation during the Atlantic period. Similar to DAN 2, relative high values for *Tilia* suggest the presence of lime rich oak forest in the vicinity of the site. The high proportion of wild grass-type pollen (up to 20%) probably relates to the local presence of reed vegetation (*Phragmites*) rather than to a terrestrial herb component. Records of *Plantago lanceolata*-type in the uppermost two spectra and the corresponding decline of *Ulmus* are indicative of the Atlantic-Subboreal transition dating to c. 3900 cal BC.

Table 4. Description of sediment stratigraphy at coring point DAN 4, Oldenburg-Dannau LA 77.

Depth below sediment surface (cm)	Depth above sealevel (m NN)	Description
0–20.0	-1,400–-1.600	Dark brown, sandy, peaty top soil
–33.0	–-1.730	Dark brown to dark grey organic rich sand
–37.5	–-1.775	Dark brown strongly decomposed peat
–57.5	–-1.975	Dark grey silty gyttja
–135.0	–-2.750	Grey-brown to dark-brown silty calcareous gyttja with mollusc remains between 77–84 cm
–245.0	–-3.850	Dark brown moderately decomposed peat with wood remains
–330.0	–-4.700	Grey sand with long vertical orientated wood remains of 2–5 cm diameter of *Alnus glutinosa* (roots?)

DAN 4

Coring at this point revealed a 330 cm long sediment sequence (Tab. 4). Below 245 cm sandy deposits of probably glacial origin prevailed. These included remnants of vertical roots of *Alnus glutinosa*. These probably have their origin in the upper-lying peat layer between 235 and 245 cm. Between 57.5 and 135.0 cm aquatic deposits were found. The uppermost part was characterised by an alternation of sandy and peaty deposits which were regarded to be secondary deposits of dug out material from the close by drainage ditch.

No pollen samples have been analysed from this sequence.

Detailed analyses of profile DAN 1

Profile DAN 1 provided the thickest Holocene sediment sequence recorded during coring in the lowlands south of the main excavation site and was therefore chosen for further analyses. The detailed investigations are limited to the section 65–220 cm (Fig. 3), which according to the preliminary pollen-analytical investigations comprises late Atlantic and Subboreal sediments.

Methods

Sediment analyses (LOI and XRF measurements)

In addition to the description of the sediment stratigraphy (see Tab. 1), loss on ignition (LOI) and X-ray fluorescence measurements (XRF) were performed for a more accurate reconstruction of the sediment changes. LOI was performed on 1 cm thick slices of approximately 5 g sediment (wet weight) according to the standard procedure proposed by Heiri et al. (2001). XRF measurements were conducted at the Institute of Geoscience, Kiel University, using an Avaatech XRF Core Scanner (1 cm resolution, Al to Fe with 10 kV, 0.75 mA) and 10 sec measurement time; Fe to Mo with 30 kV, 1.5 mA and 20 sec measurement time).

^{14}C-dating

For the construction of an absolute chronology, a total of 18 samples were submitted for AMS ^{14}C-dating (Tab. 5). Therefore sieving residues (>300 µm) of 1 cm thick sediment slices were scanned for

Table 5. Overview of ^{14}C datings from profile DAN 1, Oldenburg-Dannau LA 77.

Depth (cm)	Lab. no.	^{14}C age	delta ^{13}C	Material
65.0–66.0*	KIA 49170	4527±33	-25.11	peat bulk sample
100.0–101.0	KIA 47707	3455±49	-29.38	leaf fragments, charcoal particles, 2 *Alnus* fruits
105.0–106.0	KIA 49696	3397±27	-28.90	16 *Alnus* cone fragments, 7 *Alnus* fruits
105.0–106.0	Poz-65181	3365±35	-28.50	seed and fruit fragments, charcoal particles
110.0–111.0	KIA 49167	3551±35	-26.58	*Alnus* cone fragments, see and fruits (*Alnus*, 2 *Carex*, 2 *Urtica*)
110.0–111.0	KIA 49697	3497±25	-25.01	charcoal particles
115.0–116.0*	KIA 49698	3838±40	-22.50	charcoal particles, leaf fragments, *Alnus* cone fragments, seed and fruits (2 *Epilobium*, 1 *Thypha*, 3 *Eupatorium cannabinum*, *Lycopus europaeus*, 11 *Juncus*, 1 *Bolboschoenus maritimus*, 3 *Carex*)
120.0–121.0*	KIA 49168	3967±45	-26.53	charcoal particles, leaf fragments, seed and fruits (*Eupatorium cannabinum*, *Phragmites*)
125.0–126.0	KIA 49699	3611±47	-24.84	3 *Alnus* cone fragments, seed and fruits (2 *Urtica*, 4 *Eupatorium cannabinum*, 5 *Cicuta virosa*, *Carex*)
125.0–126.0	KIA 49997	3680±39	-25.35	charcoal particles
130.0–131.0*	KIA 49700	4020±34	-26.15	charcoal particles, bud scale indet., seed and fruits (1 *Rubus idaeus*, 2 *Rumex* cf. *palustris*, 2 *Eupatorium cannabinum*, *Carex*, *Suaeda maritima*)
135.0–136.0	KIA 49701	–	–	charcoal particles, bud scale indet., leaf fragments, seed and fruits (*Juncus*, 2 *Typha*, 2 *Carex*, *Epilobium*, 2 *Eupatorium cannabinum*, 2 *Alnus*, *Bolboschoenus maritimus*)
140.0–141.0	KIA 49169	5444±57	-27.22	charcoal particles, seed and fruits (8 *Eupatorium cannabinum*, 2 *Chenopodium*)
139.5–140.5	KIA 49316	4140±30	-24.91	seed and fruits (8 *Cladium mariscus*, 5 *Scirpus lacustris*, 1 *Scirpus maritimus*, 1 *Betula*)
157.5–158.5	Poz-65182	5710±50	-34.70	charcoal particles
159.5–160.5	KIA 49317	5657±38	-24.39	charcoal particles, bud scales indet., *Alnus* cone fragments
179.5–180.5	KIA 46291	6030±39	-25.20	charcoal particles, leaf fragments, *Alnus* bud scales, seed and fruits (*Alnus*, Asteraceae indet.)
209.5–210.5	KIA 46922	6373±40	-25.87	15 *Alnus* antheres, 40 *Alnus* bud scales, *Alnus* cone fragments, 6 *Alnus* fruits

* treated as outlier in age-depth modelling

terrestrial macrofossil remains and charcoal fragments. Due to the lack of suitable material, in one case a bulk sample of the fine peat matrix was used.

Pollen- and macrofossil analyses

In a first step, 1 cm thick samples were taken every 5 cm from core sequence DAN 1C. In order to get a complete sediment sequence, the area of the gap between the two core segements was subsampled from the parallel core DAN 1A (Fig. 3). In a second step the subsampling resolution for the Neolithic part was increased to continuous 1 cm thick samples. Sample processing followed standard practices including HCl, KOH and acetolyse treatment (cf. Moore et al. 1991). *Lycopodium* spore tablets were added at the beginning to facilitate calculation of pollen concentration (Stockmarr 1971). The coarse fraction (>200 µm) was removed by initial sieving and subsequently scanned for identifiable macrofossil remains. After a final sieving (6 µm) the samples were stored and mounted in Glycerol. The samples were counted under phase contrast and x400 magnification. Cereal-type and critical pollen grains were examined at x1000 magnification. Pollen identification follows mainly Beug (2004) and Faegri and Iversen (1989). Charcoal particles were counted in two size classes; as micro-charcoal (<200 µm) in the pollen samples and so-called meso-charcoal (>200 µm but too small for species identification) in the remains of the initial sieving.

Results

Sediment analyses (LOI and XRF measurements)

The results of the LOI and XRF measurements are shown in Figure 5. As expected, the peat below 140 cm has a high organic content (>80 % LOI550). The increase of bromine (Br in XRF measurements) from about 190 cm upwards, in context of a more or less constant organic content in this section, is interpreted to indicate an increasing importance of a marine component (cf. Ziegler et al. 2008). At 140 cm the sediment composition changes abruptly. Noteworthy is the strong deflection in the LOI550 curve which is not reflected in the XRF curves. This can be explained by the corresponding sand layer at this position (cf. Tab. 1), which was not equally represented in all cores. The section between 140 and 125 cm is characterized by a slightly lower organic content (LOI550) and slightly higher carbonate content (LOI950). In the XRF measurements, the beginning increase of calcium (Ca) and strontium (Sr) also speaks for higher carbonate contents. In addition, silicium (Si) is slightly elevated. Between 125 and 100 cm high LOI950 as well as Ca and Si values indicate carbonate-rich deposits. Above, between 100 and 50 cm, high LOI550 and rising bromine contents indicate a peat development under increasing marine influence.

^{14}C-dating and chronology

The results of the ^{14}C-datings are summarized in Table 5. An age-depth model was generated using OxCal 4.2 (Bronk Ramsey 2008) and the Intcal13 calibration curve (Reimer et al. 2013) (Fig. 6). Due to age inversions three samples (KIA 49170, 49168 and 49698) have been treated as outliers in this context. The first one relates to the peat bulk sample and could indicate a carbon reservoir effect of some of the material included. The latter two samples both originate from an interval of limnic deposits with peaty inclusions. The too old ages are therefore interpreted to relate to secondary reworked material from shore-near peat deposits. For the same reason sam-

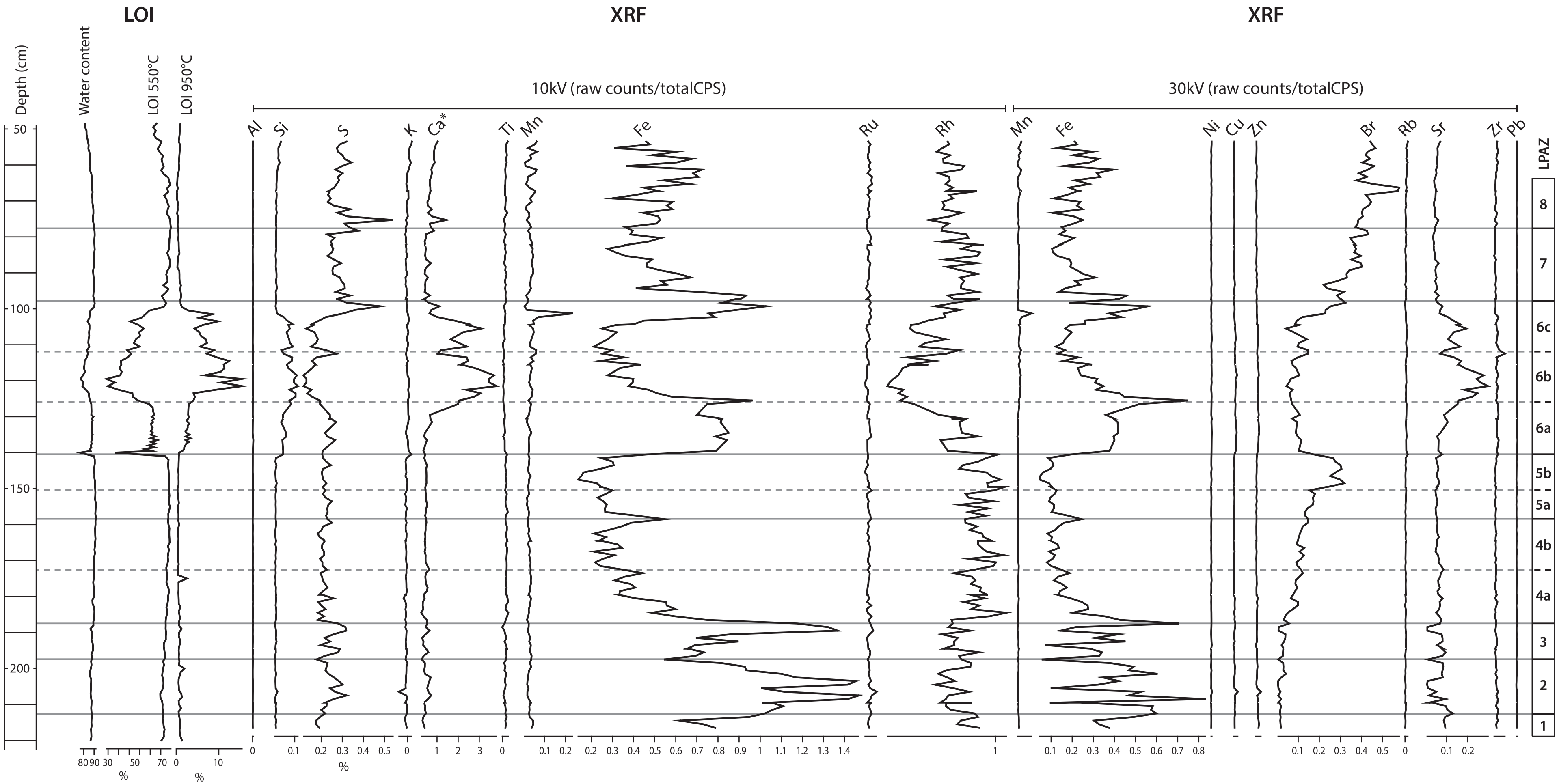


Fig. 5. Results of loss on ignition (LOI) and XRF measurements for profile DAN 1, Oldenburg-Dannau LA77. Local pollen assemblage zones (LPAZ) are indicated.

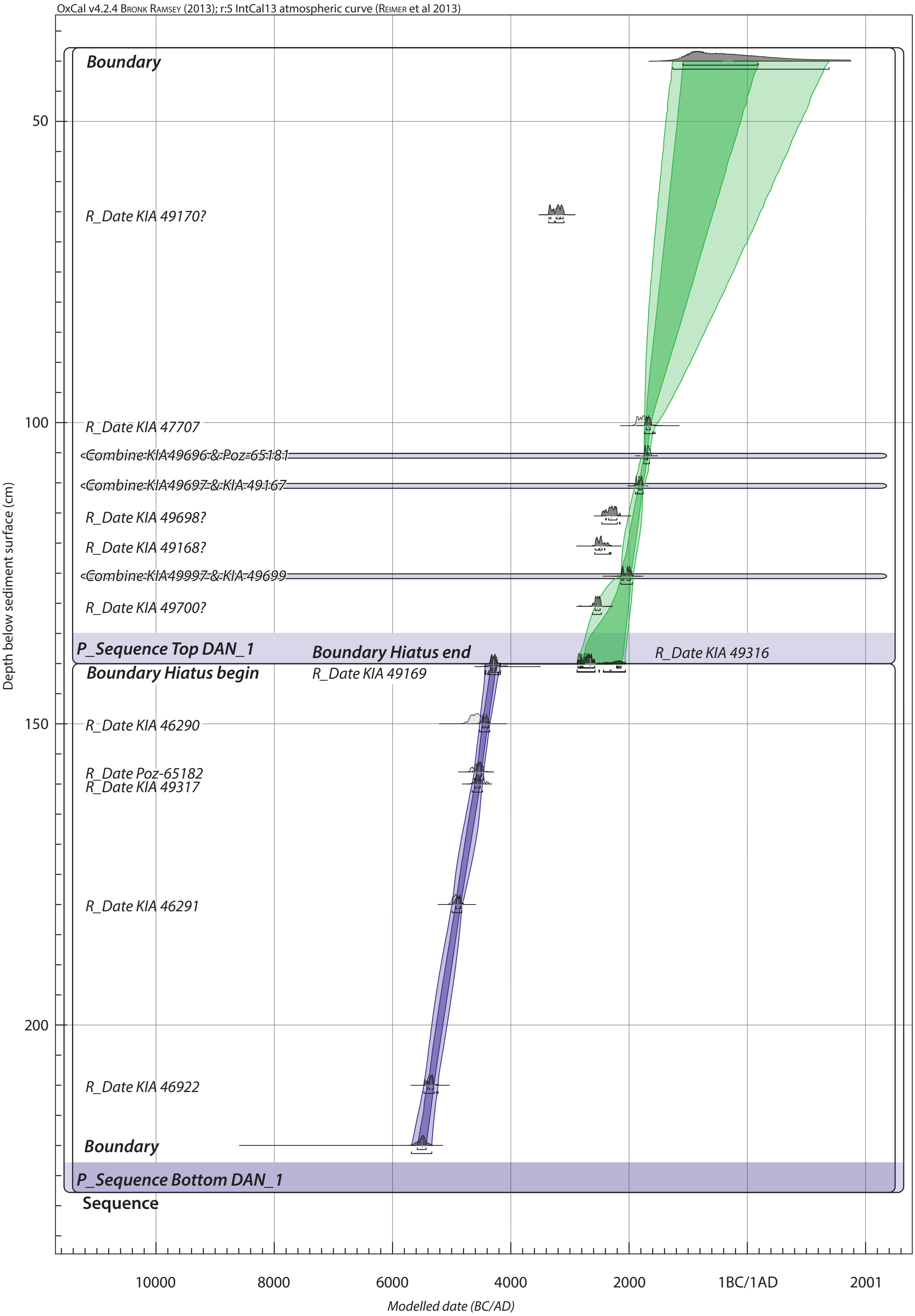


Fig. 6. Age-depth model for profile DAN 1, Oldenburg-Dannau LA 77.

ple KIA 49700, again with a potentially too old age, was treated as an additional outlier. The large age difference between two samples from an almost identical depth (KIA 49169 and KIA 49316) is interpreted to indicate a sediment hiatus. The thin sand layer at 140 cm is therefore not the result of a short-term input event, but rather the result of sediment erosion and rearrangement processes. Based on the time-depth model, the hiatus covers the period from approx. 4300 to 2700 cal BC.

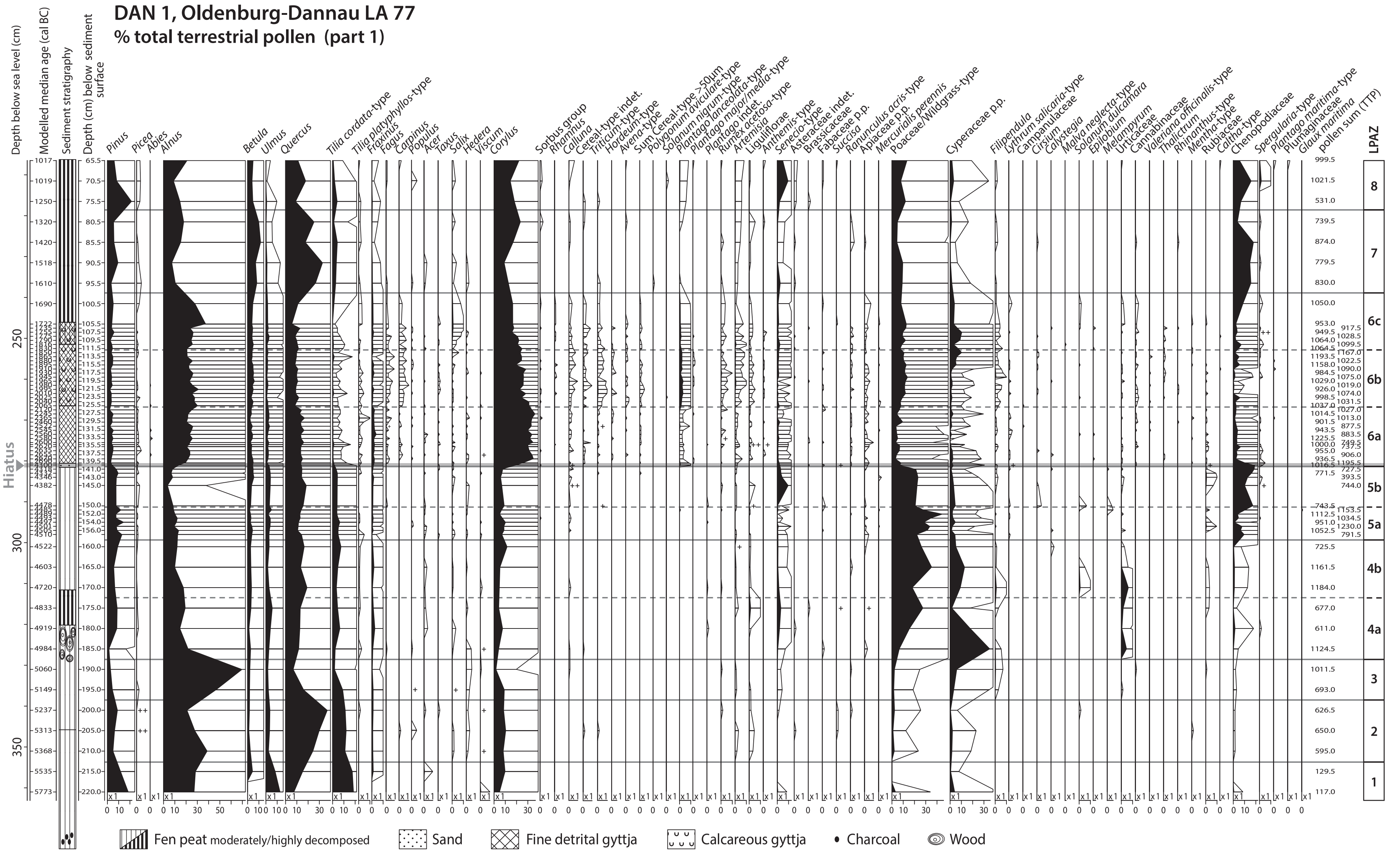
Pollen- and macrofossil analyses

In total 70 samples have been analysed. A pollen sum of at least 500 arboreal pollen was generally achieved. Sample material, equivalent to a pollen sum of another 1000 arboreal pollen grains, was additionally scanned for so far unrecorded pollen taxa. These were noted as rare-type using an '+' in the pollen diagrams. The results of the palynological investigations are given in Figure 7. This pollen diagram presents the relative frequency in relation to the total sum of terrestrial pollen. Rarely recorded pollen taxa are listed in Table 6.

Table 6. Overview of rare pollen taxa not listed in the pollen diagram from profile DAN 1, Oldenburg-Dannau LA 77. '+': taxa noted outside the counting routine.

Taxa	Depth (% Total terrestrial pollen)
Allium ursinum-type	128.5 (0.1 %)
Anagallis-type	130.5 (0.1 %); 135.5 (0.1 %); 138.5 (0.1 %)
Centaurea jacea-type	100.5 (0.1 %); 108.5 (0.1 %)
Cladium mariscus	115.5 (0.1 %); 135.5 (0.1 %); 136.5 (0.1 %); 139.5 (0.1 %)
Frangula alnus	100.5 (0.1 %)
Geranium	180 (+)
Lemnaceae	129.5 (0.2 %); 131.5 (0.1 %)
Liliaceae	151.0 (0.1 %)
Menyanthes trifoliata	141.0 (0.1 %)
Mercuriales annua	112.5 (0.1 %)
Myrica gale	107.5 (0.1 %), 113.5 (0.1 %), 115.5 (0.2 %)
Narthecium ossifragum	145.0 (+)
Papaver argemone	110.5 (0.1 %);116.5 (0.1 %)
Papaver rhoeas-type	75.5 (0.2 %)
Parnassia palustris	175.0 (+)
Plantago coronopus-type	141.0 (0.1 %)
Potentilla-type	95.5 (0.1 %); 124.5 (0.1 %), 141 (0.1 %); 200 (0.2 %)
Sambucus nigra-type	105.5 (0.1 %); 130.5 (0.1 %)
Sausurrea-type	85.5 (0.1 %)
Scrophulariaceae p.p.	106.5 (0.1 %)
Veronica-type	130.0 (+)

DAN 1, Oldenburg-Dannau LA 77
% total terrestrial pollen (part 1)



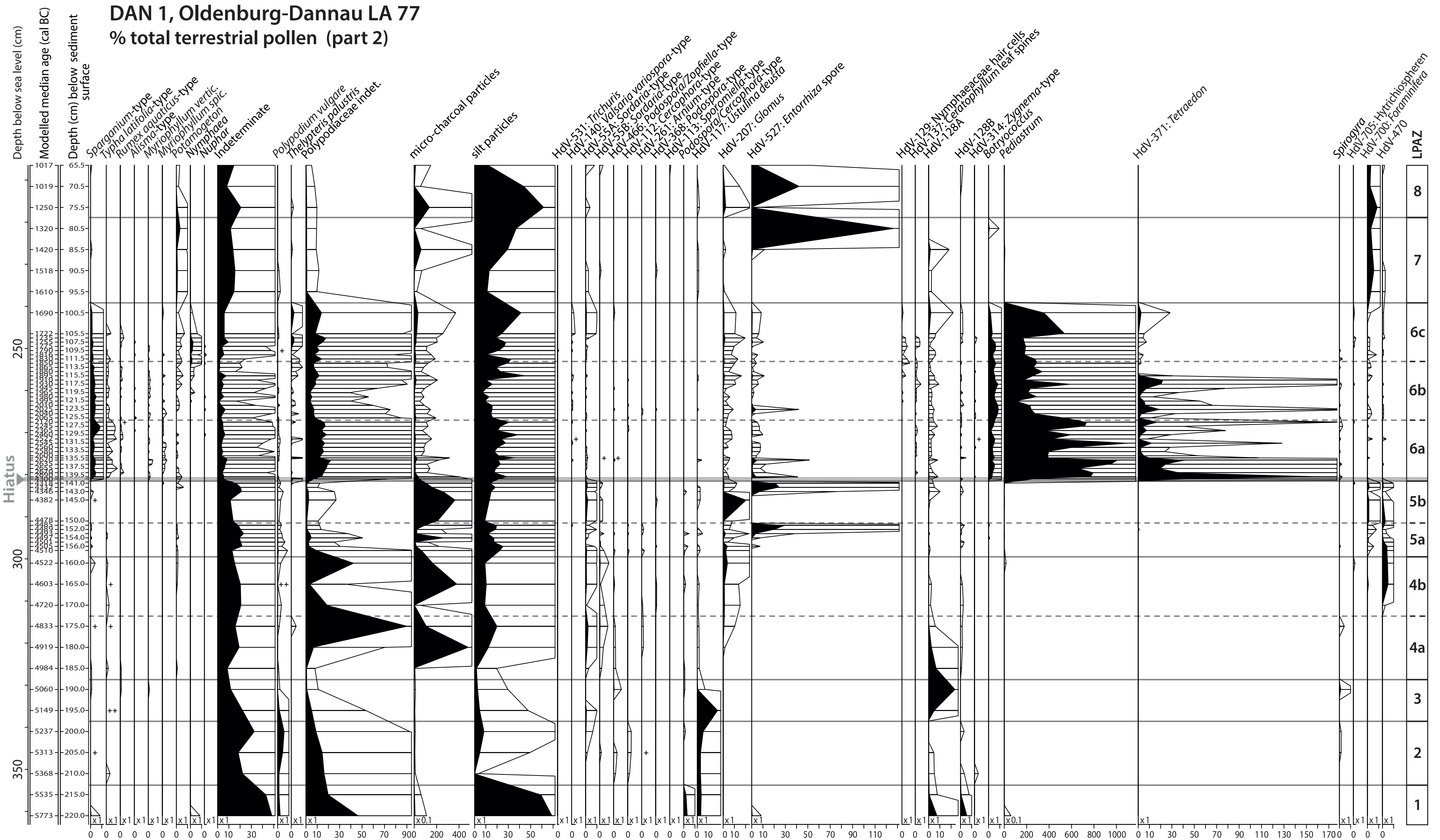


Fig. 7. Percentage pollen diagram for profile DAN 1, Oldenburg-Dannau LA77 showing selected pollen taxa, non-pollen palynomorphs and micro-charcoal and silt particle curves. The curves are plotted to different horizontal scales as indicated. Background silhouettes show exaggerated values x10 (truncated where appropriate). Rare taxa noted outside routine counting are indicated by '+'.

Interpretation of the local settlement and environmental history

Based on the age-depth model the pollen profile spans the time between c. 5800 to 1000 cal BC. Due to the hiatus between LPAZ 5 and 6, however, deposits are missing for the period between c. 4300 to 2700 cal BC. The results of the preliminary pollen analysis (cf. section "preliminary pollen analyses of DAN 1" above and Fig. 4) allow some further reconstructions about to the local vegetation and environmental history since the beginning of the Holocene about 12,000 years ago.

The pollen data was subdivided into 12 local pollen assemblage zones (LPAZ 8, main zones including 7 subzones). These generally reflect main phases of local environmental and vegetation development in relation to hydrological changes, including varying marine influence, in the Oldenburger Graben.

LPAZ DAN 1-1 (samples 220–215 cm)

High values for *Tilia cordata*-type and *Ulmus* characterize the pollen spectra of this zone and indicate lime oak dominated forests rich in elm. *Fraxinus* is only recorded towards the end of this zone and confirms the dating to the early Atlantic period (cf. Nelle/Dörfler 2008). Clear evidence of human activity, however, is missing in this part of the pollen diagram.

LPAZ DAN 1-2 (samples 210–200 cm)

With the beginning of LPAZ 2, the relative proportion of *Quercus* increases significantly, and *Ulmus* in particular, but also *Tilia cordata*-type, decreases. In context of the beginning curve for *Hedera* and the high values *Polypodium vulgare*, both representing at least partially epiphytic plants, namley ivy and common polypody, this indicates a change in the canopy structure of the forest. Unchanging representation of hazel (*Corylus*) as a light-demanding species in the undergrowth, however, suggests no major opening of the woodland structure. The increase of *Quercus* in the pollen diagram therefore most likely reflects less competition in the canopy layer, due to a decline of elm and lime. The onset of high values for *Equisetum* (horsetail) in the pollen data and an increase in macrobotanical evidence of alder (*Alnus*) – interestingly, the pollen values for *Alnus* only increase in the following pollen zone – may indicate local wetting or a rise in groundwater levels, respectively, reflecting the rapid postglacial transgression of the Baltic Sea during the first half of the Holocene.

The records of cereal-type pollen in this zone is not interpreted as an indication of arable activities. These relate to relatively small pollen grains of this type (42.2 and 40.0 µm), so that it seems more likely that they are large pollen grains from wild grasses (cf. Behre 2007a; 2007b; Feeser et al. 2016).

LPAZ DAN 1-3 (samples 195–190 cm)

The pollen spectra of this zone are characterized by the dominance of *Alnus* (alder) and are interpreted to reflect the formation of a local alder carr in the course of the progressive groundwater rise.

LPAZ DAN 1-4 (samples 185–160 cm)

A distinct decline of *Alnus* is defining the beginning of LPAZ 4. Among the trees, ash (*Fraxinus*) gains importance as indicated by increased representation. This is accompanied by a marked increase in wild grass-type pollen as well as elevated values for *Urtica* and a slight increase in Chenopodiaceae. In an early phase (LPAZ 4a; samples 185–175 cm) maximum values for Cyperaceae alternate with maxima for *Senecio*-type and Liguliflorae. At the same time values for fern spores (Polypodiaceae indet.) increase strongly. A later phase (**LPAZ 4b**; samples 170–160 cm) is characterized by maximum values of the wild grass-type.

The increasing importance of Chenopodiaceae is interpreted to indicate the spread of halophytic drift line vegetation in context of beginning marine influence in the western Oldenburger Graben. This is supported by the onset of regular records of foraminifers (HdV-700) in the macrofossil analyses as well as the XRF evidence for increasing marine organic matter in the sediment (cf. Fig. 5: Br). Therefore the decline of the local alder carr is assumed to result from the beginning of marine influence or an increase in salinity, respectively.

It is assumed that reed and fen communities replaced the local alder carr. Hereby, the high values for wild grass-type pollen in **LPAZ 4b** could well derive from *Phragmites australis*. This species is known to form dominating stands even under brakish conditions (Härdtle 1984), whereas alder as a oligohaline species (Kalis/Meurers-Balke 2005) is less salt tolerant. Interestingly, the growth limiting factor for *P. australis* under these conditions is not so much too high salinity but rather mechanical stress due to wave impact and/or grazing pressure. Further characteristic species of brackish reed communities such as *Bolboschoenus maritimus* and *Scirpus tabernaemontani* cannot be differentiated by pollen analysis and contribute to the group of Cyperaceae. Although macrobotanical remains for these species have not been recorded for this pollen zone, there is further evidence for typical species of nitrophile wetland communities (e.g. *Calystegietalis sepium*; Dierssen 1996). This includes *Calystegia sepium*, *Urtica dioica*, *Filipendula ulmaria* and *Galium aparine*. Although is not possible to identify the pollen of these plants down to species level, it seems likely that the according pollen curves, i.e. *Calystegia*, *Urtica*, *Filipendula* and Rubiaceae, represent, at least to a good degree, these species. Especially in cases of pollen taxa comprising many species, however, other potential sources have to be considered. This for example is the case with Rubiaceae, for which also *Galium palustris* has to be considered as an additional, probably important pollen source. A further common taxon from nitrophile wetland habitats is *Solanum dulcamara*, which has been sporadically detected by pollen analysis. The relatively high values for *Senecio*-type pollen probably relate to *Eupatorium cannabinum*, as indicated by the presence of fruits of this taxon in the macrofossil remain record (Fig. 8).

There is no clear palynological evidence of human activity in this zone. Typical anthropogenic indicators such as *Plantago lanceolata*-type, *Artemisia* and *Rumex acetosa*-type indicating open habitats or woodland clearance, respectively, are more or less absent from this zone. The single record of a cereal-type pollen grain is as in the previous zones not interpreted to reflect arable activity (cf. LPAZ DAN 1-2). Also the high wild grass-type values are, as mentioned above, regarded to reflect rather a change in the local wetland vegetation than increased openness in the terrestrial surrounding. Remarkable, however, are the significantly higher charcoal values compared to the previous pollen zones. In context of the archaeological evidence for increasing presence of Mesolithic groups in the region after c. 5100 cal BC (Hartz 2000; Hartz et al. 2011) this more or less contemporaneous increase in the charcoal records could point towards anthropogenic fires. Fire, for example, could have been used to improve grazing and browsing resources for herbivorous game (cf. Mellars 1976). Evidence for increased presence of large herbivores in form of dung fungal spores, however, is weak. The records of spores of type HdV-55A, 55B, 261 and 112, generally assigned to the group of coprophilous fungal spores, cannot be associated exclusively with the increased presence of herbivores, but can also be explained by fungi of the Sordariales or-

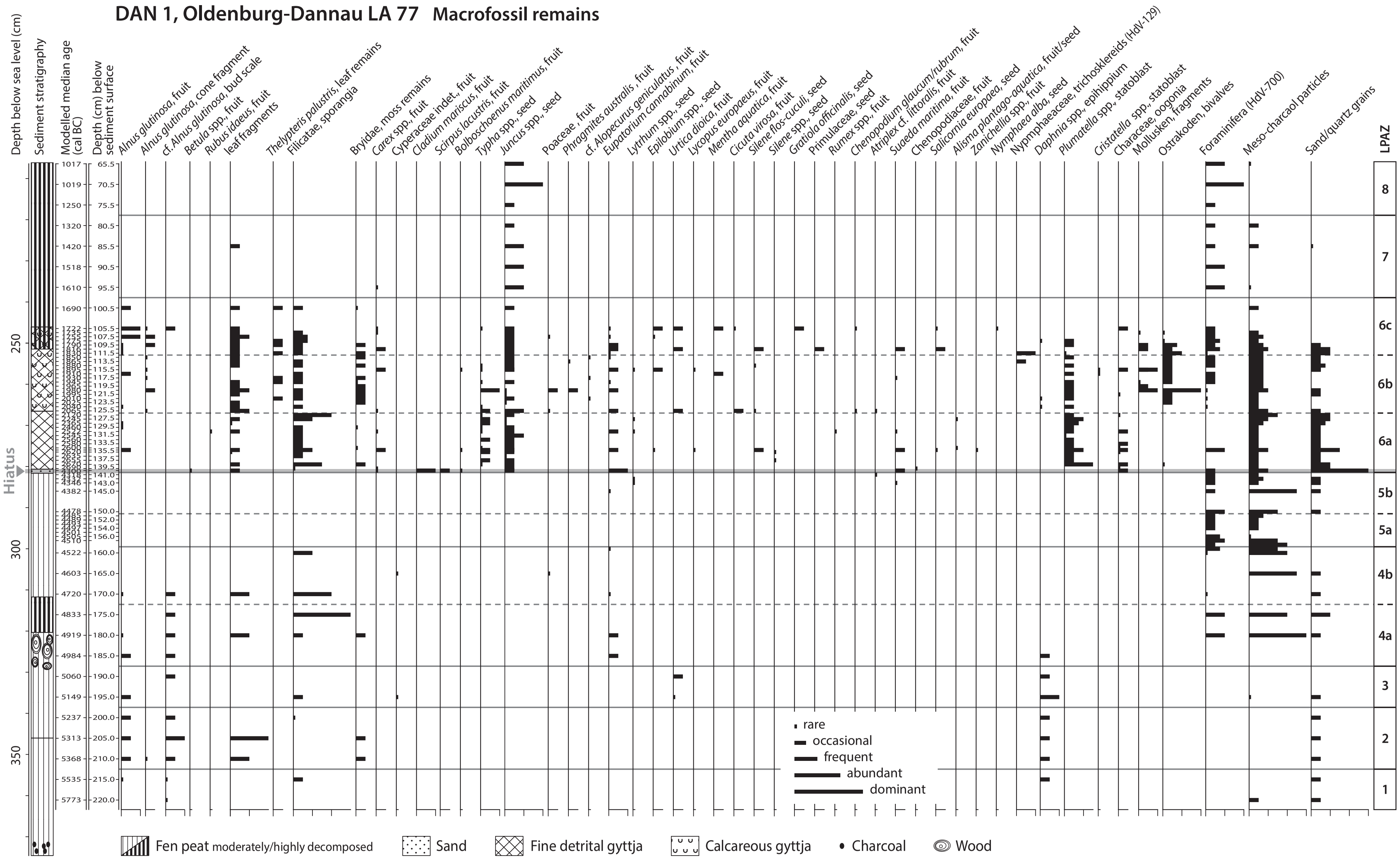


Fig. 8. Macrofossil data for profile DAN 1, Oldenburg-Dannau LA 77. Abundances were noted using a five-grade scale.

der growing on decaying plant material. Only Podospora (HdV-368), which was recorded once in this LPAZ, is generally interpreted as a reliable indicator of large herbivore presence (cf. Baker et al. 2013).

LPAZ DAN 1-5 (samples 157–141 cm)

With the beginning of LPAZ 5, the proportion of Chenopodiaceae in the pollen diagram increases distinctly. This is regarded to reflect the local formation of nitrophile drift line communities in connection with the progressing sea level rise. The strong increase of records for foraminifera (HdV-700) in the pollen and macro remain samples supports the idea of a stronger marine influence. The continuing high values for the wild grass-type suggest that reed communities remain the dominant local wetland vegetation during the second half of the 4th millenium BC. In an early phase **LPAZ 5a** (samples 157–151 cm) values for *Urtica* and fern spores (Polypodiaceae indet.) decline and *Lythrum* is, although sporadically, recorded as pollen, but also in the macrofossil remain record. This is interpreted to reflect a change within the reed vegetation due to increasing marine influence. Urtica *dioica*, for example, is less salt tolerant than *Lythrum salicaria* which could explain the observed change in the micro- and macrofossil record. The transition to **LPAZ 5b** (samples 150–141 cm) is characterized by a decline in wild grass-type pollen and the short-appearance of several, usually rare, non-arboreal pollen (NAP) taxa such as *Melampyrum*, *Cirsium*-type, *Lathyrus vicia*-type and Liliaceae. This could indicate increased biodiversity due to disturbances within the local reed stands. Further evidence for disturbance comes from high charcoal records (micro- and mesofraction) as well as a peak in *Glomus* (HdV-207). The latter fungal spore is usually interpreted as a soil erosion indicator (van Geel et al. 2003). A possible explanation is a local disturbance by fire with subsequent erosion and therophyte-rich vegetation (cf. high *Senecio*-type, but also Liguliflorae). Whether this relates to anthropogenic or natural disturbances, the later resulting from progressive marine intrusion, cannot be answered unequivocally. The first finding of a large pollen grain of the cereal-type at the end of this zone (142 cm; 59 µm diameter, *Triticum*-type, Fig. 9), however, is noteworthy in this

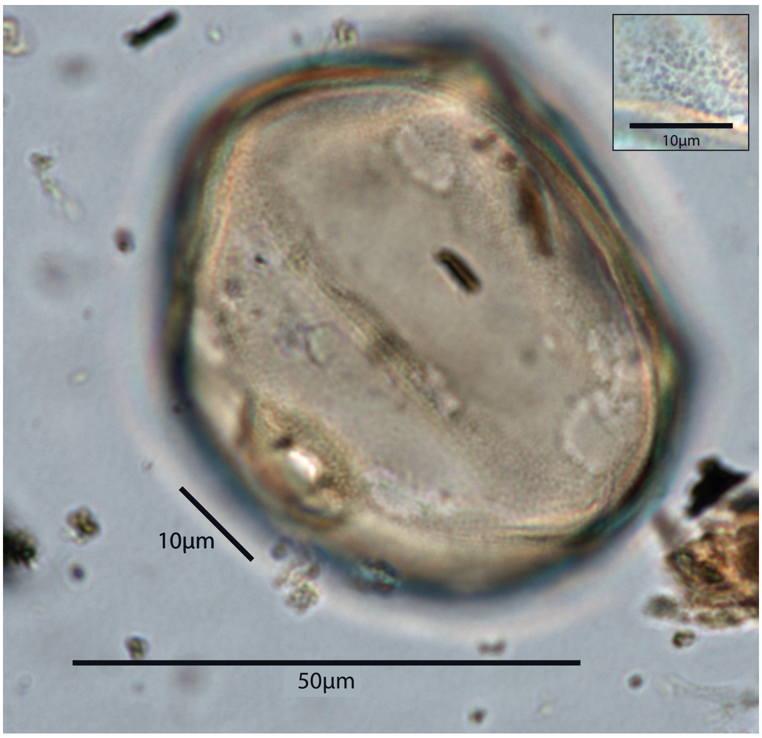


Fig. 9. Large *Triticum*-type pollen grain from pre-Neolithic context (spectra 142 cm) from profile DAN 1, Oldenburg-Dannau LA 77. The upper right image section shows the surface pattern under x1000 phase contrast.

context. Isolated evidence of large pollen grains of the cereal-type in Mesolithic context is not unusual (e.g. Innes et al. 2003; Tinner et al. 2007). However, the significance of such isolated finds with regard to proving the beginning of arable farming is critically discussed (e.g. Behre 2008). In the further course of the pollen diagram, large pollen grains of the cereal-type (>50 µm) are only regularly represented with the appearance of other anthropogenic indicators, such as *Plantago lanceolata*-type, indicating the presence of open, probably cultivated fields. Evidence for a maximum of marine influence is provided by a distinct peak in the bromine curve, indicating high marine organic content (Fig. 5: Br). In this context the high proportion of Chenopodiaceae pollen probably reflects the local establishment of nitrophile marine drift line vegetation. The macrobotanical records of *Atriplex hastata* and *Suaeda maritima*, both halophilic species of the Chenopodiaceae, support this interpretation. The associated low values for *Alnus* in the pollen record suggest a further decline of alder in the lowlands due to increased salinity in the wetlands.

LPAZ DAN 1-6 (samples 140.0–100.5 cm)

At 140 cm, an abrupt change in pollen and sediment composition suggests a hiatus. This is confirmed by the results of the ^{14}C-dating. Taxa that are more abundantly represented include *Corylus*, *Alnus* as well as *Plantago lanceolata*-type and cereal-type pollen. Significantly lower proportions are found in *Tilia cordata*-type, *Ulmus*, wild grass-type, *Senecio*-type and Chenopodiaceae. The now continuously recorded anthropogenic indicators, e.g. *Plantago lanceolata*-type, *P. major/media*-type and cereal-type pollen, as well as the high representation of the light-loving hazel (*Corylus*) indicate increased landscape openness including agriculturally used land. The deposition of subhydric sediments, i.e. gyttja, within this zone indicates the presence of open water at the coring site and rising water levels in the western Oldenburger Graben. This is also reflected in the increased and comparatively high proportion of limnic aquatic and marsh plants in the pollen record, e.g. *Sparganium*-type, *Typha latifolia*-type, *Myriophyllum* and *Rumex aquaticus*-type, as well as high values for green algae *Pediastrum*, *Botryococcus* and *Tetraedron*. Fresh water conditions or shift from marine to limnic conditions, respectively, are furthermore indicated by lower values for Chenopodiaceae in the pollen and Foraminfera (HdV-700) in the pollen and macrofossil record. Lower marine influence seems to have also favoured the recovery of alder in the wetlands of the Oldenburger Graben as indicated by distinctly higher pollen percentages for *Alnus* with respect to the previous zone. This is supported by the recommencing macrofossil remain evidence for *Alnus glutinosa* within this zone (Fig. 8). The assumed decline in reed beds – indicated by distinctly lower proportions of the wild grass-type –, however, does not necessarily have to be only related to the changed hydrological conditions and the recovery of alder carr vegetation. Considering the increased evidence for human activity in the region, including both the palynological but also archaeological record (cf. Fig. 1: Younger Neolithic sites), it is also possible that mechanical disturbance, by man and livestock, resulted in a decline of *Phragmites* dominated reed beds, as it is the case nowadays (cf. Härdtle 1984). This favours lighter reed and wetland vegetation, which could explain the regular palynological records of *Filipendula*, *Valerina officinalis*-type, *Thalictrum*, *Lytrhum salicaria*-type and *Epilobium* within this LPAZ. The regular records of Cannabinaceae pollen most likely derives from *Humulus lupulus*, another plant typical for nutrient rich wetland situations. Also the macrofossil record points at open wetland and fen vegetation with regular records for *Juncus* spp., *Thypha* spp. and *Eupatorium cannabinum* (Fig. 8).

Based on fluctuations in the curves of the anthropogenic indicators, LPAZ 6 is subdivided into three subzones.

LPAZ 6a (samples 140–126.5 cm) is characterized by maximum values for *Corylus* whereas anthropogenic indicators such as *Plantago lanceolata*-type and cereal-type pollen are continuously, but in contrast to the following zone, comparatively poorly represented.

The highest values for *Plantago lanceolata*-type, cereal-type pollen, *Rumex acetosa*-type and *Artemisia* occur during LPAZ 6b (samples 125.5–112.5 cm) and indicate increased land use or settlement activity, respectively, during the Late Neolithic. In this context, the simultaneous increase of the wild grass-type does not have to be understood as a regeneration of the *Phragmites* reed beds, but presumably as an increase of open terrestrial land due to human activity.

The sedimentological record suggest decreasing water depth at the coring point. Sediment carbonate content (cf. Fig. 5: LOI950, XRF Ca and Sr), for example, is increasing strongly. The related change from organogenic to calcareous gyttja with mollusc remains (cf. Fig. 8) is typical for hydrosere stages, i.e. the succession from open water to peatland, in lakes fed by calcareous groundwater. This, however, does not have to indicate a decrease of the absolute water level but can also be explained by a relative decrease in the course of the silting-up process. In the pollen data a change in the algae spectrum, with *Pediastrum boryanum* decreasing and *Botryococcus* increasing, might reflect the lowering of the water depth.

In the following LPAZ 6c (samples 111.5–100.5 cm) anthropogenic indicators decrease, which suggests decreasing land use at around the beginning of the Bronze Age, i.e. after c. 1850 cal BC. The beginning of peat formation within this zone is regarded to reflect the advancing hydrosere succession. Accordingly, the high relative proportions of *Nymphaea* pollen as well as the Nymphaeaceae trichosclereid (HdV-129, in both the pollen and macrofossil record) are assumed to reflect the floating vegetation stage (Nymphaeion) in the littoral zone. The concurrent increased representation of Cyperaceae pollen is likely to reflect the further inland growing fen communities. And as *Salix* is not wind pollinated and therefore probably mainly of local origin, the *Salix* curve, reaching maximum values in the middle of this zone, points to the local expansion of willow in the surrounding wetlands.

The increase of the Chenopodiaceae curve in the pollen data as well as the recommencing records of foraminifers (HdV-700; within this zone only in the macrofossil record, but in the following also in the pollen record) indicate a beginning renewed marine influence. This is also reflected in the increase of the bromide content, as an indicator for marine organic matter, in XRF measurements.

LPAZ DAN 1-7 (samples 95.5–85.5 cm)

This pollen zone is characterized by higher proportions of *Quercus*, *Tilia cordata*-type and also *Betula* in the arboreal pollen spectrum. The representation of *Alnus*, *Fagus* and *Carpinus* is weaker. At the same time, the proportions of *Corylus* and anthropogenic indicators, e.g. *Plantago lanceolata*-type, cereal-type pollen, *Rumex acetosa*-type, and Liguliflorae, strongly decrease[2]. This indicates a decrease in land use and at least partial forest regeneration that favoured climax trees such as oak (*Quercus*) and lime (*Tilia*) and reduced light-demanding species such as hazel (*Corylus*) and alder (*Alnus*). Further evidence for a decline in land use is given by lower erosion indicators, such as *Glomus* (HdV-207) and minerogenic particles in the pollen samples. Also micro-charcoal values are lower. A decline of alder populations is supported by the absence of records of *Alnus* re-

2 These developments are not just expressed in the relative percentages but also in the concentration data.

mains in the macrofossil record (Fig. 8). Beside the decrease in land use, however, also increasing marine influence probably played a role. Evidence for this is given by an increase in Chenopodiaceae and Foraminifera (HdV-700) associated with a sharp decline in *Sparganium* and evidence of green algae (*Pediastrum* and *Botryococcus*).

LPAZ DAN 1-8 (samples 80.5–65.5 cm)

The uppermost samples of profile DAN 1, summarized as LPAZ 8, are characterized by a renewed increase of *Plantago lanceolata*-type. Also, the soil erosion-related NPP *Glomus* (HdV-207) as well as silt particles increase again in the pollen samples. In the top two samples (70.5 and 65.5 cm) high values for *Senecio*-type and *Spergularia*-type are noteworthy. In combination with the increased findings of *Juncus* seeds, this observation is regarded to indicate the local formation of open saltmarsh communities, with *Juncus gerardii*, *Spergularia media* and *S. maritime*. Nowadays, this vegetation type is known in the Baltic Sea region to develop on extensively used brackish wetland (Härdtle 1984).

Profile SED35

Material and methods

Profile SED35 relates to a 88 cm high box profile from the south-eastern end of excavation area 2 (Fig. 2). According to the find distribution, the profile is located c. 20 m south of the former settlement area (cf. cultural layer in Fig. 10). The sediment stratigraphy of SED35 is summarized in Table 7.

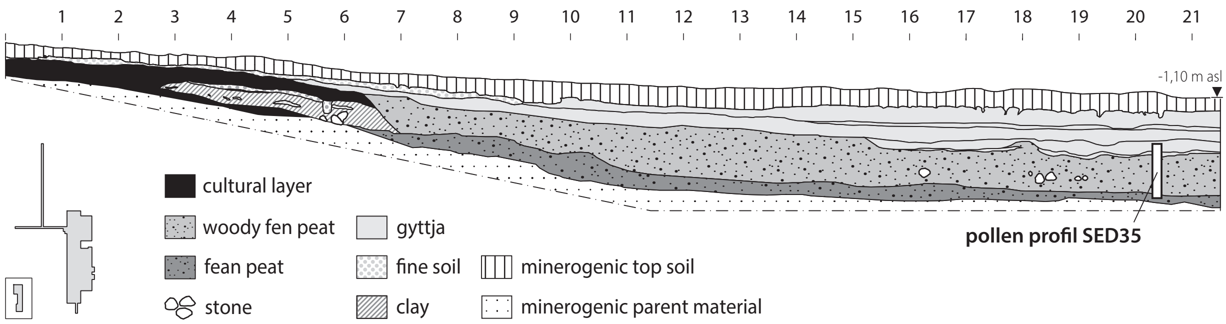


Fig. 10. Section of excavation trench 2, Oldenburg-Dannau LA 77, with position of pollen profile SED35.

Table 7. Description of sediment stratigraphy of SED35, Oldenburg-Dannau LA 77.

Depth below top of profile (cm)	Depth above sea level (m NN)	Description
0–11.0	-1.940– -2.050	Dark-brown, strongly decomposed peat with mollusc remains between 9 – 10 cm
–26.0	– -2.200	Mottled dark to light brown, strongly decomposed peat
–36.0	– -2.300	Dark-brown, strongly decomposed peat
–42.0	– -2.360	Grey-brown silty gyttja
–44.5	– -2.3850	Dark-brown, moderately sandy peat
–53.0	– -2.470	Brown, sandy silt gyttja with wood remains, charcoal and small stones
–70.0	– -2.640	Brown, moderately sandy, strongly decomposed peat
–88.0	– -2.820	Dark-brown, strongly decomposed peat

In a first step the profile was subsampled with 2 cm thick slices taken from 51–53, 63–65, 73–75 and 84–86 cm. In a second step subsampling resolution was increased by further samples of 1 cm thick slices taken every 2 cm in between the first samples. Therefore, in total 18 samples were taken for pollen and macrofossil analyses. Sample processing and analyses followed standard methods as already described for profile DAN 1 (see above). Due to the high number of cereal-type pollen grains in some samples, no further differentiation of cereal-type pollen under x1000 magnification was carried out. Instead, 25 cereal-type pollen grains from one sample (55 cm) were randomly selected and attributed to the different types described by Beug (2004).

For the construction of an absolute chronology four samples of selected terrestrial macrofossil remains were submitted for AMS ^{14}C-dating (Tab. 8).

Table 8. Overview of ^{14}C dates from profile SED35, Oldenburg-Dannau LA 77.

Depth (cm)	Lab. no.	^{14}C age	delta ^{13}C	Material
51–53	Beta 411441	4280±30	-27.5	small twigs, bud scales indet.
63–65	Beta 411442	4450±30	-28.9	small twigs
75–77	Beta 411444	3680±30	-27.5	cone fragments, fruits, and bud scales of *Alnus*
84–86	Beta 411443	5010±30	-26.4	bud scales indet., seed and fruits (*Juncus*, *Sueda*, *Atriplex hastata*, *Atriplex patula*)

Results

^{14}C-dating and chronology

The results of the ^{14}C-dating are summarized in Table 8. An age-depth model was created using the P_Sequence function of OxCal 4.2 (Bronk Ramsey 2008) and the Intcal13 calibration curve (Reimer et al. 2013). Due to an age inversion, one sample (55–57 cm, Beta 411444) was treated as an outlier during age-depth modelling. Based on the age-depth model (Fig. 11), the investigated part of profile SED35 covers the period from 3800 to 2500 cal BC.

Pollen- and macrofossil analyses

The results of the pollen and macro-remain analyses are shown in Figures 12 and 13. A pollen sum of at least 500 arboreal pollen was generally achieved. Sample material, equivalent to a pollen sum of another 1000 arboreal pollen grains, was additionally scanned for so far unrecorded pollen taxa. These were noted as rare-type using an '+' in the pollen diagrams. Relative rare pollen taxa not listed in the pollen diagram are summarised in Table 9.

The results of the further differentiation of the cereal-type pollen grains in the pollen sample 55 cm are shown in Table 10 and Figure 14. About one third of the pollen grains were too poorly preserved for further determination. The determinable grains could be assigned in equal parts to the *Hordeum*- and *Triticum*-type. Pollen grains of the *Triticum*-type (56.9 µm) were on average larger than the *Hordeum*-type (51.4 µm). However, the result of a t-test does not confirm a statistically significant difference ($p = 0.1485$). The attempt to statistically separate the groups by the ratio of maximum pollen grain diameter to annulus outer diameter also does not result in any significant result ($p = 0.0719$). The situation is different, considering only the size values of the apertures. In this case, the annulus outer diameter or pore inner diameter of the pollen grains of the *Triticum*-type is statistically significantly larger ($p = 0.0025$ and $p = 0.0006$, respectively).

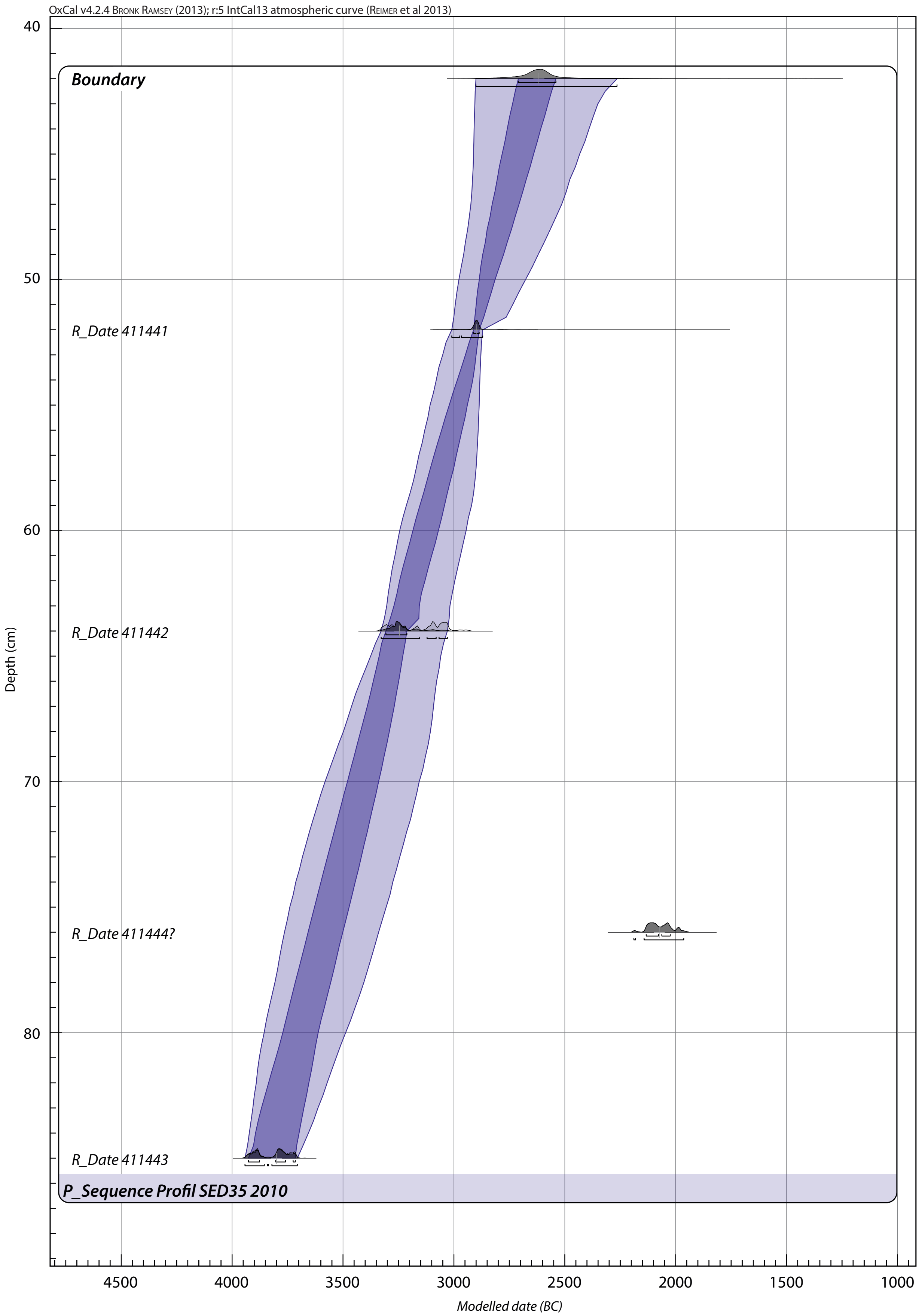


Fig. 11. Age-depth model for profile DAN SED35, Oldenburg-Dannau LA 77.

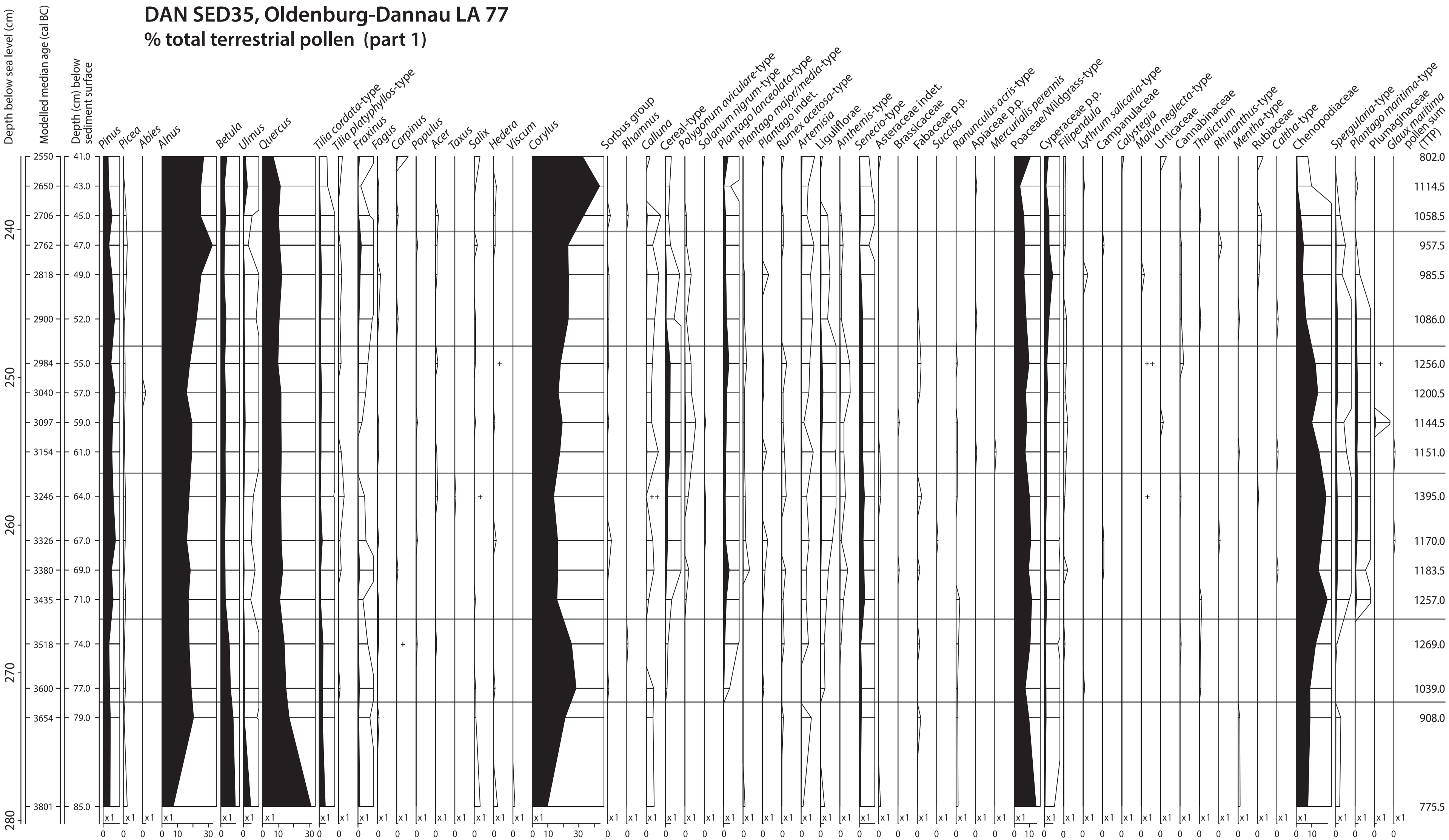


Fig. 12. Percentage pollen diagram for profile SED35, Oldenburg-Dannau LA 77 showing selected pollen taxa, non-pollen palynomorphs and micro-charcoal and silt particle curves. The curves are plotted to different horizontal scales as indicated. Background silhouettes show exaggerated values x10 (truncated where appropriate). Rare taxa noted outside routine counting are indicated by '+'.

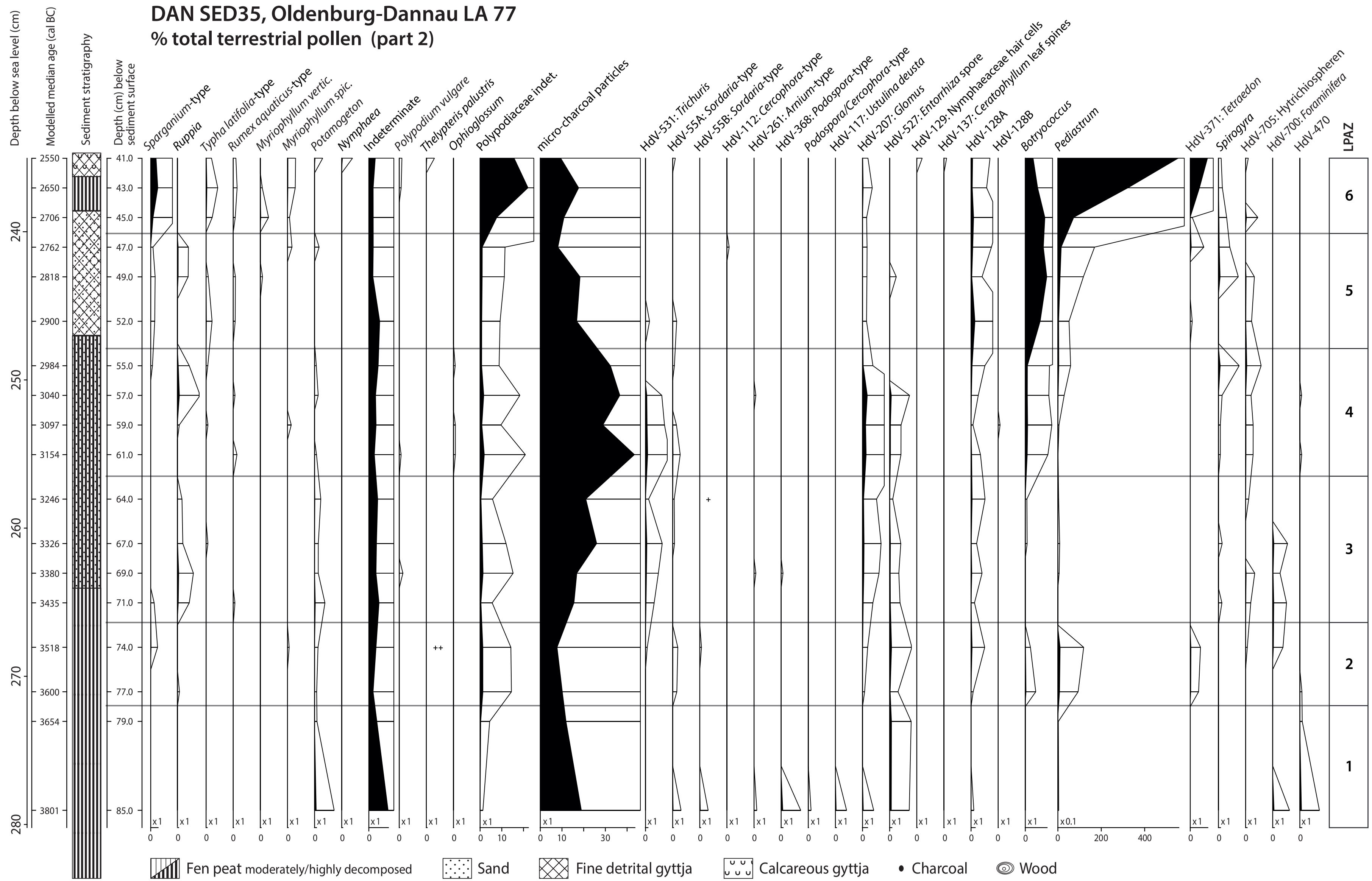

DAN SED35, Oldenburg-Dannau LA 77
% total terrestrial pollen (part 2)
Depth below sea level (cm)
Modelled median age (cal BC)
Sediment stratigraphy
Depth (cm) below sediment surface
Sparganium-type
Ruppia
Typha latifolia-type
Rumex aquaticus-type
Myriophyllum vertic.
Myriophyllum spic.
Potamogeton
Nymphaea
Indeterminate
Polypodium vulgare
Thelypteris palustris
Ophioglossum
Polypodiaceae indet.
micro-charcoal particles
HdV-531: Trichuris
HdV-55A: Sordaria-type
HdV-55B: Sordaria-type
HdV-112: Cercophora-type
HdV-261: Arnium-type
HdV-368: Podospora-type
Podospora/Cercophora-type
HdV-117: Ustulina deusta
HdV-207: Glomus
HdV-527: Entorrhiza spore
HdV-129: Nymphaeaceae hair cells
HdV-137: Ceratophyllum leaf spines
HdV-128A
HdV-128B
Botryococcus
Pediastrum
HdV-371: Tetraedon
Spirogyra
HdV-705: Hytrichiospheren
HdV-700: Foraminifera
HdV-470
LPAZ
Fen peat moderately/highly decomposed
Sand
Fine detrital gyttja
Calcareous gyttja
Charcoal
Wood

Fig. 12. Part 2

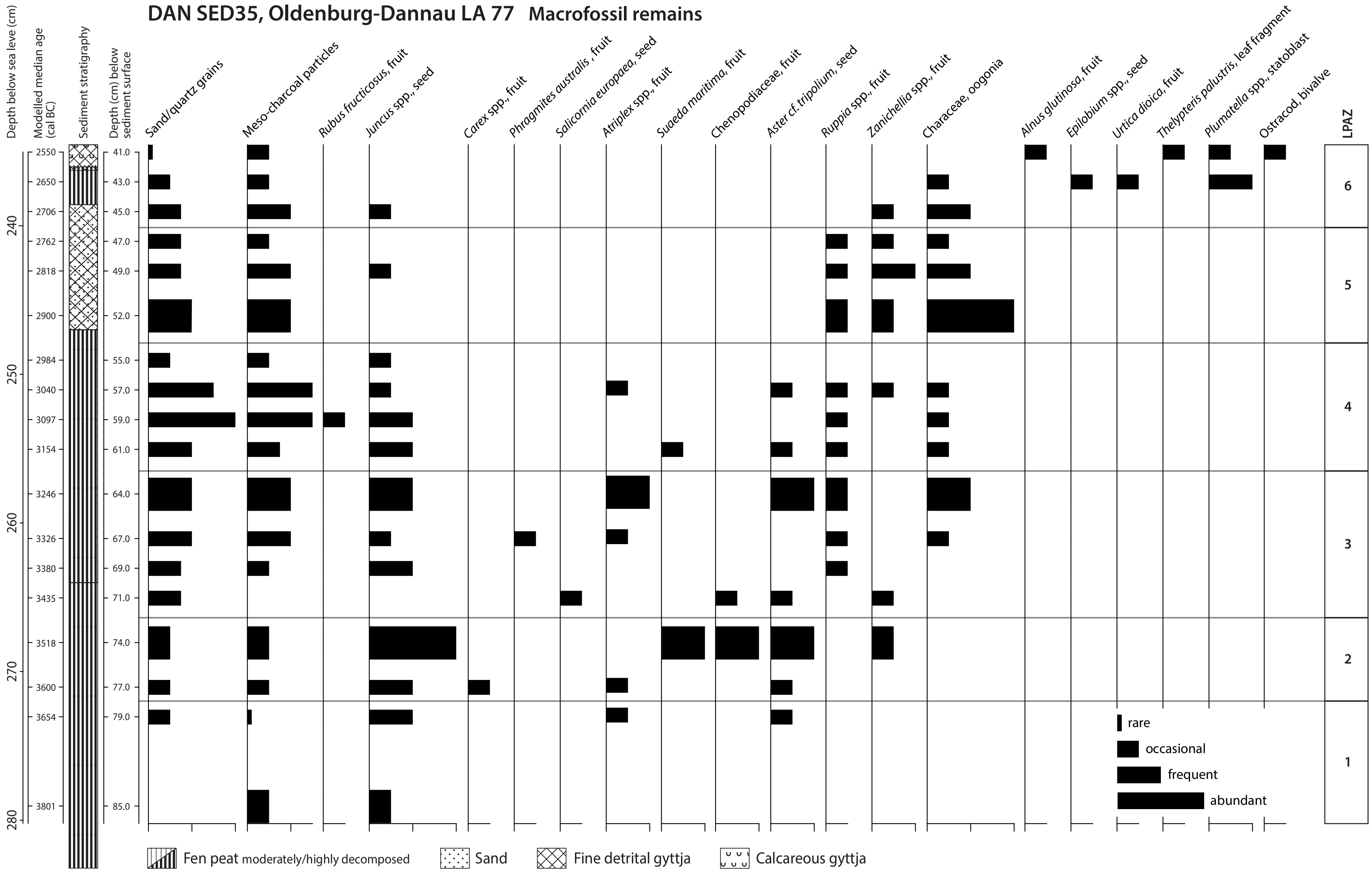


Fig. 13. Macrofossil data for profile SED 35, Oldenburg-Dannau LA 77. Abundances were noted using a four-grade scale.cated by '+'.

Table 9. Overview of rare pollen taxa not listed in the pollen diagram from profile SED35, Oldenburg-Dannau LA 77.

Taxa	Depth (% total terrestrial pollen)
Fallopia	64 (0.1 %)
Oxalis acetosella	49 (0.1 %); 55 (0.1 %)
Persicaria maculosa-type	52 (0.1 %)
Plantago coronopus-type	52 (0.1 %)
Pulmonaria-type	59 (0.1 %)
Sambucus nigra-type	57 (0.1 %)
Scrophulariaceae p.p.	43 (0.1 %); 55 (0.1 %)

Table 10. Results of morphometric measurements on 25 randomly chosen Cereal-type pollen grains from sample 55cm profile SED35, Oldenburg-Dannau LA77.

Pollen grain maximum diameter (µm)	Annulus outer diameter (µm)	Pore inner diameter (µm)
Triticum-Typ		
64	18	8
49	16	6
57	13	8
62	15	6
54	15	7
64	16	6
59	12	5
48	16	6
55	11	5
Hordeum-Typ		
51	11	4
48	10	4
39	9	3
43	12	4
58	12	4
48	10	3
62	10	3
48	12	4
66	15	7
Cereal-Typ indet.		
64	20	8
56	11	4
49	12	4
40	10	5
48	15	5
43	10	4
44	10	4

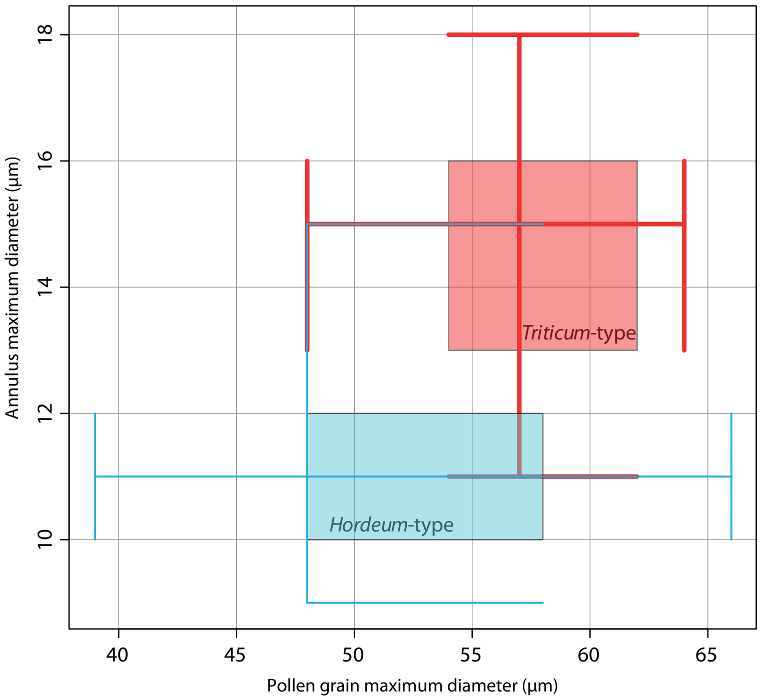


Fig. 14. Double boxplot graph for morphometric measurements of pollen grains attributed to *Hordeum*- (n = 9) and *Triticum*-type (n = 9) of pollen sample at 55 cm in profile SED35, Oldenburg-Dannau LA 77 (whiskers indicate minimum/maximum-values).

Interpretation of the local settlement and environmental history

The profile SED35 allows reconstructions of the local environmental and settlement history between c. 3800 to 2500 cal BC and therefore more or less spans the hiatus in profile DAN 1. This enabled insights to the developments during the Middle Neolithic, i.e. the settlement period of site Oldenburg-Dannau LA 77. A total of six local pollen zones (LPAZ) were distinguished, taking into account in particular changes in pollen curves reflecting the land-use and settlement history.

LPAZ SED35-1 (samples 85 and 79 cm)

This pollen zone, comprising of only two samples, is characterized by a decline in the mixed oak forest species *Ulmus* and *Quercus* and an increase in *Alnus*. At the same time, the importance of the light-demanding hazel (*Corylus*) is increasing, which speaks for an opening of the woodland structure in the catchment area. Clear indicators for open landscape and/or arable activities are missing (i.e. *Plantago lanceolata*-type, cereal-type pollen) or are only sporadically represented as single finds (i.e. *Plantago major/media*-type). Therefore, this zone dates to the early Subboreal, the time of the Middle Holocene elm decline, which is in agreement the results of the ^{14}C-dating.

LPAZ SED35-2 (samples 77 and 74 cm)

The decline of birch (*Betula*) is the most noticeable change in the tree pollen spectrum of this pollen zone. Maximal values for *Corylus* as well as the beginning of a continuous curve for *Plantago lanceolata*-type are further characteristics. This speaks for a continuous clearing of the forest with the creation of areas of open land. The singular finding of a large pollen grain of the *Hordeum*-type (57 µm diameter) indicates agricultural use of the clearings. Settlement activity in the direct vicinity, however, seems unlikely in view of the generally low anthropogenic indicator values. The decreasing importance of the birch around 3500 cal BC is a supra-regional phenomenon, which is recorded in many pollen diagrams of the Northern German young moraine landscape. As birch is a typical tree of early stages of woodland regeneration this might well reflect an intensification of agricultural activities on an over-regional scale (cf. Feeser et al. 2012)

The records of the green algae *Pediastrum* and *Botryococcus* indicate an increase in water levels. Even though the palynological evidence for halophilic vegetation is still low – recorded is just an increase in the Chenopodiaceae values – the macrofossil remains prove a marine influence for this pollen zone as reflected by the records for *Atriplex*, *Sueda*, *Aster tripolium* and *Zannichellia*.

LPAZ SED35-3 (samples 71–64cm)

With the onset of this pollen zone, a significant increase in many non-arboreal pollen taxa is recorded, which most likely is linked to the onset of settlement activity in the immediate vicinity after c. 3500 cal BC. This is reflected by increasing curves of anthropogenic indicators such as *Plantago lanceolata*-type, *P. major-media*-type, cereal-type pollen and *Polygonum aviculare*-type, which point at the presence of open disturbed ground and cereal cultivation/processing in the area. Furthermore, several taxa which can be associated with open halophytic shoreline communities show distinct increases with the beginning of this zone. This includes *Plantago maritima*-type, *Spergularia*-type, Chenopodiaceae and *Senecio*-type. In this context it has to be considered that also the records of *Polygonum aviculare*-type could derive from halophilic vegetation. This development of open saltmarsh vegetation could have been favoured by human activities (cf. interpretation of LPAZ DAN 1-8 and Härdtle 1984). Clear evidence for local human activity is provided by increased charcoal values (micro-charcoal in the pollen samples and meso-charcoal in the macro-remains) as well as increasing evidence for *Glomus* (HdV-207) and minerogenic input of quartz grains in the macro-remains. The latter two are interpreted are indicators of soil erosion and therefore are regarded to reflect disturbances in context of settlement activities on the site. Noteworthy is the evidence for whipworm eggs (*Trichuris*, HdV-532). Worms of this genus live parasitically in the large intestine of various mammals (Brinkkemper/van Haaster 2012) and point to increased faeces input into the near-shore areas. Although it remains open if these relate to human or animal parasites, the records are interpreted to be related to increased local settlement activity.

In the upper part of this zone, sample 64 cm, a decrease in various anthropogenic indicators, including cereal-type pollen, *Trichuris*, *Glomus* and micro-charcoal, points at a short-term decline in local settlement intensity at around c. 3250 cal BC.

The development of halophilic vegetation can be further linked to an increasing marine influence in the western Oldenburger Graben after c. 3500 cal BC. Palynological evidence for this is provided by the records of halophytic or marine indicators such as *Ruppia*, Hystrichosphaerideae (HdV-705) and Foraminifera (HdV-700) (cf. Fig. 12). At the same time values for *Botryococcus* and *Pediastrum*, both representing limnic green algae, are declining. Also in the macrofossil data the ending records for *Ruppia* and the beginning records for *Zannichellia* (cf. Fig. 13) could be explained by increased salinity.

LPAZ SED35-4 (samples 61–55 cm)

This zone is characterised by maximum values of several anthropogenic indicators, e.g. Liguliflorae, *Polygonum aviculare*, cereal-type pollen. It is noteworthy that cereal-type pollen reaches even higher values than *Plantago lanceolata*-type. This may be explained with grain processing in the local settlement context. The majority of pollen from most cultivated cereals is released during threshing and not during flowering as they are cleistogamous, i.e. self-pollinating, species. Furthermore, erosion indicators reach maximum values: *Glomus*

(HdV-207) in the pollen diagram and quartz grains in the macro-remains. This suggests a maximum of settlement activities for site Oldenburg-Dannau LA 77 during c. 3200 to 2950 cal BC.

The results for the differentiation of cereal-type pollen in sample 55 cm indicates the importance of at least two different cereal species, which can be separated using morphological characteristics. This is well in agreement with the results of archaeobotanical investigations which showed that emmer and free-threshing barely were dominating the crop plant assemblage (Kirleis 2019).

In the uppermost sample of this zone (55 cm) the representation of the NPPs *Glomus* (HdV-207) and *Trichuris* (HdV-531) are decreasing. This is interpreted to reflect declining local settlement activity shortly after c. 3000 cal BC. Interestingly, this coincides with elevated values for *Plantago lanceolata*-type. This apparent contradiction might be explained by a relative increase of moderately disturbed areas on the site, in context of generally decreasing settlement intensity, which in fact could have favoured *Plantago lanceolata*.

LPAZ SED35-5 (samples 52–47 cm)

The transition to this zone is marked by a decline or interruption of curves of *Plantago lanceolata*-type, cereal-type pollen, *Anthemis*-type and *Rumex acetosa*-type. Furthermore, micro- and meso-charcoal values decline. This is interpreted to reflect the end of local settlement activity at around c. 2900 cal BC. The coinciding recovery of arboreal taxa such as *Fraxinus* and *Alnus* suggests to some degree the recovery of woody vegetation.

There is evidence that the settlement abandonment was related to natural change of the local, but also regional environment. Hereby, the change in sediment composition at 53 cm from peaty to silty aquatic deposits (cf. Tab. 7) indicates fundamental hydrological changes due to an increase in water levels. This affected the local vegetation. The decline of *Entorrhiza* spores (HdV-527, Fig. 12) and the decreased records of *Juncus* seeds (Fig. 13) reflect such changes. Juncaceae and Cyperaceae are the host plants of *Entorrhiza* fungi (Bauer et al. 2015) so that the observed decline points at the local replacement of rush rich fen communities by submerged littoral plant communities. Palynological evidence for the latter is provided by increasing importance of *Sparganium*-type and *Botryococcus*. As both taxa are generally associated with limnic conditions, this furthermore suggest a decreasing marine influence. The recommencing regular records of macrofossil remains of *Zannichellia* suggest brackish shallow still water conditions.

LPAZ SED35-6 (samples 45–41 cm)

With the beginning of this pollen zone *Corylus* and fern spores (Polypodiaceae indet.) increase distinctly. This is associated with a sharp decline or break in the records of halophytic species such as *Spergularia*-type, *Plantago maritima*-type, Chenopodiaceae and *Ruppia*. At the same depth an increase of limnic elements can be observed in the pollen diagram, e.g. the green algae *Pediastrum* and *Tetraedron* (HdV-371), *Myriophyllum* and *Sparganium*. This is interpreted to indicate a shift from marine to limnic conditions in the western Oldenburger Graben.

Clear evidence for local settlement activity in form of distinctly high values for indicators of soil erosion, fire activity or cereal processing is lacking for this zone. Therefore, the moderate values of anthropogenic indicators such as *Plantago lanceolata*-type are interpreted to reflect human activity in the wider area. The associated land use obviously favoured in particular the light demanding hazel as reflected by the high values for *Corylus*.

Chronological re-evaluation of existing off-site pollen profiles

Material and methods

For the region of the western Oldenburger Graben, three off-site pollen profiles are available due to previous investigations by Venus (2004) and Averdieck (2004) (cf. Fig. 1). Generally, these can be used for the reconstruction of the regional Neolithic vegetation and settlement history. The lack of independent dating in case of the profiles Kleinwessek and Ehlerstorf (Venus 2004) and the problem of a hard-water effect in context of conventional ^{14}C bulk samples for the profile Priesterwiese (Averdieck 2004), however, raised the need for a chronological re-evaluation. This is based on pollenstratigraphical correlation using well dated pollen profiles from Schleswig-Holstein, such as Lake Belau c. 40 km southwest of the study area (Dörfler et al. 2012). The chronologies for the three profiles were constructed using a combined P_Sequence model in OxCal 4.3 (Bronk Ramsey 2008) and the Intcal13 calibration curve (Reimer et al. 2013). Therefore, palynological features regarded to be of over-regional importance, so-called pollenstratigraphical events (PSE), have been identified (Tab. 11). For these, age estimates were assigned based on well dated pollen records. Five of these pollen stratigraphic horizons have been identified in all three profiles. For the profile Priesterwiese, additional pollen stratigraphic events for the first half of the Holocene were defined (PSE 1–3). Furthermore, two pollenstratigraphical events of probably only regional significance have been defined (PSE 6 and 7). As there are no independent age estimates available for these events, they have been used as cross-referencing events between the individual P_Sequences in the combined OxCal model.

Data presentation and general considerations for the interpretation

For comparison with the other pollen profiles, relative pollen diagram based on a total terrestrial pollen sum and spanning the late Mesolithic to Early Iron Age period were created for all profiles. In order to emphasise the related uncertainties of the chronological re-evaluation, the archaeological zone boundaries indicated in the pollen diagrams are based on the ranges of the corresponding 1 sigma confidence intervals.

The main palynological features in the pollen diagrams and their related interpretation are summarized in form of tables. For more detailed information we refer to the original publication. The interpretation presented in this context is based on similar lines of evidence as outlined for the profiles DAN 1 and SED35 (see above). Generally, the fluctuation in the representation of anthropogenic indicators, including *Plantago lanceolata*-type, *Artemisia*, Liguliflorae and *Rumex acetosa*-type, is reflecting a changing degree of land-use activities. Higher values are generally regarded to reflect increased importance of open agricultural or settlement ground. Corresponding records of cereal-type pollen indicate associated arable activities. Declining and changing representation of arboreal pollen taxa related to mesophile tree species such as *Ulmus*, *Quercus*, *Tilia* and *Fraxinus* and later also *Fagus* and *Carpinus* without clear evidence for open agricultural or settlement ground are regarded to reflect changes in the woodland structure and composition. Such changes may on the one hand have their cause in natural drivers, such as changing ground water levels, but on the other also anthropogenic factors, such as woodland exploitation and in particular woodland pasture, have to be considered. A species which generally is favoured by the latter activities is the light demanding hazel (*Corylus*) (cf. Kalis/ Meurers-Balke 2005). An arboreal pollen taxon which generally gains higher values in context of increasing landscape openness is *Pinus*. The pollen of pine (*Pinus sylvestris*) is well dispersed by wind, even over long distances, and increased representation in the pollen diagrams therefore most likely reflects a stronger over-regional pollen component due to increased local and regional landscape openness.

Interpretations of hydrological changes including marine influence are mainly based on changes of the sediment and the representation of pollen of *Sparganium*-type and Chenopodiacea. As outlined above, *Sparganium*-type is associated with littoral vegetation during limnic conditions whereas distinctly high Chenopodiaceae values reflect halophytic shore line vegetation.

Results and Interpretation

Priesterwiese

The pollen diagram Priesterwiese, published by Averdieck (2004), relates to a 12.8 m long sediment profile from a wet depression in the immediate vicinity of the Slavic castle in Oldenburg, Holstein (see Fig. 1). In contrast to the other pollen profiles presented, it does not originate from the lowlands of the Oldenburg Graben and was therefore not directly affected by the post-glacial sea level rise. The environmental and hydrological development is therefore not directly influenced by marine transgression, but probably by associated changes in the groundwater level.

The chronology is based on eight pollen stratigraphic events (cf. Tab. 11) and three of the published ^{14}C-samples (Fig. 15). All other available ^{14}C-dates have been treated as outliers. In comparison with the resulting age-depth model these dates provide too old age estimates, which can be explained with a hard water effect due to the calcareous nature of the limnic deposits.

Table 11. Overview of pollenstratigraphical events and age estimates used in the construction of age-depth models for off-site pollen profiles Kleinwessek, Ehlerstorf and Priesterwiese from the western Oldenburger Graben.

Name	Description	age estimate	Depth (cm)		
			Kleinwessek	Ehlerstorf	Priesterwiese
PSE 1	End of Late Glacial	9640 cal BC (Litt et al. 2007)	–	–	1267.5
PSE 2	short *Corylus* lull during the main Boreal expansion	8300 cal BC (Poggensee unpubl. data)	–	–	1080.0
PSE 3	*Corylus* minimum („8.2k event")	6170 cal BC (Dörfler et al. 2012)	–	–	835.0
PSE 4	Begin of *Fraxinus* expansion	4715 cal BC (Dörfler et al. 2012)	1105.0	670.0	740.0
PSE 5	End of mid-Holocene elm decline	3850 cal BC (Dörfler et al. 2012)	1025.0	605.0	690.0
PSE 6	Marine/limnic transition (decline Chenopodiaceae, increase *Sparganium*)	only used for linking of profiles	715.0	507.5	–
PSE 7	*Fraxinus* increase	only used for linking of profiles	645.0	492.5	560.0
PSE 8	*Corylus* maximum*	1280 cal BC (Dörfler et al. 2012)	530.0	380.0	355.0
PSE 9	*Corylus* decline coinciding with lull in anthropogenic indicators („Migration period")	450 AD (Dörfler et al. 2012)	235.0	230.0	122.5
PSE 10	*Pinus* increase	1620 AD (Dörfler et al. 2012)	147.5	–	–

*Probably corresponds to the maximum CO_3 described by Overbeck(1975) – not included or not applicable

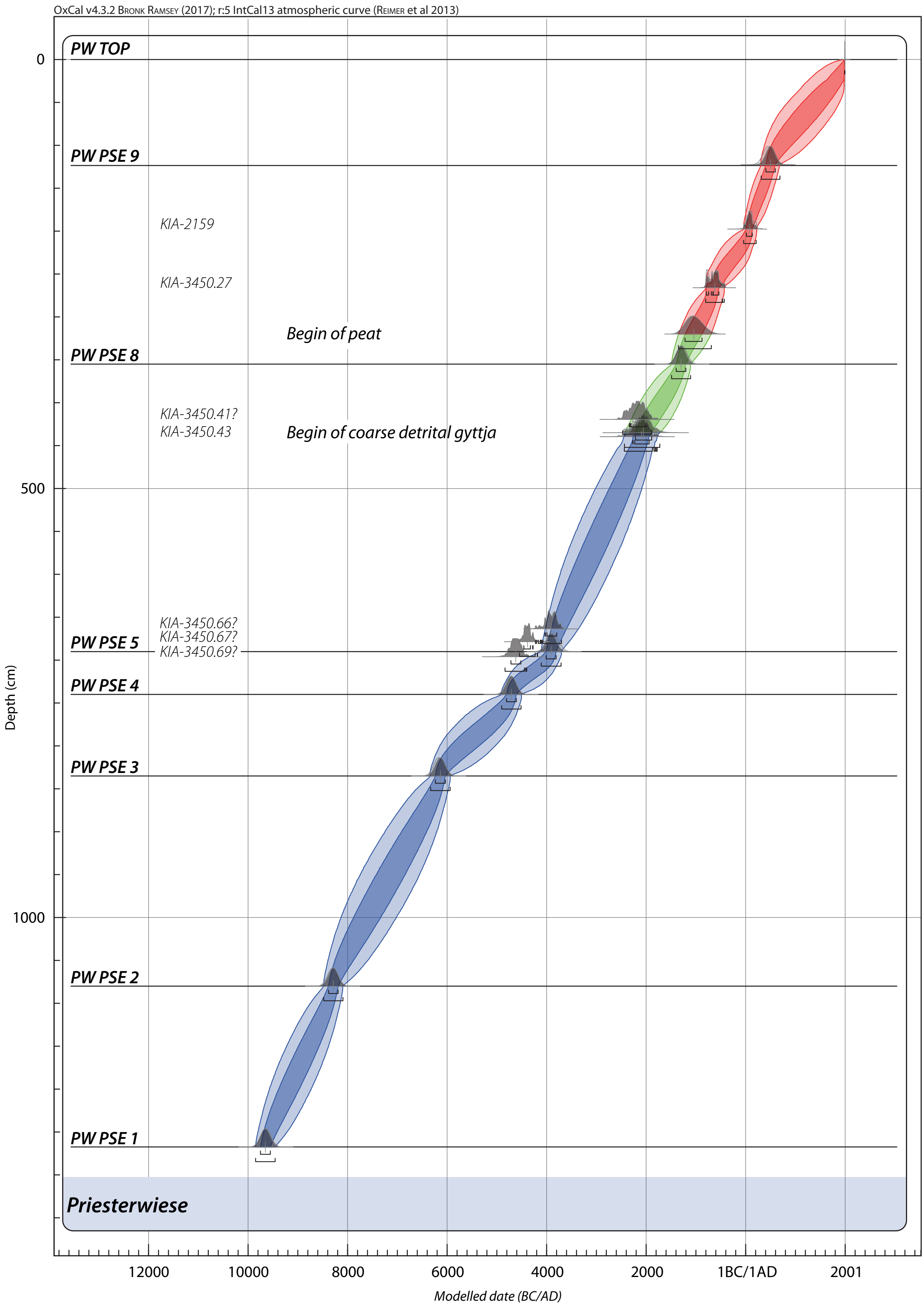


Fig. 15. Age-depth model for profile Priesterwiese.

The pollen diagram (Fig. 16) was subdivided into ten local pollen zones (LPAZ). A summary of the main palynological features and their interpretation is given in Table 12.

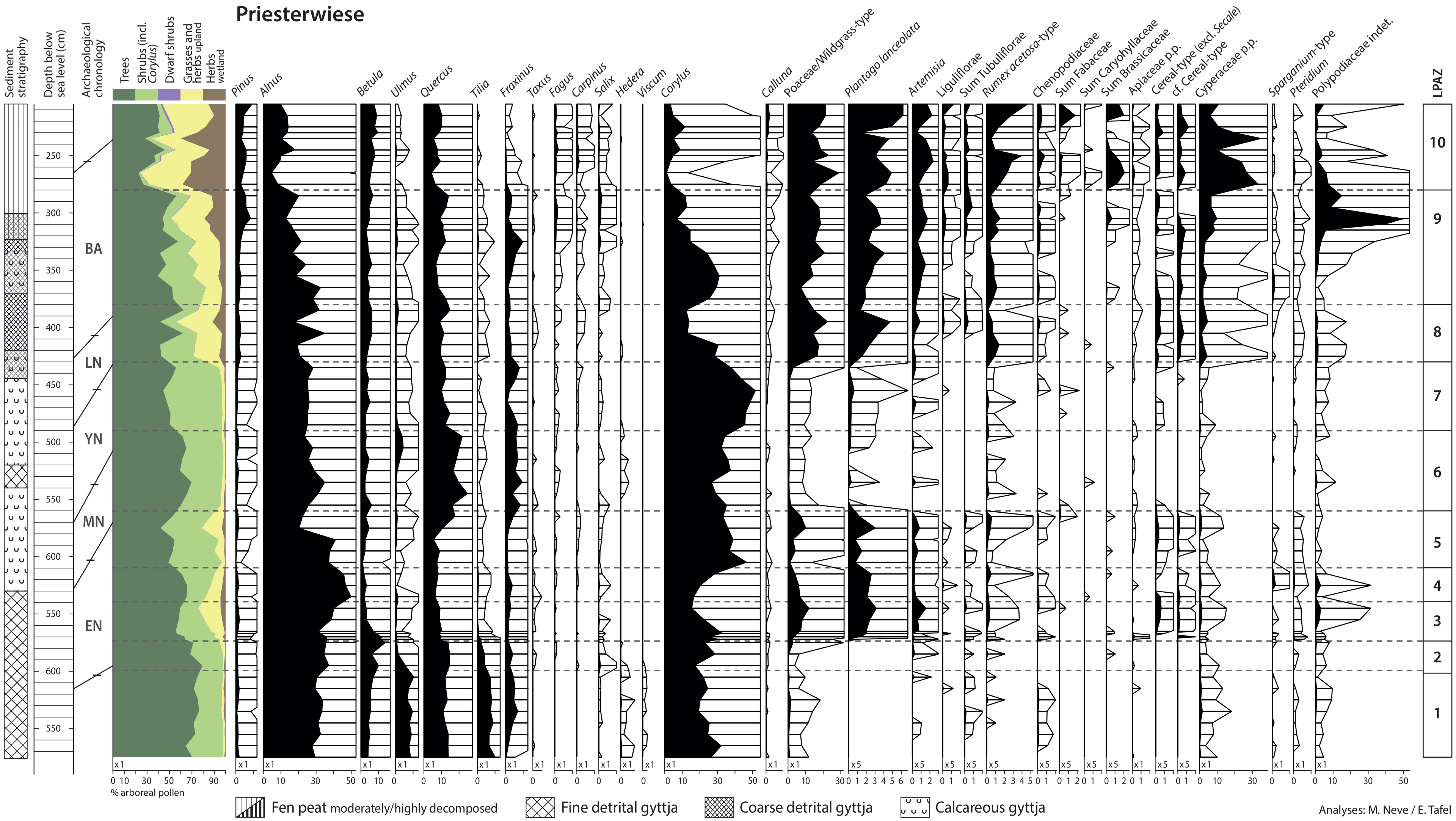


Fig. 16. Relative pollen diagram showing selected pollen taxa and spanning the time range between the Late Mesolithic and Early Iron Age period for the profile Priesterwiese analysed by Averdieck (2004). Calculations are based on a total terrestrial pollen sum. Zone boundaries indicated for the archaeological chronology are based on the result of the age-depth modelling presented in this paper. The given depth ranges represent the uncertainties related to the zone boundaries at 4100, 3300, 2800, 2200, 1800 and 530 cal BC (bottom to top) using the modelled 1-sigma age ranges. The corresponding depth for the median is also given (short horizontal bar). EN: Early Neolithic; MN: Middle Neolithic; YN: Younger Neolithic, LN: Late Neolithic, BA: Bronze Age.

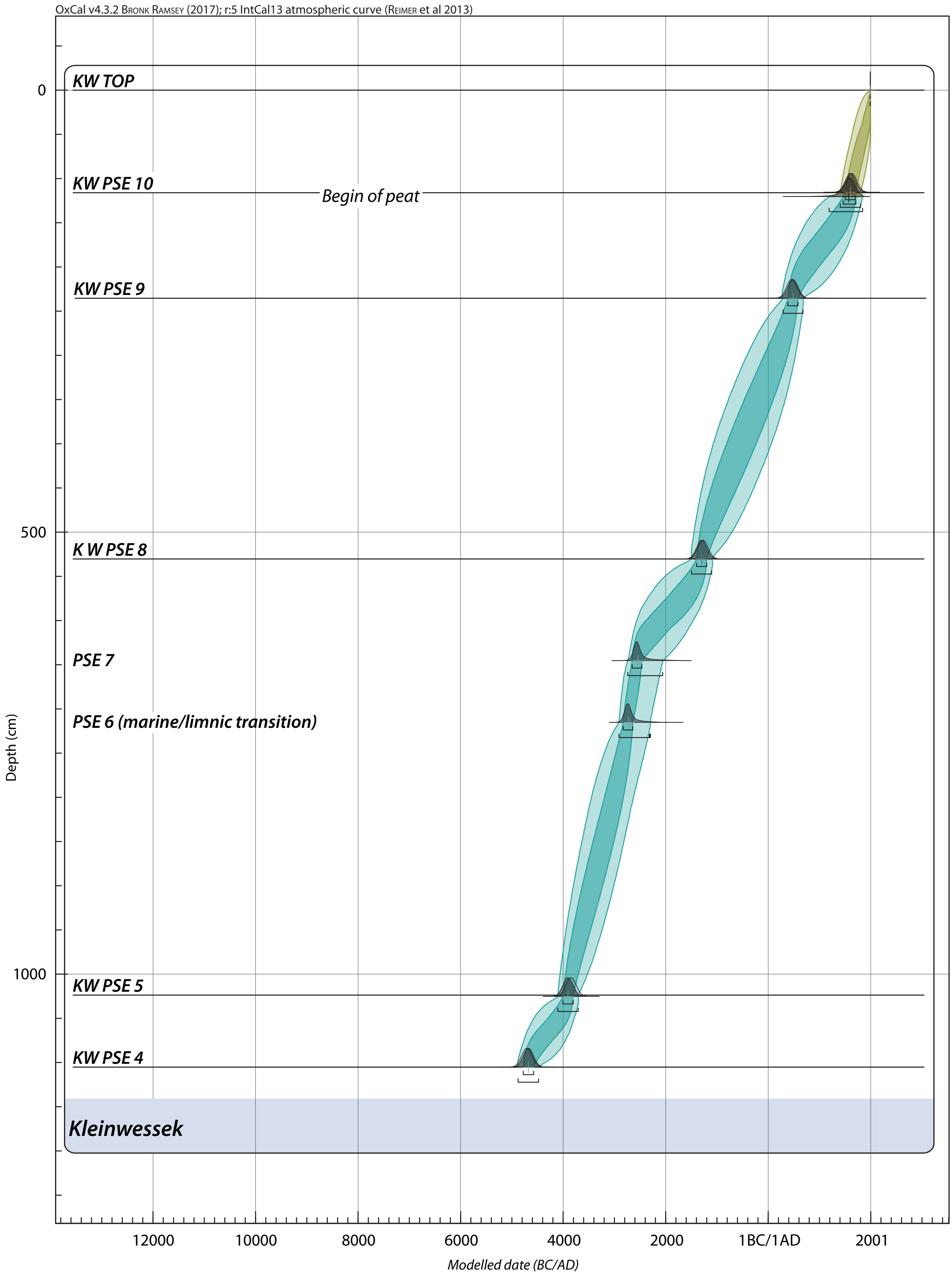
Table 12. Summary of the local pollen assemblage zone (LPAZ) description and interpretation for the off-site profile Priesterwiese. EN: Early Neolithic; MN: Middle Neolithic; YN: Younger Neolithic; LN: Late Neolithic; BA: Bronze Age. The absolute chronology follows Müller et al (2012).

LPAZ	Sample depth (cm below NN)	Main features	Interpretation
1	775 – 705	• high values for *Ulmus*, *Tilia* and *Quercus*	Atlantic mixed oak forests dominate; no human impact detectable
2	695 – 675	• strong decline of *Ulmus* and *Tilia* • increase of *Betula* and *Corylus* values	Opening of the forest structure with the beginning of the EN (c. 4100 cal BC)
3	672 – 645	• increase of *Alnus* • decline of *Quercus*, *Corylus* and *Betula* values • strong increase in curves of anthropogenic indicators (e.g. *Plantago lanceolata*, *Rumex acetosa*-type and *Artemisia)* and Wildgrass-type • regular records of Cereal-type	Woodland clearance and beginning of arable activities with probably settlement activities in the local surrounding during EN Ib and EN II
4	635 – 615	• *Alnus* maxima • declining values for Wildgrass-type and *Artemisia* • interruption of the Cereal-type curve	Reduction of land use, i.e. arable farming, towards the end of the EN
5	605 – 565	• decline of *Alnus* • higher values for *Corylus* with the beginning of this zone; • increase of Wildgrass-type and anthropogenic indicator curves towards the upper part of the zone	Generally lower human impact around the FN/MN transition with subsequent short land-use phase during the MN
6	555 – 495	• increase to generally higher values for *Quercus*, *Fraxinus* and later also *Ulmus* • *Corylus* lower values • low Wildgrass-type and lull of anthropogenic indicator curves • change from calcareous to fine detrital gytjja in the lower half of this zone	Declining land use favouring partial woodland regeneration during the late MN/early YN; change in sediment indicates higher groundwater levels
7	485 – 435	• high *Corylus* values with maxima • recovery of the anthropogenic indicator curves although at low level	Recommencement of land-use activities on a low level during the YN
8	425 – 385	• elevated values for *Betula* • strong decline of *Corylus* • increasing curves for Wildgrass-type and anthropogenic indicators including Cereal-type	Beginning of intensive, probably local, land-use phase during or at the beginning of the LN
9	375 – 285	• *Alnus* declining • at beginning strong increase of *Corylus* values with a subsequent decline • increasing representation of *Fagus, Carpinus* und *Salix* • somewhat lower values for anthropogenic indicators in the lower half including a gap in the Cereal-type curve	Decline of local and generally lower land-use activities during the older BA; increasing land-use activities during the second half of the BA; the later is associated with a change in woodland composition which could indicate changed land-use practices
10	275 – 205	• declining and lower values for most aboreal taxa and *Corylus* • increase in curves of anthropogenic indicators • elevated *Pinus* values (already beginning in the upper part of the previous zone)	Increasing land-use activities and associated woodland clearance during the late BA and early Iron Age transition; landscape openness on an unprecedented scale

Kleinwessek

The profile Kleinwessek was analysed by Venus (2004) as a standard pollen profile for the western Oldenburger Graben. The investigated profile consisted of an 11.4 m long sediment sequence from the reed belt of the Wesseker See about 500 m south-west of the village of Kleinwessek (cf. Fig. 1).

Based on the results of the age-depth modelling (Fig. 17), the Neolithic deposits comprise approximately 320 cm of sediment (between 630 and 1050 cm depth below sea level), with marine mud in the lower part and a change to lime mud in the upper third.



The pollen diagram (Fig. 18) was subdivided into ten local pollen zones (LPAZ). A summary of the main palynological features and their interpretation is given in Table 13.

Fig. 17. Age-depth model for profile Kleinwessek.

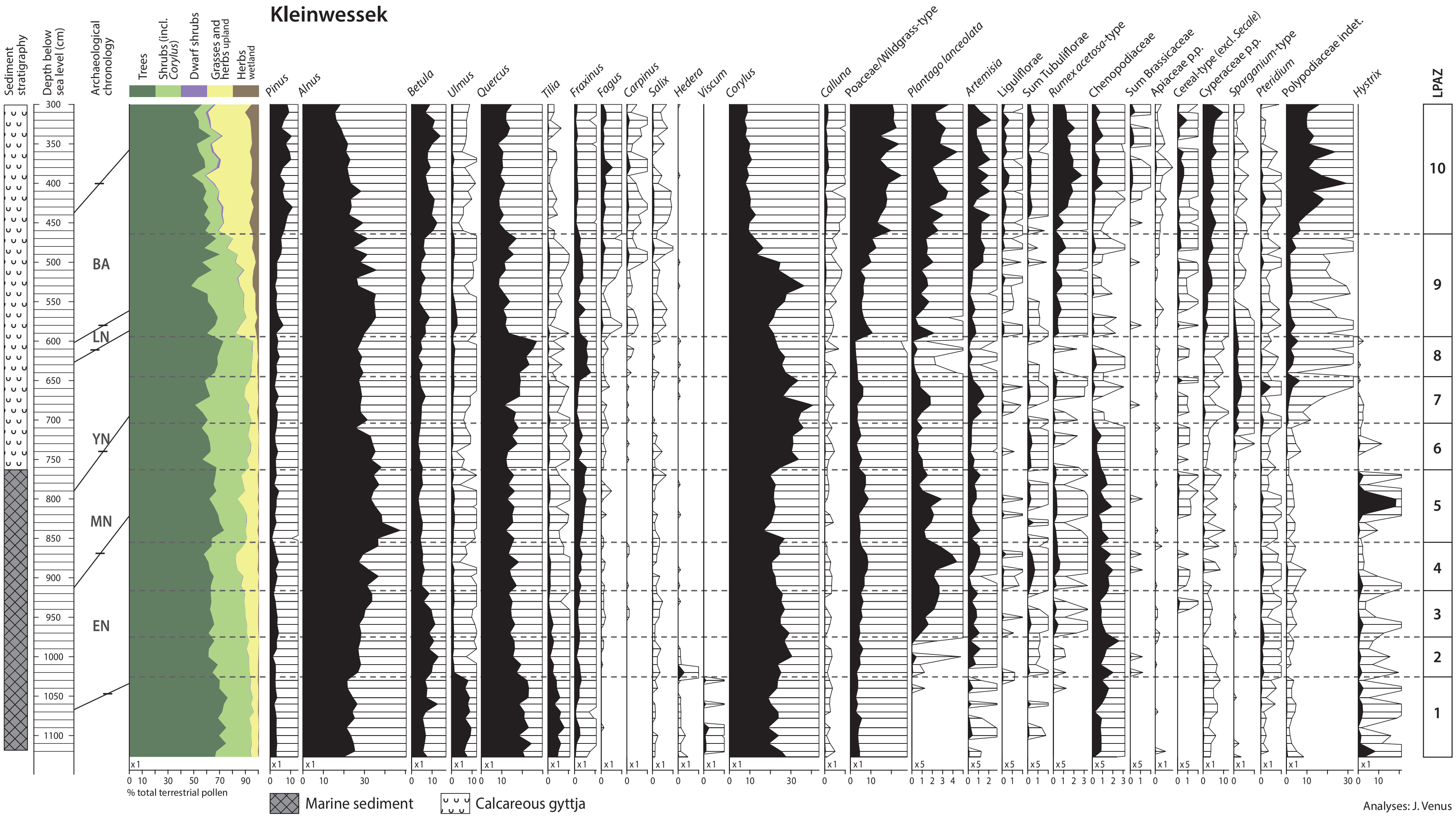


Fig. 18. Relative pollen diagram showing selected pollen taxa and spanning the time range between the Late Mesolithic and Early Iron Age period for the profile Kleinwessek analysed by Venus (2004). Calculations are based on a total terrestrial pollen sum. Zone boundaries indicated for the archaeological chronology are based on the result of the age-depth modelling presented in this paper. The given depth ranges represent the uncertainties related to the zone boundaries at 4100, 3300, 2800, 2200, 1800 and 530 cal BC (bottom to top) using the modelled 1-sigma age ranges. The corresponding depth for the median is also given (short horizontal bar). EN: Early Neolithic; MN: Middle Neolithic; YN: Younger Neolithic, LN: Late Neolithic, BA: Bronze Age.

Table 13. Summary of the local pollen assemblage zone (LPAZ) description and interpretation for the off-site profile Kleinwessek. EN: Early Neolithic; MN: Middle Neolithic; YN: Younger Neolithic; LN: Late Neolithic; BA: Bronze Age. The absolute chronology follows Müller et al (2012).

LPAZ	Sample depth (cm below NN)	Main features	Interpretation
1	1127 – 1030	• high values for *Ulmus*, *Tilia* and *Quercus*	Atlantic mixed oak forests dominate; no human impact detectable
2	1020 – 980	• strong decline of *Ulmus* and to lesser extent also *Tilia* and *Quercus* • *Betula* and *Corylus* increase • beginning of regular records of *Plantago lanceolata*	Opening of woodland structure favouring light demanding trees and shrubs and small scale woodland clearance during the EN Ia
3	970 – 920	• increase of *Alnus* • *Corylus* declining • strong increase of *Plantago lanceolata* • beginning of regular records of Cereal-type	Increased woodland clearance for arable farming during FN Ib
4	910 – 860	• lower *Betula* valueshigh values for Wildgrass-type and *Plantago lanceolata*	Phase of high human impact and land-use intensification during EN II
5	850 – 770	• high *Alnus* and elevated *Fraxinus* values • *Corylus* lower values than in previous zone • declining values for *Plantago lanceolata* with short recovery in the middle of this zone • interruption of the Cereal-type curve at beginning of this zone • maxima values for Hystrix in the middle of this zone	Decline of land use at around the EN/EN transition to generally lower levels than during the EN, favouring woodland recovery and especially ash; short phase of recovery of human activities at around the time of maximal marine influence sometime during the MN
6	760 – 690	• strong increase of *Corylus* • low values for anthropogenic indicators • increase of aquatic taxa (e.g. *Sparganium*-type) • decrease of Chenopodiaceae • sediment change from marine to to calcareous gyttja	Declining human impact with less arable activity with the beginning of the YN; hazel is favoured which could be the result of regeneration and/or a change in woodland exploitation resulting in an opening of the woodland structure, which would have favoured the light demanding hazel; sediment change and aquatic taxa indicate the shift from brackish/marine to limnic conditions
7	700 – 650	• local maxima for *Plantago lanceolata* and *Artemisia* • drop of Chenopodiaceae curve with the beginning of this zone and high values for *Sparganium*-type	Short phase of increased land use activities during the YN; limnic conditions prevail and suggest the disconnection of the western Oldenburger Graben from the sea
8	640 – 600	• increased values for *Quercus* and *Fraxinus* • decline of *Corylus* • lull in Wildgrass-type and anthropogenic indicator (*Plantago lanceolata*, *Artemisia*, *Rumex acetosa/ acteosella*) curves	Decline in land-use activities and woodland regeneration during the later YN
9	590 – 470	• drop in *Quercus* curve to lower values at the beginning of this zone • increased representation for *Fagus*, *Carpinus* and *Salix* • increase of Wildgrass-type and anthropogenic indicators	Increase of land-use activities, including arable farming and woodland clearance, during the LN
10	460 – 300	• decline in *Fraxinus*, *Tilia* and *Ulmus* • higher representation of *Betula* and *Pinus* • low *Corylus* values • further increase and high values of Wildgrass-type and several anthropogenic indicators	Increase of landscape openness in context of woodland clearance and increased arable activities at around the transition from BA to Iron Age

Ehlerstorf

The profile Ehlerstorf was investigated by Venus (2004) in order to reconstruct the changing marine influence in this part of the Oldenburger Graben. The site is about 1.1 km south-east of the coring location of Kleinwessek and about 1 km south-west of the site Oldenburg-Dannau LA 77 (cf. Fig. 1). Marine sediments were encountered between 520 and 672 cm. Based on the results of the age-depth modelling (Fig. 19), the Neolithic deposits comprise approximately 200 cm of sediment (430–630 cm below sea level).

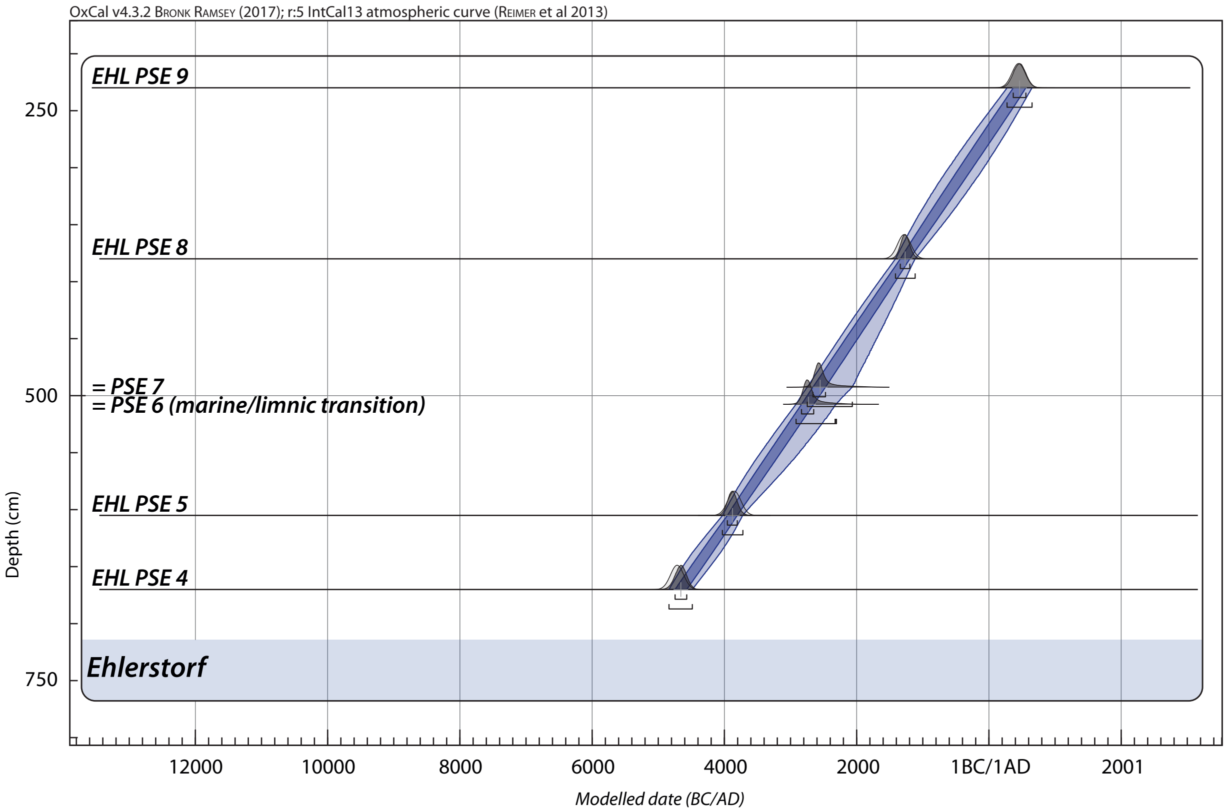


Fig. 19. Age-depth model for profile Ehlerstorf.

The pollen diagram (Fig. 20) was subdivided into ten local pollen zones (LPAZ). A summary of the main palynological features and their interpretation is given in Table 14.

Table 14. Summary of the local pollen assemblage zone (LPAZ) description and interpretation for the off-site profile Ehlerstorf. EN: Early Neolithic; MN: Middle Neolithic; YN: Younger Neolithic; LN: Late Neolithic; BA: Bronze Age. The absolute chronology follows Müller et al (2012).

LPAZ	Sample depth (cm below NN)	Main features	Interpretation
1	685 – 635	• high values for *Ulmus*, *Tilia* and *Quercus*	Atlantic mixed oak forests dominate; no human impact detectable
2	615 – 595	• Decline of *Ulmus*, *Tilia* and *Fraxinus* • Increase of *Alnus* and *Corylus*	Opening of the forest structure during EN Ia
3	575 – 537	• Drop of *Quercus* at the beginning of this curve with subsequent recovery • Beginning curves for anthropogenic indicators *Plantago lanceolata* and *Artemisia,* with initially higher and distinctly lower values in the upper part of the zone	Woodland clearance and landscape opening, respectively during EN Ib; Reduced land use at around the transition from the EN to MN
4	515 – 500	• High *Quercus* values • beginning recovery of *Fraxinus* curve • increasing curves of anthropogenic indicators • decline of Chenopodiaceae and associated increase of aquatic taxa (e.g. *Sparganium*-type) • change from marine sediment to calcareous gyttja	Short phase of increased land use at around the transition from MN to YN despite evidence for beginning woodland regeneration; aquatic pollen and sediment change indicates a shift from brackish/marine to limnic conditions
5	485 – 460	• Recovery of *Fraxinus* and to lesser extent *Ulmus* values • low values of Wildgrass-type and interruption of curves of anthropogenic indicators	Decline of land-use intensity during the YN
6	440 – 340	• Decline of *Fraxinus* and *Ulmus* values • increased representation for *Fagus* and *Carpinus* • Increase of Wildgrass-type and anthropogenic indicators • Beginning of regular records of Cereal-type	Increasing land-use intensity with arable farming during the LN
7	320 – 280	• Decline of *Tilia*, *Fraxinus* and *Corylus* • elevated *Pinus* and *Betula* values • Increase of Wildgrass-type and Plantago lanceolata	Increasing landscape openness at around the transition from BA to Iron Age

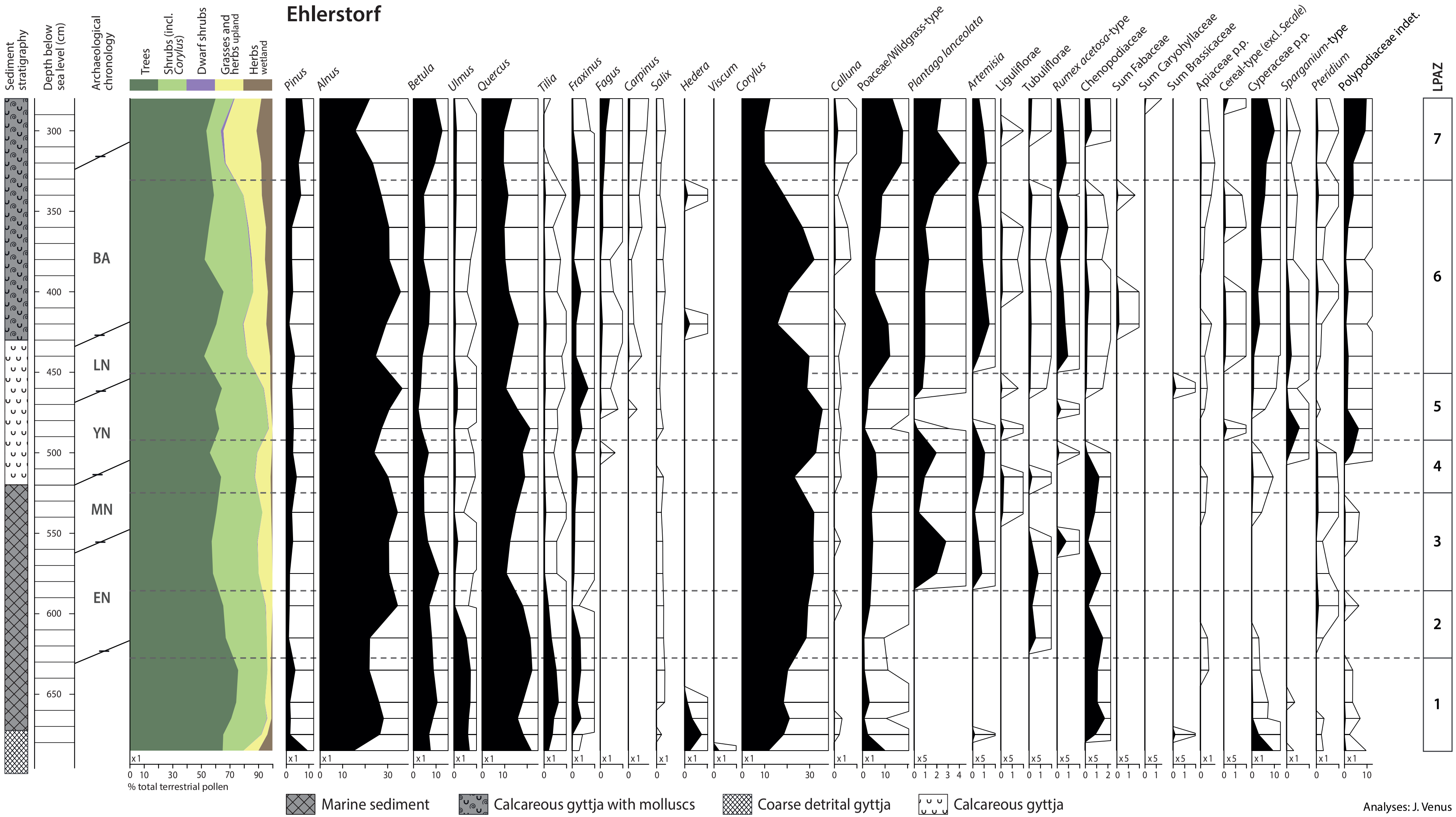


Fig. 20. Relative pollen diagram showing selected pollen taxa and spanning the time range between the Late Mesolithic and Early Iron Age period for the profile Ehlerstorf analysed by Venus (2004). Calculations are based on a total terrestrial pollen sum. Zone boundaries indicated for the archaeological chronology are based on the result of the age-depth modelling presented in this paper. The given depth ranges represent the uncertainties related to the zone boundaries at 4100, 3300, 2800, 2200, 1800 and 530 cal BC (bottom to top) using the modelled 1-sigma age ranges. The corresponding depth for the median is also given (short horizontal bar). EN: Early Neolithic; MN: Middle Neolithic; YN: Younger Neolithic, LN: Late Neolithic, BA: Bronze Age.

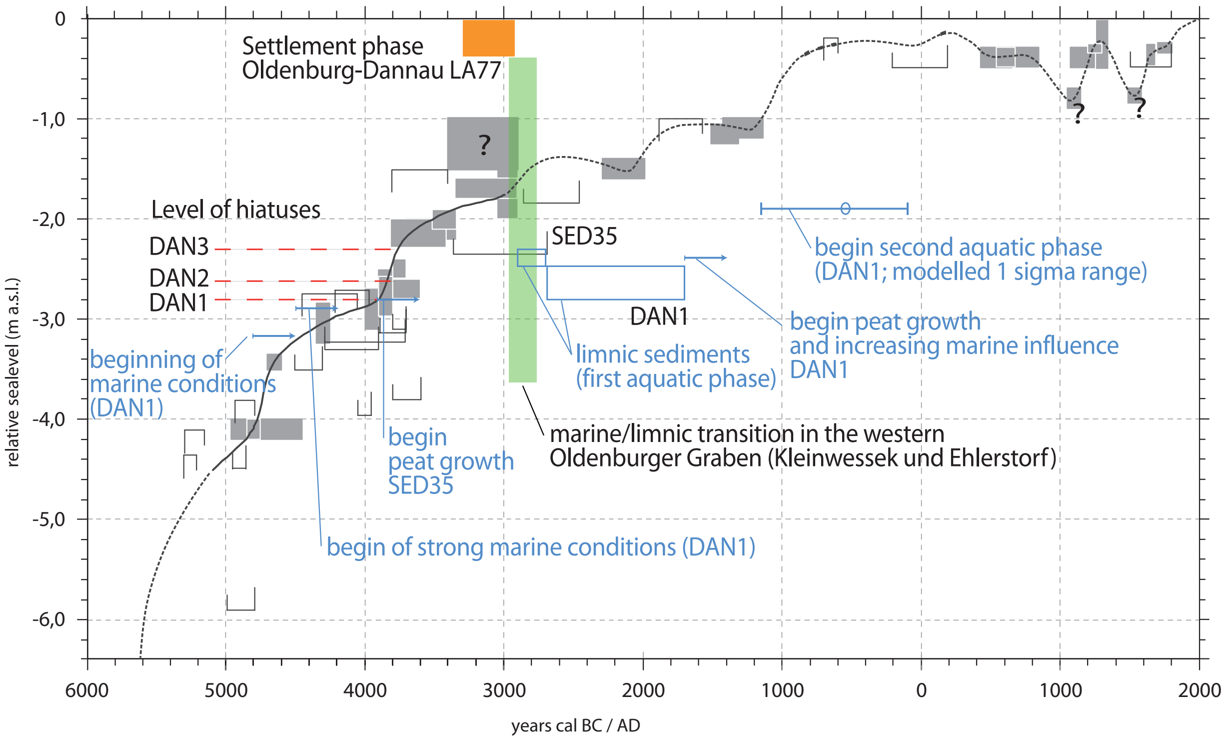


Fig. 21. Reconstructed palaeohydrology and sedimentology in the profiles DAN 1 and SED35, Oldenburg-Dannau LA 77, in comparison with the sea level curve for the western Baltic Sea from Jakobsen et al. (2004).

Discussion and conclusions

Environmental and palaeohydrological development

The chronological interpretation of the overall sediment stratigraphy and the results of the pollen and macro-analyses allows a detailed reconstruction of the local hydrological history. These are discussed in context of reconstructions of Jakobsen et al. (2004). Figure 21 shows a comparison of the reconstructed local events from the present study and their relation to the regional sea level curve of Jakobsen et al. (2004).

The local development of an alder carr forest as expressed in LPAZ DAN 1-3 (-3.25 to -3.35 m a.s.l.) between 5200 and 5000 cal BC can be related to a sea level rise to c. -4 m a.s.l. in the second half of the 6th millennium BC.

The shift from strongly to moderately decomposed peat in combination with the beginning evidence for local marine influence after 4800 cal BC in profile DAN 1 (LPAZ DAN 1-4) correlates with a rapid transgression phase of the regional sea level. In the eastern half of the Oldenburger Graben, Grube-Rosenhof, this sea level rise resulted in the "drowning" of oak forests and the expansion of brackish reed communities (Hartz et al. 2011).

At the time of the increasing local marine influence after 4500 cal BC (LPAZ DAN 1-5) the surface level of the peat lands at location DAN 1 was approx. -2.9 m a.s.l. This is well in agreement with a sea level of c. -3.1 m a.s.l. at around this time as reconstructed by Jakobsen et al. (2004).

According to the latter, the sea level at around c. 4000 cal BC was c. -2.8 m a.s.l. before it rose by about a meter during the first half of the 4th millennium BC. In the sediment cores DAN 1–3 this rapid transgression obviously resulted in the erosion of shore-near deposits. In profile DAN 1 the elevation level of the sediment hiatus is -2,8 m a.s.l. and in DAN 2 and DAN 3 -2.61 and -2.32 m a.s.l., respectively. This hiatus phenomenon seems not to be restricted to this site, but based on a summary of palynological profiles from the eastern half of the Oldenburger Graben also there deposits dating to the late Mesolithic and early Neolithic were especially affected (Hartz et al. 2011).

At the location of profile SED35, however, the increasing water levels at around 4000 cal BC resulted, interestingly at a similar elevation level (c. -2.9 m a.s.l.), in the beginning of peat growth on top of previously minerogenic soils. This indicates different sedimentation regimes along the shore line of the island, which on one hand might result from different small-scale geomorphological variation and the resulting exposure to wave action. On the other hand, with respect to potential local human activities also different activity zones are conceivable, e.g. by the destruction of the shore line vegetation in frequently accessed areas.

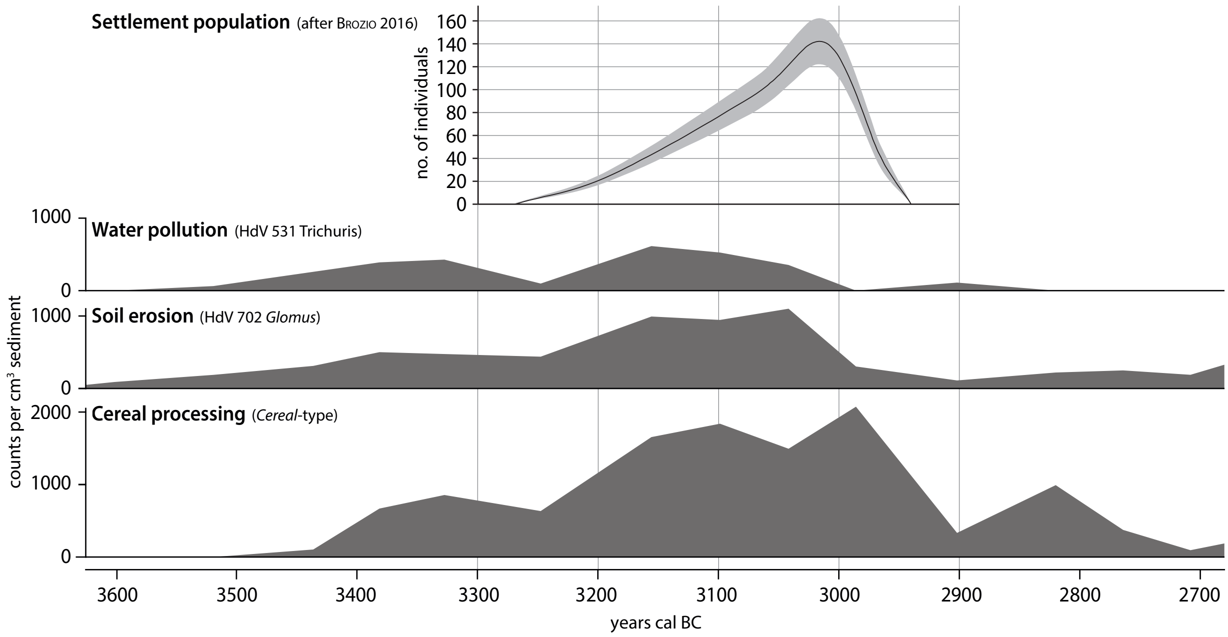
A maximum of *Alnus* between c. 3400 and 3150 cal BC as described by Kalis and Meurers-Balke (2005) is only well expressed in profile Priesterwiese (Fig. 16: LPAZ 2) among the profiles discussed. Here it is associated with evidence for increasing water levels. In context of the rapid sea level rise during the first half of the 4th millenium BC it seems likely that an associated increase in ground water levels in the hinterland favoured the spread of alder. Additionally, however, as also discussed by Kalis and Meurers-Balke (2005) for the area of the Oldenburger Graben and by Feeser et al. (2012, 184) for south-eastern Schleswig-Holstein, a shift in climate leading to wetter conditions in Northwest Europe between c. 3350 and 3000 cal BC (cf. Magny/Haas 2004) has to be considered.

At around 3000 cal BC the sea level curve of Jakobsen et al. (2004) indicates a height of c. -1.9 m a.s.l. The archaeologically reconstructed shore near zone at around 3000 cal BC – expressed by rows of wooden piles – was at a level of c -1.4 m a.s.l. (Brozio 2016). In profile SED35 peat deposits of the same age, however, are found at c. -2.5 m a.s.l. Even considering potential sediment compression in case of profile SED35 it seems plausible that the average sea level during the Middle Neolithic settlement phase was at around or somewhat lower than -2.5 m a.s.l. This suggests that the settlement LA 77, as well as the neighbouring Middle Neolithic settlements (e.g. LA 191 Hoika 1981), were located on peninsula rather than island situations. The disconnection of these areas from the mainland, i.e. the formation of islands, interestingly coincides with the abandonment of the settlements. It is around c. 2900 cal BC (LPAZ SED35-5) that the sediment as well as the semiaquatic and aquatic vegetation records indicate a rise in water levels with generally decreasing marine influence and in particular so after c. 2700 cal BC (LPAZ SED35-6 and LPAZ DAN 1-6). Also diatom analyses by König (1987) at the site Oldenburg-Dannau LA 191, c. 200 m north of site LA 77, indicate a brackish milieu with a clear marine influence during the Middle Neolithic settlement and a subsequent transition to freshwater conditions. In addition, also the independent chronological re-evaluation of the pollen diagrams from Ehlerstorf and Kleinwessek (see above and Figs. 17 and 19) indicates a change from marine to limnic conditions at around 2700 cal BC. According to Jakobsen et al. (2004), it was around the same time that a barrier beach formed at the mouth of the western Oldenburger Graben. The sealevel curve, although not very well constrained, suggests an associated transgression phase in the first centuries after 3000 cal BC (cf. Fig. 22).

At around c. 1700 cal BC the analyses of profile DAN 1 suggest a reappearing marine influence (LPAZ DAN 1-7 and -8), which could have been the result of a further marine transgression after c. 2000 cal BC. The associated increase in water levels, however, must have been moderate as the beginning peat growth at DAN 1 seems not to have been affected.

The change from peat to calcareous gyttja at around -1.9 m a. s. l. is found in all profiles, DAN 1–3, in the lowlands south-east of the site . Schütrumpf (1987) reports a similar sedimentological change at a comparable elevation level in the lowlands north of the island. Further uphill towards the main excavation site this layer changes to sand at around a depth of -1 m a. s. l. (cf. Brozio 2016, Fig. 14). This indicates a further rise in water levels and thus a second aquatic phase in the western Oldenburger Graben. In profile DAN 1 the beginning of this phase can be dated to the 1st millennium BC with a median modelled age of 550 cal BC. Therefore, this limnic phase can be correlated with the last major transgression phase by Jakobsen et al. (2004), during which the sea level reached more or less present day height.

Fig. 22. Comparison of selected palynological proxies for settlement intensity from profile SED35 with the archaeologically reconstructed population size for the settlement Oldenburg-Dannau LA 77.



Settlement and land-use history

Local development at the site Oldenburg-Dannau LA 77

Based on the interpretation of the pollen profiles DAN 1 and SED35 the local settlement and land-use history can be summarised as follows.

During Mesolithic times there is little evidence for human activities in the pollen diagrams. Only the increased evidence for fires from c. 5000 cal BC onwards (LPAZ DAN 1-4) could possibly reflect human activity of Ertebølle groups, of which several settlements are known from the Oldenburger Graben area (Hartz 2000; Hartz et al. 2011). The sporadic isolated finds of cereal-type pollen, including one large *Triticum*-type pollen grain (LPAZ DAN 1-5b), however, is not considered as a reliable indicator for agricultural activities during this period.

Due to the hiatus in DAN 1 there is a lack of information for the earliest Neolithic, i. e. the Early Neolithic Ia (EN Ia) between c. 4100 and 3800 cal BC, from the study site. Profile SED35 only begins in the Early Neolithic Ib (EN Ib; c. 3800–3500 cal BC) and indicates an opening of the forest structure and an associated increase in the light demanding hazel during the early half of EN Ib, i. e. c. 3800 to 3650 cal BC (LPAZ SED35-1). As this is a common phenomenon in pollen diagrams from the wider region or Northern Germany, respectively (Feeser/Dörfler 2015), it most likely reflects a regional development rather than land-use on the site. From c. 3600 cal BC onwards the pollen data reflects woodland clearance and beginning agricultural activities in the wider region (LPAZ SED35-2). From c. 3500 until 2900 cal BC the results indicate local settlement activities including cereal cultivation and/or processing on the site with a short phase of reduced activities at around c. 3200 cal BC. High settlement activity during the Middle Neolithic in the local surrounding, including the neighbouring peninsulas, is also documented by the archaeological record (Brozio et al. 2019; Filipovic et al. 2019). Afterwards, a maximum of settlement intensity is indicated during c. 3150–2900 cal BC (LPAZ SED35-4), which is in agreement with the reconstructed settlement activities from the archaeological record (Fig. 22). During the time of local occupation, the sandy elevation was still connected to the mainland by lower lying, at most temporarily flooded wetlands.

With the disconnection of the site from the mainland, after around 2900 cal BC, evidence for local settlement activities at Oldenburg-Dannau LA 77 ceases. The continuous but rather low values for anthropogenic indicators in LPAZ DAN 1-6a reflect human activities on a moderate level throughout the Younger Neolithic (YN, 2800–2200 cal BC). This corresponds with the archaeological record which indicates continuing settlement activities during the Middle Neolitihc/Younger Neolithic transition, i. e. c. 2900–2600 cal BC, in the area (Brozio et al. 2019).

It is with the beginning of the Late Neolithic (LN, 2200–1800 cal BC) that human impact increases distinctly (LPAZ DAN 1-6b). As there are no indications for local activities, this most likely reflects a regional phase of increased human activity which extended into the earliest Bronze Age. It was still during the earliest Bronze Age (Per. I) that land-use activities declined strongly favouring the regeneration of woodland (LPAZ DAN 1-7). A minimum of human impact dates is reached at around c. 1500 cal BC after which land-use activities increased again.

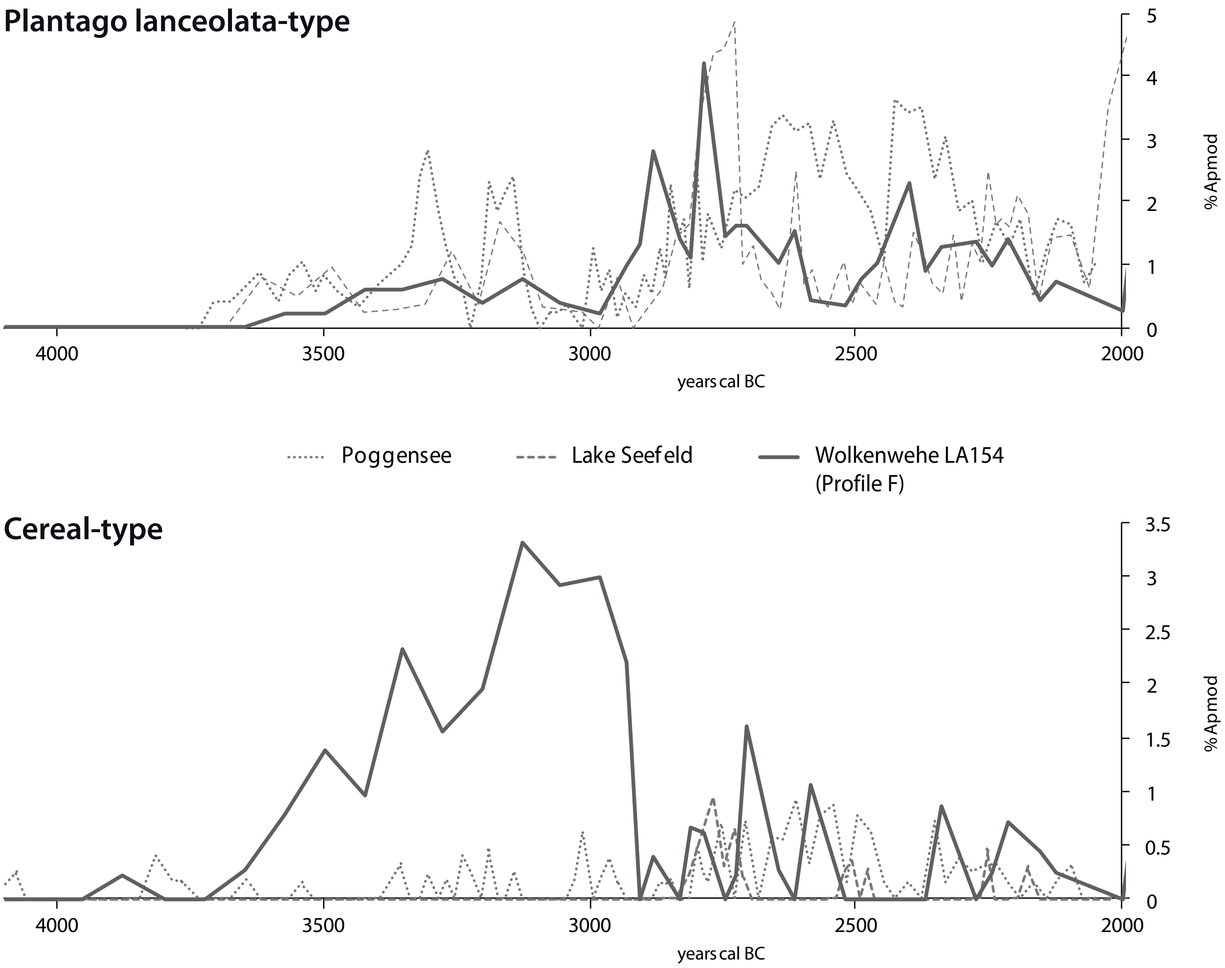
Comparison in the regional context

A comparison of the results at Oldenburg-Dannau LA 77 with the other palaeo-environmental studies from the Oldenburger Graben region and beyond shows some interesting aspects.

All off-site pollen profiles from the Oldenburger Graben (Priesterwiese: Fig. 16; Kleinwessek: Fig. 18; Ehlerstorf: Fig. 20) show a strong increase in *Plantago lanceolata*-type towards the end of the first half of the Early Neolithic period. This reflects increased settlement and land-use activity during the later EN Ib and EN II in the region, as it is also indicated for Oldenburg-Dannau LA 77.

At around the transition from the EN to the MN all profiles show a marked decline in human activity which probably corresponds to the lower settlement activity at Oldenburg-Dannau LA 77 at around 3200 cal BC. Similar evidence is also found in pollen profiles from eastern Schleswig-Holstein pointing at an over-regional phenomenon. A short but distinct phase of increased human activity towards the end of the Middle Neolithic is visible in the profiles Ehlerstorf and Priesterwiese. This could correspond to the phase of maximum settlement activity at Oldenburg-Dannau LA 77 between c. 3100 to 2900 cal BC. However, in pollen profiles further south from eastern Schleswig-Holstein a short phase of increased human activity has been dated to c. 3200 to 3100 cal BC with a subsequent distinct lull of human activity between c. 3100 to 2900 cal BC (Feeser et al. 2012). On the one hand, this could be explained with dating uncertainties of the latter record. On the other hand, it could reflect varying settlement patterns and related shifts of population concentrations. At around the time of the abrupt settlement abandonment of Oldenburg-Dannau LA 77, i.e. 2900 cal BC, settlement activity generally increases again in the more southern regions. Interestingly, palynological investigations at Bad Oldesloe-Wolkenwehe LA 154, a Neolithic settlement site c. 60 km inland in the lowlands of the River Trave (Hartz et al. 2007a; Mischka et al. 2007), indicate an abrupt end of local settlement activities, including cereal processing, at around the same time (Fig. 23). This may indicate that an increase in water levels caused by sea level rise has led to the abandonment of settlements in affected lowland areas in the wider region. The maximum values of *Plantago lanceolata*-type around c. 2800 cal BC are associated with elevated charcoal concentration (Feeser unpublished data) and archaeological evidence of wooden pile construction (Mischka et al. 2007) and suggest local human activity during the Middle Neolithic Younger Neolithic transition. Hereby, cereal processing does not seem to have played a role anymore, despite even increasing evidence for the regional importance of cereal cultivation.

Fig. 23. Comparison of relative abundance of *Plantago lanceolata*-type and cereal-type pollen in the near-site profile F (Feeser unpublished data) from the archaeological site Bad Oldesloe-Wolkenwehe LA 154 and the pollen profiles Poggensee and Lake Seefeld (Feeser et al. 2012). Apmod: modified arboreal pollen sum (arboreal pollen excluding *Alnus* and including *Corylus*).



A comparison with other near-site studies in the Oldenburger Graben allows further insights into changing subsistence practices throughout the Neolithic. The near-site profiles from Heringsdorf-Süssau at the eastern end of the Oldenburger Graben are connected to a MN III/IV settlement (Schütrumpf 1987). This site is much more exposed to the Baltic and shows high values of marine indicators during the settlement phase even though we see a marine to limnic transgression in the inner part of the Oldenburger Graben at the same time. 'Cerealia', i. e. cereal-type pollen, values of up to 20 % indicate the direct vicinity of cereal processing at the coastal site. In Siggeneben-Süd an Early Neolithic (EN I) site was excavated (Meurers-Balke 1983). The settlement is located at a slope in the eastern part of Oldenburger Graben. An increase in the marine influence is described for the time after the elm decline around 4000 cal BC. This is in good agreement with the sea level rise in the western part of the Oldenburger Graben at this time. Settlement indicators, that occur after the elm decline, show single 'Cerealia' grains and relatively high values of *Plantago lanceolata* in the near-site profiles. As cereal processing in the settlement would produce a much stronger signal comparable to that at Oldenburg-Dannau LA 77 and Heringsdorf-Süssau, cereals seem not to have played an important role, if any, at this site. At present, the earliest archaeobotanical evidence for cereals from the Oldenburger Graben comes from the settlement Grube LA 65 and dates after c. 3650 cal BC, i. e. to the EN Ib (Kirleis 2019). The single charred emmer grain from an Early Neolithic, supposedly EN Ia, pottery shard reported by Hartz et al. (2000) has been radiocarbon dated to c. 3800–3700 cal BC (Poz-62902; 4955 +/- 35 BP) and therefore dates to the EN Ib, too. Single 'Cerealia' pollen grains also occur in late Mesolithic layers in the Oldenburger Graben region (Schütrumpf 1972; Hartz et al. 2011) but no macro remains have been detected so far in the corresponding excavations.

The weak palynological and lacking archaeobotanical evidence for cereals during EN Ia, i. e. 4100–3800 cal BC, is interpreted to indicate an at the most minor cereal component in the diet. It is during EN Ib, coinciding with the establishment of extended arable fields (Feeser et al. 2012; Feeser/Dörfler 2015), that cereals probably became a major part of the every day diet.

If we turn to evidence for animal husbandry or domestic animals, respectively, this picture becomes even more complex. In contrast to the Mesolithic sites, and although wild game remains of importance during EN Ia, the bone assemblages from Siggeneben-Süd (Nobis 1983) suggest that domesticated animals played an important role in the subsistence of the Early Neolithic groups. This is also true for other parts of Northern Germany and southern Scandinavia (cf. Sørensen 2014). This coincides with palynological evidence for a change in woodland structure and an opening of the forest canopy favouring more light demanding species, which could well reflect woodland interference due to pastoral activities (Feeser/Dörfler 2014). The earliest and somewhat isolated evidence for domesticated animals in the area, however, dates to the Mesolithic period (Krause-Kyora et al. 2013). This suggests that in both cases, i. e. cereals and domesticated animals, respectively, there has been a phase with weak or only sporadic evidence, indicating no or only a minor contribution to the diet, before it was more widely used. This fits with the general adoption model of Zvelebil and Rowley-Conwy (1984) with an availability, substitution and consolidation phase. However, the adoption processes of domesticated animals and cereals seem not to be synchronous. In case of domesticated animals the beginning of the substitution phase coincides with the beginning of EN Ia (c. 4100et al.cal BC) and in case of cereals with the beginning of EN Ib (c. 3800 cal BC). This stepwise adoption of Neolithic subsistence strategies, already been indicated by Hartz et al. (2007b), supports the idea of an autochthonous development from Mesolithic to Neolithic groups in the region (cf. Brozio 2016).

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Imprint

ISSN 2197-649X

Layout draft: Holger Dieterich, Ines Reese
Technical edition: Karin Winter
Language revision: Eileen Küçükkaraca

Published by the Institute of Prehistoric and Protohistoric Archaeology, Kiel University;
For further information consult www.jna.uni-kiel.de