Acta Palaeobotanica 60(1), 156–180, 2020
https://doi.org/10.35535/acpa-2020-0007

e-ISSN 2082-0259
ISSN 0001-6594

The quick death of a lake: human impact on Lake Tresssee (N Germany) during the last 6000 years – an approach using pollen, Cladocera and sedimentology

CHRISTIAN STOLZ[1*], IRENA A. PIDEK[2] and MAGDALENA SUCHORA[2]

[1]Europa-Universität of Flensburg, Department of Biology and its didactics (Physical Geography), Auf dem Campus 1, 24943 Flensburg, Germany; e-mail: christian.stolz@uni-flensburg.de; ORCID: 0000-0002-5061-9149

[2]Marie Curie-Skłodowska University, Institute of Earth and Environmental Sciences, Al. Kraśnicka 2d, 20-718 Lublin, Poland; e-mails: i.pidek@poczta.umcs.lublin.pl, magda.suchora@gmail.com

Received 4 November 2019; accepted for publication 19 March 2020

ABSTRACT. Human-induced fluctuation of lake levels has been a common phenomenon in Europe since Neolithic times. At present, Lake Tresssee is a eutrophic lake covering less than 5 ha in northern Germany, but its sudden shrinking from ~125 ha before 1800 is considered a consequence of anthropogenic lowering of the lake level. We investigated the history of anthropogenic vegetation changes and water level fluctuations by multiproxy studies of a 4 m core from the former lake area. Our analyses of pollen and Cladocera subfossil, chemistry and sedimentological features yielded important conclusions about interactions between land-use history and climate impacts on the lake and its surroundings. The results indicate that the highest lake level persisted until the Late Atlantic. Since the Subboreal there have been several fluctuations, mostly in consequence of climate impacts. Later, different phases of sediment input to the lake from tributary streams and probably also from aeolian processes from an adjacent dune field were observed. At ~2800 BC the sedimentation rate decreased in consequence of fluvial impacts, as the lake basin was nearly filled up with deposits. As a result of greater human impacts, from the Early Bronze Age the macrophyte zone expanded in the lake, the oxygen content of the water continuously decreased, and heathlands developed in the surroundings. From the Late Iron Age and in the Early Medieval, pollutants probably from ironworks are detectable by geochemical analyses in the corresponding segments. In the pollen diagram the Migration Period is clearly visible, but the suggested radiocarbon date is younger than in Lake Belau in the neighboring region of Schleswig-Holstein. Most probably our pollen diagram did not register the absolute maximum values of *Fagus* related to the Migration Period. From the Early Medieval a clear phase of resettlement occurs. Since the Early Modern period, the lake level has shrunk rapidly in consequence of historically documented human activity.

KEYWORDS: lakes, human impact, Cladocera, Pollen Analysis, northern Germany, Dunes

INTRODUCTION

Strong human impacts on the environment since Neolithic times have been documented by palynological research at numerous sites across Europe (e.g. Mercuri et al., 2019). Vegetation changes coincide with human-induced changes in lake levels, eutrophication and heavy metal pollution. Water level fluctuations are typical of the history of small and medium-sized lakes in young moraine landscapes of Central Europe. Shallow lakes have especially been affected by these fluctuations. It is thought that hydrological changes in the surroundings of the lakes and in their catchments were triggered by climatic and anthropogenic factors. The conversion of lakes to peat bogs as a consequence of silting, and the complete disappearance of shallow

* Corresponding author

lakes of glacial, periglacial and postglacial origin, already started in the Early Boreal around 8600 BC. There are several examples from Denmark, northern Germany, northern Poland, the German Alpenvorland and the Schweizer Mittelland (Jäger, 1988: 21). A unique practice involves artificial reduction of a lake, lowering of a lake level or even complete disappearance of a lake for the purpose of creating new grassland. This has been occurring in northern Germany since the Late Medieval and especially in the 18th and 19th centuries. This practice is also known to have occurred in non-glaciated regions (e.g. volcanic lakes in the Eifel Mts., West Germany; Grewe, 1979). In north-eastern Schleswig-Holstein (landscape of Angeln) next to the border with Denmark there are also several examples (Jensen, 1844; Mager, 1930); the Rüder See (before 1800; 54.692°N, 9.627°E) and Ekeberger See (54.654°N, 9.613°E) were both completely drained, and the water level of the still-extant Havetofter See was lowered (54.642°N, 9.521°E).

A specific example is Lake Tresssee. Its surface shrank from ~125 ha before 1800 AD to less than 5 ha today (Fig. 1). During the

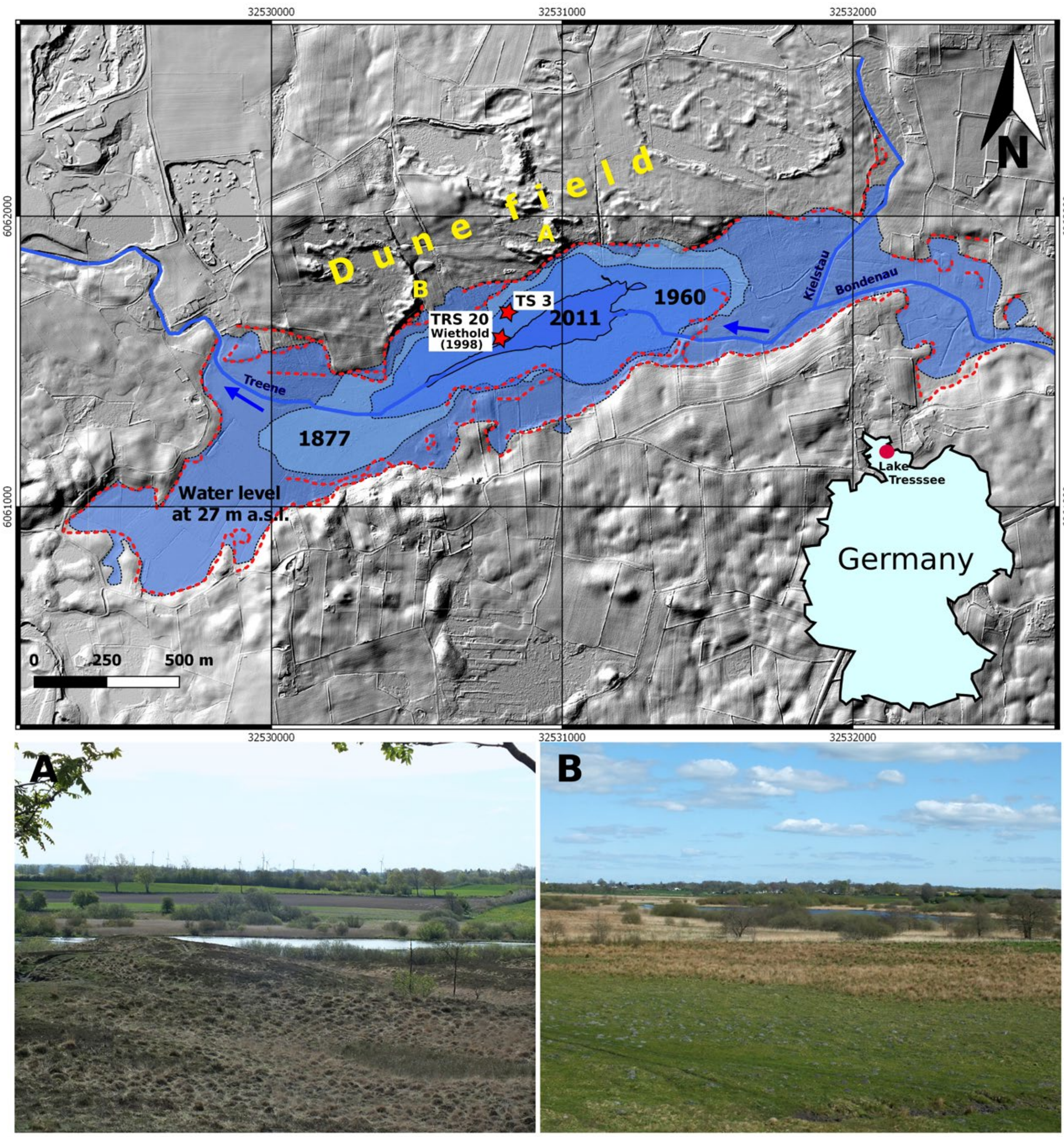

Fig. 1. Locations of profiles, topography, and water levels of Lake Tresssee. Red lines mark visible and presumed palaeocliffs in the field. Images A and B of the lake and the lake basin were taken from the locations marked on the map (DGM 1: © GeoBasis-DE/LVermGeo SH; www.LVermGeoSH.schleswig-holstein.de)

Holocene, the lake functioned as a large sedimentation trap for an extensive catchment. In the central part of the lake, Packschies (1982) documented the total thickness of Late Pleistocene/Holocene sediments at a minimum of 20 m. However, previous studies have not completely answered important questions about lake level fluctuations in the past (Packschies, 1984; Wiethold, 1998). With regard to the nearly unknown history of lake level changes and ecological conditions of Lake Tresssee, the questions for the present study were as follows: What were the palaeoenvironmental conditions of the lake in the past? How intense was the human impact of land use around the lake, especially regarding phases of increased/limited soil erosion in its catchment? What were the ecological consequences of sediment input and silting processes for the lake? When was the lake at its greatest level of expansion, what were the lake levels during different periods, and what were the reasons for fluctuations?

Evidence of pre-industrial iron works has been found in the catchment area and surroundings of the lake (Hingst, 1974). The first iron objects appear at archaeological sites in the landscape of Angeln beginning from the Younger Bronze Age. However, slag finds originate from the Iron Age, Roman Period and Migration Period, and to a lesser extent from the Medieval (Jöns, 1992/93). Regularly associated with the slag finds are deposits of bog iron ore up to 80 cm thick (Riedel, 1980). Heavy metal markers in the lake deposits are used to document pre-industrial iron works and related impacts on the landscape.

In 2018 we took a new core of lake deposits close to the previous coring site (TRS20) from the study by Wiethold (1998). The TRS20 core was not radiocarbon-dated, and unfortunately the important episodes of human impacts were not matched to an absolute chronology. A very detailed and well-dated timeline of core Q300 by Dörfler et al. (2012) was recently published for south-western Schleswig-Holstein (Lake Belau). It offers us an opportunity to reinterpret the past environmental changes around Lake Tresssee, with special attention to human and climatic impacts on the vegetation cover and lake level fluctuations. Subfossil Cladocera analysis adds important information on lake productivity, depth, and macrophyte zone development.

PREVIOUS STUDIES

Two diploma theses gave a first overview of the lake's history (Polensky, 1982; Packschies, 1982, 1984; Bronger and Polensky, 1985). There is also a pollen study (Wiethold, 1998) but without radiocarbon-dating. It contains broad descriptions and interpretations of former land-use components and further investigations from other sites on the peninsulas of Angeln and Schwansen (Wiethold, 1998). A laminated core from Lake Belau (~95 km to the SE in the Holstein area) offers high resolution and good material for comparison with our results (Dörfler et al., 2012). Nelle and Dörfler (2008) gave a summary of the late- and post-glacial vegetation history of Schleswig-Holstein, including results from Lake Belau. Dreibrodt and Bork (2005) documented the strong input of Holocene colluvial sediments from adjacent slopes to the lake sediments of Lake Belau. For the upper and middle Treene River below its outflow from Lake Tresssee there are published results on the input of clastic sediments during historical periods (Stolz et al., 2016). Other studies address the recent vegetation and hydrology of the Lake Tresssee area and the adjacent dune field (Meynke, 1985; Schröder, 1985; Rickert, 2013).

NATURAL CONDITIONS

The investigated area is located in the northern German state of Schleswig-Holstein (historical landscape of Angeln in the Duchy of Schleswig; Hamer, 1995), in Schleswig-Flensburg district ~12 km south of the city of Flensburg and 150 km north of Hamburg. It is part of a young glaciated ground moraine area in the north-eastern part of the peninsula of Jutland. Elevation ranges from 24 to 50 m a.s.l. The Tresssee basin (~3.3 × 0.9 km; Fig. 1B) runs ENE to WSW. It most likely formed from subglacial meltwater processes next to the Weichselian ice margin consisting of push moraines within the ground moraine landscape. The responsible part of the ice sheet, called the Westangelnsche Eiszunge, is a separated part of the Flensburger Förde glacier in the north and the ice lobe of the Schlei inlet in the south (Gripp, 1964; Riedel and Polensky, 1987; Zölitz, 1989). The southern edge of the basin is formed by sandy-loamy, mostly decalcified moraine with luvisols. The northern part consists of meltwater gravels and sands covered by aeolian sands with podzols and several sand dunes greater than 10 m thick (~1.1 × 0.7 km wide), partly with well-visible parabolic dunes (LLUR, 2012). The age of the dunes is still unclear (Polensky, 1982; Zölitz, 1989; Müller, 1999). Further investigations using OSL dating are in progress (Stolz et al., in prep.). However, the sand cover and inland dunes are most likely of Late Glacial origin and show visible young degradation and reactivation processes resulting from human impacts (Bronger and Polensky, 1985; Müller, 1999; Stolz et al., in prep.). At the north bank of the lake, the dune sands are intermeshed with peats and former lake sediments (Packschies, 1984; Wiethold, 1998).

Lake Tresssee (German: Treßsee; Danish Træsø; 54.701°N, 9.481°E) was originally one of the biggest lakes on the landscape of Angeln in north-eastern Schleswig-Holstein (Wiethold, 1998). Currently it is ~0.81 × 0.18 km wide. Its catchment area is 133 km^2. The surface of the lake shrank from ~125 ha before 1800 AD to less than 5 ha today, as documented by drillings of M. Packschies and R. Polensky (Packschies, 1984).

The lake is the origin of the River Treene (the name originates from the Danish term for tree, to denote "the river in the forests"; Laur, 1967), which breaks through the terminal moraines and is the most important river in northern Schleswig-Holstein. It drains along with the Eider River to the North Sea (Stolz et al., 2016). There are two bigger and several smaller streams flowing into the lake, with well-visible alluvial fans. There have been several projects since the 18th century aimed at lowering the lake level and reducing the water surface (Wiethold, 1998). Probably the outflow of River Treene was deepened and the newly created meadows were drained using ditches. In 1877 the first Prussian topographic map of the area showed the lake surface to be ~57 km^2. The lake surface covered ~30 km^2 in 1950 and, after the destruction of a weir in 1970, only 9.5 km^2 in 1980 (Königlich-Preußische Landesaufnahme, 1879; Landesvermessungsamt Schleswig-Holstein, 1953; Packschies, 1984; Wiethold, 1998). Today the lake level is at ~23.4 m a.s.l. (DGM 1; Landesamt für Vermessung und Geoinformation Schleswig-Holstein, 2017). In consequence of the hydrological and morphological situation and also influences, especially from agriculture, in its catchment, the lake is strongly eutrophic (Grudzinski, 2007) and maximally 0.5 to 1.45 m deep, with seasonal fluctuations (Hamer, 1995; MELUND, 2001). It is surrounded by large reed belts dominated by *Phragmites australis*. In summer the water surface is largely covered by water plant associations (e.g. *Myriophyllo-Nupharetum* association; Schröder, 1985). Since the 1990s the lake has been included in a large conservation area (Upper Treene Landscape conservation project).

The climate in the area is strongly oceanic and warm temperate, with mild winters and cool summers. The mean annual temperature for Flensburg (1961–1990) is 8.2°C (January: 0.6°C, July 16°C) and annual precipitation is 903 mm (Mühr, 2007). There are western weather situations in more than 55% of cases in the year.

ARCHAEOLOGY OF THE TRESSSEE AREA

The Angeln landscape has yielded particularly important archeological finds from peat bogs (e.g. well-known Germanic finds from the Roman Period, from Thorsberger Moor next to Süderbrarup village, ~25 km ESE of Lake Tresssee; Carnap-Bornheim, 2015). Willroth (1992) and Röschmann (1963) gave an overview of other archaeological sites. Härdtle (1996) described the younger history of forests and their use; this research places our palaeobotanical results within the context of land use history.

In the lake area there have been several finds from the Mesolithic along the south bank and east of the Tresssee basin (Röschmann, 1963; Wiethold, 1998). There are fewer finds from the Younger Bronze Age, mainly graves (Willroth, 1992). Later, the region was continually settled during the pre-Roman Iron Age, as evidenced by several settlement, grave and single finds, but without indications of bog iron ore smelting. Wiethold (1998) suggested that the peat bogs, floodplains and forests acted as borders for the different settlement areas. Willroth (1992) presumed a focus on the surroundings of Süderbrarup (Willroth, 1992). Important finds from the Tresssee originate from the eastern part of the lake area around the villages of Großsolt, Mühlenbrück and Bistoft.

During the Roman Imperial Period, Angeln was densely settled in an area that was open but not completely deforested, but from the immediate surroundings of Tresssee there are fewer finds. The next documented ones originate from the surrounding villages (Großsoltholz, Juhlschau). On the basis of his pollen analyses, Wiethold (1998) concluded that deforestation was not complete but that the landscape was largely open, with small heaths on podzols and also agriculture on cambisols. Several centrally located cemeteries were found, consisting of more than 1000 burials (Willroth, 1992; Wiethold, 1998). There is also some evidence of so-called "Celtic fields" from this period (Klamm, 1992; Nielsen and Dalsgaard, 2017). Sites of iron smelting from the same time have been described from Süderschmedeby (6 km to the south-west) and other locations, (Hingst, 1974; Jöns, 1992/93). A decrease in settlement activity is visible from the second third of the 4th century AD to the middle of the 5th century. After that there are only very rare finds and almost no documented settlement sites. This marks the start of the Migration Period. However, a connection with the presumed migration of the Angles and Saxons to England is uncertain (Wiethold, 1998). There are only a few finds from the 7th century (Willroth, 1992).

For the 8th and 9th centuries (early Viking Period) there is only rare evidence for settlement activity in Angeln. For the Tresssee area, finds from the villages of Sieverstedt and Großsolt are important. Presumably there was an influx of people from northern Jutland, but there are finds only from around the urban Viking settlement of Hedeby (German: Haithabu; a UNESCO World Heritage Site since 2018) along the coasts and the Schlei (a long inlet of the Baltic Sea, of subglacial meltwater origin). Settlement increased from the 10th century. In the following High Medieval settlement period, a closed cultivated landscape with fewer remaining forests arose (Wiethold, 1998). Heaths and cropland were farmed, using crop rotation and partly with plaggen fertilization. New settlements were founded. Wiethold (1998) refers to unpleasant conditions, however, with dune sands and swampy soils in the Tresssee basin and along its tributary Bondenau. Lake Tresssee and the River Treene constituted a cultural border between two different parishes.

In the following Late Medieval period (~1300–1500 AD) the number of settlements declined quickly, especially on sandier soils, and drastically after 1350 as the Black Death arrived in Angeln in several waves. Especially around the Tresssee, most likely at least four settlement sites were deserted (Kuhlmann, 1958; Wiethold, 1998).

There were several changes during the Early Modern Period after 1500. The share of forest shrank (Härdtle, 1996). Pig fattening in the forests was widespread, as well as charcoal burning, associated with overuse of the remaining forests. Coppice forests ("Kratts"), especially with oak, were frequent (Wiethold, 1998, after Mager, 1930). Heaths were widespread in other parts of the landscape, especially on sandy soils. The surroundings of the Tresssee basin must have been nearly free of forests in the 16th century. Agricultural reforms at the end of the 18th century brought an increase of cropland (Behrend, 1964). In the 18th and 19th centuries the use of forests for pasture was prohibited by new forest regulations. In consequence, new pastureland increased in wet lowland areas. These must be the reasons for the artificial lowering of the lake level and the shrinking of Lake Tresssee (Wiethold, 1998, after Mager, 1930). The main cause was artificial deepening of the outflow on the River Treene from the lake. At the end of the 19th century the former lake bed was used primarily as grassland, and the dunes in the north were heathland (probably pastured; Königlich-Preußische Landesaufnahme, 1879).

MATERIALS AND METHODS

CORING

In May 2018 a new 4 m core was obtained from the former lake area, 83 m NNE of the location of Wiethold's original TRS20 core (1998, Abb. 12), using a Russian Instorf corer. After coring, the core was packed in tubes and cooled.

CHEMICAL PARAMETERS

For chemical analyses, core samples were taken at 10 cm intervals (10 cm per sample), and for SOM (loss on ignition) at 4 cm intervals (4 cm per sample). Total values for C, N and S were measured using an Elementar vario cube EL-IR. Total values for As, Pb, Cd, Cr, Fe, Cu, Mn, Ni, Zn and P were measured according to the guidelines of DIN EN ISO 11885: 2009-09, and Hg following DIN EN ISO 12846: 2012-08. Soil organic matter (SOM) and organic carbon (C org; calculation factor 1.724) were measured after Blume (2000) using loss on ignition (430°C). The values for As, Pb, Cd, Cr, Cu, Ni, Hg and Zn were measured only for the 0–150 cm depth section because these values were needed only for evidence of iron smelting in this area (150 cm depth represents ages 1100–800 cal. BC; see radiocarbon results). Heavy metals and other pollutants are markers of pre-industrial iron production in the catchment, confirmed archaeologically, and of modern and post-modern pollution. For the previous period there is no archeological evidence of metal production in this area (Jöns, 1992/93).

Total organic C and N were employed as a parameter for increased input of sediment from streams flowing into the lake in consequence of human-caused soil erosion in the catchment. The C/N ratio (using C total and N total for calculation) shows the degree of decomposition and the Fe/Mn ratio indicates the occurrence of anoxic conditions and low oxygen content in the water (Boyle, 2001).

POLLEN ANALYSIS

As Wiethold's (1998) detailed pollen study of the TRS20 core did not give radiocarbon dates, we could not use it to date the episodes of stronger human impacts on the vegetation composition that led to regional deforestation. Samples from the new TS3 core were taken at 2 cm intervals but analyzed at intervals ranging from 2 cm to 20 cm, depending on the changes in pollen spectra, to identify characteristic episodes revealed by the pollen diagram of Wiethold (1998) and thereby to provide probable radiocarbon dates for them (Tab. 1).

The methods of pollen analysis follow the standard laboratory protocol for Erdtman's acetolysis (Berglund and Ralska-Jasiewiczowa, 1986; Faegri and Iversen, 1989). The sum for calculating pollen percentages is the sum for tree, shrub and terrestrial herb pollen, excluding water plant and reed-swamp plant pollen (AP + NAP = 100%). The percentages of water plant and reed-swamp plant pollen as well as algae of *Pediastrum* were calculated from the sum AP+NAP+given taxon = 100%. The pollen diagram (Fig. 4) was plotted using POLPAL software (Nalepka and Walanus, 2003). Within *Humulus*/*Cannabis*, *Cannabis sativa* pollen was identified based on pollen grain diameter: grains ≥ 28 μm were identified as *Cannabis sativa* (see Mercuri et al., 2002). However, differentiation of *Cannabis* from *Humulus* pollen by grain size, pore protrusion and exine thickness is an old palynological problem still not fully solved (see Whittington and Edwards, 1989; McPartland et al., 2018 and discussion therein). Our identification of *Cannabis sativa* was additionally supported by the simultaneous occurrence of the continuous pollen curve of *Secale cereale* and by the increase of the pollen values of other cereals and weeds, as suggested also by Gaillard and Berglund (1988) and other pollen studies listed by McPartland et al. (2018).

CLADOCERA ANALYSIS

The core was sampled at 2 cm intervals for Cladocera analysis. Volumetric samples (1 cm^3 sediment) were handled according to the standard procedure described by Frey (1986). Samples were heated in 10% KOH, after which the soluble organic matter was washed with distilled water on a sieve (33 μm mesh). Due to the absence of carbonates, the HCl 10% treatment was partly omitted for some samples. The remaining residues, containing Cladocera remains, were moved quantitatively to probes with scales and refilled to 10 ml with distilled water. Microscope slides were prepared from 0.1 ml homogenized samples, and 2–5 slides per sample were examined. All subfossil Cladocera remains (headshields, carapaces, postabdomens, claws, ephippia) were identified under a compound microsope at 100×, 200× and 400×, according to the key of Szeroczyńska and Sarmaja-Korjonen (2007). The results are presented as a percentage diagram supplemented with population characteristics: total sum of individuals (number of specimens in 1 cm^3 sediment), species richness, Shannon-Weiner diversity index, and percentage shares of ecological groups (planktonic, littoral, macrophyte-associated, sediment-associated). As in high-trophy conditions *Chydorus sphaercus* may be present in the open water zone, this species was separated from the planktonic/littoral graph. Taxa with only a single occurrence (*Camptocercus lilljeborgi*, *Disparalona hammata*, *Pleuroxus striatus*, *Anchistropus emarginatus*, *Polyphemus pediculus*) were excluded from the final diagram of species composition. All ecological indexes were calculated with PAST software (Hammer et al., 2001). The diagrams were drawn using Tilia software (Grimm, 1991–2011) and divided into local Cladocera assemblage zones (LCAZ) and subzones (LCASZ), using the CONISS algorithm (Figs 5, 6; Grimm, 1987).

RADIOCARBON DATING

Radiocarbon dates (AMS method) were obtained from the samples consisting of fine-detritus gyttja and pieces of terrestrial plants (leaves) from lake sediments. Samples for dating were selected according to the results of pollen analysis. In all cases, carbonates were removed before dating. Radiocarbon dating employed a mass spectrometer (Beta Analytic Radiocarbon Dating Laboratory, Miami, US) and was calibrated with OxCal 4.3 software (Bronk Ramsey, 1995), applying the INTCAL13 dataset after Reimer et al. (2013) and the NHZ1 datasets (Hua et al., 2013). To prepare an age–depth model, the absolute chronology was derived based on an age–depth model constructed using the P Sequence function (Fig. 2). Two distinct outlier dates (depths 62–64 and 144–146 cm) were excluded from the calculation of the age–depth model. The sedimentation rate was calculated based on the age–depth model.

RESULTS

DESCRIPTION OF THE CORE (see Fig. 2)

We distinguished three sedimentary units in the studied sediment core:

0.00–0.62 m – well-decomposed coarse sedge peat with admixture of algae gyttja,

0.62–2.10 m – fine-detritus gyttja with small admixture of well-decomposed sedge peat,

2.10–4.00 m – fine-detritus gyttja.

RADIOCARBON DATING AND AGE–DEPTH MODEL

We obtained nineteen radiocarbon dates from 30–372 cm depth (Tab. 1). The results show that the analyzed TS3 core covers more

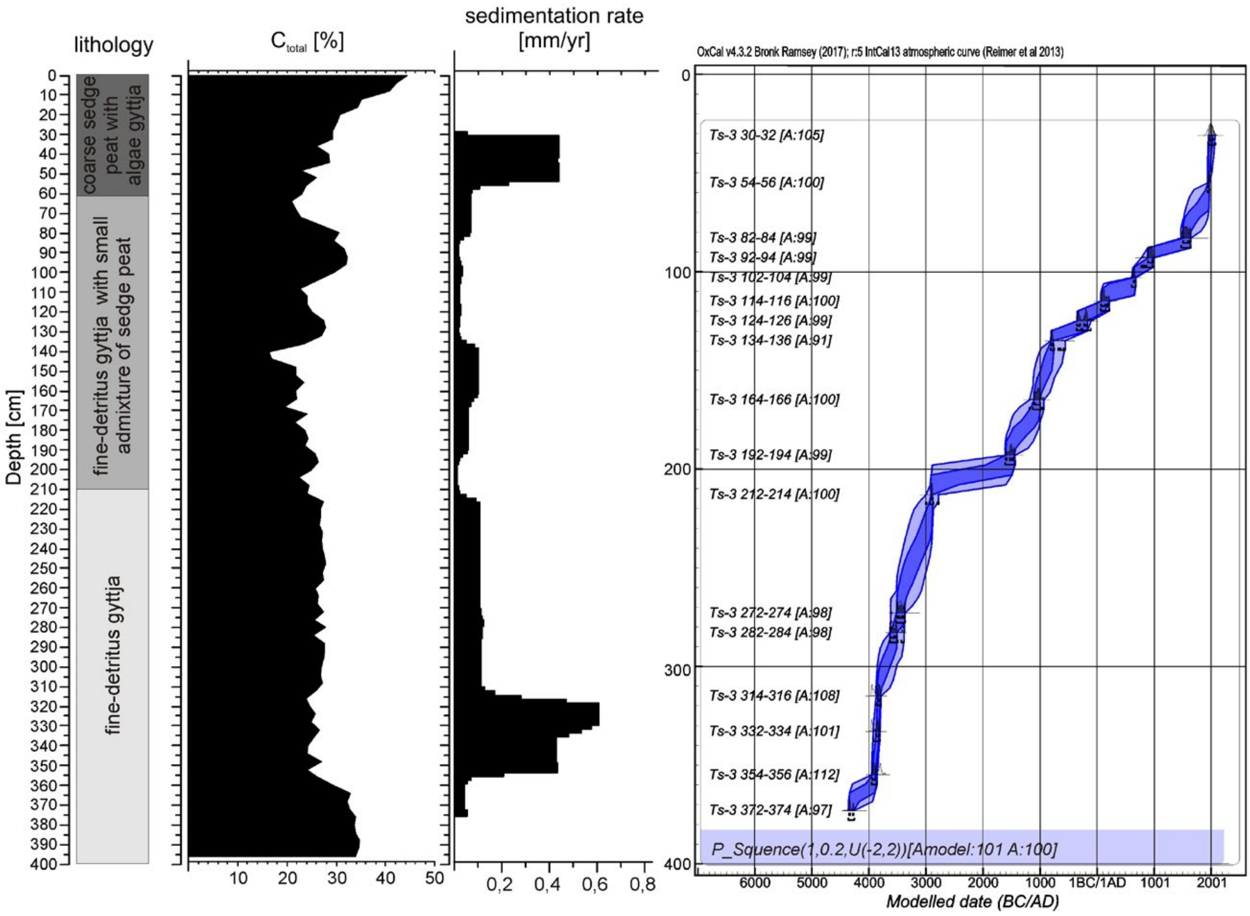

Fig. 2. Lithology, C content, sedimentation rate and age–depth model

than 5000 years from the end of the Atlantic period to modern times. In this series only two dates seem to be outliers and have been removed from the age–depth model (Fig. 2). In the Atlantic and in the Subboreal (Early Neolitic) periods the model shows a high sedimentation rate of ~15 cm per 100 yrs. From ~2800 BC until the Middle Bronze Age it decreases to 0.15 cm per 100 yrs. To the end of the Bronze Age (~800 BC) sedimentation increases again, but only to ~6.3 cm per 100 yrs. During the Iron Age until the High Medieval after the available dates, there is again a more slight decrease of sedimentation, of 2.9 cm per 100 yrs in the lake. After a hiatus detected at 56 cm (~1564–1956 AD), the sedimentation rate again increases greatly.

CHEMICAL PARAMETERS

The content of total N, C, S, Fe and Mn is generally uniform in the lower part of the core from the base until ~220 cm depth (~3000 cal. BC, Late Neolithic), with N and C showing a small first depression between 360 and 310 cm. In the upper part there are more fluctuations, often with lower values for C, N and Mn and higher values for S and Fe.

Total Pb, Cd, Cr and Cu (only tested from 150 cm depth to the top of the core) show a clear increase, and As shows a decrease. The first significant change is observed at ~110 cm depth for these elements (~0 BC/AD, Roman Period). Pb, Cd, Cr and Cu content shows nearly similar development in the core.

The diagram of geochemical parameters is divided into 9 zones (G1–G9; Fig. 3) based on changes in the composition of the analyzed elements.

Zone G1, starting from the base of the core (400–360 cm, 4300–3800 cal. BC), shows high content of C (30–33%) as well as N, S, Fe and Mn. The C/N ratio is slightly higher than in later zones.

Zone G2 (360–220 cm, 3800–3000 BC) shows a slight decrease of C to 23–27%; it remains constant for a long time, as does N, S, Fe and Mn. There is a slight depression of C and N between 310 and 360 cm. In the second half of the zone the C/N ratio declines.

Table 1. Radiocarbon dates of the TS3 core

Laboratory code – number	Depth [cm]	^{14}C date	Calibrated date 2σ range (95.4%)	Material dated
Beta – 506860	30–32	116.84 ± 0.44 pMC	39–41 cal. BP (77.9%) 9–10 cal. BP (17.5%)	Terrestrial plant
Beta – 506861	54–56	103.03 ± 0.38 pMC	6–8 cal. BP (95.4%)	Peat (plant material)
Beta – 517917	62–64	1110 ± 30 BP	1072–937 cal. BP (95.4%)	Organic sediment/gyttja
Beta – 506862	82–84	320 ± 30 BP	320 ± 30 cal. BP (95.4%)	Terrestrial plant
Beta – 506863	92–94	1120 ± 30 BP	1088–956 cal. BP (91.8%) 1172–1160 cal. BP (1.7%) 1124–1109 cal. BP (1.4%) 1141–1135 cal. BP (0.5%)	Organic sediment/gyttja
Beta – 517918	102–104	1380 ± 30 BP	1344–1270 cal. BP (95.4%)	Organic sediment/gyttja
Beta – 506864	114–116	1880 ± 30 BP	1884–1728 cal. BP (95.4%)	Organic sediment/gyttja
Beta – 506865	124–126	2160 ± 30 BP	2208–2057 cal. BP (55.3%) 2307–2228 cal. BP (40.1%)	Organic sediment/gyttja
Beta – 497428	134–136	2580 ± 30 BP	2763–2699 cal. BP (87.0%) 2565–2539 cal. BP (3.9%) 2633–2617 cal. BP (3.1%) 2586–2571 cal. BP (1.4%)	Organic sediment/gyttja
Beta – 506866	144–146	1990 ± 30 BP	1998–1878 cal. BP (95.4%)	Organic sediment/gyttja
Beta – 497429	164–166	2870 ± 30 BP	3076–2880 cal. BP (95.4%)	Organic sediment/gyttja
Beta – 506867	192–194	3240 ± 30 BP	3515–3388 cal. BP (80.3%) 3560–3522 cal. BP (15.1%)	Organic sediment/gyttja
Beta – 517919	212–214	4280 ± 30 BP	4882–4821 cal. BP (93.7%) 4957–4937 cal. BP (1.7%)	Organic sediment/gyttja
Beta – 497430	272–274	4670 ± 30 BP	5470–5316 cal. BP (93.8%) 5569–5560 cal. BP (1.6%)	Organic sediment/gyttja
Beta – 506868	282–284	4740 ± 30 BP	5584–5449 cal. BP (75.3%) 5379–5328 cal. BP (20.1%)	Organic sediment/gyttja
Beta – 506869	314–316	5090 ± 30 BP	5830–5749 cal. BP (59.5%) 5912–5844 cal. BP (35.9%)	Organic sediment/gyttja
Beta – 506870	332–334	5100 ± 30 BP	5830–5749 cal. BP (58.2%) 5917–5845 cal. BP (37.2%)	Organic sediment/gyttja
Beta – 506871	354–356	5040 ± 30 BP	5900–5713 cal. BP (94.5%) 5672–5665 cal. BP (0.9%)	Organic sediment/gyttja
Beta – 497431	372–374	5470 ± 30 BP	6310–6209 cal. BP (95.4%)	Organic sediment/gyttja

Zone G3 (220–135 cm, 3000–750 cal. BC) shows a further decrease and more fluctuations of C content (19.5–26%) and N content. At the end of the zone, P increases strongly. There is a conspicuous decrease of Mn and an increase of the Fe/Mn ratio. The end of the zone (150–135 cm) shows a decline of C (16–17%), N, Mn and Fe. The values for heavy metals and other pollutants are low and unremarkable in comparison with the geogenic background (after LABO, 2017). As and Zn content are generally quite high in the complete profile, however.

Zone G4 (135–120 cm, 750–0 cal. BC/AD) shows an increase of C again (25–28%). N, P, Fe and Mn content also increases, and the values for As and Hg are higher, but Hg content remains below the value for the geogenic background (after LABO, 2017).

Zone G5 (120–105 cm, 0 cal. BC/AD–600 cal. AD) shows a clear decline of organic carbon content (22–24%) and N. Pollutant levels are low. Later in the zone the values for Pb, Cd and Ni are slightly higher.

Zone G6 (Early Medieval; 105–82 cm, 600–900 cal. AD) once again shows increased shares of C and N (23–32%), and strikingly%). In the same time period, there are striking higher total values for As, Pb, Cd, Cu, Zn and partly Ni.

Zone G7 (Medieval to Early Modern; 82–56 cm, 900–1550 cal. AD) shows a decrease for the organic carbon curve and for N.

At 56 cm depth we detected a hiatus for 1564–1956 AD.

Zone G8 (Postmodern; 56–10 cm, 1956–1990 cal. AD) shows a strong increase of C, attributable to the fact that the site was no longer covered by water. There are high values for pollutants and heavy metals, increasing more steeply at the end of the zone. Nearly all values reach their peaks, as does the Fe/Mn ratio.

Zone G9 (10–0 cm, 1990–2018 cal. AD) shows a further increase of C to the highest level for this site, and a decrease of pollutants.

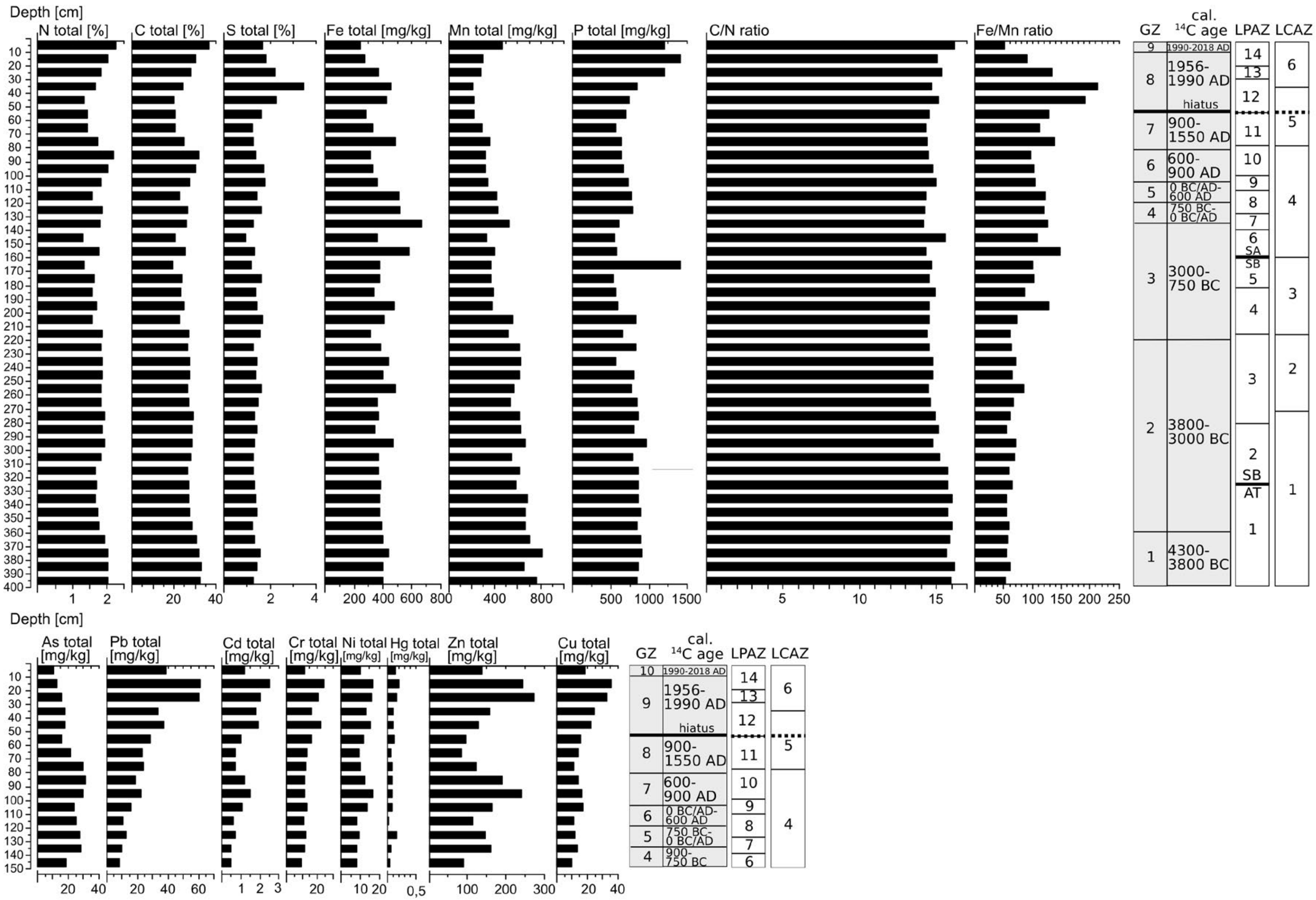

Fig. 3. Geochemical analyses with geochemical zones (GZ) and approximate ages, local pollen assemblage zones (LPAZ), chronozones (AT = Atlantic; SB = Subboreal; SA = Subatlantic) and local Cladocera assemblage zones (LCAZ). Elements were analyzed only to 150 cm depth

PALYNOLOGICAL RESULTS

The pollen diagram is divided into 14 local pollen assemblage zones (LPAZs), labeled TS3 and numbered 1–14 LPAZ starting from the bottom part of the core (Fig. 4). The TS3 core bears a record of vegetation and landscape changes from the end of the Atlantic period after the main phase of elm decline.

TS3, **LPAZ 1**: The Atlantic period is represented by pollen spectra dominated by *Alnus* (to 41.5%), *Quercus* (to 13.5%) and *Corylus* (to 18%), with low representation of *Ulmus* and *Fraxinus* (~2–3% each), and the absence of *Plantago lanceolata* and Cerealia.

Although pollen of *Plantago lanceolata*, the main indicator of pastureland, does not occur in this zone, spores of *Pteridium aquilinum* may suggest open woodland and some limited pastoral activity around Lake Tresssee.

The forests surrounding the lake were mainly alder-dominated communities with a significant admixture of *Fraxinus*. Rich riverine communities with *Ulmus* as the main tree species were poorly represented. Riverine communities with *Ulmus* as the main tree species were poorly represented at that time, because the discussed period comes after the phase of elm decline, a phenomenon in which the elm population was reduced throughout Europe.

TS3, **LPAZ 2**: Although *Alnus* still dominates the pollen spectra, indicating that wet alder forests were widespread at that time, the increase of *Quercus* and *Fraxinus* and the still-high values for *Corylus* give evidence of small-scale human disturbances in rich dry-ground communities. The drop in the values of *Tilia* may be connected with the use of its different products. *Carpinus* is not present yet. The first pollen grains of *Fagus* may indicate the presence of scattered beech trees.

TS3, **LPAZ 3**: A slight increase of *Betula* to 7.5%, with more frequent *Pinus* and significant percentages of *Quercus* (to 22%) and *Fraxinus* (to 2.56%) suggests regeneration of the forest, starting with secondary succession of birch and pine in cleared areas. *Tilia* increases in the upper part of the zone to 3.3%. The first pollen grains of *Plantago lanceolate*, Cerealia and *Urtica* appear among the human-impact indicators, providing evidence of small-scale clearing of the forest surrounding settlement areas. A slight decrease of *Alnus* pollen may suggest lowering of the water level.

TS3, **LPAZ 4**: More frequent *Betula* pollen and the beginning of the continuous pollen curve of *Fagus*, with a slight increase to 2.5%, together with the first pollen grains of *Carpinus*, the maximum of *Tilia* (6%), and higher *Fraxinus* (4.5%) and *Ulmus* values (to 2.4%), provide evidence of a phase of regeneration of rich dry-ground forest. Between the two samples of this zone there is a visible drop of *Alnus* from 47.5% to 38.5% that may testify to further lowering of the lake level, perhaps due to grazing activity, as suggested by *Rumex acetosella* t. with a continuous pollen curve, and a single pollen grain of *Plantago lanceolata* that occurs after a break in its curve in the upper sample. Crop cultivation must have been very confined, as Cerealia occurs only as a single pollen grain.

The overall reconstruction of vegetation and landscape from the pollen spectra of this zone suggests at first forest regeneration after deforestation that is partly observable in the sample from the 212 cm depth. It shows a considerable amount of *Rumex acetosella* t., a continuous pollen curve of *Calluna*, and single pollen grains of Cerealia.

TS3, **LPAZ 5**: Although the *Fagus* pollen curve is continuous, suggesting the development of beech, the significant decrease of *Tilia*, *Fraxinus* and *Corylus* suggests more intense human intervention, further confirmed by significant increases in *Plantago lanceolata*, *Rumex acetosella* and *Calluna*. *Pteridium aquilinum* spores are more frequent as well. The gradual decrease of the *Alnus* pollen curve is continuous from the previous zone, suggesting further restriction of alder woods. The slight increase in *Quercus* may be connected with better production of its pollen in thinned forests.

TS3, **LPAZ 6**: Higher values of *Plantago lanceolata*, increased *Calluna* and still-significant percentages for *Pteridium aquilinum*, with the continuous appearance of Cerealia pollen, suggest more intense anthropopression from grazing and cereal cultivation. A slight increase of *Betula* (to 11%), along with breaks in the *Fagus* and *Carpinus* pollen curves that temporarily drop to zero, may suggest regeneration of birch communities in areas partly cleared of forests. The slight increases of *Tilia*, *Fraxinus*, *Ulmus* and *Corylus* seem to suggest that clearing was not done on a large scale. Surprisingly, the percentages of *Rumex acetosella* t. pollen temporarily drop to zero.

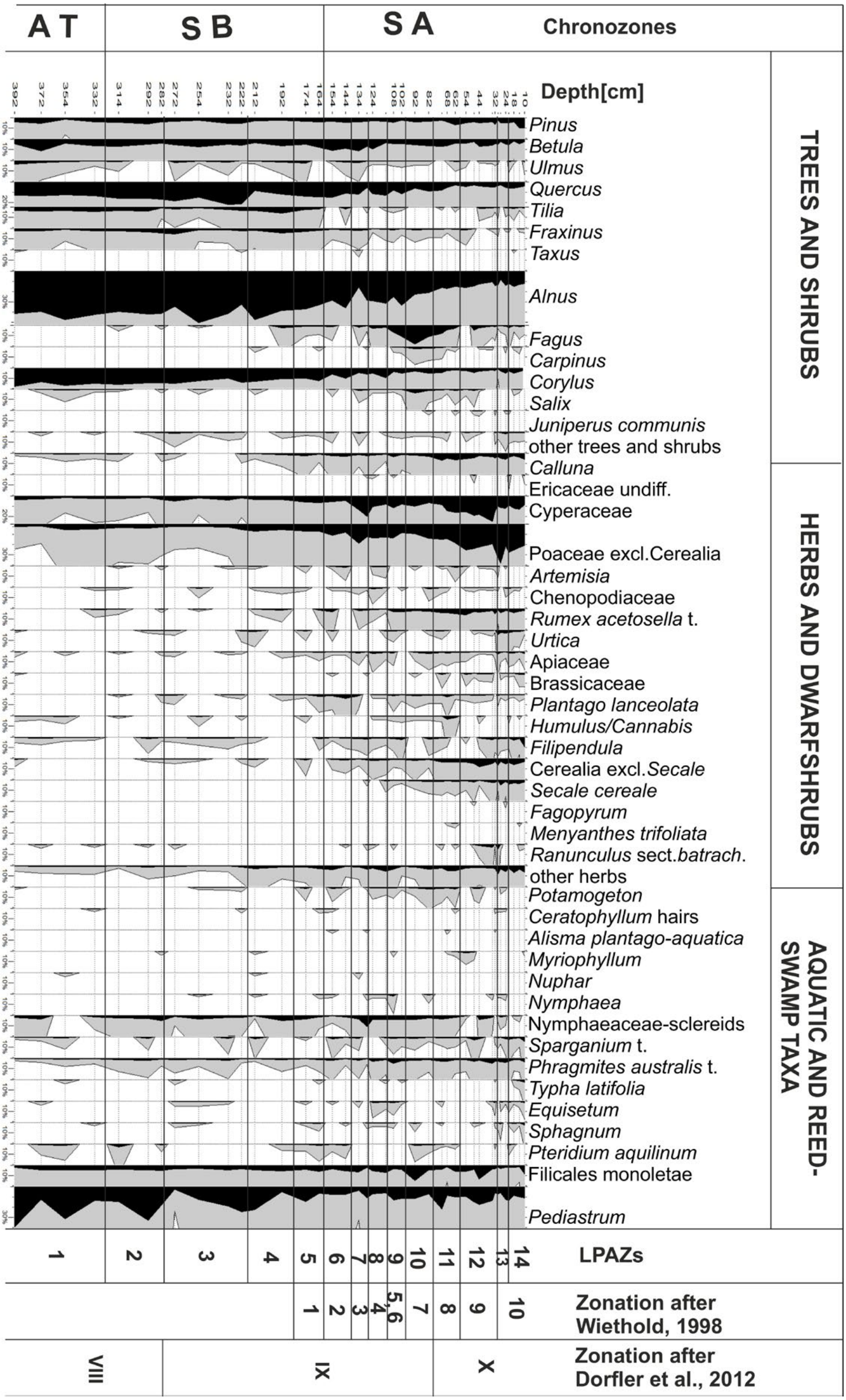

Fig. 4. Pollen diagram

It is difficult to interpret the composition of the pollen spectra, especially from 144 cm depth where the outlier from the ^{14}C data series occurs, where at the same time the lakeshores began to be overgrown by a wider belt of macrophytes, among which *Sparganium* may have played an important role. A single *Menyanthes trifoliata* pollen grain that occurs in this zone may indicate the development of transitional bog around the lake.

TS3, **LPAZ 7**: A strong decrease of *Alnus* (to 15.5%) again suggests further lowering of the lake level. An immediate increase of *Alnus* to 28.5% in the next sample may suggest an increase of the lake level and regeneration of alder woods. These changes coincide with a slight decline of *Calluna* and an increase of Poaceae and Cyperaceae. *Plantago lanceolata* drops to zero in the upper sample, together with a decline of *Artemisia* and the disappearance of *Pteridium aquilinum* spores. These changes suggest a lessening of human pressure, but the forests were already more heavily exploited, as seen in the dramatic fall of *Tilia* and *Quercus* from 12% to 5%. In addition, *Corylus* falls significantly from 10% to 4.5%, and *Ulmus* and *Fraxinus* decrease slightly. On the other hand, the continuous pollen curve of *Fagus* after a break (to 2%), as well as single pollen grains of *Carpinus*, may suggest forest regeneration but with a change in the tree species composition. After intensive exploitation of oak, lime, elm, ash and hazel, beech and hornbeam started to play a more important role. The continuous pollen curve of *Salix* apparently indicates that willow shrubs began to appear around the lakeshores. *Sparganium* and *Potamogeton* disappear from the pollen spectra, while Nymphaeaceae increase. The latter is evidence of overgrowing of the reed belt zone on the lakeshores by nympheids.

TS3, **LPAZ 8**: The composition of the pollen spectra testifies to stronger anthropopression, with *Secale cereale* cultivation as well as removal of many trees. There is a further drop in *Ulmus*, *Fraxinus* and *Corylus* pollen values. The values for *Fagus* pollen remain low and *Carpinus* drops to zero, suggesting more extensive human impacts on forest communities. The beginning of the continuous curve of *Secale cereale* in the sample from 114 cm coincides with the drop in the values for *Artemisia* and Chenopodiaceae after their brief increase. These changes may be evidence of the presence of cleared areas around settlements that were spontaneously overgrown by ruderal communities. The lake's eutrophication and its overgrowth by nympheids are indicated by increased percentages of Nymphaeaceae. Again, *Potamogeton* occurs among the water plants. Reed swamp communities were richer at that time, as supported by the presence of *Typha latifolia* and *Sparganium* pollen. At the same time, the reed swamp belt around the eutrophic lake expanded again, and plants typical of transitional bogs (*Comarum*, *Lythrum*, *Sphagnum*, *Equisetum*) occurred.

TS3, **LPAZ 9**: The sharp increase of *Fagus* pollen values and the continuous pollen curve of *Carpinus*, with increasing values, strongly indicate forest regeneration, with beech as the tree gaining dominance. Single pollen grains of other trees (*Tilia*, *Picea*) appear, and the values of *Ulmus*, *Fraxinus*, *Salix* and *Corylus* remain similar to those in the previous zones. These trees and hazel were also components of regenerating forest, while birch communities withdrew (significant drop of *Betula* pollen percentages). All human-impact indicators show declining pollen curves (*Secale cereale*, Cerealia, *Artemisia*, *Plantago lanceolata*). The characteristic feature of this pollen zone is the increase of *Pteridium aquilinum* and Filicales monolete spores, which can be interpreted as the probable development of ferns in wetter types of forest, while the edges and openings of regenerating forests on drier ground were occupied by *Pteridium aquilinum*. The values for Nymphaeaceae and *Potamogeton* remain comparable to those of the previous zone, suggesting no significant fluctuations of the water lake level. The upper border of the zone is marked by a decrease of *Calluna* and *Tilia*.

TS3, **LPAZ 10**: The most characteristic feature of this zone is the maximum of *Fagus* pollen values (18.5%), decreasing in the upper part of the zone to 11%. Moreover, *Carpinus* reaches maximum in the profile (1.8%), along with the maximum for *Salix* and higher values for *Quercus* (9%) and *Tilia*. *Alnus* has a 22% share. The percentages of human-impact indicators are very low; among them, *Calluna* falls markedly.

The whole character of the pollen spectra indicates regeneration of forest communities in which *Fagus* has a dominant role.

Secale cereale is still present as a closed curve. Other Cerealia pollen types appear but in general there is no increase in human-impact indicators. *Urtica* pollen is absent and *Artemisa* and Chenopodiaceae are very rare.

TS3, **LPAZ 11**: *Alnus* percentages drop to 15–17% and those of *Betula* decrease slightly. A decrease of *Fagus* from 8.0% to 3.0% is characteristic for this zone. The values for *Carpinus* fall from 1.2% to 0.5%. The curve of *Quercus* declines slightly and *Corylus* falls from 4.5% to 2%. Pollen of several other trees (*Ulmus*, *Tilia*, *Pinus*) is more frequent. There is a considerable increase in *Calluna*, as well as in other indicators of human impacts (*Artemisia*, *Plantago lanceolata*, *Rumex acetosella*). The *Humulus*/*Cannabis* pollen curve reaches maximum. *Urtica* is frequent.

The overall composition of the pollen spectra signals a new phase of anthropopression, with strong deforestation and extensive cultivation of cereal crops, including rye and probably hemp. Pore shape and pollen grain size enabled us to unequivocally identify *Cannabis sativa* among the pollen of *Humulus*/*Cannabis* type. Grazing activity also intensified, resulting in the development of heathland over large areas. Juniper also occurred. The cultural landscape also hosted abundant ruderal communities with Chenopodiaceae, *Artemisia* and *Urtica*. The very low percentages of *Alnus* suggest a very low water level in the lake, which may have been intentionally lowered by settlers.

TS3, **LPAZ 12**: A strong decrease in the *Fagus* and *Carpinus* pollen curves and a sharp increase of Poaceae and Cyperaceae are the most characteristic features of this zone. Among the crop plants, Cerealia pollen is more frequent, among which *Secale cereale* reaches ~1.5%; the first maximum of Cerealia pollen occurs in the sample from 44 cm depth. *Fagopyrum* pollen is present. The *Artemisia* percentages increase. Still high is *Calluna*, *Betula* increases, and *Alnus* has values similar to those in the previous zone, but fluctuating. *Quercus* and *Corylus* values remain similar to those in the previous zone. *Tilia*, *Ulmus* and *Fraxinus* are more frequent in the upper part of the zone, where *Sparganium* reaches maximum, preceded by the continuous presence of *Myriophyllum* species.

The vegetation composition inferred from the pollen spectra again points to strong deforestation, especially in *Fagus* forests, but also in dry-ground forests in which *Carpinus* began to spread previously. Arable fields or meadows occupied all possible habitats. Apart from cereals, *Fagopyrum* was also cultivated, but no more hemp cultivation was present. Wet meadows with members of Cichoriodeae and Apiaceae and with *Filipendula* were expanded, in addition to the vast heathland areas. *Juniperus* was also present in the latter.

TS3, **LPAZ 13**: *Alnus*, *Betula*, *Ulmus* and *Fraxinus* decline in the sample from 28 cm depth, followed by increased values for *Pinus* and later for *Quercus*, *Fagus*, *Tilia* and *Carpinus*. The percentages for *Corylus* are similar to those in the previous zone. Still high are the values for Poaceae, which increase considerably in the sample from 30 cm depth and are followed by a strong increase of Cyperaceae pollen. Cerealia pollen, including *Secale cereale*, is frequent. Still high are other indicators of human activity (*Artemisia*, *Calluna*, Chenopodiaceae). A strong increase of *Urtica* percentages is conspicuous in the younger part of the zone. A *Ranunculus* sect. *Batrachium* pollen curve forms in the lower part of the zone and culminates together with high values of Nymphaeaceae pollen.

The vegetation composition shows human impacts even more strongly than in the previous zone. High values of Poaceae pollen, coinciding with high values for *Filipendula* and *Urtica*, are preceded by a considerable increase of Cyperaceae pollen. These can be interpreted as anthropogenic drying of wet sedge communities to open new land for pastures. The new land was overgrown with grasses, and higher numbers of grazing animals raised the nitrogen content of the soil, which was suitable for *Urtica* and *Filipendula*.

The *Ranunculus* sect. *Batrachium* community occurred in the lake close to the edges. Other water plants of eutrophic lakes (e.g. Nymphaeaeceae) accompanied them. The reed belt was well developed, as seen from very numerous pollen grains of *Phragmites australis* t. *Pediastrum* algae were abundant in the lake water. The pollen curves of *Ranunculus* and *Urtica* seem to replace each other, as if the *Urtica* community followed *Ranunculus* at the edge of the lake.

This suggested scenario of vegetation development during this period is supported by the radiocarbon date from 30 cm depth (1988–1990 cal. AD).

TS3, **LPAZ 14**: The pollen spectra change considerably on the border between 13 LPAZ and 14 LPAZ. There is a decrease of *Betula* and an increase of *Pinus* pollen values.

Alnus values range between 12% and 15%. *Fagus*, *Carpinus* and *Tilia* have continuous pollen curves with values less than 1%, and *Quercus* fluctuates between 4% and 6%. *Corylus* values drop from 5% to 2.2%, but those for *Calluna* are still high (up to 6%), accompanied by high values for Poaceae (21–25.5%). Cyperaceae pollen percentages decrease from 12.5% to 8.5%, *Secale cereale* and other Cerealia pollen are frequent, as are *Urtica*, *Rumex acetosella* t., *Filipendula*, Apiaceae and Brassicaceae, while *Artemisia* pollen is absent. *Typha latifolia* and *Sparganium* have clear increases in their pollen curves.

The pollen spectra composition represents the most modern vegetation, which is very open but signals an increase in the pine population. This is due to protective measures and is observed in increased pine pollen values in the upper samples. The lake today is surrounded by a reed belt in which *Typha latifolia* has a considerable share, together with *Sparganium* species.

CLADOCERA RESULTS

In the Cladocera diagram (Fig. 5) we distinguished six assemblage zones (CAZs) reflecting changes in lacustrine conditions during sediment deposition. Overall, 40 taxa belonging to five families were identified: Leptodoridae, Sididae, Daphniidae, Bosminidae and Chydoridae.

CAZ 1. Deep-water conditions are indicated in this phase by a well-developed planktonic community with dominant *Bosmina longirostris* and *B.* (*E.*) *longispina*, and the constant presence of *Daphnia longispina*-gr. as well as *Leptodora kindti*. The total share of planktonic taxa is high and stable (52–62% of the total community), and only at the end of the phase is a slight decline (to 47%) observed. The codominance of *Bosmina longirostris*, *Alona rectangula* and *Chydorus sphaericus* imply a high trophic state.

CAZ 2. This zone is characterized by high total Cladocera abundance (23000–26500 spec/cm^3). *Bosmina longirostris* is still the dominant planktonic taxon, with a lower contribution of *B.* (*E.*) *longispina* than in CAZ 1. This is the only zone with the continuous presence of *B.* (*E.*) *coregoni*. Remains of *Leptodora kindti* and *Daphnia longispina*-gr. are present but not continuous. The declining but still-high abundance of *Chydorus sphaericus*, increasing *Alona rectangula* as well as *Leydigia leydigi* indicate a high trophic state. A supposed hiatus at 217 cm depth seems to indicate a quite rapid and profound change at this depth.

CAZ 3. After the maximum of Cladocera abundance (29700 spec/cm^3) a constant and abrupt decline is observed, mostly due to a decrease in the previously dominant *Chydorus sphaericus* and, after an initial increase at the onset of the zone, also *Bosmina longirostris* and *Alona rectangula*. However, some species (e.g. *Alona quadrangularis*, *Pleuroxus uncinatus*, *Leydigia acanthocercoides*, *Disparalona rostrate*) benefit from the changing conditions, as shown by their increased abundance. These are mostly sediment-associated littoral species preferring eutrophic waters. Despite this profound change in the taxonomic composition, the high proportion of planktonic taxa (41–49%), with dominance of *Bosmina longirostris* and *Bosmina* (*E.*) *longispina* as well as the occasional occurrence of *Daphnia longispina*-gr. and *Leptodora kindti*, indicate that the lake was still relatively deep, despite the increasing importance of littoral habitats.

CAZ 4. In this zone the total abundance of Cladocera is distinctly lower (7400–22800 spec/cm^3) than in the previous phases, and the high fluctuation of abundance corresponds to the share of planktonic taxa. Moreover, macrophyte-associated taxa play an increasing role. Perhaps the littoral zone becomes closer to the coring site as a result of lowering of the lake level. Among the planktonic taxa, whose abundance in this zone greatly fluctuates (28–60%), *Bosmina* (*E.*) *longispina* has an increasing share, as do, among the littoral community, *Alona quadrangularis*, *Pleuroxus uncinatus*, *Leydigia acanthocercoides* and *Disparalona rostrata*. *Leydigia leydigi* declines in this zone.

CAZ 5. Low total abundance of Cladocera (1600–5200 spec/cm^3) results from a sharp decline of Bosminidae as well as many littoral taxa (e.g. *Alona rectangula*). The dominant taxa in the community were macrophyte-associated (*Alona affinis*, *Acroperus harpae*, *Eurycercus lamellatus*) and also the macrophyte-sediment associated *Alona quadrangularis*. Also conspicuous is the presence of *Monospilus diapar*,

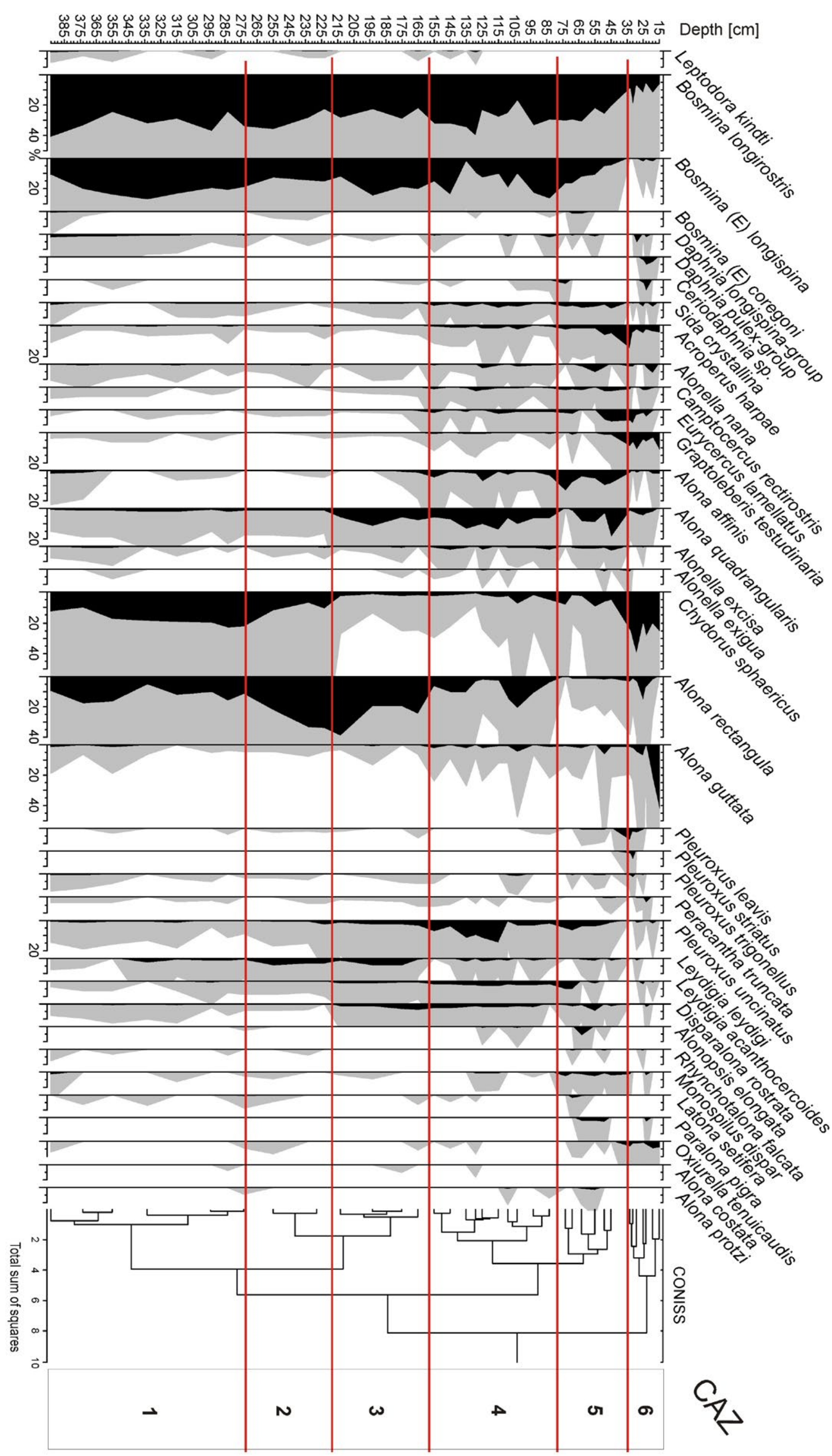

Fig. 5. *Cladocera* diagram

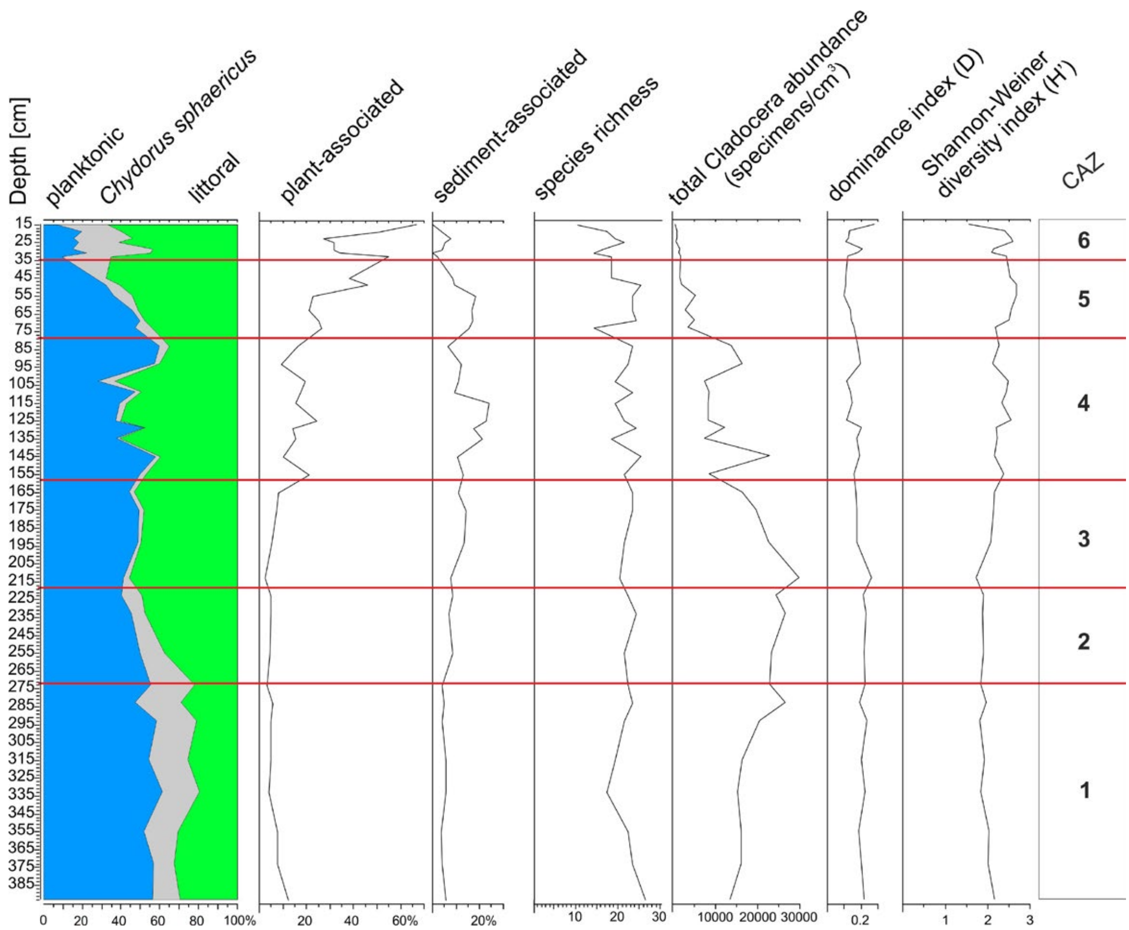

Fig. 6. Ecological groups of Cladocera

Alonopsis elongata, *Rhynhotalona falcata*, *Paralona pigra* (taxa associated with mineral bottom substrate) and *Phreatalona protzi*.

CAZ 6. This zone is marked by very low total Cladocera abundance (500–1700 spec/cm^3) as well as low species richness (10–21), with very few Cladocera associated with the open water zone. The littoral Cladocera are mainly associated with vegetation: plant-associated taxa constitute 27–66% of the total Cladocera. There is an increase in the abundance of *Graptoleberis testudinaria*, *Chydorus sphaericus* and *Oxiurella tenuicaudis*.

DISCUSSION

In view of the great thickness of Late Pleistocene/Holocene sediments in the lake (minimum 20 m thick) and the lowering of water in the modern lake, depth in the middle of the lake must have exceeded 20 m at the end of the Pleistocene. In a deep lake the velocity of water flow is lower, leading to increased sedimentation. This is seen in the sedimentation rate up to 310 cm depth (~3200 cal. BC; Fig. 2). From this time on, the sedimentation rate fell sharply because the lake basin was nearly filled and the flow rate increased.

THE ATLANTIC PERIOD

We compared the LPAZs of the TS3 core with the original pollen assemblage zones from Wiethold's (1998) TRS20 diagram and the Firbas zonation used for the Q300 diagram by Dörfler et al. (2012). The latter diagram comes from Lake Belau in south-eastern Schleswig-Holstein. The comparison reveals that the beginning of our TS3 pollen diagram **(LPAZ 1**), with alder domination (above 40%) and abundant oak, represent the Atlantic period and correlate with the ~450 cm depth samples from Wiethold (1998, Abb. 12), who characterized the Atlantic period in the Schleswig-Holstein region as a time when alder occupied wetter sites and oak was the main tree in woodland, where it formed communities with elm, lime, ash and hazel.

The period of elm decline, the major change in the vegetation of the Atlantic/Subboreal transition, needs to be described in more detail, as this was a longer process involving both pathogenic fungi and human intervention in forests. Both Wiethold (1998) and Dörfler et al. (2012) show the elm pollen values in high resolution and describe the elm decline phenomenon in Schleswig-Holstein (Wiethold, 1998; Nelle and Dörfler, 2008). They stress that it is essential to make it clear whether the beginning, middle or end of this event is meant. We suppose that the **TS3 LPAZ 1** exhibits the last phase of elm decline, where elm-dominated riverine communities were not extensive, because many elm trees had disappeared from the vegetation. Human impacts are seen in the closed curve of *Pteridium aquilinum* spores, which possibly indicates fires.

According to Nelle and Dörfler (2008), during the Late Atlantic *Acer* and *Taxus* also immigrated to the region; this is confirmed in the pollen spectra from TS3 1 LPAZ by single pollen grains of *Taxus* and the continuous pollen curve of *Acer* in local pollen zones 1–3. The same part of the core correlates with pollen spectra from the Lake Belau pollen diagram in Dörfler et al. (2012). The period was dated to ~4300 cal. BC. Our interpretation of the TS3 LPAZ 1 is supported by the 4361–4260 cal. BC date from 372–374 cm depth in the TS3 core.

The gyttja sediments of the bottom of the TS3 core formed during the Atlantic exhibit high content of planktonic Cladocera remains. The assemblage records a period of high water level until ~285 cm (Atlantic/Subboreal transition). This closely coincides with the pollen diagram, in which *Pediastrum simplex*, typical for large eutrophic lakes, occurs.

In LPAZ 1 and the first half of LPAZ 2 (Fig. 3), no chemical markers of anthropogenic impacts on the lake are observed. Probably the lake catchment was forested to the greatest extent.

THE SUBBOREAL PERIOD

In the course of the Subboreal, reflected in LPAZs 2–5 of the TS3 diagram (Fig. 4), many other changes in forest composition occurred due to changing climate and increased anthropopression. The overall interpretation of pollen results for the **TS3 LPAZ 2** agrees both with Wiethold (1998) and with the pollen diagram of the Q300 core from Lake Belau (Dörfler et al., 2012). That part of the Q300 core was dated to 3500–2500 cal. BC, covering the early Subboreal period. In our TS3 core this is supported by three radiocarbon dates from depths of 354–356 cm, 332–334 cm and 314–316 cm. Especially interesting are the dates from 332–334 cm and 314–316 cm depths, as they fit the elm decline phenomenon in this region, dated to 3800 cal. BC.

After the elm decline there is a drop of *Tilia* values in the early Subboreal, attributable to use of the woodland by humans. This drop is very clear in our TS3 pollen diagram in LPAZ 2. Nelle and Dörfler (2008) gave a long list of 19 various possible uses of woodlands, including timber for construction and wood for fuel. The first more intensive use of forest resources we recorded in LPAZ 2 coincides with a brief lowering of the lake level at ~285–277 cm, dated to the early Subboreal. This may be associated with a climate shift towards lower precipitation. All the dates from 354–282 cm depth clearly confirm this Atlantic/Subboreal transition.

Among the human-impact indicators given in pollen diagrams (Behre, 1981), in the TS3 pollen diagram *Plantago lanceolata* – the main indicator of pastoral activity – started to occur at the Atlantic/Subboreal transition (sample from 314–316 cm depth, TS3 LPAZ 2, 3881–3800 cal. BC). It is accompanied by *Artemisia*, *Rumex acetosella* and Chenopodiaceae pollen.

In the Cladocera diagram of TS3, 258 cm depth is an important border, as it marks a change from stable conditions to slightly increased trophy and coincides with elm decline in the pollen diagram.

In **TS3 LPAZ 3** and the second half of TS3 LPAZ 2 the environment seems to have been undisturbed, but there is a first increase of clastic sediment input, presumably in consequence of the presence of Neolithic humans. The slight depression of C and N between 310 cm and 360 cm depth marks climate change at the beginning of the Subboreal.

Fagus sylvatica and later also *Carpinus betulus* began to establish as newcomers during the Subboreal in the forests of the region. The establishment of *Fagus sylvatica* is especially well seen in the TS3 pollen diagram, where beech pollen values increase and start to form a closed curve before the Subatlantic period (TS3 LPAZ 4). This matches not only Wiethold's (1998) pollen diagram but core Q300 from Lake Belau (Dörfler et al., 2012). The latter publication dates the beginning of this expansion in detail. Single pollen grains of *Fagus sylvatica* occur at 3700 cal. BC and distinctly increase at ~1000 cal. BC. Thus, our data further support the age determination for beech expansion in Schleswig-Holstein.

Nelle and Dörfler (2008) suggest that only small clearings appeared along the seacoast and around lakes in the first phase of neolithisation in Schleswig-Holstein. This small-scale pastoral activity and agriculture had only minor effects on the landscape. In the Middle Neolithic there is an increase of the *Plantago lanceolata* pollen curve, accompanied by increases of other human-impact indicators, marking the first large-scale opening of the landscape. This is visible in LPAZ 1 of Wiethold's pollen diagram (TRS 20 core) and correlates with **TS3 LPAZs 3** and **4**, and is seen even better in the Lake Belau pollen diagram as a dramatic increase of *Plantago lanceolata* along with *Rumex acetosella*, *Artemisia* and Chenopodiceae at ~3000 cal. BC, coinciding with decreasing values for many trees. The pollen values of *Quercus*, *Tilia*, *Ulmus* and *Fraxinus* are lower at that time.

As Nelle and Dörfler (2008) stressed, with the emergence of the funnel beaker culture at 4100 cal. BC, agrarian food production by the early settlers imposed the first human-caused changes in the vegetation composition. The beginning of the formation of the cultural landscape is dated to the transition from the Early to the Middle Neolithic at ~3500 cal. BC.

In our pollen diagram, *Calluna* pollen becomes more frequent at 1566–1439 cal. BC (in **TS3 LPAZ 4** at 192 cm depth), showing that heathland began to spread in the middle of the Subboreal, simultaneously with an increase of *Plantago lanceolata*. These signals of increased human pressure on the environment are in line with Lütjens and Wiethold (1999), who point to characteristic features such as a significant decrease of *Tilia* pollen in diagrams, observable in TS3 at 174 cm depth. According to Nelle and Dörfler (2008) there must have been large open areas around settlements at ~1700 cal. BC. The first indications of heathland appear, pointing to deterioration of soils by continuous exploitation (Nelle and Dörfler, 2008). The pollen spectra from **TS3 LPAZ 5** suggest that the landscape around villages was parkland-like but that woodland still occurred in remote places. The cited authors interpret the still-significant values of *Corylus* and *Pteridium aquilinum* as indicators of forest grazing on a larger scale (Nelle and Dörfler, 2008).

The water level of Lake Tresssee remained relatively high during the Subboreal (up to 144 cm depth, dated to 49 cal. BC–72 cal. AD) as evidenced by the abundance of planktonic Cladocera (40–58%), but some fluctuations are evident. A small-scale fluctuation towards higher water levels (~228–225 cm depth) was followed by an episodic drop, coinciding with the decline in the *Alnus* pollen curve and the repeated occurrence of anthropopression indicators (*Plantago lanceolata*, *Artemisia*) in the sample from 212 cm depth, dated to 2933–2872 cal. BC.

In geochemical zone G3 (135–220 cm depth; LPAZ 4–6; Late Neolithic to Bronze Age), human impacts are now clearly seen in higher input of clastic sediment from forest clearing, soil erosion and increased agriculture within the catchment. One sample with much higher phosphorus content at 165 cm depth may indicate animal husbandry but may also be an outlier (perhaps due to contamination at this depth). Later, from ~150 cm on, there is a stronger impact, probably in consequence of more intensive clearing of forests in the catchment and initial soil erosion processes, but no evidence of iron smelting (low content of heavy metals). The C/N ratio is higher than usual. This is an indication of less decomposition. The higher Fe/Mn value is a marker of lower oxygen content in the water, due to eutrophication.

THE SUBATLANTIC PERIOD

In **TS3 LPAZ 6** there is an increase of tree pollen but the date from 144 cm depth is problematic (too young; excluded from the age–depth model). This incidental increase of tree pollen values can be interpreted as washed out pollen transported by the river, confirmed by an increase in the frequency of psammophilous species among the Cladocera. Such a disturbance might also have influenced the pollen date.

In comparing our pollen diagram to those of the TRS20 and Q300 cores, the flattened pollen curves for all taxa draw attention. This was also a problem for Wiethold (1998), who saw disturbance processes connected with the rivers that flow in and out of the lake as the most probable reason for these flattened curves. Nevertheless, the pattern of vegetation development and human disturbance of the landscape described in his study and found in our investigation agree very well.

The radiocarbon date from 134 cm depth confirms the transition between the Subboreal and Subatlantic periods, which is also the transitional period from the Bronze Age to the Iron Age in northern Germany. The distinct decrease in *Corylus* pollen values is characteristic for this period, as is the gradual increase of the *Fagus* and *Carpinus* pollen curves. Nelle and Dörfler (2008) stated that by the 1st century AD *Fagus* reached only a 2% share of the arboreal pollen in their diagrams. Charcoal from oak and alder was used for iron smelting. *Fagus* would reach higher values but other trees like *Ulmus*, *Fraxinus* and *Tilia* decline during the Subatlantic. The higher values of birch indicate forest secondary succession. The formation of heathlands, which started in the Bronze Age, continued in the Iron Age (Lütjens and Wiethold, 1999). In the Roman Period the first *Secale cereale* cultivation occurred. Forest vegetation persisted in Schleswig-Holstein, although the Iron Age settlers altered the composition of woodlands.

Other changes at the beginning of the Subatlantic include simultaneous rises of sea level in the North Sea (Behre, 2007) and Baltic Sea (Hoffmann, 1998). Blaauw et al. (2004) and Mauquoy et al. (2004) stress climatic shifts dated to ~850 cal. BC.

Geochemical analysis (zone G4) indicates that there probably was a diminution of human impacts or stabilization of the landscape following the first big forest clearings in the previous zone. The first higher values for As and Hg presumably are the first indications of iron smelting. The higher P content is associated with animal husbandry. In zone G5 (**LPAZs 8 and 9**; Roman Period and Migration Period) there is a slight decline of organic carbon content, probably in consequence of further forest clearing and a higher share of clastic sediment in the water of inflows. At first the pollutant values are low. Later there are slightly higher values for Pb, Cd and Ni. Both indicators may be related to iron smelting in the catchment.

In zone **TS3 LPAZ 9** the date from samples 102–104 cm indicates the 7th century (606–680 cal. AD) but does not coincide with the maximum *Fagus* pollen percentages. The maximum occurs in the next pollen zone. The whole character of the pollen spectra for **TS3 LPAZ 10** indicates regeneration of forest communities in which *Fagus* has a dominant role. This and other features of this zone correlate with LPAZ 7a from the TRS20 core (Wiethold, 1998); one of the strong supports for this correlation is the maximum of *Fagus* and the strong decrease of *Alnus*. The *Fagus* peak in the pollen diagram from Lake Belau occurred between 400 and 700 cal. AD. Thus, our radiocarbon date of the *Fagus* maximum (862–994 cal. AD; **TS3 LPAZ 10**) seems too young. However, in Wiethold's (1998) pollen diagram it comes even later. We suppose that the true maximum of *Fagus* pollen was not registered in our TS3 pollen record, an assumption based on the good correlation of the sharp increase in *Fagus* pollen values and the continuous pollen curve of *Carpinus* between our TS3 LPAZ 9 and in LPAZ 5 of Wiethold's (1998) TRS20 diagram.

We stress that from TS3 LPAZs 6 to 7 there is a strong increase of Cladocera taxa associated with sediment, again indicating input of river water. The Cladocera remains confirm a distinct lowering of the water level correlated with TS3 LPAZs 7 and 8 (97–128 cm depth), coinciding with the pre-Roman Period and Roman Period.

Another important border in the Cladocera diagram is 158 cm depth (transition between TS3 LPAZs 5 and 6), which marks disturbances in the lake water and a slight lowering of the lake level. It coincides with a drop in *Tilia* pollen values and is followed by the problematic radiocarbon date from 144 cm depth.

The pollen spectra from TS3 LPAZ 10 are typical for the Migration Period in Schleswig-Holstein. Nelle and Dörfler (2008) state that the whole settlement area in Schleswig-Holstein was reforested at that time, but single cereal pollen grains and the gradually decreasing pollen curves of *Artemisia* and *Plantago lanceolata* indicate some human impact.

Phreatalona protz, a rare Cladocera taxon associated with lotic habitats (Van Damme et al., 2009), is discontinuously present in the TS3 profile from 110 cm to 54 cm depth, before which it has only a single occurrence at 272–274 cm.

This and other psammophilous Cladocera taxa (*Monospilus dispar*, *Paralona pigra*, *Rhynchotalona falcata*, *Alonopsis elongata*) seem to confirm the influence of inflow of river water to the lake. These species are associated with lower trophy (Whiteside, 1970).

The evidence from geochemical zone G6 shows that the forests in the catchment expanded during the Migration Period and still in the Early Medieval. People who possibly may have migrated in this period from the north to Angeln (Wiethold, 1998) did not clear the forests immediately. Pollutants suspected to be the result of iron smelting are observed, confirming archaeological results (Jöns, 1992/93).

An increase of the lake level can be seen in the Cladocera remains from 97 cm to 80 cm. After that there is a further increase of Cladocera species associated with the macrophyte zone (78–33 cm).

TS3 LPAZ 11 can be compared to LPAZ 8 from the TRS20 diagram (Wiethold, 1998), in which *Fagus* and *Carpinus* values fall and *Alnus* reaches its minimum for the whole profile. A very distinct feature is the strong increase of *Calluna* pollen percentages. At the same time, *Secale cereale*, *Plantago lanceolate*, *Rumex acetosella* t. and other indicators of human activity increase. Very characteristic is the maximum of the *Humulus*/*Cannabis* pollen curve, followed by a sharp drop. Several herbaceous taxa such as Brassicaceae, Chenopodiaceae, Rubiaceae, Caryophyllaceae and *Artemisia* are common. Among the spores, *Pteridium aquilinum* is more frequent. The period of these events is determined by radiocarbon dating to 878–1013 cal. AD (62 cm depth) but surprisingly the date from 82 cm depth is much younger (1482–1646 cal. AD) in our record; based on comparisons with Wiethold (1998), it seems probable that the dating from around the 15th century is valid, so it was accepted in the age–depth model and the date from 62 cm depth was excluded as an outlier.

On the other hand, **TS3 LPAZ 11**, with its decreasing values for *Fagus* and *Carpinus* pollen and especially the strong drop of *Alnus*, corresponds to the Lake Belau pollen diagram (Dörfler et al., 2012) at ~1000 cal. AD. This date can be accepted for our TS3 pollen diagram, due to uncertainties connected with the radiocarbon date from 62 cm depth, which is probably an outlier. The carbon content of the lake sediments indicates renewed clearing of forests and expansion of agricultural areas. However, there is no further evidence for High Medieval iron smelting.

TS3 LPAZ 12 can be correlated with LPAZ 9 from the TRS20 diagram (Wiethold, 1998). The maximum of NAP, the maxima of *Secale cereale*, *Fagopyrum*, *Calluna* and *Rumex acetosella* t., and the high values for *Plantago lanceolata* are the most typical features of that author's LPAZ 9. Another important feature is the decline of the *Humulus*/*Cannabis* pollen curve. Both **TS3 LPAZ 13** and **TS3 LPAZ 14** can be correlated with LPAZ 10 of the TRS20 diagram (Wiethold, 1998: Abb. 4).

After the hiatus in the profile between 1564 AD and 1956 AD, sedimentation was high in consequence of shrinking of the lake (geochemical zone G8; Postmodern Period). The sampling site dried out in recent years (a weir was destroyed in 1970; Wiethold, 1998). The content of pollutants (also phosphorus) reached maximum (e.g. from leaded petrol and wastewater, probably in the 1970s). The strong increase of the Fe/Mn ratio indicates anoxic/eutrophic conditions in the lake. The appearance of algae and Cladocera (e.g. planktonic *Daphnia pulex*) in this upper part of the profile is an indicator of episodic flooding at this site close to the now-smaller lake.

Later, in geochemical zone G9 (0–10 cm; (~1990 AD), sedimentation with organic-rich material continued. It was characterized by swampy conditions and overgrown by semiterrestrial plants. The content of different pollutants decreases again, in consequence of strengthened environmental protection since the 1980s. The high C/N ratio shows less decomposition under wet conditions.

From 78 cm to 35 cm depth the lake level drops continually. The number of planktonic Cladocera species declines, while those associated with macrophytes increase. In the pollen diagram this is accompanied by an increase of nympheids (both pollen and sclereids) and the occurrence of *Sparganium*/*Typha angustifolia* pollen. From 35 cm to 15 cm depth the lake level is very low, and from 30 cm depth there is a significant drop in the total abundance of Cladocera as well as species associated with sandy bottom substrate (lower sand input). The two high peaks of planktonic Cladocera can be attributed to a brief rise in the lake level after 1990 cal. AD (30 cm depth dated to 1988–1990 cal. AD).

The extent of the lake and its lentic character is reflected in the composition of Cladocera (high abundance, predominance of open-water taxa as well as taxa preferring eutrophic conditions). Cladocera prefer stagnant water, and their abundance typically correlates positively with trophy (Korhola and Rautio, 2001). High trophy also seems supported by the elevated dominance index (D mean = 0.22), which is due to the numerous presence of *Bosmina longirostris*, *Chydorus sphaericus* and *Alona rectangula*.

As the lake was nearly filled in at ~2800 BC, sedimentation decreased due to faster water flow. This lowered the sedimentation rate, even though anthropopression increased, and with it the inflow of sediment.

In the youngest part of the core, the sampling site is a transitional bog with a reed zone and swamp vegetation with a high growth rate in the profile.

CONCLUSIONS

Our analyses of pollen and Cladocera data support the scenario described below. Over the last 6000 years, Lake Tresssee was a eutrophic lake with a distinct macrophyte zone. Its biggest continuous expansion occurred at the end of the Atlantic. From the Subboreal on, there were several phases of fluctuating lake levels, at first mostly induced by climatic factors. A trend of decreasing lake levels appeared in the early Subboreal (~3500 cal. BC and 2900 cal. BC; Fig. 7) in consequence of cooler temperatures and lower precipitation in Central Europe (e.g. Dotterweich, 2008, after Jäger, 2002). Similar conditions are seen at the end of the Preboreal and probably also in the Early Medieval, in which human impacts must have had a greater influence on the lake level than climate changes did during this period. We presume that the level of the shallow lake was controlled by the outflow of the River Treene and by conditions in its floodplain. When the vegetation was denser, with big trees falling into the river, the outflow was dammed. More frequent flooding in the wetter Subboreal would have flushed the riverbed, and cultivation of the floodplain would have had a similar effect. As a result, outflow increased and the lake level fell.

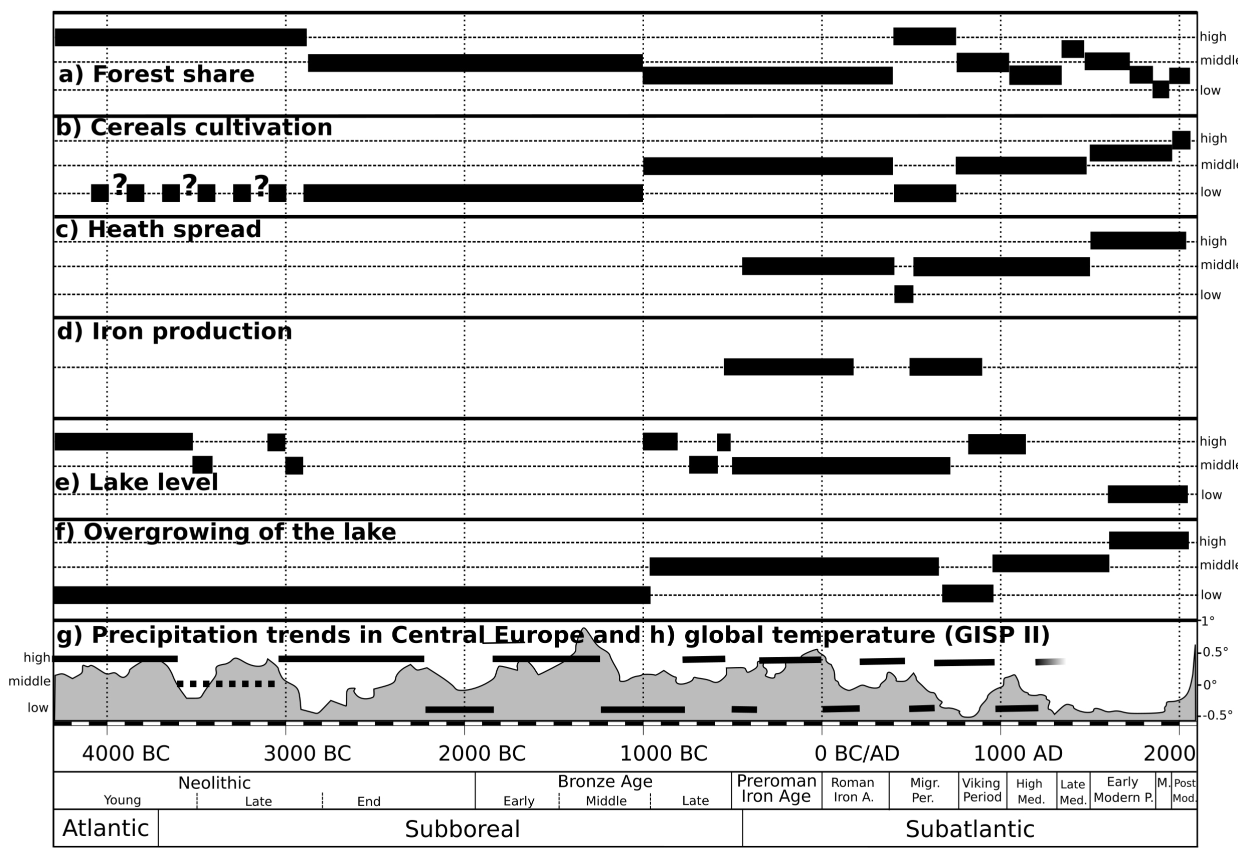

Fig. 7. Timeline for comparison of different variables related to the palaeoenvironment of Lake Tresssee: **a**) Forest share, from our pollen data and (for later than 1650 AD) after Härdtle, 1996, supplemented by data from Dörfler et al., 2012 and Nelle and Dörfler, 2008; **b**) cereals cultivation and **c**) spreading of heath, from our pollen data; **d**) iron production, from our chemical analyses of lake sediments and after Jöns, 1992/93 and Hingst, 1974; **e**) lake level and **f**) overgrowing of the lake, from our Cladocera results and map data (after 1850); and **g**) precipitation trends in Central Europe, from Dotterweich, 2008 after Jäger, 2002 and **h**) global temperature, from GISP II ice core, after Alley, 2004. Information about lake levels is not available for all time slices, due to equivocal Cladocera results

From the Young Neolithic on (~3800 cal. BC), human impacts in the surroundings are detected from indicators such as *Plantago lanceolate*, *Rumex acetosella* t. and *Pteridium aquilinum*. The organic carbon content of the lake sediments decreased due to increased input of clastic sediments from soil erosion in the catchment and probably sand blown in from the adjacent dune field north of the lake. This is associated with the spread of heath vegetation and intensive grazing in the surroundings, seen in the content of *Calluna* pollen from ~500 cal. BC. Sediment-associated Cladocera species were detected especially from the Roman Period and Early Medieval, interrupted by the Migration Period.

From the Early Bronze Age (~2200 cal. BC) on, the lake becomes more eutrophic and macrophytes continue to expand. As judged by the occurrence of Cladocera, the lake is in a state of high trophy from the Late Neolitic at the latest. Oxygen depletion is reflected in a lower Fe/Mn ratio. From the Iron Age to the Migration Period and the beginning of the Early Medieval (~500 cal. BC–750 cal. AD) the lake level was lower. In the Migration Period and and for the next 200 or so years, pollen spectra and chemical parameters show a general but not complete absence of humans in western Angeln. It is remarkable that the start and end of this period were more or less consistent with the previous pollen diagram from Wiethold (1998) but slightly later than Dörfler et al.'s (2012) pollen diagram of Lake Belau. From the Early Medieval, the lake level fell again and human impacts increased, with an increase of pollen indicators of farming and grazing, presumably due to an influx of people from the north. From that period on, there probably were several serious efforts to lower the lake by artificially deepening the outflow of the River Treene from the lake.

From the later Iron Age to the Early Medieval (especially ~600–900 cal. AD) there are not only indications of forest clearing but also higher content of heavy metals in the sediments, confirming documented archeological finds (Jöns, 1992/93) of iron smelting in the Angeln area.

The uppermost part of the core belongs to the Postmodern Period after 1950, with increased values for pollutants such as heavy metals and phosphorus, and the development of a transitional bog at the sampling site as a consequence of artificial lowering of the lake. Today the lake level is lower than ever before in its Holocene history, especially in consequence of the artificial deepening of the River Treene outflow. This is confirmed by the plant-associated Cladocera species, which reached their maximum occurrence.

Concerning the age–depth model, we offer a new interpretation based on the special situation of the lake in relation to the tributaries flowing through to the River Treene. Against the presumable increase of the input of anthropogenic sediments to the lake, average sedimentation fell starting from 2800 BC. This can be explained by the function of the lake as a strong sediment trap. After a phase of continuous infill, the flow velocity of the water increased, leading to lowered sedimentation in the central lake basin (except on alluvial fans next to inflows).

ACKNOWLEDGEMENTS

The authors are grateful to Anna Maria Mercuri and an anonymous reviewer for their valuable comments, which helped improve an earlier version of the manuscript, Britta Gottburg (Schrobach Foundation) for supporting the fieldwork in the Obere Treenelandschaft conservation area, Prof. Wolfgang Riedel for help in understanding the landscape history of Schleswig-Holstein, student assistants Celina Buhr, Tim-Niklas Klöpping, Lisa Hamer, Jakob Picker, Katharina Vogel and Hauke Weidler, and the students of four methodology lectures in Physical Geography at Europa-Universität Flensburg in 2016–2018. The German Research Foundation DFG (DFG Stolz 912/4-1) funded the project.

REFERENCES

Alley, R.B., 2004. GISP2 Ice Core Temperature and Accumulation Data IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2004-013 NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.

Behre, K.E., 1981. The interpretation of anthropogenic indicators in pollen diagrams. Pollen et Spores 23(2), 225–245.

Behre, K.E., 2007. A new Holocene sea-level change for the southern North Sea. Boreas 36, 82–102.

Behrend, H., 1964. Die Aufhebung der Feldgemeinschaften: die große Agrarreform im Herzogtum Schleswig unter Mitwirkung der Schleswig-Holsteinischen Landkommission 1768–1823. Quellen und Forschungen zur Geschichte Schleswig-Holsteins 4. Wachholtz, Neumünster.

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (ed.), Handbook of Holocene Palaeoecology and palaeohydrology. John Willey & Sons, Chichester, pp. 455–484.

Blaauw, M., Geel, B. van, Plicht, J. van der, 2004, Solar forcing of climatic change during the mid-Holocene: indications from raised bogs in The Netherlands. The Holocene 14, 35–44.

Blume, H.P., 2000. Handbuch der Bodenuntersuchung Terminologie, Verfahrensvorschriften und Datenblätter; physikalische, chemische, biologische Untersuchungsverfahren; gesetzliche Regelwerke. Weinheim, New York.

Boyle, J.F., 2001. Inorganic geochemical methods in palaeolimnology. In: Last, W.M., Smol, J.P. (eds), Tracking Environmental Change Using Lake Sediments. Physical and Geochemical Methods 2. Kluwer Acad. Publishers, Dordrecht.

Bronger, A., Polensky, R., 1985. Geoökologische Untersuchungen des Binnendünengebietes am Treßsee und seiner Umgebung als Beitrag zur Naturschutzplanung. Die Heimat 91(10), 303–319.

Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37(2), 425–430.

Carnap-Bornheim, C. von, 2015. Das Thorsberger Moor. Verein zur Förderung des Archäologischen Landesmuseums e.V., Schloss Gottorf, Schleswig.

Dörfler, W., Feeser, I., Bogaard, van den C., Dreibrodt, S., Erlenkeuser, H., Kleinmann, A., Merkt, J., Wiethold, J., 2012. A high-quality annually laminated sequence from Lake Belau, Northern Germany: Revised chronology and its implications for palynological and tephrochronological studies. The Holocene 22, 1413–1426.

Dotterweich, M., 2008. The history of soil erosion and fluvial deposits in small catchments of central Europe: deciphering the long-term interaction between humans and the environment – a review. Geomorphology 101(1–2), 192–208.

Dreibrodt, S., Bork, H.R., 2005. Historical soil erosion and landscape development at Lake Belau (North Germany). A comparison of colluvial deposits and lake sediments. Zeitschrift für Geomorphologie, Supplement 139, 101–128.

Faegri, K., Iversen, J., 1989. Textbook of Pollen analysis, IV Edition Faegri K., Kaland P.E. and Krzywinski. K.J. Wiley and Sons, Chichester.

Firbas, F., 1949. Spät- und nacheiszeitliche Waldgeschichte Mitteleuropas nördlich der Alpen 1. Fischer, Jena.

Frey, D.G., 1986. Cladocera analysis 7. In: Berglund, B.E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology, pp. 677–692.

Gaillard, M.J., Berglund, B.E., 1988. Land-use history during the last 2700 years in the area of Bjäresjo, Sweden. In: Birks, H.H. et al. (eds), The cultural landcapre – past, present and future. Cambridge University Press, Cambridge, pp. 409–425.

Grewe, K., 1979. Der Fulbert-Stollen am Laacher See Eine Ingenieurleistung des hohen Mittelalters. Zeitschrift für Archäologie des Mittelalters 7, 3–38.

Grimm, E.C., 1991–2011. Tilia Graph, Version 1716. Illinois State Museum Research and Collection Centre, 1011 East Ash Street, Springfield, IL62703 USA.

Grimm, E.C., 1987. Coniss a fortran 77 program for stratigraphically constrained cluster analysis by method of incremental sum of squares. Computer and Geosciences 13, 13–35.

Gripp, K., 1964. Erdgeschichte von Schleswig-Holstein. Wachholtz, Neumünster.

Grudzinski, A., 2007. Beurteilung der Wasserqualität von eutrophen Seen im Norddeutschen Tiefland unter Aspekten der historischen und heutigen Landnutzung im Einzugsgebiet. Master thesis University of Kiel.

Hamer, B., 1995. Topographie der Landschaft Angeln. Vol. 1 and 2. Husumer Verlagsgesellschaft, Husum.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. Paleontological statistics software package for education and data analysis Palaeontologia Electronica 4(1), 9. http://palaeo-electronicaorg/2001_1/past/issue1_01htm.

Härdtle, W., 1996. Zur Nutzungsgeschichte schleswig-holsteinischer Wälder unter besonderer Berücksichtigung des Landesteils Schleswig. Schriften des Naturwissenschaftlichen Vereins Schleswig-Holstein 66, 43–69.

Hingst, H., 1974. Eine eisenzeitliche Waldschmiede auf dem Auberg bei Süderschmedeby, Kreis Flensburg. Jahrbuch Schleswigsche Geest 22.

Hoffmann, D., 1998. Wasserspiegelveränderungen an der schleswig-holsteinischen Ostseeküste im 1. Jahrtausend n. Chr. In: Wesse, A. (ed.), Studien zur Archäologie des Ostseeraumes – von der Eisenzeit zum Mittelalter (Festschrift Müller-Wille). Wachholtz, Neumünster, pp. 111–116.

Hua, Q., Barbetti, M., Rakowski, A., 2013. Atmospheric radiocarbon for the period 1950–2010. Radiocarbon 55(4), 2059–2072.

Jäger, K.D., 2002. Oscillations of the water balance during the Holocene in interior Central Europe–features, dating and consequences. Quaternary International 91(1), 33–37.

Jäger, H., 1988. Frühere Umwelten in Mitteleuropa. Siedlungsforschung 6, 9–24.

Jensen, H.R.U., 1844. Angeln. Zunächst für die Angler historische beschrieben. Chr. Andersen, Flensburg.

Jöns, H., 1992/93. Zur Eisenverhüttung in Vor- und Frühgeschichtlicher Zeit in Schleswig-Holstein. Offa 49/50, 41–55.

Klamm, M., 1992. Aufbau und Entstehung eisenzeitlicher Ackerfluren ("celtic fields") Neue Untersuchungen im Gehege Ausselbek, Kr. Schleswig-Flensburg. Archäologische Untersuchungen 16(1), 122–124.

Königlich-Preußische Landesaufnahme, 1879. Topographische Karte 1:25000, sheet 1222, Flensburg-Süd Berlin.

Korhola, A., Rautio, M., 2001. Cladocera and other branchiopod crustaceans. In: Smol, J.P., Birks, H.J.B., Last, W.M. (eds), Tracking environmental change using lake sediments. Springer, Dordrecht, pp. 5–41.

Kuhlmann, H.-J., 1958. Besiedlung und Kirchspielorganisation der Landschaft Angeln im Mittelalter. Wachholtz, Neumünster.

LABO (Bund/Länder Arbeitsgemeinschaft Bodenschutz) 2017. Hintergrundwerte für organische und anorganische Stoffe in Böden 4th edition (appendix). Available from: https://www.labo-deutschlandde/documents/LABO_HGW_Anhang_02_2017pdf. Accessed May 2019.

Landesamt für Vermessung und Geoinformation Schleswig-Holstein, 2017. Digitales Geländemodell (DGM) 1 Kiel. © GeoBasis-DE/LVermGeo (www.LVermGeoSH.schleswig-holstein.de).

Landesvermessungsamt Schleswig-Holstein, 1953. Topographische Karte 1:25000, sheet 1222, Flensburg-Süd. Kiel.

Laur, W., 1967. Historisches Ortsnamenlexikon von Schleswig-Holstein. Gottorfer Schriften zur Landeskunde Schleswig-Holsteins 8. Wachholtz, Neumünster.

LLUR (Landesamt für Landwirtschaft, Umwelt und Ländliche Räume Schleswig-Holstein), 2012. Geologische Übersichtskarte von Schleswig-Holstein 1:250 000. Flintbek.

Lütjens, I., Wiethold, J., 1999. Vegetationsgeschichtliche and archäologische Untersuchungen zur Besiedelung des Bornhöveder Seengebietes und seines Umfeldes im Neolithikum. Archäologische Nachrichten aus Schleswig-Holstein (9–10), 30–67.

Mager, F., 1930. Entwicklungsgeschichte der Kulturlandschaft des Herzogtums Schleswig in historischer Zeit 1. Veröffentlichungen der Schleswig-Holsteinischen Universitätsgesellschaft 25, I. Ferdinand Hirt, Breslau.

Mauquoy, D., Geel, B. van, Blaauw, M., Speranza, A., Plicht, J. van der, 2004. Changes in solar activity and Holocene climatic shifts derived from ^{14}C wiggle-match dated peat deposits. The Holocene 14(1), 45–52.

McPartland, J.M., Guy, G.W., Hegman, W., 2018. *Cannabis* is indigenous to Europe and cultivation began during the Copper or Bronze age: a probabilistic synthesis of fossil pollen studies. Vegetation History and Archaeobotany 27, 635–648.

Meynke, R., 1985. Vegetationskundliche Untersuchungen im Naturschutzgebiet „Düne am Treßsee". Die Heimat 92(1–2), 49–59.

MELUND (Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung Schleswig-Holstein) 2001. Treßsee: Tiefellinienkarte. Available from: http://www.umweltdaten.landsh.de/nuis/wafis/seen/seenpopup.php?sBildDatei=seen/tresssee/tresssee_tief.gif&sWebBasis=http://www.umweltdaten.landsh.de/nuis/wafis/seen/&sModus=vergr&iseenr=0421. Accessed February 2019.

Mercuri, A.M., Accorsi, C.A., Mazzanti, M.B., 2002. The long history of *Cannabis* and its cultivation by the Romans in central Italy, shown by pollen records from Lago Albano and Lago di Nemi. Vegetation History and Archaeobotany 11, 263–276.

Mercuri, A.M., Florenzano, A., Burjachs, F., Giardini, M., Kouli, K., Masi, A., Picornell-Gelabert, L., Revelles, J., Sadori, L., Servera-Vives, G., Torri, P., Fyfe, R., 2019. From influence to impact: The multifunctional land use in Mediterranean prehistory emerging from palynology of archaeological sites (8.0–2.8 ka BP). The Holocene 29(5), 830–846.

Mühr, B., 2007. Flensburg. Available from: http://www.klimadiagrammede/Deutschland/flensburg.html. Accessed February 2019.

Müller, M.J., 1999. Genese und Entwicklung schleswig-holsteinischer Binnendünen. Berichte zur Deutschen Landeskunde 73(2–3), 129–150.

Nalepka, D., Walanus, A., 2003. Data processing in pollen analysis. Acta Palaeobotanica 43(1), 125–134.

Nelle, O., Dörfler, W., 2008. A summary of the late-and post-glacial vegetation history of Schleswig-Holstein. Mitteilungen der Arbeitsgemeinschaft Geobotanik in Schleswig-Holstein und Hamburg, 65, 45–68.

Nielsen, N.H., Dalsgaard, K., 2017. Dynamics of Celtic fields – A geoarchaeological investigation of Øster Lem Hede, Western Jutland, Denmark. Geoarchaeology 32(3), 414–434.

Packschies, M., 1984. Untersuchungen zur eiszeitlichen Entstehung und nacheiszeitlichen Entwicklung des Treßsees. Die Heimat – Zeitschrift für Natur und Landeskunde von Schleswig-Holstein und Hamburg 91, 7–20.

Packschies, M., 1982 (unpubl.). Der Treßsee Morphologische, sedimentologische und geochemische Untersuchungen eines Feuchtgebietes. Diploma thesis University of Kiel.

Polensky, R., 1982 (unpubl.). Das Binnendünengebiet am Treßsee und seine Umgebung Geomorphologische, bodenkundliche und vegetationsgeographische Untersuchungen als Beitrag zu einer Naturschutzplanung. Diploma thesis University of Kiel.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4), 1869–1887.

Rickert, B.-H., 2013 (unpubl.). Nutzungsgeschichte, Morphologie und Hydrologie des Binnendünengebietes am Treßsee. Stiftung Naturschutz Schleswig-Holstein Molfsee.

Riedel, W., 1980. Bemerkungen zu den Raseneisenerzbildungen auf der schleswigschen Geest. Jahrbuch Schleswigsche Geest 28, 223–225.

Riedel, W., Polensky, R., 1987. Umweltatlas für den Landesteil Schleswig. Deutscher Grenzverein, Flensburg.

Röschmann, J., 1963. Vorgeschichte des Kreises Flensburg. Wachholtz, Neumünster.

Schröder, H., 1985. Der Treßsee – ein eutropher See. Die Heimat – Zeitschrift für Natur- und Landeskunde von Schleswig-Holstein und Hamburg 92, 194–204.

Stolz, C., Nass, D., Fülling, A., 2016. Process – response systems on the flood plains of lowland rivers: Results from the Treene River in the northernmost part of Germany concerning human impact and carbon budgeting. Zeitschrift für Geomorphologie, Supplement 60 1, 49–77.

Stolz, C., Pidek, I.A., Suchora, M., Fülling, A., (in prep.). The intermeshing of inland dunes with a lake: The story of Lake Tresssee (Schleswig-Holstein, North Germany).

Szeroczyńska, K., Sarmaja-Korjonen, K., 2007. Atlas of subfossil Cladocera from central and northern Europe. Friends of the Lower Vistula Society, 84 p.

Van Damme, K., Brancelj, A., Dumont, H.J., 2009. Adaptations to the hyporheic in Aloninae (Crustacea: Cladocera): allocation of Alona protzi Hartwig, 1900 and related species to Phreatalona gen. nov. Hydrobiologia 618(1), 1–34.

Whiteside, M.C., 1970. Danish chydorid Cladocera: modern ecology and core studies. Ecological Monographs 401, 79–118.

Whittington, G., Edwards, K.J., 1989. Problems in the interpretation of Cannabaceae pollen in the stratigraphic record. Pollen Spores 31, 79–96.

Wiethold, J., 1998. Studien zur jüngeren postglazialen Vegetations- und Siedlungsgeschichte im östlichen Schleswig-Holstein. Universitätsforschungen zur prähistorischen Archäologie 45, Habelt, Bonn.

Willroth, K.-H., 1992. Untersuchungen zur Besiedlungsgeschichte der Landschaften Angeln und Schwansen von der älteren Bronzezeit bis zum frühen Mittelalter: eine Studie zur Chronologie, Chorologie und Siedlungskunde. Offa-Bücher 72. Wachholtz, Neumünster.

Zölitz, R., 1989. Landschaftsgeschichtliche Exkursionsziele in Schleswig-Holstein. Wachholtz, Neumünster.