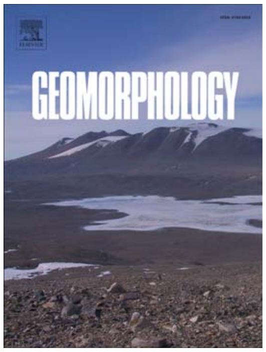
Kaiser, K., Küster, M., Fülling, A., Theuerkauf, M., Dietze, E., Graventein, H., Koch, P. J., Bens, O., Brauer, A. (2014): Littoral landforms and pedosedimentary sequences indicating late Holocene lake-level changes in northern central Europe – a case study from northeastern Germany. - *Geomorphology*, *216*, pp. 58—78.

DOI: http://doi.org/10.1016/j.geomorph.2014.03.025



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PII: S0169-555X(14)00159-7
DOI: doi: 10.1016/j.geomorph.2014.03.025
Reference: GEOMOR 4707

To appear in: *Geomorphology*

Received date: 16 August 2013
Revised date: 3 March 2014
Accepted date: 10 March 2014

Please cite this article as: Kaiser, Knut, Küster, Mathias, Fülling, Alexander, Theuerkauf, Martin, Dietze, Elisabeth, Graventein, Hagen, Koch, Paul Jörg, Bens, Oliver, Brauer, Achim, Littoral landforms and pedosedimentary sequences indicating late Holocene lake-level changes in northern central Europe – a case study from northeastern Germany, *Geomorphology* (2014), doi: 10.1016/j.geomorph.2014.03.025

Littoral landforms and pedosedimentary sequences indicating late Holocene lake-level changes in northern central Europe – a case study from northeastern Germany

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Abstract

A multidisciplinary study was carried out at Lake Großer Fürstenseer See (LFS) in order to explore the potential of littoral sediments, palaeosols and landforms as indicators of historical lake-level changes. This research was initiated to investigate the extent to which lakes in northern central Europe responded hydrologically to climatic and land-use changes in the last millennium. Specific landforms investigated comprise lake terraces, beach ridges, local basins/peatlands and dunes, revealing a wealth of sedimentary sub-environments at the lakeshore. Eleven sections were recorded with subsequent sedimentological-pedological, geochronological (OSL, ^{14}C) and palaeobotanical (pollen, macro remains) analyses. Most of the pedosedimentary littoral sequences show a succession of basal glacial sand, intermediate palaeosols and lacustrine sand on top. A broader number of (semi-)terrestrial buried palaeosols along the lakeshore were systematically identified and analysed, providing evidence for changing hydrological conditions during the late Holocene. Additional historical data from the last centuries (e.g. maps, aerial photos, public records) allow the lake-levels reconstructed from geoarchives to be connected with modern gauging data. All local data sources available enable a tracing of lake level changes of the LFS during the last millennium, comprising periods of relatively low (c. 1200 AD, 2000s AD) and relatively high water levels (c. 1250-1450 AD, c. 1780 AD, 1980s AD). The amplitude of lake-level changes during the last c. 1000 years amounts to c. 3 m, so that the fluctuations of the last 30 years recorded by lake-level monitoring only reflect a small amount of the potential variability. Regional climate and local land-use history suggest that the Medieval lake-level dynamics of LFS were primarily governed by climate and secondarily influenced by human impact on the drainage system. At present the lake level is additionally influenced by the impact of highly water-consuming pine plantations in the catchment area. The regional significance of the local development at LFS can be demonstrated by comparison with other regional and supra-regional lake-level data. The present study underlines the potential of a closer examination of the littoral zone for lake-level reconstructions with high altitudinal precision.

Keywords: palaeohydrology, lake level, lake terrace, beach ridge, palaeosol, peatland

1. Introduction

Natural lakes are a characteristic of the Weichselian (last) glacial belt in northern central Europe (Böse, 2005), numbering c. 5200 lakes larger than one hectare and covering a total area of c. 1700 km^2 in northern Germany (Korczynski et al., 2005; Bleile, 2012). They are of great importance for the wider region hydrology (e.g. storage of water, feeding of the headwaters of several rivers), ecology (e.g. preservation of biodiversity), climate protection (e.g. by wetland conservation), and economy (e.g. tourism, water consumption, release of cleaned waste water, shipping, fishery). A key component of the region’s water cycle is the amount of water stored in these lakes and the temporal variability of that storage, depending on water-level changes. Changes in the lake level over time can also heavily affect littoral processes (e.g. erosion and deposition of sediments, formation of landforms; e.g. Dearing, 1997), ecosystems (e.g. lakes’ trophic status, adjacent wetlands; e.g. Hofmann, 2008) and human activities (e.g. use of shorelines, navigability; e.g. Wilcox et al., 2007).

For the last decades monitoring has revealed decreasing or intensively fluctuating water levels for several lakes in northern central Europe and adjacent areas (e.g. Dąbrowski, 2004; Jöhnk et al., 2004; Mooij et al., 2005; Taminskas et al., 2007; Ledolter, 2008; Germer et al., 2011; Kaiser et al., 2014). The trends, extent and reasons for these changes, as well as the ecological consequences differ, however, depending on regional climate, hydrological lake characteristics and catchment properties including local human impact. Modern lake-level dynamics have been ascribed in part to recent anthropogenic climate change that generally influences the terrestrial water balances from the global to the local scale (e.g. Milly et al., 2005; Bates et al., 2008; Gerten et al., 2008; Kundzewicz et al., 2008). Furthermore, a decline in water resources (‘drying up’) is projected for northeast central Europe in the next decades (e.g. Huang et al., 2010; Hattermann et al., 2011), while corresponding and widespread decreases in lake levels are expected (e.g. Roithmeier, 2008; Natkhin et al., 2012; Kaiser et al., 2012a).

In order to identify the causes of regional hydrological changes and to project probable changes in the future, an understanding of the long-term behaviour of the water cycle and its elements is necessary. But knowledge on lake-level and groundwater-level changes as well as discharge changes in northern central Europe are based on relatively short-term gauging records only, generally covering a few decades at most. This period is too short, however, to cover the full extent of hydrological changes. Historical hydrology (with a temporal focus largely of 10^2-10^3 years, using public archives) and palaeohydrology (with a temporal focus largely of >10^3 years, using geoarchives) meanwhile allow for hydrological data to be extended into the past (e.g. Brown, 2002; Benito and Thorndycraft, 2005; Gregory et al., 2006; Brázdil et al., 2006; Baker, 2008). In particular, the frequency and magnitude of certain events, such as river floods and droughts as well as exceptionally high and low lake levels, can be detected retrospectively (e.g. Duck et al., 1998; Magny, 2004; Czymzik et al., 2013). However, as the historical and geoarchive records are generally based on proxy data, substantial differences in precision and temporal resolution between observed contemporary hydrological dynamics and those of the past which were reconstructed have to be considered. Present knowledge on late Quaternary lake-level variation in northern central Europe is based on a few records of predominantly low temporal resolution from northern Germany (e.g. Brande, 1996; Kleinmann et al., 2000; Jäger, 2002; Kaiser et al., 2012b; Wieckowska et al., 2012) and northern Poland (e.g. Ralska-Jasiewiczowa and Latałowa, 1996; Starkel et al., 1996; Wojciechowski, 1999; Starkel, 2003). Generally, this area is still a ‘blank spot on the map’ of lake level-derived climatic reconstructions (Gaillard and Digerfeldt, 1990; Harrison and Digerfeldt, 1993; Harrison et al., 1993, 1996; Yu and Harrison, 1995). Hence, further research focussing on the lake-level dynamics at time-scales of 10^1 to 10^4 years is needed to explore how hydrological changes are related to climate variability and human impact. Advanced knowledge of the long-term dynamics enables a better understanding of the mechanisms of the present and thereby hopefully better anticipation of future hydrological changes. As several of the above-cited studies on palaeohydrology of lakes show, mostly sublittoral and profundal sediment cores have been studied, usually leading to qualitative (= relative) lake-level characterisation in terms such as ‘increase’, ‘decrease’ and ‘no change’. In contrast, the potential of (nowadays) ‘dry’ littoral sections for quantitative characterisation of past lake-level stands was clearly not exploited to the full.

The objective of the present case study of Lake Großer Fürstenseer See (Mecklenburg Lake District, northeastern Germany; Figs. 1A-C) is to explore the potential of supra- and eulittoral landforms and pedosedimentary sequences (for terminology see Wetzel, 2001; Muhs, 2007), indicating local lake-level changes during the last millennium. For this reason sedimentological-pedological, geochronological and palaeoecological data derived from lake shore sections as well as additional information, such as that derived from lake-level monitoring and historical maps, will be presented and discussed below.

2. Study area

In this study the term 'Lake Großer Fürstenseer See' (LFS) refers to the combined areas of the homonymous lake (c. 2 km^2) and Lake Hinnensee (c. 0.5 km^2), lying in the Müritz National Park. Both lakes are connected by a c. 2 m-deep sub-aquatic sill (Fig. 1C). The maximum water depth of LFS is 24.5 m and its mean water depth is 6.7 m. The lake and its catchment area are being investigated in detail at a monitoring site which is situated within the overarching global change observatory 'TERENO' (Terrrestrial Environmental Observatories of the Helmholtz Association; Zacharias et al., 2011; Blume et al., 2013; Kaiser et al., 2014). The southern part of LFS is embedded in an outwash plain, whereas the northeastern part borders on the terminal moraine of the late Weichselian Pomeranian Phase (c. 20 ka BP; LUNG, 2000; Lüthgens et al., 2011; Börner, 2012; Fig. 1B). The lake is encircled mainly by sandy and partly by gravelly glaciofluvial sediments. In the lake basin and surrounding peatlands lacustrine sediments (gyttjas) and peat are found. At the shoreline aeolian and colluvial sands occur locally. LFS and surrounding lakes belong to a system of subglacial channels running NE to SW. They are connected by depressions along a NW-SE axis. Palynologically dated lacustrine sequences (Müller, 1961; Theuerkauf and Joosten, 2009) and the occurrence of the late Pleistocene Laacher See tephra at the bottom sections of nearby lake fills (Müller, 1959; Theuerkauf, 2002) show that LFS was formed by dead-ice melting during the late Pleistocene/early Holocene (Kaiser et al., 2012b). The relief (max. 116 m HN; HN = altitudinal reference system in the eastern part of Germany relating to the Baltic Sea level) is mainly flat and slightly undulating in the southern part but steep in the northern part. Several lacustrine landforms shape the shoreline of LFS, such as terraces, beach ridges and fossil cliffs (for details see section 4).

LFS has two inlets and two outlets (Fig. 1C); all are artificial (see section 5.2). According to the hydrological lake classification by Mauersberger (2006), LFS is a so-called ‘stream lake’ fed predominantly both by groundwater inflow originating from the first unconfined aquifer and by precipitation on the lake surface. A small amount of feeding comes from stream water inflow in wet years. There several aquifers in the subsurface lake catchment. The shallowest (first/unconfined) one is located below the terrain surface having no confining sediment cover with low hydraulic conductivity (aquitard). The groundwater flows from NE to SW (ZGI, 1987). The subsurface catchment of LFS is asymmetric, skewed towards the east and about half as large as the surface catchment area (c. 39.5 km^2; Koch, 2012).

The present climate of the study area is documented by data from the nearby German Weather Service (DWD) climate station in Neustrelitz (c. 5 km to the west of LFS), showing a mean annual temperature of 8.0 °C and a mean annual precipitation of 584 mm (range 428-814 mm) with dominating summer rainfalls for the reference period between 1961-90 (Stüve, 2010; Kaiser et al., 2014).

Gauging reveals multiple oscillations of the lake level since 1985 with an overall negative trend from 1995 to 2010 (Fig. 2). The mean water level of LFS during the period 1985-2012 is 63.4 m HN, with an amplitude of 1.2 m. The intra-annual amplitude over that period ranges from 7 to 47 cm, with a mean of 22 cm. Groundwater wells in the surroundings show that lake-level changes correspond to groundwater-level changes of the upper unconfined aquifer (Stüve, 2010; Kaiser et al., 2014).

The vegetation around LFS consists largely of (formerly managed) forests dominated by Scots Pine (*Pinus sylvestris*). Forests (63 %) dominate even the wider catchment area, complemented by arable land and pastures (18 %), lakes (13 %), peatlands (5 %) and settlements (1 %; Koch, 2012). Neither large-scale settlement nor industrial activities, including noteworthy (drinking) water abstractions, have ever taken place in the catchment. But during the last centuries drainage measures, water milling (Kniesz, 2002) and intensive forest management (Müller, 1961; Zerbe and Brande, 2003) have significantly changed the local hydrography (formation of numerous ditches, initiation of surface drainage, drainage of peatlands) and the groundwater recharge (e.g. by multiple clear-cuttings and forestations) as well as the groundwater level in the catchment.

3. Methods

3.1 Field-work, sedimentology and pedology

After reconnaissance excursions along the shoreline of LFS as well as in adjacent sub-basins and peatlands, a total of 89 sections (52 auger explorations, 27 soil pits, 10 peatland corings) were recorded in the study area from 2010 to 2011. For the documentation and sampling of 10 from the 11 sections presented here (Figs. 3, 4), which represent the palaeohydrologically most representative local shoreline sequences known so far, soil pits were dug with depths from 1.5 to 3 m. Section FUER14 was retrieved from the shallow lake water by a percussion corer. All sections were referenced to m HN.

The sections were described and sampled according to the German pedological standard (Ad-hoc-AG Boden, 2005). Designations of soil horizons are given using this standard (in text, figures, tables) and an international standard (FAO, 2006; only in Table 1), whereas soil types were classified according to the 'World Reference Base for Soil Resources' (IUSS-ISRIC-FAO, 2006). The colours of sediments and soils were determined in the field using the 'Munsell Soil Color Charts'. The content of coarse matter (>2 mm), comprising mostly gravels and rarely stones, was estimated in the field (Ad-hoc-AG Boden, 2005; FAO, 2006). The graphical image of sediments and landforms followed, where suitable, the suggestion of Gustavsson et al. (2006).

From eight sections and a total of 56 samples sedimentological laboratory analyses were performed on the matrix <2 mm (Tab. 1) in order to assist the designation of sedimentary facies and diagnostic soil horizons.

After air drying, careful hand-crushing and, if the components were present, humus and carbonate removal (by 30 % H_2O_2 and 10 % HCl, respectively) two different methods were used to determine the grain-size distribution. For sections FUER1, FUER2, FUER3, FUER6, and FUER14 grain-size compositions were determined by laser diffraction (Fritsch Analysette 22), whereas for FUER15, FUER16-4, and FUER19-2 a wet-sieving test was applied. The classification of sand grain-size (ranging from fine via medium and to coarse) is generally defined by the class sizes <0.2 mm, <0.63 mm and <2.0 mm respectively (Ad-hoc-AG Boden, 2005; FAO, 2006). The content of organic matter, which is crucial for the classification of some sediments (e.g. peat) and soil horizons, was estimated by combustion at 550 °C (loss-on-ignition/LOI; Heiri et al., 2001). $CaCO_3$ was determined volumetrically by a Scheibler-apparatus.

3.2 Geochronology

Radiocarbon (^{14}C) dating was performed on a total of 15 samples in the Poznan and Erlangen ^{14}C laboratories by accelerator mass spectroscopy (Table 2). As macrofossils were largely absent from the sediments/palaeosols because of high decomposition, mainly bulk samples were dated. The ^{14}C ages presented were calibrated (cal. yrs BC/AD values) with the programme Calib 6.0 using the IntCal09 data set with a range of 2 sigma standard deviation for analysis (http://calib.qub.ac.uk/calib/). The given calibrated ^{14}C ages represent the age ranges with the highest corresponding probability (cf. Argyilan et al., 2010).

Nine OSL ages were determined at the luminescence dating laboratory at Humboldt University, Berlin (Tab. 3). The OSL analytical procedures followed standard routines as given by Stolz et al. (2012) for the Berlin laboratory, using the sand-size sediment fraction of 90 to 250 µm (coarse grain technique). Small aliquots (2 mm) were prepared containing approx. 200 grains each. This grain number is considered to be appropriate to detect partial bleaching and thus possible age overestimation often observed in colluvial sediments (Fuchs and Wagner, 2005). Most samples yielded equivalent dose distributions with over-dispersion values between sigma b = 0.09 and 0.11, suggesting a good resetting of the latent OSL signal during the last sedimentation process. Equivalent doses were thus calculated using the Central Age Model (CAM). Only HUB-0324 and HUB-0190 showed broad or positively skewed equivalent dose distributions and therefore the Minimum Age Model (MAM) was applied (Galbraith et al., 1999; Supplement 1).

The pre-heat temperature was set at 180°C (10 s) and the test dose cut-heat temperature at 160°C. These settings were verified while performing dose recovery tests on samples HUB-0191 and HUB-0325. After resetting the luminescence signal (blue stimulation for 600 s) 20 aliquots of both samples were irradiated with a beta dose of 1.1 Gy and subsequently measured applying the SAR protocol (varying pre-heat temperatures from 180 to 240 °C for 10s, cut-heat of 160 °C, four aliquots per temperature point). On sample HUB-0325 a pre-heat test was carried out using the same temperature steps (Supplement 2).

The sediment dose rates were estimated by measuring the contents of uranium, thorium and potassium applying high resolution gamma ray spectrometry. The cosmic ray dose rates were estimated from site position, elevation and burial depths (Barbouti and Rastin, 1983; Prescott and Hutton, 1994). The gamma ray spectrometry did not reveal any radioactive disequilibrium.

To clearly differentiate ^{14}C and OSL data in the text and in the figures, they are indicated by different terms (e.g. ^{14}C age = cal. AD 1259-1307, OSL age = 1320 ± 40 AD).

3.3 Palaeobotany

Pollen analysis was performed both on single samples from palaeosols/peats in sections FUER3 and FUER6, and on a 34 cm-long continuous peat-palaeosol sequence in section FUER15. Preparation (cf. Fægri and Iversen, 1989) of the pollen samples (0.25 ml volume) included addition of one *Lycopodium* tablet (Lund University, batch-Nr. 938934, N~10679 *Lycopodium* spores), treatment with 10 % HCl, 20 % KOH, sieving (120 µm), acetolysis (7 min) and HF digestion (3 days in a shaker). Samples were mounted in silicone oil. Counting was carried out at 400-x magnification. We aimed at a minimum count of 100 pollen sum grains per sample. Pollen identification and nomenclature follows Moore et al. (1991). Pollen can usually not be identified to a species or even higher taxonomic level. To clearly separate between the original pollen data and the inferred presence of plant taxa we use small capitals for pollen types and standard notation (italics) for plant taxa (cf. Joosten and de Klerk, 2002). SPARGANIUM EMERSUM TYPE and SPARGANIUM ERECTUM TYPE were determined with Punt (1975). POLYPODIALES MONOLET INCOMPLET includes Polypodiaceae spores with no outer coat. We included all tree pollen types, CORYLUS, and pollen types attributed to upland herbs in the pollen sum. In section FUER15 the sieving residue was studied to characterise the sample composition. Abundances are given in numbers for countable objects and percentage of total volume (estimated by eye) for other remains (e.g. tissues and sand).

4. Results

In general, presently supra-aquatic landforms/sedimentary environments of the shoreline and in the immediate hinterland can be divided into those of aggradational character (e.g. aggrading terraces, beach ridges, dunes, lagoons/lake mires, glacial kettle-holes) and those of erosional character (e.g. fossil cliffs, wave-cut terraces). Because of their restricted dating potential, however, erosional landforms were not considered for further analysis.

4.1 Terrace sites

The shoreline of LFS is widely accompanied by a flat terrain fringe, ranging from a few decimetres to c. 2.5 m above the mean water level of 63.4 m HN (roughly encompassed by the 66 m contour line in Fig. 1C). This fringe also extends into surrounding lake basins, partly forming peatlands there. At LFS both the topographic and sedimentary properties (lacustrine sands partly overlying palaeosols, peats and gyttjas) suggest that the fringe represents lacustrine terraces, which indicate former higher lake levels. According to historic maps (see section 5.2) and gauging data (Fig. 2), the very low terrace sections of a few decimetres above the lake are of relatively recent age. Their sedimentary structure is rather simple, consisting of planar beds of lacustrine sand, while buried palaeosols, peats and gyttjas are rare. In general, the facies assignation of lacustrine sands is clearly proven by both sedimentological properties (medium to coarse grained sands with rounded gravels and some pebbles) and connection of the sections/layers with littoral landforms (e.g. Reineck and Singh, 1981).

Between c. 1 and 2 m above the mean lake level, a distinctly higher terrace level exists. The surface of these terraces is either horizontal or slightly inclined lakeward. The terraces are between a few metres to decametres (eastern shoreline) and a few hundred metres (western shoreline) wide. The higher terrace bodies are mostly of aggradational character, regularly bearing buried palaeo-surfaces. The covering medium-sized lacustrine sands bear a distinct coarse sand content, some gravel and cobble (Table 1). They can be differentiated from the basal glacial sands by a coarser texture, better sorting and their stratigraphical position above Holocene palaeosols.

4.1.1 Sections FUER1 and FUER2

A well-developed terrace site is located east of Fürstensee village, encompassing an isolated kame hill. In section FUER1 (Figs. 1C, 3-4, Tables 1, 2) two humic soil horizons (IIfAa, IIfAh) form a fossil, in part strongly humic Gleysol. Its upper horizon (IIfAa) is dated to cal. AD 1039-1208. The boundary of the palaeosol to the overlying lacustrine sand is slightly undulating; small pieces of fossil soil matter embedded in the lacustrine sands immediately above indicate both minor erosion of the palaeosol surface and post-sedimentary bioturbation. In section FUER2 (Figs. 1C, 3-4, Tables 1-3), c. 70 m northwest from FUER1 and c. 0.7 m lower in altitude, a buried 17 cm-thick peat (IIIfHa, fossil Histosol) is underlain by a humic soil horizon (IVfAh, fossil Gleysol) developed from glaciofluvial sand. The peat, dating to cal. AD 644-716, shows properties of decomposition and drying (no preservation of plant macro remains, strong humification, aggregation, cracking). The peat’s surface is uneven. Immediately above that peat layer, an 8 cm-thick mixed layer with peat and lacustrine sand (IIrGo+fHa) is found. It indicates a partial erosion of the original peat layer, which would explain why the peat layer is significantly older than the lithostratigraphically similar humic horizon in FUER 1. The lacustrine sand layer on top is heavily influenced by bioturbation by small mammals, creating many refilled burrows. OSL dating of an undisturbed portion of that sand yielded an age of 80 ± 240 BC which is in conflict with the ^{14}C age from the underlying peat. The overestimation of that OSL age can be explained by insufficient resetting of the latent OSL signal during deposition. This assumption is supported by the strongly scattered equivalent dose distribution with an overdispersion of sigma b = 0.72 (see Supplement 1).

4.1.2 Section FUER15

This section (Figs. 1C, 3-4, Tables 1, 2) was recorded at a terrace site in Fürstensee village, c. 500 m northwest from the present lakeshore. The section represents both the highest lacustrine sedimentary level (65.7 m HN) and the thickest sandy lacustrine deposits found on the shore of LFS so far. A 140 cm-thick layer of lacustrine sand overlays an 18 cm-thick peat layer (IIfHv1, IIfHv2) above a humic soil horizon (IIIfAh). In the lacustrine sand two larger pieces of potsherds (grey, thin, very solid, reductively fired) were found at depths of 60 and

80 cm. The edges of the sherds are sharp, so that substantial moving of these objects can be excluded. According to its properties this ceramic can be clearly identified as Medieval, more specifically as so-called ‘Harte Grauware’ (in German) which dates back to the time between the very late 12th/early 13th century AD and the 16th century AD (Kirsch, 2004). The sherds might originate from a nearby Medieval tower hill fortification (‘Turmhügel’ in German) in Fürstensee village, which is only c. 30 m away, dating back to the late 13th/early 14th century AD (Schwarz, 1987; Manske, 2009). Most probably the sherds were embedded in the lacustrine sand during the lake’s rise, providing a maximum age estimate of this event.

The transition to the underlying 18 cm-thick peat horizon is sharp and undisturbed, widely excluding local erosion during the lake’s rise. The peat bed is divided into an upper horizon (IIfHv1), bearing a larger amount of wood remains probably of Alder, and a lower horizon (IIfHv2), having no macroscopically distinguishable plant remains. Both peat horizons are highly decomposed. The upper and lower boundary of the peat is dated to cal. AD 1118-1221 and cal. AD 596-667, respectively. A IIIfAh horizon (fossil Gleysol), underlying the peat, is developed from lacustrine sand. Arc-shaped vertical structures at its lower boundary might represent traces of trampling by humans or animals, wheel-tracks or even cultivation/ploughing. As these structures are filled with IIIfAh-matter they clearly corroborate the assignation as terrestrial soil horizon.

All pollen samples from the peat and the IIIfAh horizon are characterised by high decomposition, so that fragile and less distinctive pollen types might be under-represented. The low pollen sums (i.e. mostly below 200 pollen grains per sample) result from the poor pollen preservation and the low pollen concentration in most of the samples. Consequently, we are careful with the interpretation of the pollen data and do not attempt any quantitative interpretation. Four zones are recognisable in the pollen diagram (from below/older to above/younger; Fig. 5):

Zone I (156-174 cm) includes the IIIGr, IIIfAh and the lower part of the IIfHv2 horizon. It is mainly composed of sand; the proportion of organic components (TISSUE INDET., including rootlets and other plant remains) is only higher in the upper samples of this zone. Pollen samples from this zone are dominated by PINUS DIPLOXYLON (~60 %) and ALNUS (~20 %). Pollen of further deciduous trees (BETULA, CORYLUS, TILIA, QUERCUS, ULMUS) is remarkably rare, which may be attributed to either poor pollen preservation or to the formation of the studied sediments; the sands may have been deposited in the vicinity of *Alnus* and *Pinus* stands. The presence of deciduous tree pollen still indicates that the sand was deposited during the Holocene. Herb pollen and spores are rare, limiting the reconstruction of the local herbal vegetation. *Zone II (149-156 cm)* is mainly composed of TISSUE INDET.; the proportion of sand is lower than in zone I. PINUS DIPLOXYLON (~50 %) is rarer, ALNUS (~30 %) more abundant than before. Also the WILD GRASS GROUP (produced by grasses) arrives at higher values. The presence of MOUGEOTIA spores might point to episodic flooding. *Zone III (144-149 cm)* is mainly composed of TISSUE INDET. and CHARCOAL (latter reaching maximum 40 %). PINUS DIPLOXYLON (~60 %) is again the predominant pollen type, ALNUS (~15 %) rarer than before. QUERCUS occurs regularly. Pollen grains of FAGUS and of cultural indicators (including SECALE CEREALE) indicate that this zone was deposited not earlier than approx. cal BC 800 (cf. Jahns, 2007). High values of POLYPODIALES MONOLET INCOMPLET show that fern-rich vegetation had developed. Increased values of CYPERACEAE, SPHAGNUM and TYPE 143 point at wet conditions; furthermore MOUGEOTIA might indicate episodic flooding. Also *zone IV (140-144 cm)* is dominated by TISSUE INDET.; the proportion of CHARCOAL declines. PINUS DIPLOXYLON is rarer than before (~40 %), ALNUS (~20 %) more abundant, BETULA and QUERCUS reach about 10 %. Cultural indicators (CERELIA UNDIFF., SECALE CEREALE, RUMEX ACETOSELLA TYPE) are well present and suggest that zone IV was not deposited before the Medieval (cf. Jahns, 2007), which is corroborated by the ^{14}C age (cal. AD 1118-1221) of the uppermost centimeter of the peat. The presence of TYPHA LATIFOLIA TYPE, SPARGANIUM

ERECTUM TYPE and SPARGANIUM EMERSUM TYPE points to the existence of reed vegetation. CHARA OOSPORES and POTAMOGETON SEED indicate that the site was at least occasionally flooded.

4.1.3 Section FUER16-4

This section (Figs. 1C, 3-4, Tables 1, 2) was recorded at a relatively low terrace site, located c. 1 m above the average lake level. It is more complex than FUER1, 2 and 15, showing three layers of lacustrine sand separated by two peat layers. The upper peat layer is 33 cm thick. Its upper part (IIfHa) is highly decomposed (no preservation of macrofossils, aggregation, bioturbation) and shows indications of desiccation as well as erosion (cracks, small peat pieces embedded in the adjacent lacustrine sand). Its lower part (IIfHr) has clear planar bedding. It contains largely well preserved macro-remains of alder wood and is rich in macroscopic charcoal, partly forming thin charcoal layers. The ^{14}C ages from the upper peat range from cal. AD 318-469 (IIfHa) to cal. BC 1695-1505 (IIfHr). The upper peat rests on a humic soil horizon (IIIfAh, fossil Gleysol) that is developed from lacustrine sand. The lower peat layer, a 4 cm-thick IVfHr horizon, consists of well-preserved remains of sedges and brown-mosses, dating to cal. BC 3820-3657.

4.2 Beach ridge site

At a site on the southern shore a set of two higher and three lower sandy beach ridges occurs (Fig. 6A-C). The higher ones rest on a base of peat layers/palaeosols. These ridges are positioned between the present lake and a fossil, E-W oriented cliff, which is up to 10 m high. The cliff cuts the outwash plain that consists of glaciofluvial sand and gravel. The ridges are up to c. 300 m long and a few metres wide. They are partly attached to the cliff, stretching diagonally NE to the present lakeshore. The higher ridges close to the cliff reach a maximum altitude of 65.4 m HN, which is 2 m above the mean water level of LFS. The lowest ridge, close to the lake, is only a few decimetres above the lake level. The surface of adjacent swales, partly filled by peat, lie up to c. 1 m below the higher ridges crests. Depending on this topography, a longitudinal pattern of dry-site (Pine, Oak and Beech with herbs) and wet-site vegetation (Alder and Birch with sedges) has developed.

4.2.1 Section FUER6

Sedimentology and geomorphology in and around section FUER6 (Figs. 1C, 3-4, 6A-C, Tables 1-3) clearly corroborate the classification of the local set of ridges as beach ridges (e.g. Taylor and Stone, 1996; Otvos, 2000; Baedke et al., 2004). FUER6 represents the highest ridge crest position. The ridge body contains of 0.8 m of lacustrine sand (medium sand bearing a considerable amount of coarse sand, some gravel and cobble) that covers a sequence of peat and palaeosol horizons (IIfHa, IIIfAa, IIIfAh). Below the IIIfAh horizon lies a slightly silty and humic layer of sand, that is classified as sandy gyttja. The bedding of the lacustrine sand follows the shape of the ridge (arc-shaped beds), but partly small-scale variations occur (e.g. steeply inclined laminae/cross-bedding).

The lacustrine sand is dated to 1410 ± 40 AD, while the top of the underlying peat (IIfHa) appears to be older, dating to cal. AD 989-1053. This c. 450 year-long gap between the end in peat deposition and the sandy (beach ridge) deposition may be the result of dry site conditions between both depositional phases. Alternatively, the gap may result from erosion of an upper section of the peat. There are no obvious signs of erosion at FUER6 but at a nearby site c. 50 m away, where the boundary from peat to lacustrine sand is truncated by small-scale hollows/carvings, revealing local erosion of the peat bed.

Pollen spectra from the peat (Fig. 7) are dominated by PINUS DIPLOXYLON (> 95 %), which may primarily result from the poor pollen preservation. PINUS DIPLOXYLON pollen is rather robust and distinguishable also in highly decomposed material. A single FAGUS pollen grain in the uppermost sample may indicate that the peat was deposited *after* the mass expansion of

Fagus in the wider region at around cal BC 800 (cf. Jahns, 2007). The occurrence of PEDIASTRUM in the uppermost sample points at wetter conditions with (episodic?) flooding. All samples are rich in charred particles, indicating that fire played an important role during local soil/peat formation.

Altogether the local pedosedimentary sequence reveals a complex site history, starting with a glaciolacustrine phase at the base followed by a sequence from lake (gyttja) to dry site conditions (IIIfAh) via wet site conditions (IIIfAa, IIfHa) again to lake (lacustrine sand), and finally to the present dry site conditions.

4.3 Peatland sites

Several larger peat-filled depressions connect LFS with surrounding lake basins (Fig. 1C). Furthermore, a multitude of small peat-filled kettle holes occurs in the study area, perforating the surface of the outwash plain. Some kettle holes are directly attached to the shoreline (Figs. 1C, 6A). In general, the local groundwater levels of these peatlands are connected with the supra-local groundwater (and thus the lake) level due to permeable glaciofluvial sands. Thus these peat-filled kettles provide opportunity to record the long-term dynamics of the groundwater level around LFS (accordingly of the lake level) and, in the case of kettles immediately attached to the shoreline, even to detect potentially occurring lake ingressions.

4.3.1 Section FUER10-2

FUER10-2 (Figs. 1C, 6A) originates from the margin of a small kettle-hole peatland (40 m in diameter) in the southeastern bay of LFS. A central, c. 4 m-long sequence with peat, gyttia layers and palaeosols developed from peat shows that the water level in that basin fluctuated greatly. However, the sequence does not cover the last 1000-1500 years (Graventein, 2013). This youngest layer was possibly degraded by dry conditions, following groundwater lowering during the last decades (Stüve, 2010; Kaiser et al., 2014).

Section FUER10-2 (Figs. 1C, 3-4, 6A, Tables 1, 2) is taken from the south-eastern periphery of the kettle hole, at the base of a steep slope. It shows a complex sequence of lacustrine sediments, peat and colluvial sand as well as two terrestrial palaeosols. Colluvial sands on top of the sequence originate from local soil erosion (see the nearby profile FUER5 in section 4.4.2). The top level of the upper lacustrine sand of 65.4 m HN (Fig. 8) points to a lake-level high stand, during which the kettle hole has been part of LFS. However, this sand cannot be found in the central sequence of the kettle-hole (potentially placed in between peat layers) probably due to younger peat degradation as mentioned above. A 7 cm-thick, highly decomposed peat horizon (VfHa) below this lacustrine sand and gyttia is dated to cal. AD 986-1052. This peat layer is thus similarly old and occurs at a similar altitude as the peat layer in FUER6, located c. 350 m towards the NW.

4.3.2 Section FUER19-2

FUER19-2 (Figs. 1C, 3-4, Tables 1-3) originates from a widely peat-covered basin that connects LFS and Lake Plasterinsee. The sequence consists of lacustrine sands above peat (IVfHr). The sand is parallel-bedded and partly coarse. It is divided by a thin, organic horizon (IIGr+fAh) which is interpreted as a mixture of eroded peat and lacustrine sand. The upper sand layer dates to 1300 ± 50 AD. The peat consists of parallel beds of well-preserved remains of reed and sedge species in an amorphous matrix, dating in the uppermost centimetre to cal. AD 1283-1399. The peat layer reaches down to at least 2 m depth. It has possibly been compacted substantially by the overlying sands, so that the altitudes of the dated layers might have been higher originally.

4.4 Further sites

4.4.1 Section FUER3 (dune)

South of Fürstensee village, a forested area with small hillocks on the lake terrace adjoins the lakeshore. These hillocks, consisting of aeolian sand, are dunes of a few metres length and are less than 1 m in height. They have a round to oval planform. Locally, they are situated next to the surrounding wet Alder forest, reed belt or open water of LFS.

Section FUER3 (Figs. 1C, 3-4, Tables 1-3) originates from the lakeward slope of a dune. It covers a sandy sediment sequence of aeolian, lacustrine and glaciofluvial origin. The upper layers of aeolian and lacustrine sand are interrupted by three thin, humic horizons (initial soils), whereas in the basal glaciofluvial sand a VIfAh horizon (fossil Gleysol) has developed. OSL dates suggest that the aeolian cover was deposited between 1530 ± 40 AD and 1690 ± 20 AD. The underlying lacustrine sand dates to 1320 ± 40 AD. The low uncertainty in these OSL ages can be explained by very narrow equivalent dose distributions, yielding relative standard errors between 2 and 5 % (e.g. HUB-0325; Supplement 1). A piece of charcoal from this layer is similarly old (cal. AD 1259-1307). The basal VIfAh horizon dates to cal. BC 671-478. This gap of c. 800 years could be caused by partly erosion of the VIfAh during the lake level rise, which is indicated by an intermediate mixed layer (VrGr+fAh).

The three pollen samples from palaeosol horizons consist largely of (uncountable) charred particles (Fig. 7) and are characterised by poor pollen preservation, which hampers the interpretation. All samples are dominated by PINUS DIOLOXYLON, suggesting that Pine did occur at or near the site. Pollen of deciduous tree taxa is correspondingly rare but could indicate at least for the uppermost sample rather diverse tree vegetation (Alder, Birch, Oak, Hazel, Beech). The presence of SECALE CEREALE (representing Rye) in the uppermost sample reveals that the initial humic soil horizon in lacustrine sands (fAi) developed not before the Medieval period (cf. Jahns, 2007).

4.4.2 Section FUER5 (slope above cliff)

FUER5 (Figs. 1C, 3-4, 6A, Table 2) is located above a fossil cliff, at the base of an adjacent slope, c. 4 m above the mean water level of LFS. No lacustrine sediments were detected in this section, indicating that during the Holocene the lake level of LFS has probably never exceeded an altitude of c. 67 m HN. Moreover, the presence of the Lateglacial 'Finow soil' – a regionally well-investigated palaeosol dating into the Allerød-Younger Dryas period (Kaiser et al., 2009; Küster and Preusser, 2009; Küster et al., 2014) – and of overlying aeolian sands, probably of Younger Dryas age, indicate that the (potentially existing) LFS did not exceed this altitude even in the final Lateglacial period. Two sandy colluvial layers (identified as slope wash by their sedimentological properties) in the upper part of the section date to 1190 ± 60 AD and 1710 ± 20 AD. They indicate local Medieval and pre-modern soil erosion, respectively, and thus local forest clearing and probably agriculture. However, the upper OSL age has to be interpreted carefully because of the equivalent dose distribution characteristics, suggesting partial bleaching (see Supplement 1). Some prehistoric but uncharacteristic potsherds were found in the lower colluvial layer, originating from local soil redistribution.

4.4.3 Section FUER12 (rampart of a drainage ditch)

An artificial ditch connects LFS with Lake Zwirnsee (Fig. 1C). During construction the overburden was deposited on the western side of the ditch, forming a c. 1 m-high rampart. It buries a pre-existing land surface. In profile FUER12 (Figs. 1C, 3-4, Table 2) the 80 cm-thick sandy overburden, showing a less-developed humic surface soil, overlies a well-developed terrestrial palaeosol of Arenosol type (IIfO-IIfAeh-IIfBsv sequence). The 2 cm-thick IIfO horizon yielded an age of cal. AD 1512-1601, suggesting that the ditch was built and the lakes were connected at that time.

4.4.4 Section FUER14 (sublittoral)

This sediment core (Figs. 1C, 3-4, Tables 1, 2) was retrieved by a percussion corer from the shallow water of the central basin of LFS, consisting of a gyttja-peat-gyttja sequence above lacustrine sand. The peat was possibly formed between cal. BC 7610-7465 and cal. BC 6505-6351. It indicates that during the early and mid-Holocene the lake level was at least periodically around 62.5 m HN. This altitude is well below all late Holocene lake levels reconstructed and measured so far for LFS.

5. Discussion

5.1 Summarising local lake-level data from landforms and pedosedimentary sequences

In general, the investigations at LFS revealed a wealth of littoral sediments, landforms and wet-site palaeosols on a regionally unprecedented scale. Whilst terraces, partly even sequences of terraces, form a ubiquitous relief feature around lakes in the region (e.g. Kaiser et al., 2007; Lorenz, 2007; Lampe et al., 2009; Küster et al., 2012), the record of beach ridges (Figs. 1C, 6A-C) at this relatively small lake is remarkable. So far, such landforms were recorded only at considerably larger lakes in the region (e.g. at the 117 km^2 Lake Müritz or at the 16 km^2 Lake Krakower See; Kaiser et al., 2002; Lorenz, 2007). Next to the beach ridges relatively high cliffs (Fig. 1C), cut into the outwash plain, probably served as a dominant sediment source for the ridge accumulation. However, in comparison to larger recessional strand plains with higher and longer beach ridges, the forms at LFS appear simpler with pure water-based structures as similarly found, for instance, by Briggs et al. (2005) and Hesp et al. (2005). The ridges lack a vertical facies differentiation from above to below into dune, foreshore and upper shoreface, which was reported from several other sites both in a lacustrine and marine setting (e.g. Thompson, 1992; Taylor and Stone, 1996; Otvos, 2000; Baedke et al., 2004). Furthermore, the number of higher ridges per site at LFS is small (n = 1-2), probably reflecting a rather short, (storm?-) event-like record. In general, an origin of these ridges by ice-push towards the lakeshore (cf. Forbes and Taylor, 1994) can be excluded, as the sedimentological properties (non-diamicton character, missing boulders, no scouring) show that these beach ridges were solely formed by (higher) turbulent water/wave action.

Most of the sections recorded at LFS show a succession of basal (glacio-)lacustrine/-fluvial sands, intermediate palaeosol(s) and topping lacustrine sand (Fig. 8). The designation of basal sands as of glacial origin (‘glacio…’) is based solely on sedimentological properties (e.g. no organic content, no underlying palaeosols) and on their stratigraphical position, fitting well with local Quaternary geology (Börner, 2012). However, there is no well-documented sediment record at LFS during the transition from Pleniglacial to Lateglacial available so far.

The intermediate palaeosols mostly show a lower humic (terrestrial) horizon (…fAa or …fAh) covered by a peat (…fH…) horizon, indicating a transition to wetter (semi-terrestrial) site conditions. In FUER15 this transition is clearly reflected in the reconstructed vegetation shift from tree stand (moist), via occasionally flooded Alder carr (wet) to flooded reed swamp (very wet). Peat formation here encompasses an age interval of c. 600 years, ending in the late Medieval period. Pollen data suggest that the humic horizon formed in the mid- to late Holocene. The presence of highly decomposed layers with cracks within the peat layers (FUER2, FUER6, FUER16-4) indicates that the water level of LFS was fluctuating during or after peat formation.

In all profiles investigated, except FUER5 and FUER12, lacustrine sands occur, partly alternating with buried humic soil horizons and peats (e.g. FUER10-2, FUER16-4). Both palaeosols and lacustrine sands are mostly found in an altitudinal range between 63.0 and 65.5 m HN (Fig. 8). Their ages cover various periods in the late Holocene, clustering between 1100 and 1450 AD (Fig. 9A). In FUER3, FUER6 and FUER19-2, deposition of lacustrine sand is dated by OSL to the period 1250-1450 AD (Fig. 9B). The upper limit of sandy deposition (FUER1, FUER6, FUER15 = 65.4-65.7 m HN) suggests that the lake level during the late Medieval period reached a maximum level of c. 66 m HN, i.e. nearly 2 m above the observed (gauging) maximum. There is no evidence that lacustrine sands were deposited in several phases during the Medieval or afterwards, which indicates that they were deposited during a single lake-level highstand (period). With respect to the reliability of OSL ages from lacustrine sands, other studies have confirmed the suitability of these materials (e.g. Argyilan et al., 2010). But generally waterlain sands can be very difficult to date, as is apparent with aeolian or colluvial sands (e.g. Preusser et al., 2008; Alexanderson and Murray, 2012).

The palaeosols in FUER3, FUER15 and FUER19-2 date to an interval of cal. AD 1118-1399 (Fig. 9B), which supports the evidence from OSL dating that the overlying lacustrine sands were deposited in the late Medieval period. The buried peat layer in a quasi-fixed position in profile FUER15 indicates that the lake-level was at about 64.3 m HN during the high Medieval period (c. 1200 AD).

5.2 Lake-level changes since the 18th century AD according to historical records

For the past c. 300 years, historical documents (e.g. maps, public records, aerial photos) and oral traditions may elucidate the water-level history of lakes in the region (e.g. Driescher, 2003; Kaiser et al., 2012b) and, accordingly, the LFS.

Historical maps from the 18th and 19th centuries AD show quite precisely the shoreline of the LFS and topographical features of the surroundings. The map of Graf von Schmettau (1780) shows that LFS and adjacent lakes were larger than they are today. The displacement of the western shoreline points at a lake level of c. 64.5 m HN around 1780 AD (Koch, 2012). Nearly the same lake-size/water-level situation is given in a map from c. 1824 AD (Draesecke, 1824). The ‘Messtischblatt’ map from the late 19th century AD (Reichsamt für Landesaufnahme, 1883/1932) shows a shoreline that is nearly analogous to the present one. A small island, to be found NE of Fürstensee village (Fig. 1C), is not shown on the maps before 1883/1932 AD, indicating that the lake level was higher than it is today during the late 18th to early 19th century AD. Finally, the analysis of a sequence of aerial photos since the 1930s, the lake-gauge record since 1985, photographs and the oral tradition reveal that lake level has fluctuated over a range of c. 1.5 m (c. 63-64.5 m HN) during the last c. 70 years (Stüve, 2010; Kaiser et al., 2012a; Koch, 2012; Kaiser et al., 2014).

5.3 Discussing local and regional Late Holocene lake-level changes

Our findings at LFS suggest changes in centennial- to millennial-scale lake-level variability. Whereas the lake-level change amplitude in the last c. 30 years is 1.2 m according to monitoring data, the amplitude in the last c. 1000 years amounts to c. 3 m. Sandy lacustrine deposits indicate that the historical lake-level maximum was c. 66.0 m HN within the period c. 1250-1450 AD. The lake level minimum in the gauging record is 62.9 m HN (2006 AD). Whether that is actually the lowest lake level of the last millennium is difficult to test, yet during the high Medieval period at c. 1200 AD (c. 64.3 m HN) and the 18/19th century (c. 64.5 m HN) lake levels were higher. During the late Medieval period the high lake level of LFS resulted in a connection to several lakes in the immediate surroundings, which remained separate before and afterwards (Fig. 10). High water levels possibly also activated the cliffs at LFS and adjacent lakes, which are all inactive today.

Potentially, lake levels in northern central Europe may be influenced by climate, land cover change and anthropogenic drainage or damming (Gaillard and Digerfeldt, 1990; Duck et al., 1998; Magny, 2004). Furthermore, it should be mentioned here that stream and river lakes of the region can be potentially influenced by hydrogeomorphological effects of European beaver populations (*Castor fiber*; Gurnell, 1998). This applies to changes in the past and in the present. The most recent lake-level changes of LFS in the last decades, as documented in the gauging record (1985-2012 AD; Fig. 2), mainly resulted from meteorological conditions and a changing forest structure (Koch, 2012; Kaiser et al., 2014). Lower seasonal precipitation, higher evaporation and increasing interception by trees and ground vegetation have led to reduced groundwater recharge and thus to an overall falling lake level in the 1990s and 2000s. Germer et al. (2011), Kaiser et al. (2012a), Nathkin et al. (2012) and Kaiser et al. (2014) show a similar trend for further lakes in the region.

A centennial proxy record of climate change could give some hints on the long-term water budget of the region, but such a record is still lacking from northeast Germany. A synthetic summer temperature and spring precipitation record based on Oak dendrochronology for the late Holocene in central Europe (Büntgen et al., 2011) shows that the Medieval Warm Period (10th to 12th centuries AD; Jansen et al., 2007) was moderately humid while the 13th/14th centuries AD were characterised by markedly wetter summers. A first cold spell c. 1300 AD corresponds to the onset of the Little Ice Age in the northern hemisphere (e.g. Frank et al., 2010). Whereas temperature minima occurred in the early 17th and 19th centuries AD, partly accompanied by very wet spells, the temperature rose at the end of the 20th and the beginning of the 21st century AD (Büntgen et al., 2011). In northeast Germany the period 1951-2003 showed an increase of the mean annual air temperature up to 1.4 K (Wechsung et al., 2008). In general, higher temperatures, as in the early and high Medieval period as well as in very modern times, can potentially cause relatively low lake levels, whereas lower temperatures, as in the late Medieval period and partly in modern times, cause relatively high lake levels (e.g. Magny, 2004). We observe a similar lake-level response at LFS. Furthermore, underwater archaeology of the lakes of northeastern Germany show that occupation layers of the very late Slavonic age (ending 12th century AD) lay often about 1 m below the present lake levels (Bleile, 2012). This either corresponds to the potential hydrological effects of the Medieval Warm Period (preferably detectable in closed lake basins) or indicates late Medieval hydrological changes driven by human impact, such as mill stowage and deforestation (preferably detectable in open lake basins; Kaiser et al. 2012b).

Of particular interest is the marked lake-level increase of LFS in the period c. 1250-1450 AD because it possibly represents the highest local lake level of the Holocene. The structure of terraces and beach ridges at LFS and adjacent lakes show that this extreme might be connected to a particular event, probably a well-known meteorological phenomenon in the late Medieval period. In the first half of the 14th century AD heavy rainfalls occurred in the whole of central Europe (Dotterweich, 2008; Dreibrodt et al., 2010). The heaviest rainfalls of the last millennium took place in summer 1342 AD, triggering widespread and disastrous river floods, sheet floods, gully erosion and landslides (e.g. Bork et al., 1998; Glaser, 2001) as well as marked, yet mostly likely short-term, lake-level increases in northeast Germany, as exemplified probably by LFS.

Land-cover change is the second important potential driver of lake-level changes of LFS because it heavily influences groundwater recharge (Nathkin et al., 2012). Under (theoretical) constant climate conditions, forest openings induce higher groundwater recharge and thus increasing lake levels. Today, the surroundings of LFS are largely forested, with arable fields covering only some 10 %.

Pollen records from three sites directly east of LFS (Müller, 1961; Figs. 1C, 11) suggest that land-use intensity has also been low during the Medieval. All three sites show comparatively low values of indicators for land-use activity during the high to late Medieval period (c. 1100-1500 AD). Pollen percentages of POACEAE (representing grasses), the best indicator for overall landscape openness, remain below 10 % (Plasterinsee) and 5 % (Fürstenseer See Moor and Moor nördlich Plasterinsee; Fig. 11), while CEREALIA pollen (representing cereals) is hardly identified. Much higher Medieval values of POACEAE (20-40 %) and CEREALIA (~5 %) are observed in Neu Heinder See and Löddigsee (Fig. 11). Both sites are located in the flat morainic landscape c. 80 km northwest and west of LFS, respectively, which has obviously been used more intensively during the Medieval. Pollen data thus suggest that the catchment area of LFS remained largely forested, despite some opening by potential grazing of livestock, local clearing and selective timber extraction. There is no indication that the marked lake-level increase in the period c. 1250-1450 AD could result from forest clearance and intensified land use.

Another potential driver for lake-level changes is anthropogenic drainage or damming. The first direct human impact on the local hydrographical system is recorded in 1636 AD (Krüger, 1921), when a water mill at the outlet of Lake Domjüchsee is mentioned (Fig. 1B). The mill was in use until the early 20th century AD. To bring sufficient water from a larger catchment area to this mill, Lake Domjüchsee was connected, via ditches, to neighbouring lakes including LFS. Section FUER12 suggests that the connection between LFS and Lake Zwirnsee was built in the 16th century at the latest. According to the map of Graf von Schmettau (1780), Lake Domjüchsee was connected to several lakes. This map also shows that at least since that time LFS received additional surficial water via a ditch from the east, which was probably built to operate a water mill at nearby Lake Schweingartensee (Fig. 1B). According to results on anthropogenic changes of the hydrography in the region (Kaiser et al., 2002; Kniesz, 2002; Driescher, 2003; Bleile, 2012), this connection may already have been established during the Medieval period, suggesting that LFS has been potentially influenced by anthropogenic drainage since the 13th/14th centuries AD. Regarding the surface water this drainage could potentially result into a water surplus (via an enlargement of the surface catchment) or a water deficit (via a decreasing drainage threshold). With the connections described above, LFS was transformed from a groundwater lake with a small surface catchment area into a stream lake with a larger surface catchment area (cf. Mauersberger, 2006). With a larger surface catchment area, water-level fluctuations could be potentially stronger following extreme precipitation events. Thus, the unusually high lake level in the period c. 1250-1450 AD might result from extreme precipitation as primary factor, enhanced by an artificially enlarged catchment area as secondary factor.

Further regional records on long-term water-level and drainage changes (e.g. Lorenz, 2007; Küster and Kaiser, 2010; Kaiser et al., 2012b) suggest almost identical lake-level variations during the last c. 800 years with increases in the 13th/14th centuries AD (partly up to the 17th/18th centuries AD) and decreases (relative to the Medieval) in the 18th/19th centuries AD.

Taking different hydrological lake types into account, these changes are influenced or even caused by man to different degrees, who became a major factor in lake hydrology during the last millennium due to the construction of mill and fish weirs, drainage of originally closed lake basins, canal construction and forest clearing (e.g. Jeschke, 1990; Bork et al., 1998; Böse, 2002; Driescher, 2003; Wolters, 2005; Böse and Brande, 2009; Bleile, 2012; Küster et al., 2012).

In a broader geographic context there are several well-documented records available on lake-level changes during the last millennium in central Europe and southern Scandinavia.

Data from southwestern central Europe (Jura mountains, northern French Pre-Alps, Swiss Plateau) indicate that an episode between c. 1200-1300 AD with high lake levels is contrasted by episodes with low lake levels (c. 650-850 AD, c. 1400 AD; Magny, 2004). This pattern was interpreted to be of climatic causation. A review of lake-level records from northern Poland shows inconsistent water levels for the last c. 1000 years (Starkel, 2003) that were probably influenced by both climatic and anthropogenic factors, triggering different hydrological responses of lakes. In the Ostholstein Lakeland area (NW Germany) extremely high lake levels were reconstructed for the period between c. 1300 and 1800 AD, which may correspond with both the cold-humid climate influence of the Little Ice Age and artificial control (damming) of the regional river system (Wieckowska et al., 2012). A compilation of several lake-level records in southern Sweden came to the conclusion that the successively increased humidity during the late Holocene resulted in a general rise in lake levels, particularly from c. 500 AD onwards (Berglund et al., 1996). Several findings on mire development in Denmark show that at c. 1200 AD a marked increase of mire wetness took place that was controlled by climate (Andersen et al., 1996). Additionally, a climatically driven late Medieval (after c. 1350 AD) to early modern lake-level increase of Lake Bliden (Danish Zealand island) suggest that the Little Ice Age in that area was wet (Olsen et al., 2010).

Beyond the areal focus described above a comparison of widespread major river flooding episodes in Spain, Great Britain and Poland of the last millennium (at c. 1080 AD, 1290 AD, 1380 AD) with phases of higher lake levels in central Europe shows that the late Medieval flooding episodes at c. 1290 and 1380 AD coincide well with higher lake levels in that time. The geographically widespread nature of these episodes suggests that a hydroclimatic change played a significant – probably dominating – role beside large-scale forest removal and agricultural development (Macklin et al., 2006). The same will likely be true for LFS.

6. Conclusions and outlook

Past lake-level changes may reflect the long-term dynamics in regional water budgets and the amplitude of hydrological changes. Reconstructing lake-level changes thus enables a better understanding of present-day dynamics and allows for estimations of potential future hydrological changes.

By recording a larger number of sedimentary sections with subsequent sedimentological-pedological, geochronological and palaeoecological analyses, we were able to show that littoral landforms and pedosedimentary sequences are suitable geoarchives for reconstructing past lake-levels in northern central Europe. A broader number of (semi-) terrestrial buried palaeosols along a lakeshore were systematically identified and analysed, providing evidence for changing hydrological site conditions during the late Holocene.

Our record suggests that periods of relatively low and of relatively high lake levels have alternated during the last millennium. According to the data available so far the amplitude of lake-level changes during the last c. 1000 years amounts to c. 3 m so that the fluctuations of the last c. 30 years (amplitude 1.2 m) only reflect a small amount of the potential variability. Climate may have been the major driver, whereas human impact seems to have played a minor role. Of particular interest is a probable event-like, significant lake-level rise in the late Medieval period that can be tentatively ascribed to heavy rainfall in central Europe, occurring in the first half of the 14th century AD. The present study underlines that absolute lake levels may be reconstructed with high altitudinal precision if the littoral zone is given closer attention.

This study is a step forward in developing lake-level chronologies for northern central Europe with new combinations of methods and data of high spatial (altitudinal) precision and temporal resolution. Ongoing work at LFS and surroundings combines data from supra- and eulittoral pedosedimentary sequences, as presented, with those from sublittoral and profundal sediment cores in order to both refine the record for the last millennium and to extend the local lake-level record over the last c. 15.000 years.

Acknowledgements

This research was undertaken within the 'Terrrestrial Environmental Observatories' (TERENO) and the 'Integrated Climate and Landscape Evolution Analyses' (ICLEA) projects of the Helmholtz Association, based at the GFZ German Research Centre for Geosciences in Potsdam. We are grateful to the representatives of Müritz National Park for their extensive supports. Sincere thanks goes to Peter Stüve (Neustrelitz) for providing the gauging data of Lake Großer Fürstenseer See. Bathymetric data were provided by the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern; airborne laserscanning data were provided by the Amt für Geoinformation, Vermessungs- und Katasterwesen Mecklenburg-Vorpommern. We thank Ross Beveridge (Berlin) for improving the English. Else Kolstrup (Sønderborg), an anonymous referee and Andrew Plater (Liverpool) are greatly acknowledged for suggestions to improve this manuscript.

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Figures

Fig. 1: A – Location of Lake Großer Fürstenseer See in Germany. B – Geological-geomorphological sketch map of the wider study area (after LUNG, 2005, adapted). C – Topographical-geomorphological sketch map of Lake Großer Fürstenseer See and surroundings with location of the sections investigated as well as the pollen records discussed in the text (map details after LiV, 2008, and own observations; bathymetric data for lakes Großer Fürstenseer See and Hinnensee from Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern). The lake surfaces range between 63.8 and

64.3 m HN according to LiV (2008). The 66 m HN contour line encompasses an area that is characterised by widespread lake terraces and peatlands.

Fig. 2: Lake-level gauging record of Lake Großer Fürstenseer See by reading of a graduated rod for the period 1985-2012. The record is based on monthly data.

Fig. 3: Photographs of the sections investigated with sedimentological and geochronological information. The total length of the ruler varies between 120 and 200 cm. One coloured section is equivalent to 10 cm.

Fig. 4: Simplified logs of the sections investigated with sedimentological (left column), pedological (right column) and geochronological information (radiocarbon and OSL ages: arrows point to sample position).

Fig. 5: Simplified pollen und macrofossil/compartment diagram FUER15. Macrofossils/compartments are given in total numbers (for countable objects) or estimated proportions of the total volume for charcoal, sand, tissues and wood.

Fig. 6: Visualisation of beach ridges at the southern shoreline of Lake Großer Fürstenseer See according to a digital elevation model (airborne laser scanning data with 1 m pixel size and ± 0.2 m vertical precision; provided by Amt für Geoinformation, Vermessungs- und Katasterwesen Mecklenburg-Vorpommern). A – Overview showing the quasi-flat topography along the lakeshore and the contrasting uneven topography of the surrounding outwash plain that consists of glaciofluvial sand and gravel. Pedosedimentary sections in that area are marked by dots. B – Detail around section FUER6, showing longitudinal landforms that are identified as beach ridges. C – Relief transects from the lakeshore via the beach ridges and

swales to the fossil cliff. The relief graphs along the transects were obtained by analysis of airborne laser scanning data by means of the program ArcGIS 10.1.

Fig. 7: Simplified pollen diagrams FUER3 and FUER6 comprising single pollen samples of these profiles. The pollen sum includes all tree pollen types, CORYLUS, and pollen types attributed to upland herbs. The low pollen sums result from poor pollen preservation and concentration in most of the samples. The samples of FUER3 consist nearly entirely of charcoal particles, so that explicit counting of charcoal particles, as performed in FUER6, was unfeasible.

Fig. 8: Sections investigated arranged in altitudinal order. For details of radiocarbon and OSL dates see Tables 2 and 3, respectively. The lake levels given are both specific situations measured within the last decades and the lake level reconstructed for the c. 1250-1450 AD period, respectively.

Fig. 9: A – Age to altitude relationship of geochronological data available from Lake Großer Fürstenseer See as well as selected gauging data from the observation period 1985-2012. For details of radiocarbon and OSL dates see Tables 2 and 3, respectively. The radiocarbon ages represent the age ranges with the highest corresponding probability (cf. Argyilan et al., 2010). B – Selected geochronological data covering the late Medieval (c. 1250-1450 AD period) lake-level rise onto c. 66 m HN.

Fig. 10: Approximated areas of Lake Großer Fürstenseer See for the measured low-stand in 2006 AD (lake level: 62.9 m HN; lake area: 2.24 km^2) and the reconstructed high-stand in the late Medieval (c. 1250-1450 AD) period (lake level: 66 m HN; lake area: 5.04 km^2), using a digital elevation model (airborne laser scanning data with 1 m pixel size and ± 0.2 m vertical

precision; provided by Amt für Geoinformation, Vermessungs- und Katasterwesen Mecklenburg-Vorpommern) and bathymetric data (provided by Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern). Area calculations and imaging were performed with the program ArcGIS 10.1. As the focus lies on changing areas of Lake Großer Fürstenseer See, no further adjacent lakes (see Fig. 1C) are depicted.

Fig. 11: Late Holocene land-use intensity as indicated by three pollen diagrams (selected palynomorphs) next to the eastern shoreline of Lake Großer Fürstenseer See (see Fig. 1C) in comparison with pollen diagrams from Lake Löddigsee (c. 85 km to the west) and Lake Neu Heinder See (c. 80 km to the northwest). The supposed high to late Medieval period (c. 1100-1500 AD) is shaded grey.

Tables

Table 1: Sedimentological data of the sections investigated from Lake Großer Fürstenseer See. For altitudes and coordinates of the sections see Table 2. In the case of sections FUER14, FUER15 and FUER16-4 the colour is characterised by common terms. In the case of profiles FUER10-2, FUER15, FUER16-4 and FUER19-2 the value of silt represents the clay-silt-sum. The grain-size composition is given in weight percentage. The content of gravel is given using a volumetric estimation (Ad-hoc-AG Boden, 2005; FAO, 2006). For sections FUER5 and FUER12 no sedimentological data are available.

Table 2: Geographical site properties and radiocarbon data of the sections investigated from Lake Großer Fürstenseer See. Data calibration was performed with Calib 6.0 (http://calib.qub.ac.uk/calib/) with a range of two sigma deviation for analysis. The calibrated

^{14}C ages given in the text and figures represent the age ranges with the highest corresponding probability (cf. Argyilan et al., 2010) that are indicated in the table by bold numbers.

Table 3: Optical dating (OSL) results and radioisotope concentrations of the sections investigated from Lake Großer Fürstenseer See. For altitudes and coordinates of the sections see Table 2.

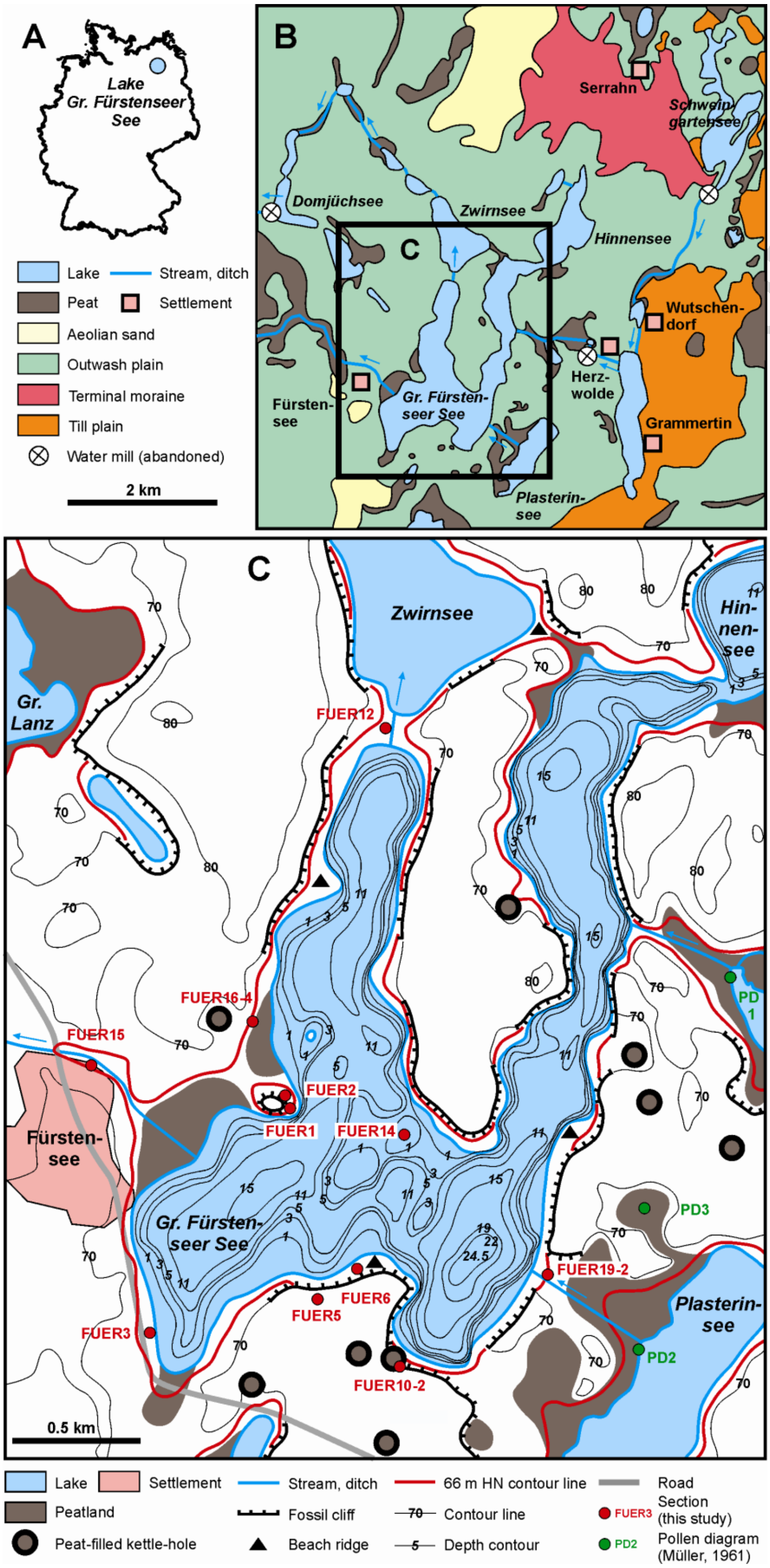
A
Lake Gr. Fürstenseer See
Lake
Stream, ditch
Peat
Settlement
Aeolian sand
Outwash plain
Terminal moraine
Till plain
Water mill (abandoned)
2 km
B
Serrahn
Schweingartensee
Domjüchsee
Zwirnsee
Hinnensee
C
Wutschendorf
Herzwolde
Fürstensee
Gr. Fürstenseer See
Grammertin
Plasterinsee
C
Zwirnsee
Hinnensee
Gr. Lanz
FUER12
FUER16-4
FUER15
FUER2
FUER1
FUER14
Fürstensee
Gr. Fürstenseer See
FUER6
FUER5
FUER3
FUER10-2
FUER19-2
PD 1
PD3
PD2
Plasterinsee
0.5 km
Lake
Settlement
Stream, ditch
66 m HN contour line
Road
Peatland
Fossil cliff
Contour line
Section (this study)
Peat-filled kettle-hole
Beach ridge
Depth contour
Pollen diagram (Müller, 1961)

Figure 1

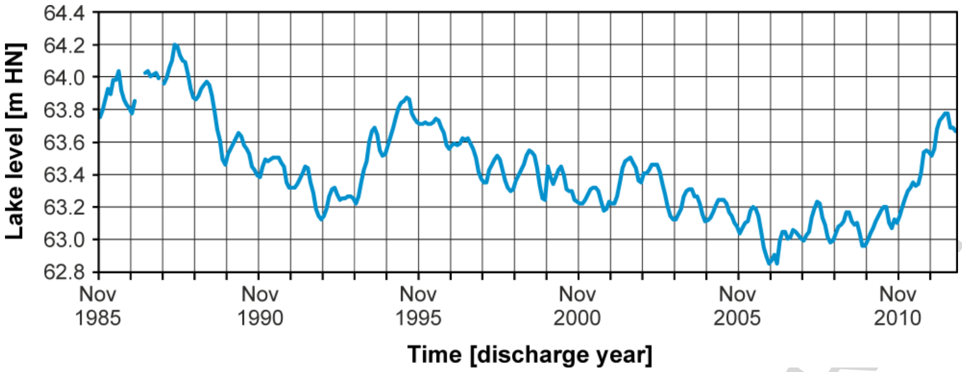
Lake level [m HN]
64.4
64.2
64.0
63.8
63.6
63.4
63.2
63.0
62.8
Nov 1985
Nov 1990
Nov 1995
Nov 2000
Nov 2005
Nov 2010
Time [discharge year]

Figure 2

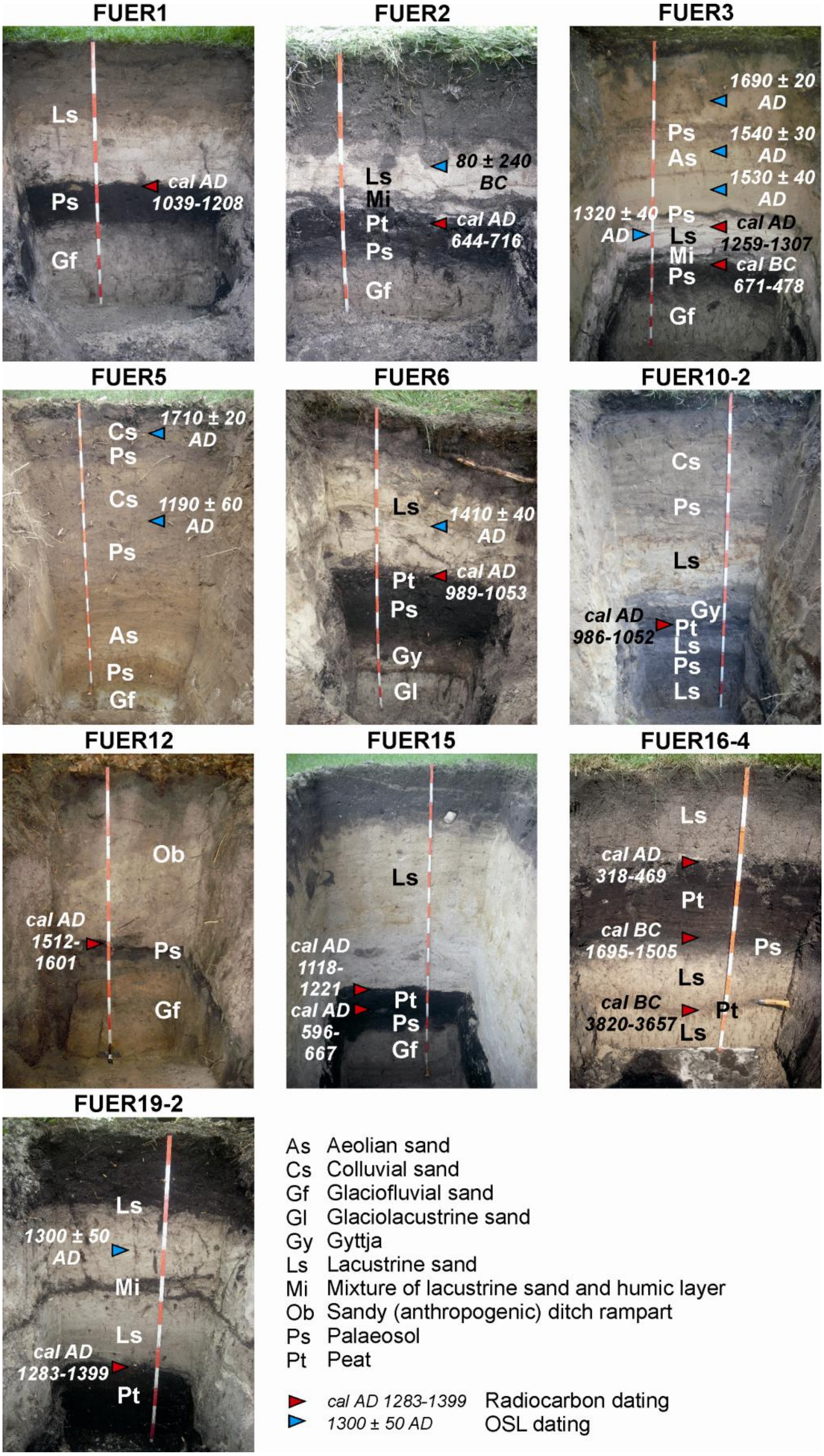
FUER1
Ls
Ps
Gf
cal AD 1039-1208
FUER2
Ls
Mi
Pt
Ps
Gf
80 ± 240 BC
cal AD 644-716
FUER3
1690 ± 20 AD
Ps
As
1540 ± 30 AD
1530 ± 40 AD
1320 ± 40 AD
Ps
Ls
Mi
Ps
Gf
cal AD 1259-1307
cal BC 671-478
FUER5
Cs
Ps
Cs
Ps
As
Ps
Gf
1710 ± 20 AD
1190 ± 60 AD
FUER6
Ls
Pt
Ps
Gy
Gl
1410 ± 40 AD
cal AD 989-1053
FUER10-2
Cs
Ps
Ls
Gy
Pt
Ls
Ps
Ls
cal AD 986-1052
FUER12
Ob
Ps
Gf
cal AD 1512-1601
FUER15
Ls
Pt
Ps
Gf
cal AD 1118-1221
cal AD 596-667
FUER16-4
Ls
Pt
Ps
Ls
Pt
Ls
cal AD 318-469
cal BC 1695-1505
cal BC 3820-3657
FUER19-2
Ls
Mi
Ls
Pt
1300 ± 50 AD
cal AD 1283-1399
As Aeolian sand
Cs Colluvial sand
Gf Glaciofluvial sand
Gl Glaciolacustrine sand
Gy Gyttja
Ls Lacustrine sand
Mi Mixture of lacustrine sand and humic layer
Ob Sandy (anthropogenic) ditch rampart
Ps Palaeosol
Pt Peat
cal AD 1283-1399 Radiocarbon dating
1300 ± 50 AD OSL dating

Figure 3

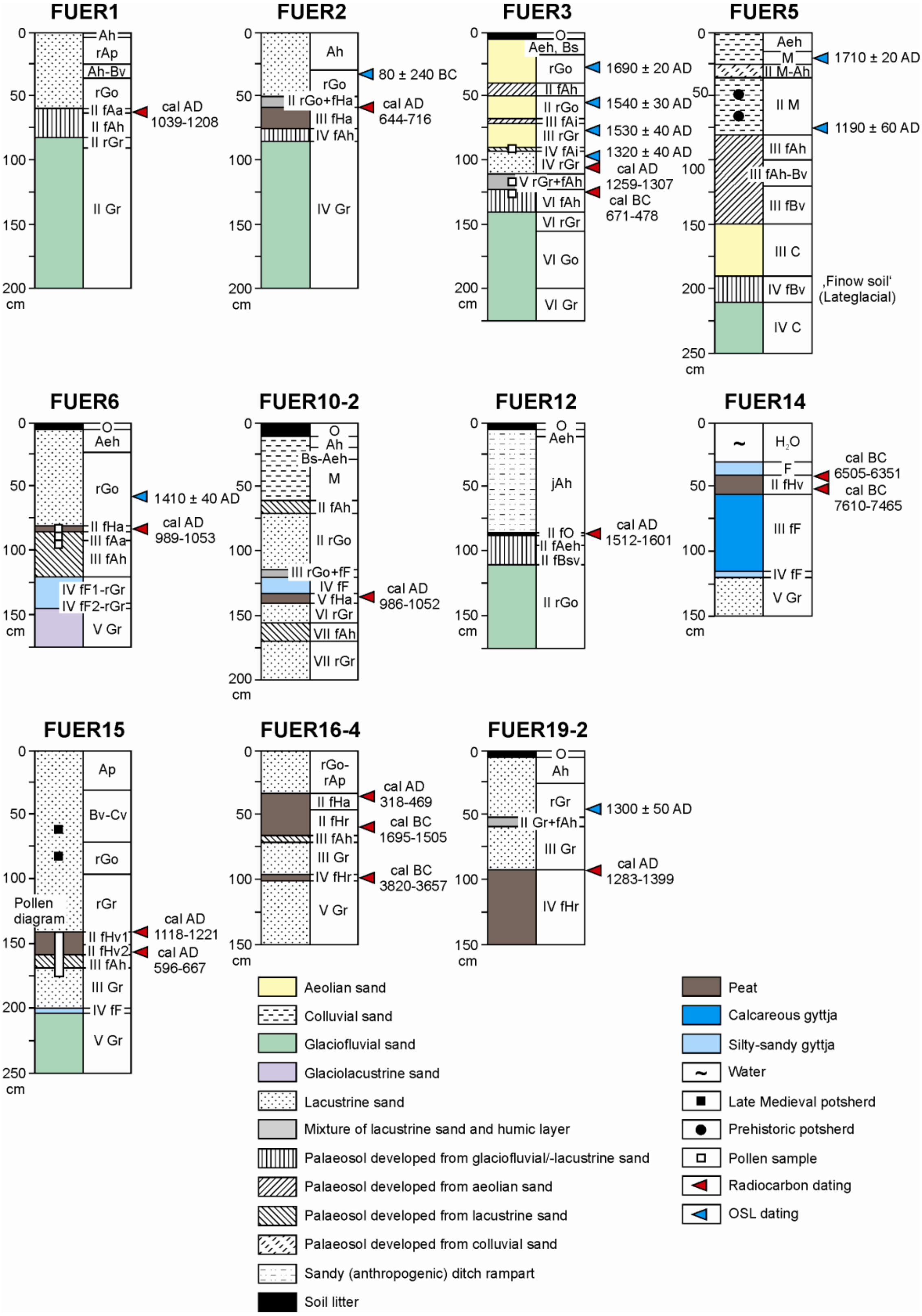
FUER1
Ah
rAp
Ah-Bv
rGo
II fAa
II fAh
II rGr
II Gr
cal AD
1039-1208
FUER2
Ah
rGo
II rGo+fHa
III fHa
IV fAh
IV Gr
80 ± 240 BC
cal AD
644-716
FUER3
O
Aeh, Bs
rGo
II fAh
II rGo
III fAi
III rGr
IV fAi
IV rGr
V rGr+fAh
VI fAh
VI rGr
VI Go
VI Gr
1690 ± 20 AD
1540 ± 30 AD
1530 ± 40 AD
1320 ± 40 AD
cal AD
1259-1307
cal BC
671-478
FUER5
Aeh
M
II M-Ah
II M
III fAh
III fAh-Bv
III fBv
III C
IV fBv
IV C
1710 ± 20 AD
1190 ± 60 AD
‚Finow soil'
(Lateglacial)
FUER6
O
Aeh
rGo
II fHa
III fAa
III fAh
IV fF1-rGr
IV fF2-rGr
V Gr
1410 ± 40 AD
cal AD
989-1053
FUER10-2
O
Ah
Bs-Aeh
M
II fAh
II rGo
III rGo+fF
IV fF
V fHa
VI rGr
VII fAh
VII rGr
cal AD
986-1052
FUER12
O
Aeh
jAh
II fO
II fAeh
II fBsv
II rGo
cal AD
1512-1601
FUER14
~
H_2O
F
II fHv
III fF
IV fF
V Gr
cal BC
6505-6351
cal BC
7610-7465
FUER15
Ap
Bv-Cv
rGo
rGr
Pollen
diagram
II fHv1
II fHv2
III fAh
III Gr
IV fF
V Gr
cal AD
1118-1221
cal AD
596-667
FUER16-4
rGo-
rAp
II fHa
II fHr
III fAh
III Gr
IV fHr
V Gr
cal AD
318-469
cal BC
1695-1505
cal BC
3820-3657
FUER19-2
O
Ah
rGr
II Gr+fAh
III Gr
IV fHr
1300 ± 50 AD
cal AD
1283-1399
0
50
100
150
200
250
cm
Aeolian sand
Colluvial sand
Glaciofluvial sand
Glaciolacustrine sand
Lacustrine sand
Mixture of lacustrine sand and humic layer
Palaeosol developed from glaciofluvial/-lacustrine sand
Palaeosol developed from aeolian sand
Palaeosol developed from lacustrine sand
Palaeosol developed from colluvial sand
Sandy (anthropogenic) ditch rampart
Soil litter
Peat
Calcareous gyttja
Silty-sandy gyttja
Water
Late Medieval potsherd
Prehistoric potsherd
Pollen sample
Radiocarbon dating
OSL dating

Figure 4

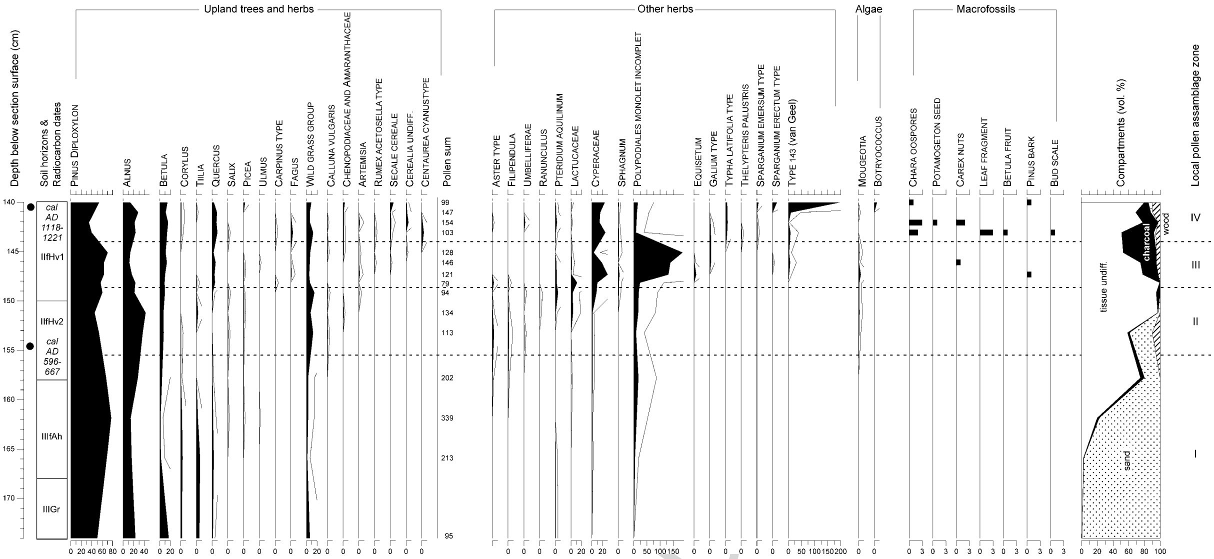
Upland trees and herbs
Other herbs
Algae
Macrofossils
Depth below section surface (cm)
Soil horizons &
Radiocarbon dates
Pinus Diploxylon
Alnus
Betula
Corylus
Tilia
Quercus
Salix
Picea
Ulmus
Carpinus type
Fagus
Wild grass group
Calluna vulgaris
Chenopodiaceae and Amaranthaceae
Artemisia
Rumex acetosella type
Secale cereale
Cerealia undiff.
Centaurea cyanustype
Pollen sum
Aster type
Filipendula
Umbelliferae
Ranunculus
Pteridium aquilinum
Lactucaceae
Cyperaceae
Sphagnum
Polypodiales monolet incomplet
Equisetum
Galium type
Typha latifolia type
Thelypteris palustris
Sparganium emersum type
Sparganium erectum type
Type 143 (van Geel)
Mougeotia
Botryococcus
Chara oospores
Potamogeton seed
Carex nuts
Leaf fragment
Betula fruit
Pinus bark
Bud scale
Compartments (vol. %)
Local pollen assamblage zone
140
145
150
155
160
165
170
cal AD 1118-1221
IIfHv1
IIfHv2
cal AD 596-667
IIIfAh
IIIGr
99
147
154
103
128
146
121
79
94
134
113
202
339
213
95
tissue undiff.
charcoal
wood
sand
IV
III
II
I
0 20 40 60 80
0 20 40
0 20
0 50 100 150
0 50 100 150 200
0 3
0 20 40 60 80 100

Figure 5

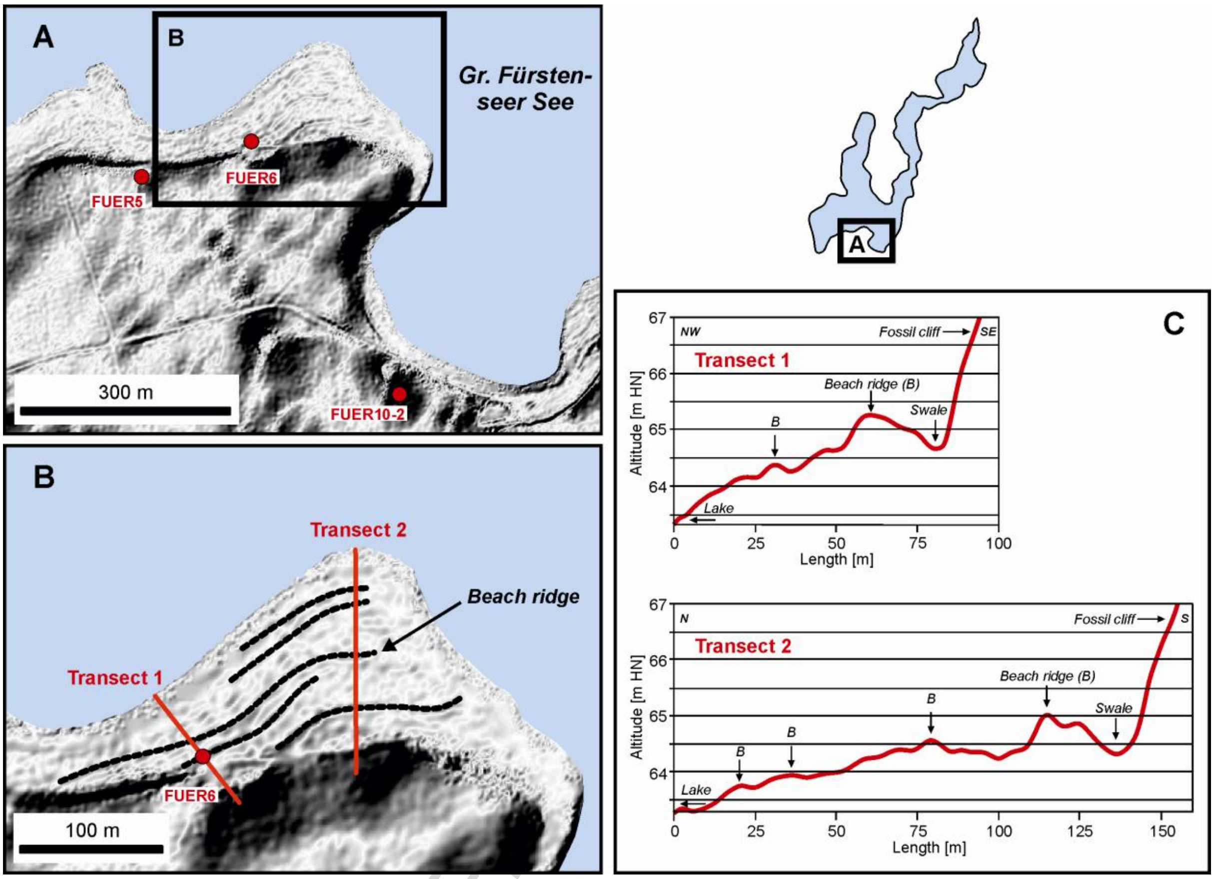
A
B
Gr. Fürsten-
seer See
FUER5
FUER6
300 m
FUER10-2
B
Transect 2
Beach ridge
Transect 1
FUER6
100 m
A
C
Transect 1
NW
SE
Fossil cliff
Beach ridge (B)
Swale
B
Lake
Altitude [m HN]
67
66
65
64
0
25
50
75
100
Length [m]
Transect 2
N
S
Fossil cliff
Beach ridge (B)
Swale
B
B
B
Lake
Altitude [m HN]
67
66
65
64
0
25
50
75
100
125
150
Length [m]

Figure 6

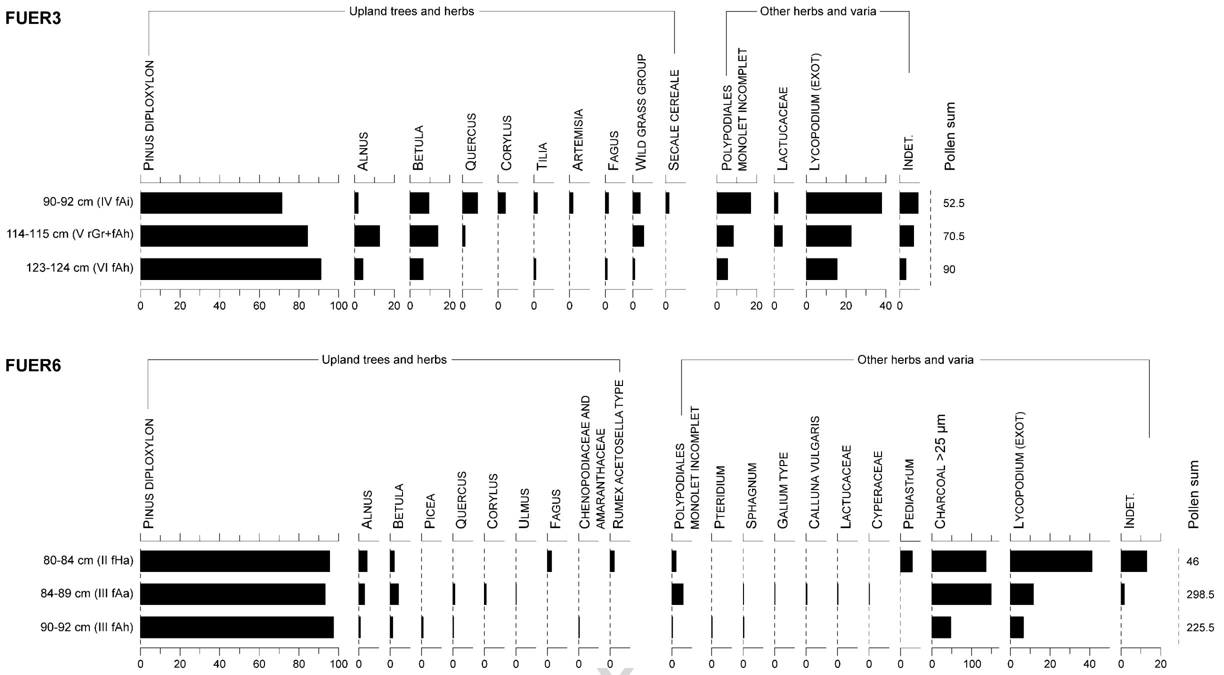
FUER3
Upland trees and herbs
Other herbs and varia
PINUS DIPLOXYLON
ALNUS
BETULA
QUERCUS
CORYLUS
TILIA
ARTEMISIA
FAGUS
WILD GRASS GROUP
SECALE CEREALE
POLYPODIALES MONOLET INCOMPLET
LACTUCACEAE
LYCOPODIUM (EXOT)
INDET.
Pollen sum
90-92 cm (IV fAi)
114-115 cm (V rGr+fAh)
123-124 cm (VI fAh)
52.5
70.5
90
0 20 40 60 80 100
FUER6
Upland trees and herbs
Other herbs and varia
PINUS DIPLOXYLON
ALNUS
BETULA
PICEA
QUERCUS
CORYLUS
ULMUS
FAGUS
CHENOPODIACEAE AND AMARANTHACEAE
RUMEX ACETOSELLA TYPE
POLYPODIALES MONOLET INCOMPLET
PTERIDIUM
SPHAGNUM
GALIUM TYPE
CALLUNA VULGARIS
LACTUCACEAE
CYPERACEAE
PEDIASTRUM
CHARCOAL >25 µm
LYCOPODIUM (EXOT)
INDET.
Pollen sum
80-84 cm (II fHa)
84-89 cm (III fAa)
90-92 cm (III fAh)
46
298.5
225.5
0 20 40 60 80 100

Figure 7

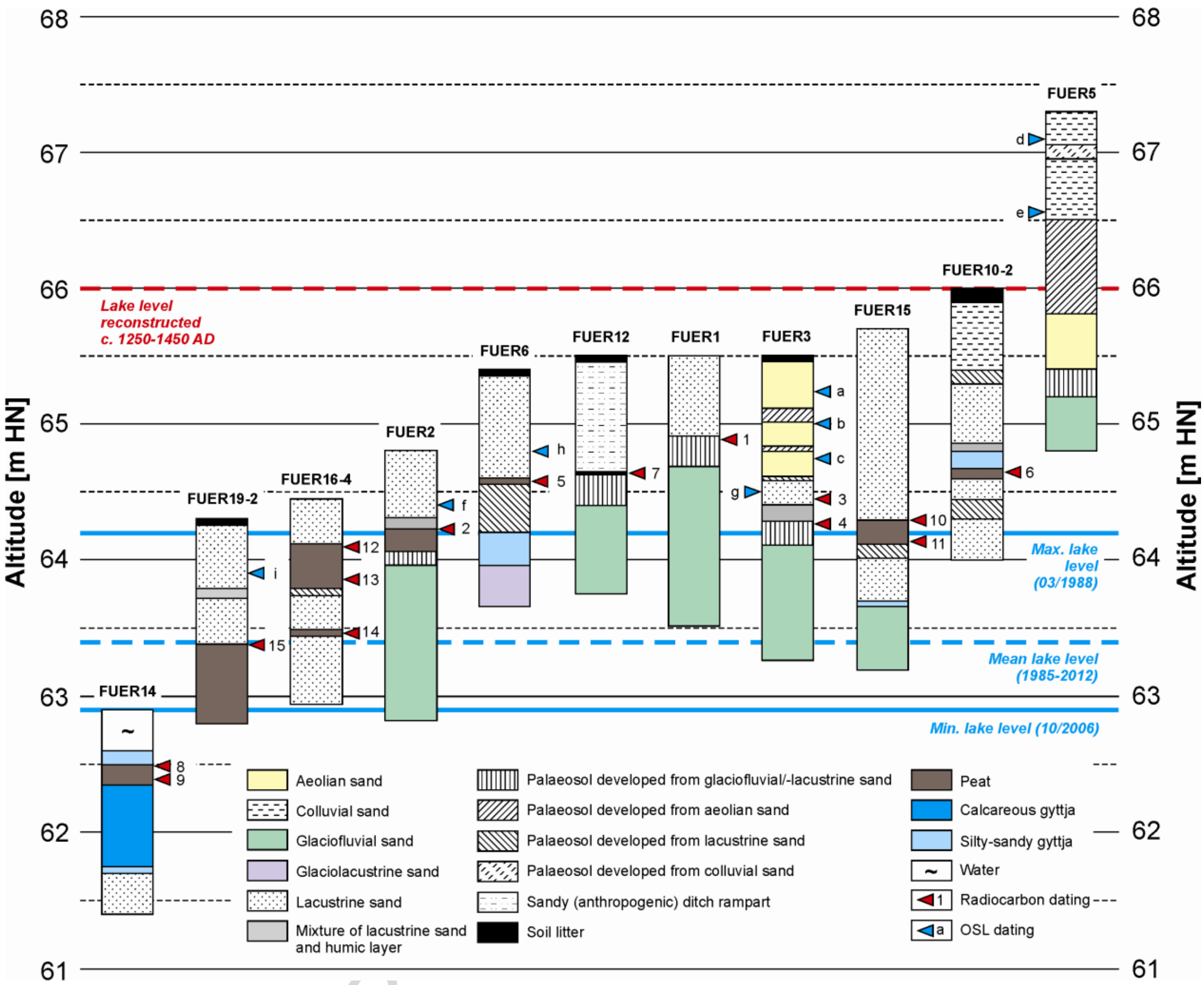
68
67
66
65
64
63
62
61
Altitude [m HN]
Lake level reconstructed c. 1250-1450 AD
Max. lake level (03/1988)
Mean lake level (1985-2012)
Min. lake level (10/2006)
FUER14
FUER19-2
FUER16-4
FUER2
FUER6
FUER12
FUER1
FUER3
FUER15
FUER10-2
FUER5
~
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
a
b
c
d
e
f
g
h
i
Aeolian sand
Colluvial sand
Glaciofluvial sand
Glaciolacustrine sand
Lacustrine sand
Mixture of lacustrine sand and humic layer
Palaeosol developed from glaciofluvial/-lacustrine sand
Palaeosol developed from aeolian sand
Palaeosol developed from lacustrine sand
Palaeosol developed from colluvial sand
Sandy (anthropogenic) ditch rampart
Soil litter
Peat
Calcareous gyttja
Silty-sandy gyttja
Water
Radiocarbon dating
OSL dating

Figure 8

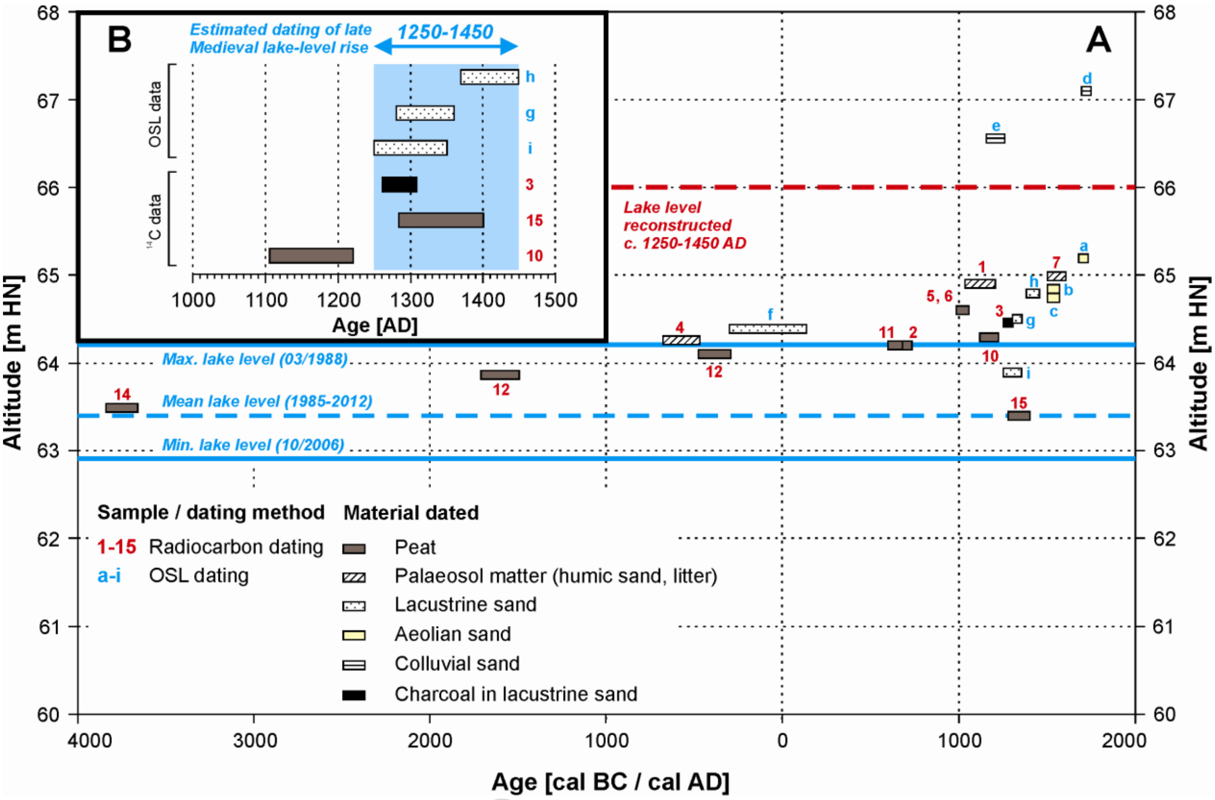
A
B
Estimated dating of late Medieval lake-level rise
1250-1450
OSL data
14C data
h
g
i
3
15
10
1000
1100
1200
1300
1400
1500
Age [AD]
68
67
66
65
64
63
62
61
60
Altitude [m HN]
Lake level reconstructed c. 1250-1450 AD
Max. lake level (03/1988)
Mean lake level (1985-2012)
Min. lake level (10/2006)
d
e
a
7
1
5, 6
b
c
4
f
11
2
12
14
Sample / dating method
1-15 Radiocarbon dating
a-i OSL dating
Material dated
Peat
Palaeosol matter (humic sand, litter)
Lacustrine sand
Aeolian sand
Colluvial sand
Charcoal in lacustrine sand
4000
3000
2000
1000
0
1000
2000
Age [cal BC / cal AD]

Figure 9

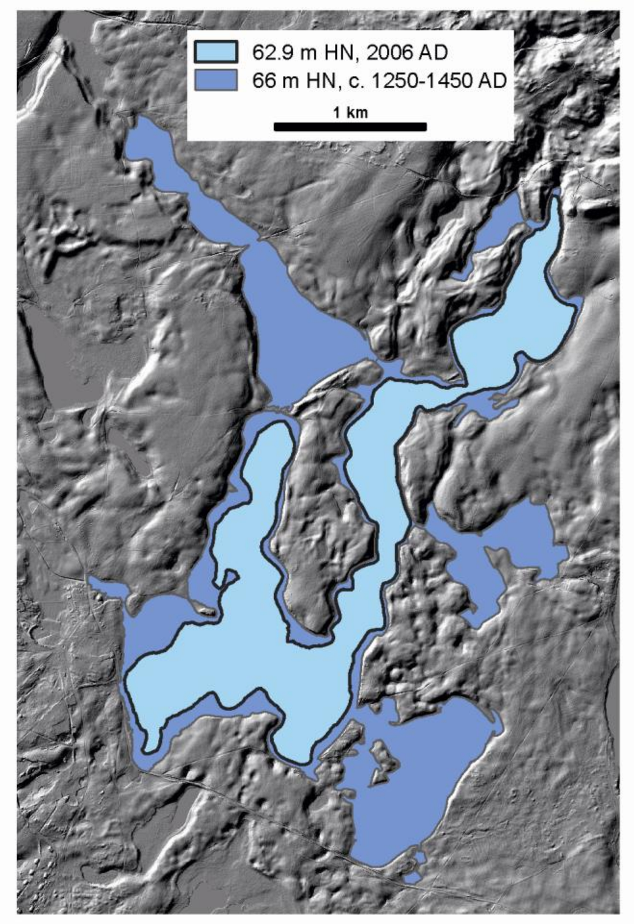

Figure 10

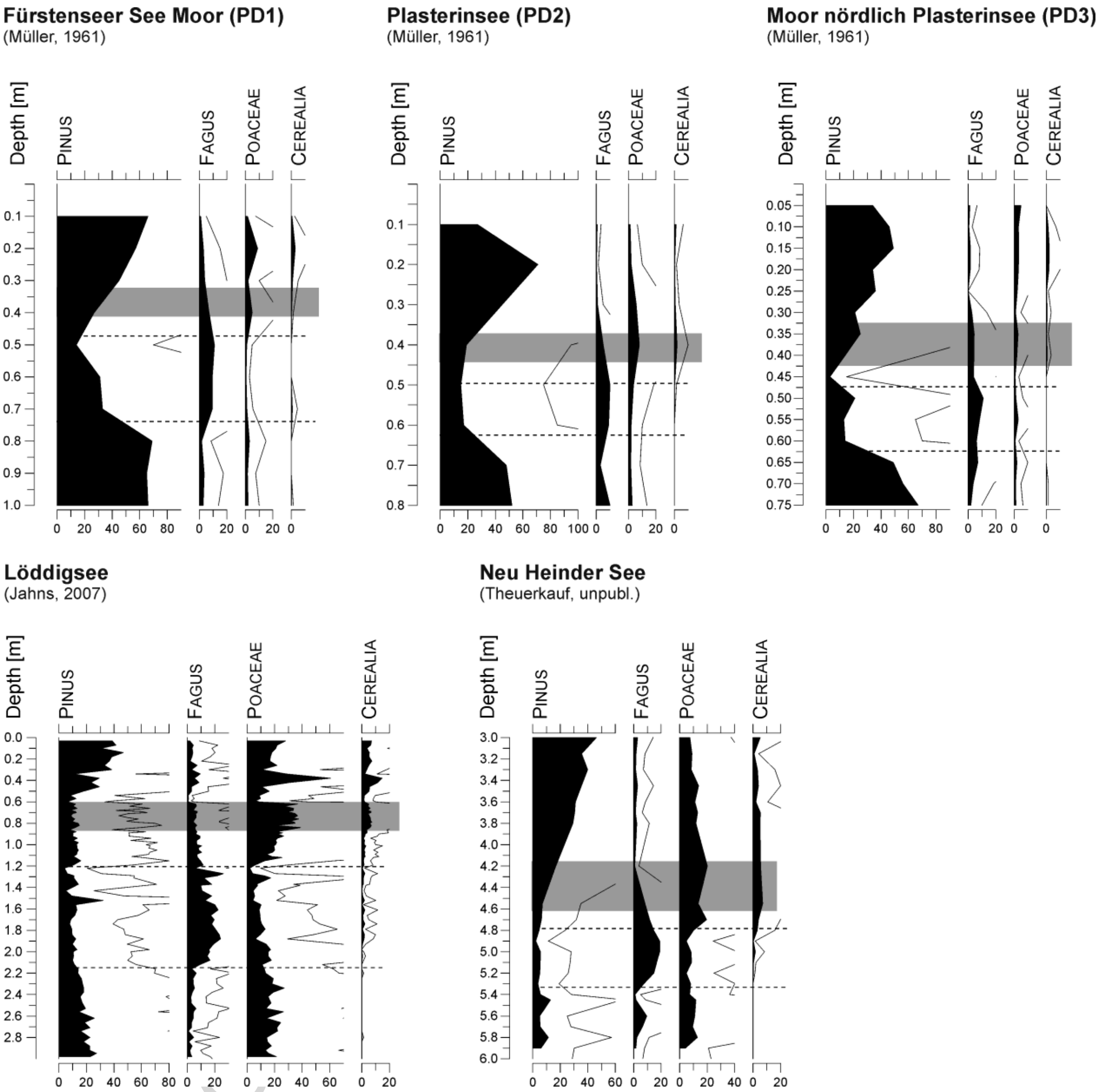
Fürstenseer See Moor (PD1)
(Müller, 1961)
Plasterinsee (PD2)
(Müller, 1961)
Moor nördlich Plasterinsee (PD3)
(Müller, 1961)
Löddigsee
(Jahns, 2007)
Neu Heinder See
(Theuerkauf, unpubl.)
Depth [m]
PINUS
FAGUS
POACEAE
CEREALIA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
0
20
40
60
80
100

Figure 11

Table 1

Section	Site character (landform)	Sample	Sampling depth	Sediment classification	Soil horizon	Soil horizon	Colour	Grain-size composition, total			Grain-size composition, sand fraction			Textural class	Gravel	LOI	$CaCO_3$
								Clay <0.002 mm	Silt <0.063 mm	Sand <2 mm	Fine <0.2 mm	Medium <0.63 mm	Coarse <2 mm				
			[cm]		[KA5]	[FAO]	[Munsell]	[%]	[%]	[%]	[%]	[%]	[%]	[KA5]	[%]	[%]	[%]
FUER1	Terrace	a	8-25	Lacustrine	rAp	Ap	10YR4/3	0.6	1.4	98.0	20.9	58.7	18.4	Ss (mSgs)	5	1.0	0
		b	34-60	Lacustrine	rGo	Cl	10YR7/4	0.2	0.3	99.5	5.7	58.2	35.6	Ss (mSgs)	7	0.2	0
		c	62-81	Glaciofluvial	II fAh	2Ahb	10YR2/1	0.5	3.7	95.8	13.4	64.0	18.4	Ss (mSgs)	5	4.4	0
		d	90-200	Glaciofluvial	II rGr	2Cr	2.5Y6/3	0.4	0.7	98.9	13.6	67.8	17.5	Ss (mSgs)	<1	0.3	0
FUER2	Terrace	a	0-30	Lacustrine	Ah	Ah	2.5Y3/2	0.3	1.4	98.3	14.2	54.4	29.7	Ss (mSgs)	<1	4.1	0
		b	30-50	Lacustrine	rGo	Cl	2.5Y7/4	0.2	0.2	99.6	0.2	61.6	37.8	Ss (mSgs)	0	0.2	0
		c	50-58	Lacustrine	II rGo+fHa	2Hab/Cl	2.5Y7/4	0.2	0.7	99.1	2.1	59.4	37.6	Ss (mSgs)	0	2.8	0
		d	58-75	Peat	III fHa	3Hab	10YR3/2	1.7	38.2	60.1	5.4	36.9	17.9	(Su3)	0	74.8	0
		e	75-85	Glaciofluvial	IV fAh	4Ahb	2.5Y4/1	0.4	1.5	98.1	12.4	61.3	24.4	Ss (mSgs)	0	3.6	0
		f	85-200	Glaciofluvial	IV Gr	4Cr	2.5Y6/4	0.4	0.8	98.2	22.4	52.7	18.7	Ss (mSgs)	0	0.5	0
FUER15	Terrace	a	0-30	Lacustrine	Ap	Ap	dark grey	-	11.1	88.9	29.9	49.2	9.7	-	0	2.6	0
		b	30-70	Lacustrine	Bv-Cv	CBw	light yellowish brown	-	2.0	98.0	15.1	68.1	14.8	-	2	0.3	0
		c	70-95	Lacustrine	rGo	Cl	gray, yellowish brown	-	2.0	98.0	19.4	68.2	10.4	-	2	0.3	0
		d	95-140	Lacustrine	rGr	Cr	gray	-	2.0	98.0	15.1	71.8	11.2	-	<1	0.2	0
		e	140-150	Peat	II fHv1	2Heb1	dark brown	-	-	-	-	-	-	-	0	73.9	0
		f	150-158	Peat	II fHv2	2Heb2	dark brown	-	-	-	-	-	-	-	0	37.8	0
		g	158-168	Lacustrine	III fAh	3Ahb	dark brown	-	13.2	86.8	46.5	39.7	0.6	-	0	4.2	0
		h	168-200	Lacustrine	III Gr	3Cr	gray	-	4.6	95.4	70.0	25.3	0.1	-	0	0.5	0

FUER16-4	Terrace	a	0-32	Lacustrine	rGo-rAp	ApCl	dark gray	-	13.5	86.5	25.5	47.6	7.0	-	0	6.4	0
		b	32-45	Peat	II fHa	2Hab	black	-	-	-	-	-	-	-	0	72.3	0
		c	45-65	Peat	II fHr	2Hib	dark brown	-	-	-	-	-	-	-	0	63.3	0
		d	65-69	Lacustrine	III fAh	3Ahb	black	-	6.1	93.9	40.2	47.9	3.0	-	0	2.8	0
		e	69-96	Lacustrine	III Gr	3Cr	gray	-	2.4	97.6	45.8	49.3	1.8	-	0	0.6	0
		f	96-100	Peat	IV fHr	4Hib	dark brown	-	-	-	-	-	-	-	0	81.2	0
		g	100-150	Lacustrine	V Gr	5Cr	gray	-	11.6	88.4	36.7	49.4	1.5	-	0	0.7	0
FUER6	Beach ridge	aS	5-10	Lacustrine	Aeh	Arh	10YR2/2	0.3	1.5	98.2	2.2	69.7	26.3	Ss (mSgs)	0	7.6	0
		bS	10-80	Lacustrine	rGo	Cl	10YR6/4	0.2	0.4	99.4	2.74	63.54	33.1	Ss (mSgs)	<5	0.4	0
		cS	80-84	Peat	II fHa	2Hab	10YR2/1	0.7	8.7	90.6	10.7	54.3	25.6	Ss (mSgs)	0	31.9	0
		aP	80-84	Peat	II fHa	2Hab	10YR2/1	0.6	9.5	89.9	2.5	45.4	42.0	Ss (gS)	0	32.3	0
		bP	84-89	Lacustrine	III fAa	3Ahb1	10YR2/1	0.6	7.5	91.9	14.9	50.1	26.8	Ss (mSgs)	0	22.2	0
		cP	90-92	Lacustrine	III fAh	3Ahb2	10YR2/1	0.6	5.5	93.9	13.5	54.2	26.2	Ss (mSgs)	5	14.2	0
		dS	90-120	Lacustrine	III fAh	3Ahb2	10YR2/1	0.5	4.3	95.2	16.4	52.9	25.9	Ss (mSgs)	5	9.9	0
		eS	120-140	Lacustrine	IV fF1-rGr	4Lrb1	2.5Y4/3	1.2	11.1	87.7	20.4	47.1	20.4	Su2	0	3.1	0
		fS	140-142	Lacustrine	IV fF2-rGr	4Lrb2	10YR4/4	0.7	11.1	88.2	23.4	44.0	20.8	Su2	0	7.9	0
		gS	142-150	Glaciolacustrine	V Gr	5Cr	2.5Y6/3	1.3	7.9	90.8	64.8	23.8	2.2	Ss (fSms)	0	0.4	0
FUER10-2	Peatland	a	0-8	Colluvial	Ah	Ah	7.5YR2.5/1	-	21.7	78.3	15.1	50.2	13.1	-	1	12.6	0
		b	18-50	Colluvial	M	C	10YR4/4	-	7.2	92.8	21.2	59.1	12.5	-	1	1.4	0
		c	60-104	Lacustrine	II rGo	2Cl	10YR6/6	-	2.7	97.3	14.2	65.0	18.2	-	2	0.6	0
		d	110-123	Lacustrine	IV fF	4Lb	10YR4/2	-	62.9	37.1	27.8	8.6	0.7	-	0	12.3	0
		e	123-130	Peat	V fHa	5Hab	10YR2/1	-	12.7	87.3	20.1	60.0	7.3	-	0	28.4	0
		f	130-144	Lacustrine	VI rGr	6Cr	2.5Y4/2	-	10.2	89.8	28.9	47.8	13.1	-	2	2.4	0
		g	144-160	Lacustrine	VII fAh	7Ahb	10YR3/1	-	7.3	92.7	39.9	42.4	10.5	-	2	1.1	0
FUER19-2	Peatland	a	5-25	Lacustrine	Ah	Ah	10YR2/2	-	13.7	86.3	7.2	55.7	10.1	-	0	13.4	0
		b	25-51	Lacustrine	rGr	Cr	10YR6/4	-	0.5	99.5	2.3	91.3	5.6	-	2	0.3	0
		c	51-57	Lacustrine	II Gr+fAh	2Ahb/Cr	10YR2/2	-	4.2	95.8	5.3	31.2	55.9	-	5	3.4	0
		d	91-110	Peat	III fHr	3Hib	10YR2/2	-	-	-	-	-	-	-	0	81.2	0
FUER3	Dune	aS	50-70	Aeolian	II rGo	2Cl	10YR5/3	0.7	0.5	98.8	34.3	55.0	9.5	Ss (mSfs)	0	0.4	0

		aP	90-92	Lacustrine	IV fAi	4Ahb	10YR3/3	0.6	6.8	92.6	23.1	35.1	34.4	St2	0	3.0	0
		bS	92-103	Lacustrine	IV rGr	4Cr	2.5Y7/2	0.3	0.4	99.3	12.6	52.7	34.0	Ss (mSgs)	<5	0.3	0
		bP	114-115	Lacustrine	V rGr+fAh	5Ahb/Cr	10YR2/1+2.5Y7/2	0.7	4.2	95.1	21.1	54.6	19.5	Ss (mSgs)	0	13.1	0
		cP	123-124	Glaciofluvial	VI fAh	6Ahb	10YR2/1	0.5	2.2	97.3	16.7	53.7	26.9	Ss (mSgs)	0	13.7	0
		cS	123-140	Glaciofluvial	VI fAh	6Ahb	10YR2/1	0.7	5.4	93.9	22.4	52.7	18.7	St2	0	6.7	0
FUER14	Lake shallow	a	30-40	Lacustrine	F	L	gray	0.1	0.3	99.7	-	-	-	Ss	0	9.8	21.7
		b	40-55	Peat	II fHv	2Heb	dark brown	0.0	14.4	85.6	-	-	-	(St2)	0	85.6	0
		c	55-115	Lacustrine	III fF	3Lb	pale brown	3.7	79.5	16.8	-	-	-	(Us)	0	5.5	85.6
		d	115-120	Lacustrine	IV fF	4Lb	pale brown	0.5	1.6	98.0	-	-	-	Ss	0	1.1	12.1

Table 2

Sample ID-1	**Sample ID-2**	**Section altitude** [m HN]	**Northing**	**Easting**	**Depth** [cm]	**Material dated**	**Lab ID**	**Age** [yrs BP]	**Age calibrated** [cal yrs BC/AD]
FUER1	1	65.5	53°18'26.8"	13°09’30.4"	60-62	humic sand	Poz-37353	905 ± 30	cal AD **1039-1208 (1.000)**
FUER2	2	64.8	53°18'23.5“	13°09'32.9“	58-59	peat	Poz-37390	1340 ± 30	cal AD **644-716 (0.871)**, 744-768 (0.129)
FUER3a	3	65.5	53°17'57.9“	13°09'02.9“	109	charcoal	Poz-37354	705 ± 30	cal AD **1259-1307 (0.848)**, 1362-1386 (0.152)
FUER3b	4	65.5			123-124	humic sand	Poz-38930	2465 ± 35	cal BC 760-682 (0.279), **671-478 (0.593)**, 471-414 (0.128)
FUER6	5	65.4	53°18'03.4“	13°09'43.4“	80-84	peat	Poz-37355	990 ± 30	cal AD **989-1053 (0.601)**, 1079-1153 (0.399)
FUER10-2	6	66.0	53°17'52.9"	13°09'53.9"	123-124	peat	Poz-46604	995 ± 30	cal AD **986-1052 (0.670)**, 1080-1129 (0.250), 1132-1153 (0.080)
FUER12	7	65.5	53°19'14.6"	13°09'88.1"	80-82	soil litter	Poz-38927	280 ± 30	cal AD 1497-1504 (0.010), **1512-1601 (0.563)**, 1616-1666 (0.404), 1784-1795 (0.023)
FUER14a	8	62.9 (lake surface)	53°18'34.0"	13°09'79.8"	41-42[1]	plant macro-remains[2]	Poz-38928	7570 ± 50	cal BC **6505-6351 (0.960)**, 6310-6262 (0.040)
FUER14b	9	62.9 (lake surface)			49-50[1]	peat	Poz-38929	8510 ± 60	cal BC 7630-7626 (0.002), **7610-7465 (0.998)**
FUER15a	10	65.7	53°18'48.3"	13°08'87.8"	140-141	peat	Poz-47654	880 ± 30	cal AD 1043-1106 (0.280), **1118-1221 (0.720)**
FUER15b	11	65.7			154-155	sandy peat	Poz-47655	1405 ± 30	**cal AD 596-667 (1.000)**
FUER16-4a	12	64.5	53°18'55.7"	13°09'40.1"	32-34	peat	Erl-16596	1656 ± 44	cal AD 258-299 (0.100), **318-469 (0.764)**, 477-534 (0.135)
FUER16-4b	13	64.5			57-58	peat	Erl-16597	3331 ± 46	cal BC 1737-1710 (0.054), **1695-1505 (0.946)**
FUER16-4c	14	64.5			96-99	peat	Erl-16598	4987 ± 47	cal BC 3942-3857 (0.238), 3842-3838 (0.005), **3820-3657 (0.757)**
FUER19-2	15	64.3	53°18'07.0"	13°10'38.3"	91-92	peat	Erl-16599	637 ± 41	cal AD **1283-1399 (1.000)**

[1] Depth below water surface (lake level). [2] The plant macro-remains comprise seeds of *Carex* and *Eupatorium*.

Table 3

Sample ID-1	**Sample ID-2**	**Material**	**Lab. No.**	**Depth**	**U**[a]	**Th**[a]	**K**[a]	**Cosmic dose rate**[b]	**Water cont. measured**[c]	**Water cont. estimated**	**Dose rate**	**Equivalent dose (ED)**[d]	**OSL age**	**OSL age**
				[cm]	[ppm]	[ppm]	[%]	[Gy/ka]	[%]	[%]	[Gy/ka]	[Gy]	[ka]	[yrs BC/AD]
FUER3-1	a	aeolian sand	HUB-0187	27	0.58 ± 0.05	1.88 ± 0.17	1.01 ± 0.02	0.21 ± 0.01	5.7	6 ± 4	1.39 ± 0.07	0.44 ± 0.01	0.32 ± 0.02	1690 ± 20 AD
FUER3-2	b	aeolian sand	HUB-0188	55	0.62 ± 0.09	1.96 ± 0.19	1.02 ± 0.02	0.20 ± 0.01	10.0	10 ± 5	1.34 ± 0.08	0.63 ± 0.01	0.47 ± 0.03	1540 ± 30 AD
FUER3-3	c	aeolian sand	HUB-0189	76	0.62 ± 0.07	1.70 ± 0.11	1.00 ± 0.02	0.20 ± 0.01	9.3	10 ± 5	1.31 ± 0.08	0.63 ± 0.03	0.48 ± 0.04	1530 ± 40 AD
FUER5-1	d	colluvial sand	HUB-0190	12	0.85 ± 0.07	3.06 ± 0.11	1.17 ± 0.03	0.21 ± 0.01	8.2	8 ± 4	1.64 ± 0.08	*0.49 ± 0.03*	*0.30 ± 0.02*	*1710 ± 20 AD*
FUER5-2	e	colluvial sand	HUB-0191	75	1.20 ± 0.12	3.67 ± 0.22	1.19 ± 0.03	0.20 ± 0.01	10.5	11 ± 5	1.70 ± 0.11	1.40 ± 0.06	0.82 ± 0.06	1190 ± 60 AD
FUER2	f	lacustrine sand	HUB-0324	40	0.79 ± 0.08	2.49 ± 0.12	1.07 ± 0.03	0.21 ± 0.01	9.1	10 ± 5	1.46 ± 0.09	*3.05 ± 0.29*	*2.09 ± 0.24*	*80 ± 240 BC*
FUER3	g	lacustrine sand	HUB-0325	100	0.62 ± 0.05	1.74 ± 0.07	1.20 ± 0.03	0.20 ± 0.01	9.5	10 ± 5	1.49 ± 0.09	1.02 ± 0.02	0.69 ± 0.04	1320 ± 40 AD
FUER6	h	lacustrine sand	HUB-0326	60	0.61 ± 0.06	1.83 ± 0.09	1.05 ± 0.02	0.20 ± 0.01	3.0	10 ± 5	1.36 ± 0.08	0.81 ± 0.03	0.60 ± 0.04	1410 ± 40 AD
FUER19-2	i	lacustrine sand	HUB-0327	40	0.55 ± 0.06	1.72 ± 0.14	0.80 ± 0.02	0.21 ± 0.01	11.4	10 ± 5	1.12 ± 0.07	0.80 ± 0.02	0.71 ± 0.05	1300 ± 50 AD

[a] U-238 and Th-232 contents were determined via gamma spectrometry using the equivalent U and Th contents of following natural daughter products: U-238: Th-234 (63.3 keV),

Ra-226 (186.1 keV), Pb-214 (295.2 keV, 351.9 keV),

Bi-214 (609.3 keV, 1120.3 keV, 1764.5 keV), Pb-210 (46.5 keV). Th-232: Ac-228 (338.3 keV, 911.2 keV, 969.0 keV), Pb-212 (238.6 keV), Bi-212 (727.3 keV), Tl-208 (583.2 keV).

K-40: 1461.0 keV.

For dose rate calculation the weighted mean of all peaks was used (U-238 and Th-232).

[b] Cosmic dose rates were estimated regarding geographic position, altitude and sampling depth.

[c] Water content of sediment samples in % of dry mass (24 h oven drying at 105 °C).

[d] Equivalent doses were calculated using the Central Age Model (CAM) and the Minimum Age Model (MAM) respectively (Galbraith et al. 1999).

EDs calculated according to the MAM (with sigma b = 0.1) are written in italics. 48 aliquots per sample were measured for samples FUER5-1, FUER2, FUER3 and FUER19-2.

24 aliquots were measured for all other samples.

Highlights

- Littoral sediments, palaeosols and landforms are explored as indicators of historical lake-level changes
- Sedimentological, geochronological, palaeobotanical and gauging data analyses
- Tracing of lake-level dynamics of the last millennium
- Lake-level dynamics are probably primarily governed by climate, secondarily influenced by human impact
- Lake levels may be reconstructed with high altitudinal precision if the littoral zone is given closer attention