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The Lateglacial and Holocene in Central Europe: a multi-proxy environmental record from the Bohemian Forest, Czech Republic

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The Hercynian mountain ranges were islands of mountain glaciation and alpine tundra in a Central European ice-free corridor during the Late Pleistocene. Today they are notable areas of glacial landforms, alpine-forest free areas, peatlands and woodlands. However, our knowledge of the Lateglacial and early Holocene environmental changes in this region is limited. We present a new multi-proxy reconstruction of a mid-altitude environment in the Bohemian Forest spanning this period. A core (5.2 m length) in the Černé Lake cirque (1028 m a.s.l.) was subjected to lithological, geochemical, pollen and macrofossil analysis supplemented by two optically stimulated luminescence (OSL) and 10 AMS radiocarbon dates. We determined the impact of regional and supraregional climate changes on the environment. The two most significant changes in sedimentation during the Lateglacial (17.6 and 15.8–15.5 cal. ka BP) were synchronous with regional glacial chronostratigraphy. Unlike Central European mountain ranges, in the Bohemian Forest the Younger Dryas was not coincident with glacier re-advance, but was a dry, cold episode with low lake levels, which prevailed until the early Preboreal. Plant macrofossils indicate local establishment of *Betula nana* and *Betula pendula*/*pubescens* at 15.4–13.4 cal. ka BP. Comparison with Holocene records from Central Europe shows a similar immigration history of vegetation at mid and higher altitudes. The tree line exceeded an altitude of ~1000 m a.s.l. around 10.5 cal. ka BP and coincided with rapid geochemical changes in the sediment. The 8.2 ka BP event did not have any response in the sedimentary record, but corresponded to stabilization of the *Picea abies* population and expansion of *Fagus*. *Fagus* colonized the Bohemian Forest earlier than other Hercynian mid-mountains, but never predominated in the composition of the forest at higher elevations. *Abies alba* was the last tree species that immigrated to the study area.

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In Central Europe, the end of the Last Glacial was characterized by restoration of a temperate climate and interglacial vegetation and thus by the return of widespread woodlands. The spread of forest ecosystems from glacial refugia and lowlands to mountain habitats followed not only altitudinal/latitudinal gradients, but also local climate and edaphic conditions. During the Late Pleistocene, Central Europe was located between extensive Alpine and Scandinavian ice sheets and sedimentary or biological archives (e.g. lake sediments, cave deposits, loess/palaeosol sections) remained undisturbed by any significant glaciation. Therefore, this part of Europe represents an attractive area for Lateglacial and early Holocene palaeoenvironmental studies (e.g. Goslar *et al.* 1999; Leroy *et al.* 2000; Pokorný 2002; Voigt *et al.* 2008). Nevertheless, reliably dated multi-proxy studies from Central Europe, especially from mid-altitude mountain ranges, are still very limited (Pražáková *et al.* 2006; Engel *et al.* 2010; Mentlík *et al.* 2010). The Hercynian uplands affected by local Pleistocene glaciation represented areas between boreal and alpine environments that could react sensitively to climate and environmental changes at the end of the Late Pleistocene and beginning of the Holocene.

The Bohemian Forest, as one of these Hercynian mountain ranges, can provide key information about the development of upland areas during the Late Pleistocene and inform our understanding of the natural forces of climate change during the early Holocene. The Pleistocene moraines, glacial lake sediments and peat-bog areas preserved in the Bohemian Forest have significant potential as a natural geoarchive for palaeoenvironmental reconstruction.

The objectives of this study were (i) to compare the sedimentary record and local Lateglacial and Holocene chronologies from the Bohemian Forest, (ii) determine environmental changes in the Bohemian Forest linked to regional and supraregional (European) climate changes, (iii) assess their impact on the environment and the dynamics of natural processes in the Central European mid-altitudes.

The palaeoenvironmental reconstruction in our study is based on analyses of a core sampled from lacustrine deposits overlain by a Holocene peat bed in the lateral moraines of the Černé Lake cirque in the

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Bohemian Forest (Czech Republic). This core is one of the longest and best-dated complete sedimentary records of the conditions of mountain glaciation in the Czech Republic, covering the Late Pleistocene and the entire Holocene. The unique combination of pollen and macrofossil records facilitated the differentiation of long-distance pollen and the local presence of tree species. This dual analysis thereby distinguished between local and regional climate variations.

Regional setting and study area

The Bohemian Forest is located on the southwest border of the Czech Republic and Germany (Fig. 1) and constitutes the eastern fringe of the Hercynian mountain system in Central Europe. The mountain range is about 190 km long and 45 km wide with a predominant NW–SE direction of the main ridge. The highest summit, Mt Grosser Arber (1456 m a.s.l.), is located in the northwestern, German part of the range.

During the Last Glacial Maximum (LGM, *c.* 24–21.5 ka; Ivy-Ochs *et al.* 2008), the Bohemian Forest was located only ~100 km north/northeast of the terminal moraines of the Alpine piedmont glaciers and ~250 km southwest of the Krkonoše/Giant Mountains, the other glaciated Hercynian mountain range, and ~330 km from the Scandinavian Ice Sheet.

The LGM-equilibrium line altitude of the Bohemian Forest's glaciation was about 1050–1150 m a.s.l. and glaciers had the character of cirque glaciers with shorter tongues (Hauner 1980; Mentlík *et al.* 2010; Křížek *et al.* 2012). There is no consensus on the number and extent of glaciers in the range. More glacial landforms have been described on the western, windward (German) side than on the Czech side of the range (Hauner 1980; Raab & Völkel 2003). Only three local chronologies have been established; for the Kleiner Arbersee valley, the Prášilské Lake valley and the Laka Lake valley (Reuther 2007; Mentlík *et al.* 2013). The chronology of glaciation in the Bohemian Forest is based mainly on ^{10}Be exposure dating of moraine boulders (Reuther 2007; Mentlík *et al.* 2013). Radiocarbon data related to the localities of the Pleistocene glaciation are very rare (Raab & Völkel 2003; Pražáková *et al.* 2006; Mentlík *et al.* 2010). Almost all the dated relics of glaciation are of Late Weichselian age.

Late Pleistocene and Holocene vegetation development is recorded in the sediments taken from glacial lakes (Veselý 1998; Raab 1999; Jankovská 2006) and numerous peat bogs across the Bohemian Forest (Svobodová *et al.* 2002; Mentlík *et al.* 2010; Pidek *et al.* 2013). These records show a gradual shift from Late Pleistocene steppe-tundra vegetation to Late Holocene climax forest in the summit areas. Human impact, above all during the Middle Ages, was also well documented in these records (Veselý 2000).

The study area is the Černé Lake cirque on the Czech side of the Bohemian Forest (latitude 49°10′46″ N, longitude 13°10′53″E, 86.3 ha, altitude range 353 m, the deepest point of the cirque basin is 967.5 m a.s.l.). This cirque is the second deepest and the third

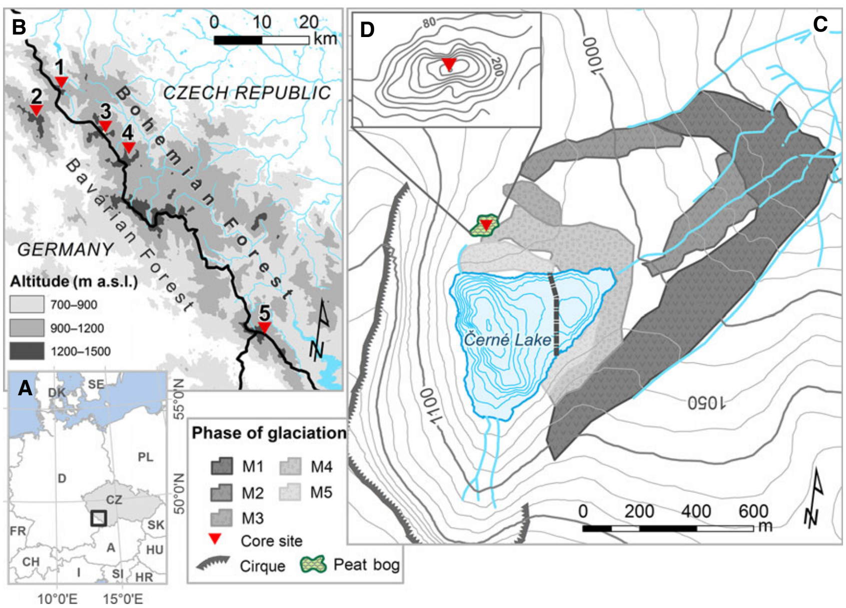

Fig. 1. A. Position of the Bohemian/Bavarian Forest in Central Europe. B. The investigated area. Numbers refer to sites mentioned in the text. 1 = Černé Lake (this study); 2 = Kleiner Arbersee (Raab & Völkel 2003); 3 = Laka Lake (Mentlík *et al.* 2013); 4 = Prášilské Lake (Mentlík *et al.* 2010); 5 = Plešné Lake (Jankovská 2006; Pražáková *et al.* 2006). C. Location of the coring site and the extent of glacial accumulation in the Černé Lake cirque (dashed line in the lake marks a postulated submerged moraine). Depth contour interval is 5 m. D. Contour map showing depths of peat in the peat bog at the coring site. Contour interval is 40 cm.

largest cirque in the mountain range (Křížek *et al.* 2012). The cirque has a mica schist and paragneiss bedrock with quartz and quartzite intercalations. In general, five generations of moraines (M1–M5), recording two phases of Weichselian glaciation, are preserved (Vočadlová *et al.* 2006). The moraines have not been dated.

Material and methods

A sediment core was taken at the deepest point of a peat bog north of Černé Lake (Černé jezero, 49°10′57″ N, 13°10′48″E, 1028 m a.s.l.; peat bog area ~0.5 ha). The peat bog is situated in a shallow topographical depression bounded by moraines and a cirque headwall (Fig. 1). A map of the peat bog's depth was constructed using a network of probing points. A 5.20-m-long core was retrieved using a standard Russian peat borer (the core was assembled from a section of uncompressed cores 5 cm in diameter and 50 cm in length) for the first 400 cm and a percussion gouge sampler (core 6 cm in diameter and 200 cm in length) for the lower 120 cm.

Ten radiocarbon samples were dated at the Center for Applied Isotope Studies at the University of Georgia, USA (UGa). Two samples in the lowermost minerogenic part were dated by optically stimulated luminescence dating (OSL) in the Research Laboratory for Archaeology and the History of Art, Oxford, UK. Calibration of radiocarbon data and construction of an age-depth model (including OSL data) were carried out using Clam software (Blaauw 2010). A 'classic' age-depth model based on linear interpolation between dated levels was applied to determine sediment accumulation rates. The sediment accumulation rate (SAR mm a^{-1}) was derived for individual sections of the model. The Lateglacial chronological units following Mangerud *et al.* (1974) and the INTIMATE Event Stratigraphy scheme (*sensu* Blockley *et al.* 2012) are used in the text and figures. The Holocene chronology was delimited according to Walker *et al.* (2012).

Particle size analysis was performed in the lowermost part of the core (515–357 cm) at 3-cm intervals. The uppermost part of the core did not contain a sufficient amount of minerogenic matter suitable for analysis. Samples were prepared according to Gale & Hoare (1991). Grain-size distribution was determined using a laser-diffraction particle size analyser Sympatec Helos/KF-MAGIC with a Quixel dispersion unit. Two lenses were used: 0.4–200 μm and 1–3500 μm. The median grain size (D_{50}, μm) of all samples was calculated by Gradistat software v. 8.0 (Blott & Pye 2001).

Magnetic susceptibility (MS) was determined in samples taken at 3-cm intervals from depths of 520–230 cm using a Kappabridge KLY-2 device (Agico, Czech Republic). The data were normalized to mass-specific magnetic susceptibility (10^{-9} m^3 kg^{-1}). Measurements were not taken in the uppermost part of the core. This is comprised peat, the high organic content of which limits the interpretive value.

Loss-on-ignition (LOI) was measured at 3-cm intervals at depths of 520–230 cm and at 5-cm intervals at depths of 225–0 cm. All samples were dried at 105°C for 24 h and ignited at 550°C for 3 h (Heiri *et al.* 2001).

Exoscopic analysis was carried out on one sample (from a depth of 514 cm). Fifty quartz grains from the sample were divided by washing to yield a size fraction of 250–500 μm and analysed under an electron scanning microscope (Cameca SX 100; Fitzpatrick & Summerson 1971; Cremer & Legigan 1989; Mahaney 2002).

Geochemical element analyses were carried out for samples at 3-cm intervals at depths of 520–302 cm. The analyses were performed by energy dispersive X-ray fluorescence spectrometry (XRF) using a MiniPal 4.0 device (PANalytical, Almelo, The Netherlands) with an Rh lamp and a Peltier cooled Si PIN detector. Five geochemical lithological zones (GLZ, Fig. 3) were distinguished according to selected geochemical components and ratios (Rb, P, S, Zr/Ti, Al/Si, Rb/K). Zirconium (Zr) and titanium (Ti) are weathering-resistant elements used for interpretation of temporal variations in silicate mineral input to the catchment or could be a grain size proxy. Zr associates with medium-coarse silt and Ti with the finer fraction (Shala *et al.* 2014). High rubidium (Rb) content has been used as a proxy of cold climate conditions and of an influx of minerogenic material during the Lateglacial in some published studies (Pražáková *et al.* 2006; Hošek *et al.* 2014; Shala *et al.* 2014). Phosphorus (P) and sulphur (S) are associated with organic matter. The high aluminium-–silicon ratio (Al/Si) may be associated with an abundance of clay fraction material (Grygar *et al.* 2010).

Subsamples for pollen analysis were taken at 3-cm intervals at depths of 400–230 cm and at 5-cm intervals at depths of 230–5 cm. Pollen samples were processed following the standard acetolysis method including hydrofluoric acid treatment (Moore *et al.* 1991). At least 500 pollen grains per sample were counted. Pollen identifications follow Moore *et al.* (1991), Beug (2004) and Reille (1995, 1998). A pollen diagram was created using POLPAL software (Nalepka & Walanus 2003). The local pollen-analytical zones (LPAZ 1–5) were determined by ConSLink and PCA analysis in POLPAL to distinguish the main changes in vegetation development and to try to avoid any background noise of local pollen assemblage fluctuations. Samples from the depth range of 520–400 cm were not included in the analysis because they contained a scarce, incoherent residuum of pollen, which was damaged and could not be properly identified.

Each sample for plant macrofossil analysis comprised 150–300 mL of sediment. Samples were soaked in water and if necessary boiled with 5% KOH. Extraction of plant macrofossils from the sediments followed standard flotation and wet-sieving procedures (Warner 1988; Pearshall 1989; Jacomet & Kreuz 1999) using a 250-μm mesh sieve. Botanical macrofossil samples were removed from the recovered fraction and scanned using a stereoscopic microscope (8–56× magnification). Quantitative and qualitative results of identifications are presented in the macrofossil diagram plotted using TILIA 1.5.12 software (Grimm 2011). The local macrofossil assemblage zones (LMAZ 1–4) were visually determined according to changes in both occurrence and frequency of macrofossils with respect to lithology.

Results and interpretation

Chronology

The two OSL dates at depths of 500.5 cm (17.57±1.97 ka) and 445.5 cm (16.15±1.36 ka) indicate the maximum age at the end of the LGM (Fig. 2). A series of 10 AMS ^{14}C samples (Table 1), ranging from the Lateglacial to the late Holocene, was measured.

The sediment accumulation rate (SAR) varies between 0.03 and 0.66 mm a^{-1} (Fig. 2). The section with the highest rate of sedimentation is at a depth of 80–200 cm (4310–2500 cal. a BP) and is composed of peat. Other sections with a higher SAR (depths of 369–382 cm and 397–501 cm), conversely, represent sediments with a very low content of organic material.

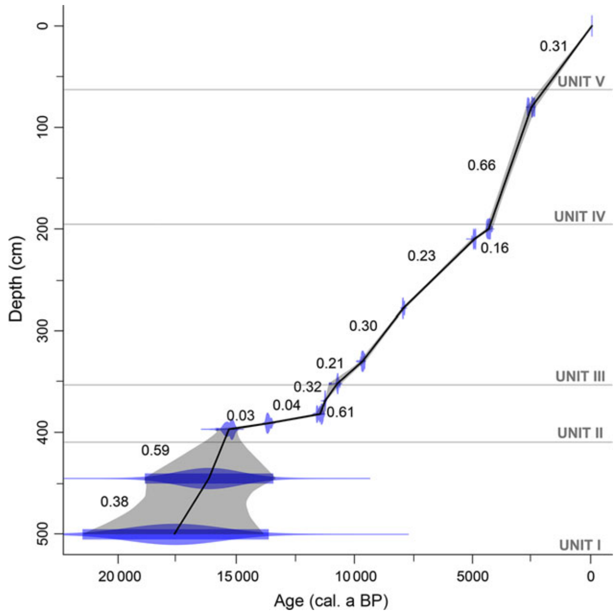

Fig. 2. Age-depth model based on radiocarbon and optically stimulated luminescence data from the study site. The shading represents the 2σ probability range; numbers on the graph represent sediment accumulation rate in mm a^{-1}. The lithostratigraphical units I–V are marked.

The lowest SAR values (0.03 and 0.04 mm $year^{-1}$) were recorded at a depth of 397–382 cm (15 320–11 450 cal. a BP, Fig. 2).

Unfortunately, the sedimentation gap or slowdown during the terminal stage of the Lateglacial and the beginning of the Holocene (15.3–11.4 cal. ka BP, at a

Table 1. Radiocarbon and optically stimulated luminescence dates from the study site. The weighted average of all estimated calendar years was used as the best central-point estimate (Telford *et al.* 2004). The margin of error of the model was 2 SD.

Litostr. unit	Depth (cm)	Dating method	Laboratory code	Material	LOI (%)	$\delta^{13}C$ (‰)	Age (a BP)	Calibrated age (cal. a BP, 2σ range)	Calibrated intercept age (cal. a BP)
IV	80.0	AMS	UGAMS-3933	Spruce needle, moss	100.0	–29.9	2440±25	2698–2357	2510
III	200.0	AMS	UGAMS-3934	Spruce needle, fruit scale	94.9	–24.8	3870±25	4412–4165	4310
III	210.0	AMS	UGAMS-3935	Bulk sample (gyttja)	94.8	–28.7	4360±25	5028–4857	4924
III	278.0	AMS	UGAMS-3936	Bulk sample (gyttja)	87.8	–27.2	7100±30	7995–7854	7925
III	330.0	AMS	UGAMS-3937	Spruce fruit	52.4	–28.3	8710±30	9762–9551	9652
III	352.5	AMS	UGAMS-3938	Bulk sample (gyttja)	39.9	–29.0	9470±30	11 058–10 588	10 717
II	369.0	AMS	UGAMS-3939	Bulk sample (sandy silt)	7.4	–27.0	9840±30	11 301–11 201	11 239
II	382.0	AMS	UGAMS-3940	Moss	26.4	–29.9	9990±30	11 612–11 284	11 453
II	391.5	AMS	UGAMS-3941	Bulk sample (silt)	7.5	–22.8	11 790±30	13 774–13 465	13 634
I	397.0	AMS	UGAMS-3942	Bulk sample (silty sand)	6.1	–22.5	12 840±40	15 845–14 961	15 324
I	445.5	OSL	X3854	Sandy silt	2.7	–	16 150±1360	13 356–18 850	16 152
I	500.5	OSL	X3853	Silty sand	2.4	–	17 570±1970	13 858–21 460	17 615

depth of 397–382 cm) decreases the accuracy of the age-depth model and complicates identification of the particular environmental changes at the coring site during this time-span.

Lithostratigraphy and geochemistry

Five lithostratigraphical units (Units I–V, Figs 3, 4) were distinguished according to the macroscopic characteristics of the sediment. The study site sediments are primarily inorganic in the lower portion of the core (Units I and II), sharply becoming more organic towards the top (Units II/III). Fluctuations in magnetic susceptibility, grain size, geochemical elements and ratios are described in Fig. 4. Generally, LOI in the whole core exhibits a strong negative correlation with MS ($r = -0.95$, level of significance $p = 0.05$) and so provides a proxy of organic material. The levels of S and P correlate closely with LOI (Fig. 3). Both the sharp decrease in MS and the increase in LOI correspond clearly to the beginning of the organic-rich portion of the core. The Zr/Ti and Al/Si ratios are negatively correlated with each other. The Rb curve is similar to the Al/Si curve in the lower part of the record.

Unit I consists of massive layers of poorly sorted silty sand and sandy silt devoid of organic matter (Figs 3, 4). Microtexture features indicating *in situ* moraine material or short-distance transported glacial material (e.g. angular outlines, rounded outlines, medium reliefs, low reliefs, conchoidal fractures, straight steps, striations and curved grooves) were found on the surfaces of quartz grains from a depth of 514 cm.

The fine sediment, absence of gravel and high sedimentation rate in Unit I indicate highly dynamic glaciolacustrine depositional processes at the coring site during the Lateglacial. Important variations in the mode of deposition in the lake basin are indicated by

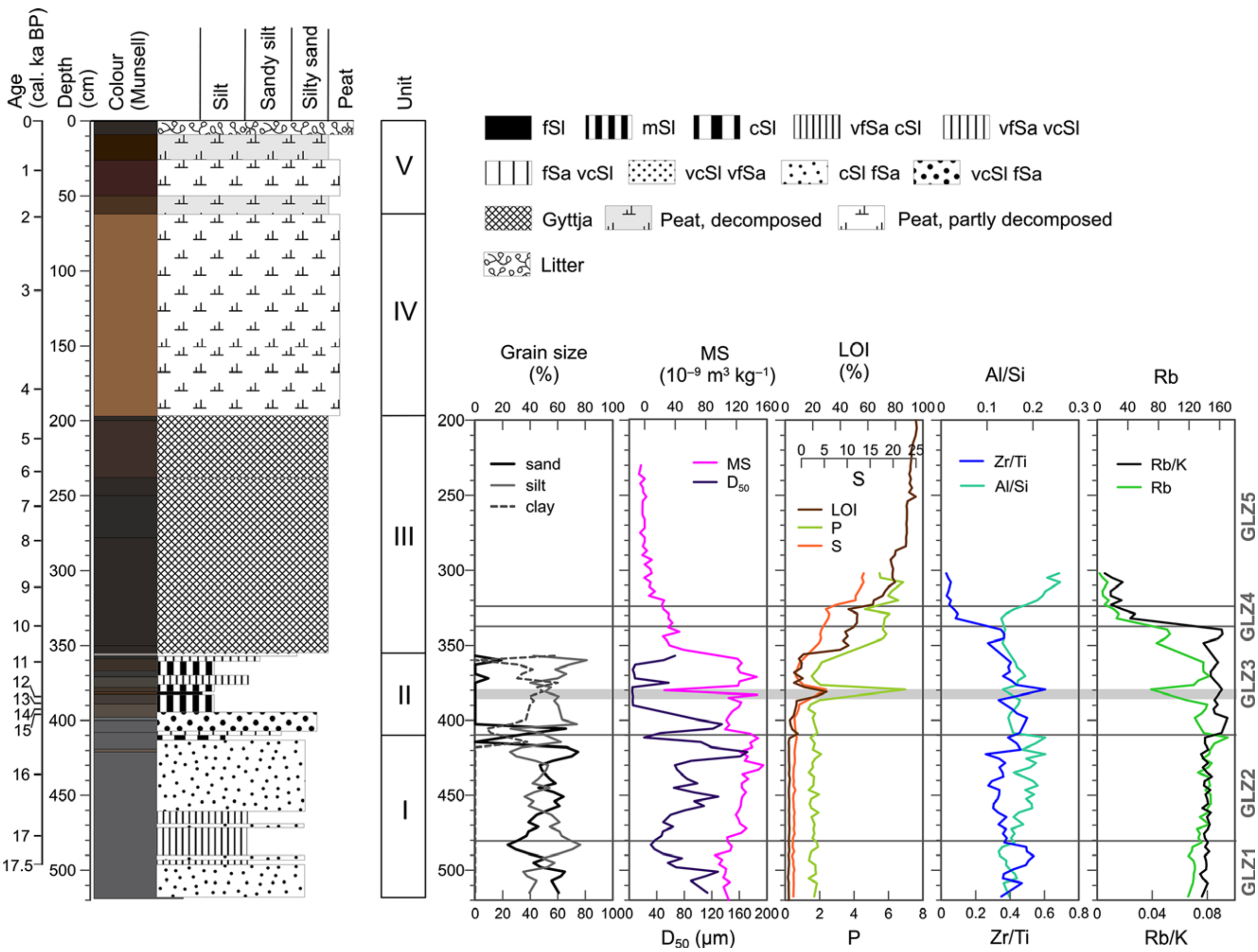

Fig. 3. Lithological, chronological and geochemical data from the study site. The core is subdivided into five lithological units (I–V). Broad grey stripe highlights an intercalation of high-organic fine silt with abundant undecomposed macrofossils in Unit II. The peat layers (Units IV and V) were not used for geochemical and lithological analyses. MS = magnetic susceptibility; LOI = loss-on-ignition; GLZ = geochemical lithological zones; Sl = silt; Sa = sand; f = fine; m = medium; c = coarse; v = very. Rb, S and P are quoted in ppm.

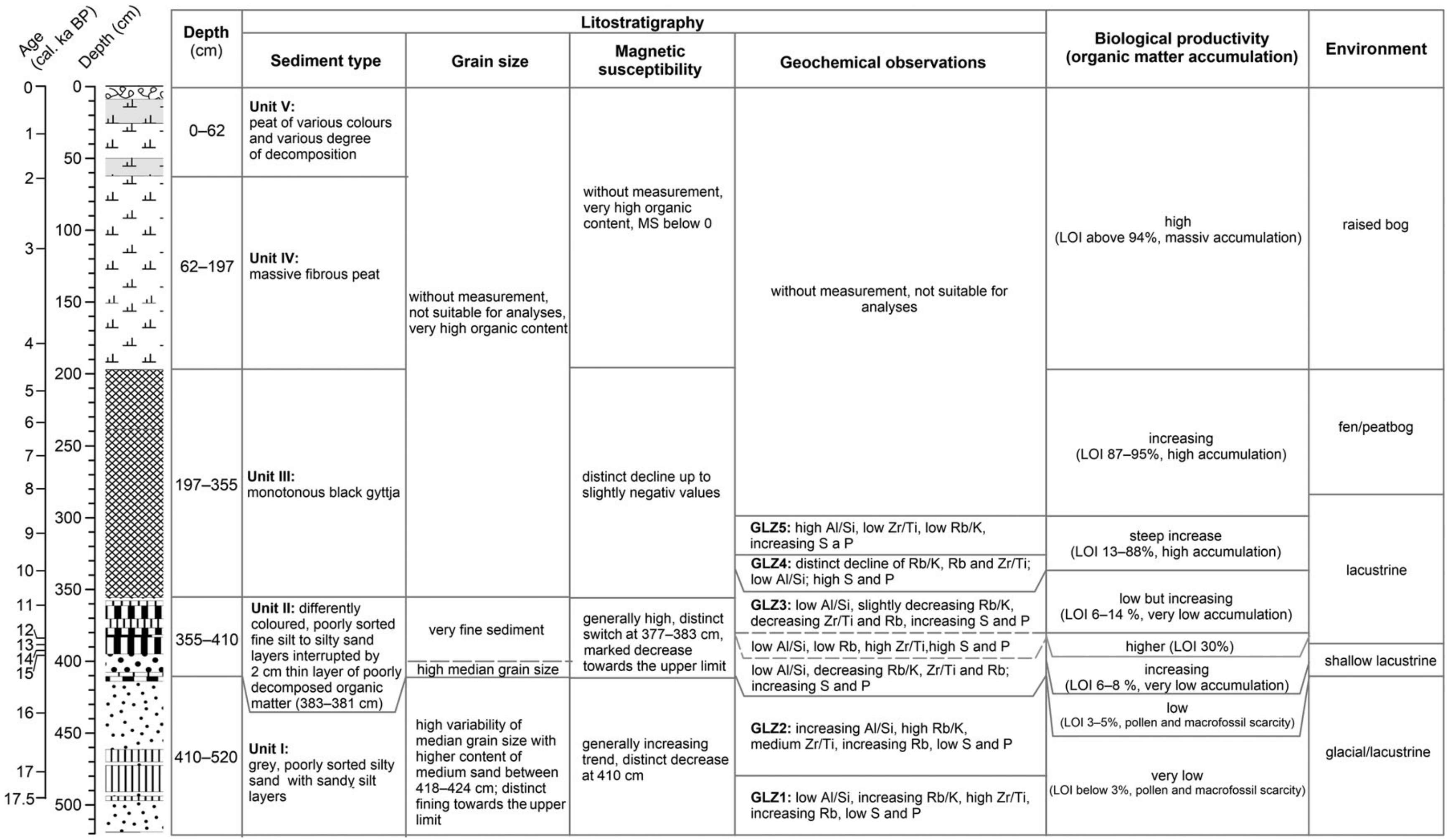

Fig. 4. Sedimentological and geochemical characteristics of the core from the study site. Age in cal. a BP according to the age-depth model. Sediment type corresponds to the macroscopic characteristics and colour. Grain size corresponds to median grain size and sand, silt and clay portions. Geochemical observations correspond to Rb, S, P, Rb/K, Zr/Ti and Al/Si. GLZ = geochemical lithological zones. Biological productivity corresponds to loss-on-ignition and sediment accumulation rate.

alterations in sand and silt content (medium grain size, D_{50}), the MS and geochemical logs (Rb, Zr/Ti, Al/Si). These depositional changes could reflect lake-level fluctuation and/or changing sediment input to the basin. The absence of organic matter reflects the limited productivity of the ecosystems and the poorly developed soils in the catchment. An abrupt change in the local or regional environment is recorded by the sharp boundary of Unit I (decreases in Rb, MS and Al/Si) at a depth of 410 cm (15.5 cal. ka BP, Fig. 3).

Unit II differs from Unit I in its macroscopic and geochemical characteristics. It consists primarily of differently coloured, poorly sorted layers of fine silt to silty sand (Figs 3, 4). Upwards, the increasing production of organic matter in the catchment and a distinct decrease in minerogenic inputs are recorded. The sediment succession in this unit reflect very variable sedimentary conditions with very low sediment input interrupted by an event of high organic deposition at the end of the Lateglacial (high organic intercalation, Fig. 3) characterized by a clearly visible intercalation of high-organic fine silt with an abundance of undecomposed macrofossils at a depth of 383–381 cm (11.7–11.5 cal. ka BP).

Unit III is delimited by the occurrence of a monotonous black mud (Fig. 3). The minerogenic siliciclastic input to the basin decreases with an abrupt and massive accumulation of organic matter in an anoxic environment (gyttja). The switch from minerogenic to organic sedimentation reflects an enriched supply of organic matter from an expanding catchment vegetation cover.

Unit IV is composed of massive, brown fibrous peat and differs from the previous unit in colour, with a lower degree of organic material decomposition (Fig. 3).

Unit V comprises four peaty layers of varying colours and degree of decomposition (Fig. 3).

Biological evidence

Palynological analysis. – ConSLink and a PCA analysis distinguished five local pollen zones between 0 and 400 cm (Fig. 5). The first corresponds to the Lateglacial (LPAZ-1), the second is transitional and the three further zones belong to the Holocene (LPAZ-3-5).

Throughout the lower zone (LPAZ-1, 400–391 cm), which covers the period 15.4–13.6 cal. ka BP (Fig. 5), open herb vegetation of tundra or cool steppe prevails in the mountain range of the Bohemian Forest. Non-arboreal pollen grains dominate (AP/NAP ratio is ~25%). *Pinus* (10%) and *Betula* (10%) are the dominant tree components. Grasses (~50%) dominate in the non-arboreal pollen spectrum. Rare occurrences of *Sanguisorba minor* (394 cm) and *Valeriana* (394 cm) indicate open, disturbed sites.

A distinct increase in the AP/NAP ratio to 70–90% around 390 cm delimits the second pollen zone (LPAZ-2, 391–368 cm, 13.6–11.2 cal. ka BP). *Pinus* and *Betula* are the clearly dominating tree components (Fig. 5). Grasses and heliophilous herbaceous plants (*Cyperaceae*, *Artemisia*) are still present. *Sanguisorba minor* (388 cm) and *Armeria* (377 cm) were also recorded. The rising plant diversity from this time period is connected with higher diversity of herbaceous plants. This zone covers the transitional phase between open vegetation and forest formation in the mountain range. First, shrub or small tree vegetation starts to expand within the herb vegetation. Open vegetation is replaced by birch-pine and pine-birch forest followed by a short-term opening of the vegetation at the end of the zone (377–368 cm, 11.4–11.2 cal. ka BP).

LPAZ-3 (368–323 cm, 11.2–9.4 cal. ka BP) is defined by an expansion of birch-pine forest and a definite retreat of open vegetation. A marked increase of *Ulmus* and *Corylus* occurs in the uppermost part of the zone. *Lysimachia* (353 cm), indicating damp conditions, is also recorded within this zone. The expansion of *Picea*, *Quercus*, *Tilia* and *Alnu*s begins at the boundary with the uppermost zone.

The fourth pollen zone, LPAZ-4, is subdivided into two subzones (LPAZ-4a and 4b) and covers the period between 9.4 and 4.2 cal. ka BP (323–195 cm). Tree taxa dominate in the pollen spectrum of both subzones (Fig. 5). Pine-birch forest declines. *Quercetum mixtum* together with *Corylus* and *Picea* appears in the forest composition at the beginning of LPAZ-4a (9.4 cal. ka BP). *Sanguisorba officinalis* (317 cm) and *Circea* (302 cm) were rarely detected. LPAZ-4b (284–195 cm) is defined by an abrupt expansion of *Fagus* into the tree spectrum during the middle Holocene. The first appearance of *Fagus* pollen is recorded at *c.* 8.0 cal. ka BP (~280 cm) and of *Abies* at *c.* 6.2 cal. ka BP (239 cm).

LPAZ-5 is subdivided in two subzones, LPAZ-5a and 5b. The lower boundary of LPAZ-5a (195–30 cm, 4160–900 cal. a BP) correlates with increasing frequencies of *Abies alba* (Fig. 5). *Viscum* (155 cm) and *Taxus baccata* (65 cm) are recorded only sporadically. LPAZ-5b (30–5 cm, 900–100 cal. a BP) is defined by indicators of a human impact: *Cerealia*, *Plantago lanceolata*, *Sambucus nigra*, *Rumex acetosella*-type and in some cases also *Urtica* pollen. The increase in *Secale cereale* pollen marks the human occupation and agricultural activities. A lower AP/NAP ratio (15–10 cm), the significant decrease of *Fagus* and *Abies* and the increase of *Picea* reflect intense forest management in the mountain range.

Macrofossil analysis. – Macrofossil plant assemblages revealed clearly the vegetation succession from an oligotrophic lake vegetation and swamp to a raised bog (Fig. 6). The core showed a dominance of stress-tolerant

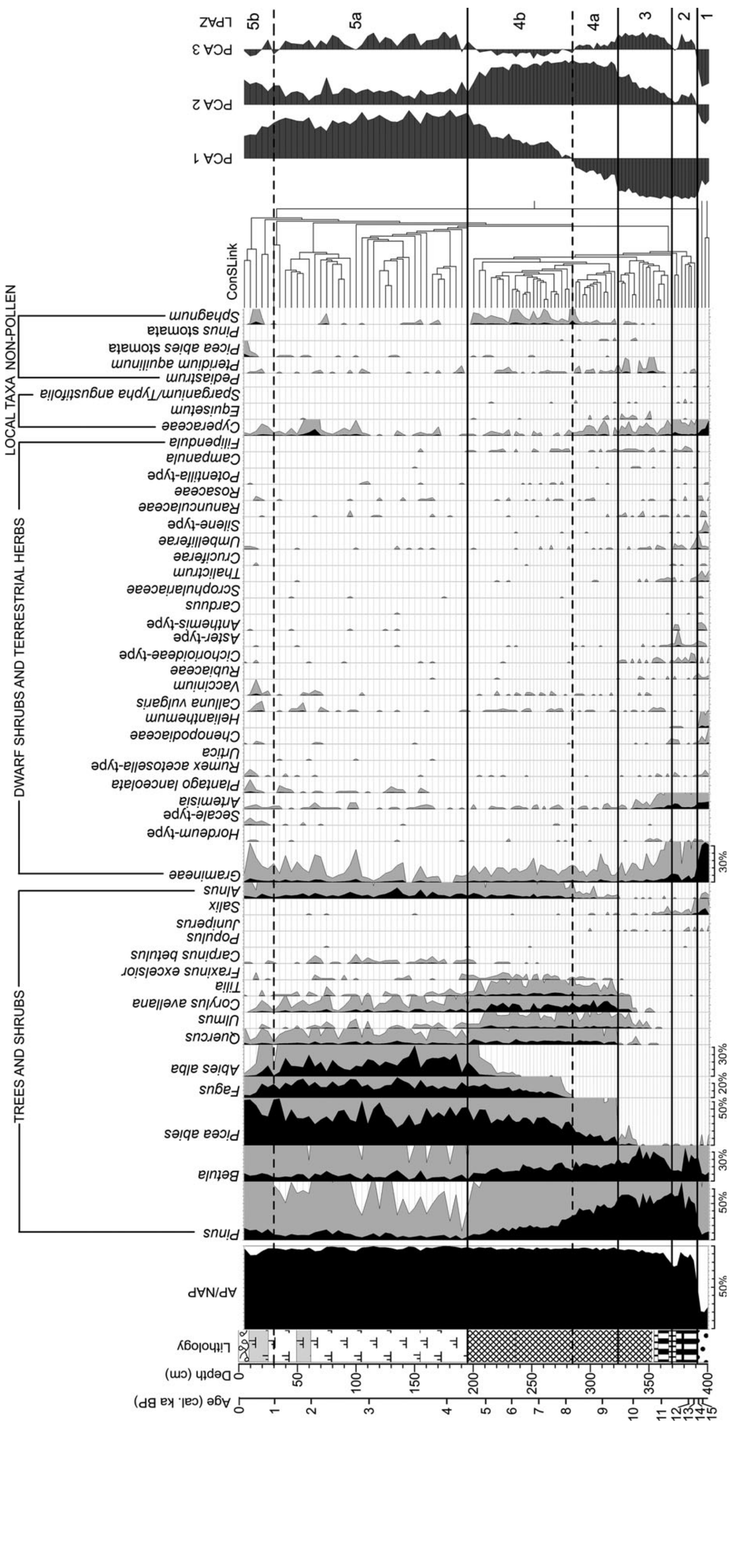

Fig. 5. Simplified percentage pollen diagram of the core from the study site.

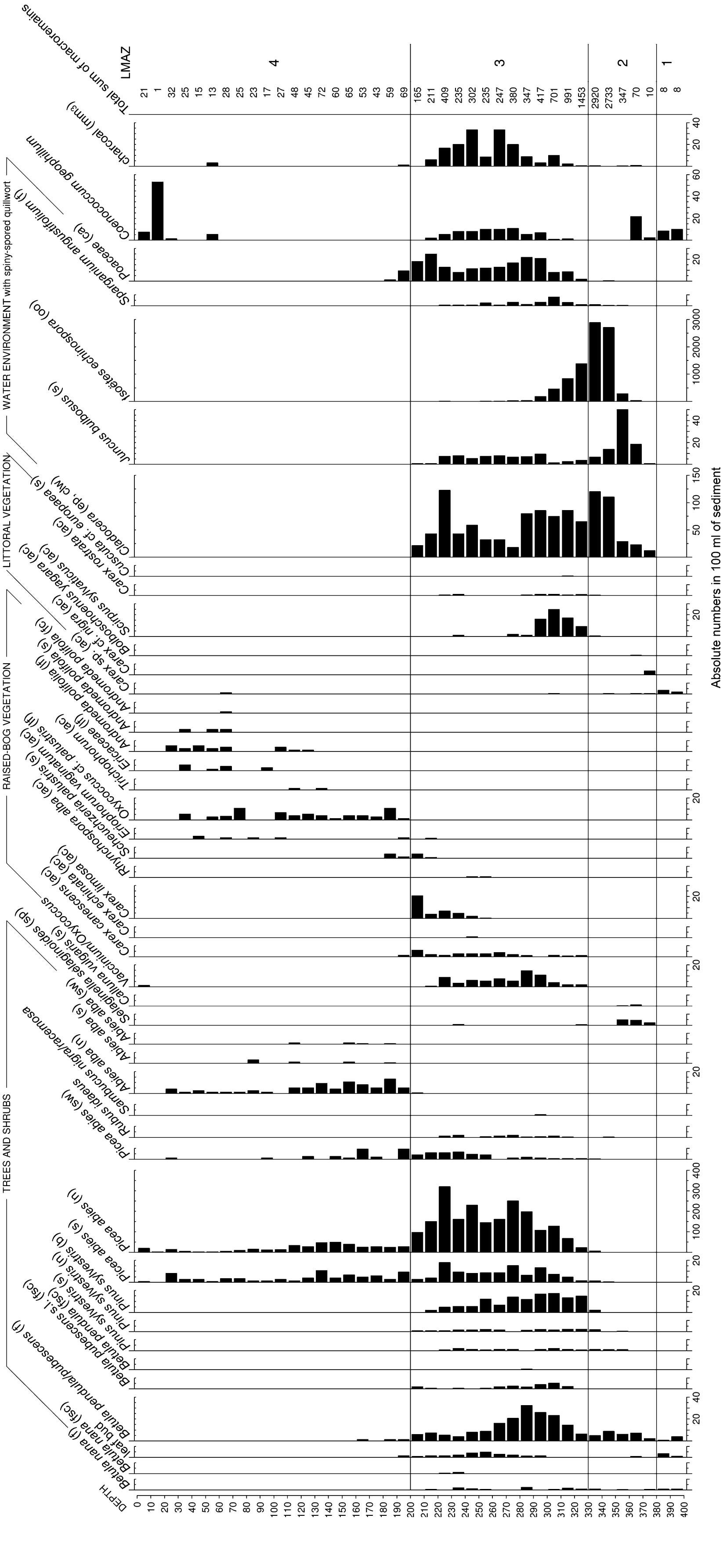

Fig. 6. Macrofossil diagram from the core from the study site for the depths of 0–400 cm. Abbreviations: (ac) = achene; (b) = brachyblast; (ca) = caryopsis; (clw) = claw; (ep) = ephippium; (f) = fruit; (fc) = fruit capsule; (fsc) = fruit scale; (lf) = leaf; (n) = needle; (oo) = oospore; (s) = seed; (sp) = spore; (sw) = seed wing.

vegetation with sporadic dwarf or small birch trees, suggesting a cold, unstable environment and soil erosion in the earliest stage of the succession (400–380 cm, 15.4–11.4 cal. ka BP). The presence of littoral vegetation (*Carex* sp.) could suggest a waterlogged soil but other indicators of waterlogged conditions are missing.

The early Holocene (380–330 cm) is identified by the first appearance of arctic water plants, littoral vegetation and zoological remains of *Cladocera* (Fig. 6). The abundance of nutrients allowed expansion of cold-adapted aquatic pteridophytes of the genus *Isoëtes.* These species indicate an oligotrophic mountain lake (<2 m deep). Local presence of trees is supported by macrofossils of birch fruits (*Betula nana*, *Betula pendula/pubescens*), *Pinus sylvestris* and *Picea abies* seeds. Nevertheless, *Betula* dominates. Higher altitudes of the catchment with acidic and nutrient-poor soils were still covered by sparse, open vegetation (*Selaginella selaginoides* and *Calluna vulgaris*). The abundance of *Cenococcum geophilum* indicates soil erosion.

The early/middle Holocene boundary is indicated by a transition from the lake to a bog environment. The appearance of peat-bog vegetation (*Carex limosa*, *Rhynchospora alba*, *Vaccinium/Oxycoccus*) was followed by the gradual overgrowing of the basin. Small pools or hollows indicated by *Scheuchzeria palustris* and *Carex limosa* were initially on the surface of the peat bog. *Betula*, *Picea* and *Abies* dominated amongst tree macrofossils during the middle Holocene (330–200 cm, 9.7–4.3 cal. ka BP).

Raised bog vegetation (Fig. 6) and spruce forest with fir prevailed during the late Holocene (200–0 cm, from 4.3 cal. ka BP) onwards. Surface layers of the profile were degraded during the 20th century by draining of the peat bog and planting of a spruce monoculture.

Discussion

Evidence of glaciation in the sedimentary record

The lake at the coring site formed on the margin of a cirque basin subsequent to deglaciation during the Late Weichselian (GS-2a *sensu* Blockley *et al.* 2012). The bottom age of the studied core suggests a potential age for deglaciation of this part of the cirque (17.57±1.97 ka BP) that is in accordance with the time frame of two regional glacier advances recorded at other equivalent cirques in the Bohemian/Bavarian Forest (Reuther 2007; Mentlík *et al.* 2013; Fig. 7). However, the massive deposition of fine-grained sediment and low LOI values (Fig. 3) suggest a very cold and dry climate between 17.6 and 15.5 ka BP. Therefore, the presence of a glacier in the immediate neighbourhood of the coring site cannot be definitively dismissed. A site-specific Late Weichselian glacial chronology based on absolute dating does not exist, but we suggest that the infilling of the coring site began between two glacial stages when the neighbouring moraines (M4 and M5, see Fig. 1) stabilized. This hypothesis accords with the regional chronology (Mentlík *et al.* 2013) and is supported by the location of the lake between these two moraines and the fact that, reflecting the continuous nature of the sedimentary record, sedimentation has probably not been interrupted by any later advance of the glacier at the coring site.

However, we assume that the environmental change marked by a distinct shift in the sedimentation pattern (first coarsening followed by fining of the sediment between 15.8 and 15.5 cal. ka BP, 424–410 cm, Fig. 3) could be connected to a glacier advance. Additonally, geochemical proxies imply a decrease in erosion and sedimentation in the catchment. The cause could be the deposition of the youngest ‘lake’ moraine (M5) and the final separation of the sedimentation basin at the coring site from the glacier as the main source of meltwaters/material after its retreat into the cirque. This event coincides with the stabilization of moraines not only in the local mountain range (Mentlík *et al.* 2013), but also in the Krkonoše Mts (Engel *et al.* 2014) or Clavadel/Senders glacier advances of GS-2a in the Eastern Alps (Ivy-Ochs *et al.* 2008) (Fig. 7).

Any later glacier re-advance is not evident in the sediment record. The glacier might have fluctuated further inside the cirque floor as reported e.g. from the Krkonoše Mts (Engel *et al.* 2014) or as supposed for the Kleiner Arbersee glacier in the Bavarian Forest (Raab & Völkel 2003). The deepest part of the Černé Lake basin is separated by a distinct threshold covered probably by a submerged moraine (Vočadlová *et al.* 2006) (Fig. 1).

Lateglacial vegetation expansion

A distinctive Lateglacial expansion of vegetation was registered first at the regional level (in the pollen record) around 14.5–13.6 cal. ka BP and afterwards at the local level (in the macrofossil record) around 13.4–11.4 cal. ka BP. In the study area, an initial phase of vegetation succession began with a shift from open, grassy vegetation to an expansion of pioneer cold-resistant woody species (Figs 5, 7). This documented vegetation shift coincided with palaeovegetation changes during the Bølling-Allerød warm period (GI-1 *sensu* Blockley *et al.* 2012) recorded across Europe (Mangerud *et al.* 1974; Leroy *et al.* 2000; Pokorný 2002; Lang 2006; Theuerkauf & Joosten 2012; Hošek *et al.* 2014).

The time inconsistency between the occurrence of tree pollen and tree macrofossils (primarily *Betula* and *Pinus*) in the record indicates that the upper areas of the Bohemian Forest were above the tree line during

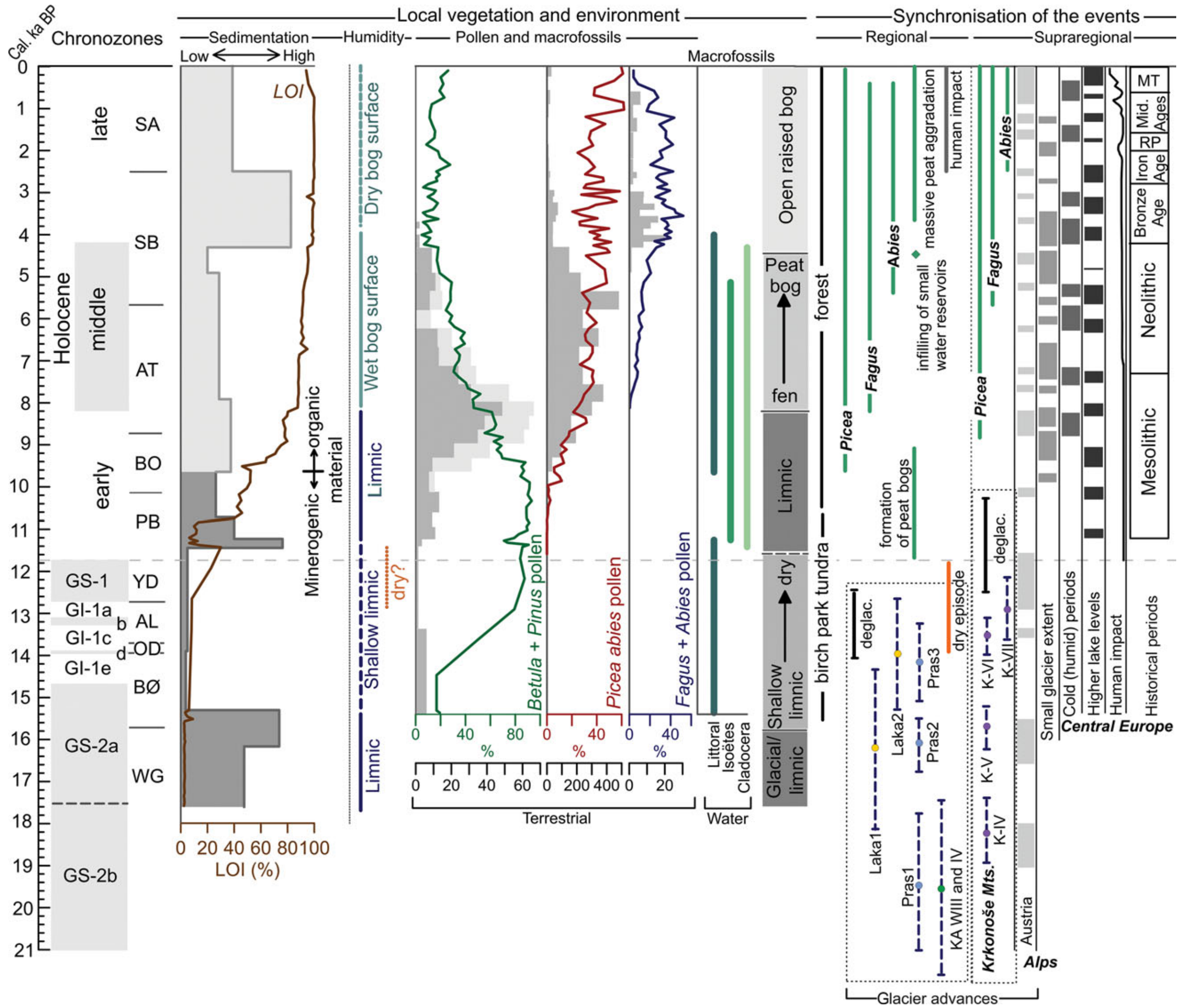

Fig. 7. Synthesis for the interpretation of biotic and abiotic data illustrating the phases of landscape development and vegetation history at a local (study site), regional (the Bohemian Forest) and supraregional level (Central Europe). Lateglacial chronozones (GICC05) are defined following Björck *et al.* (1998) and Blockley *et al.* (2012), Holocene chronozones following Walker *et al.* (2012), and Lateglacial and Holocene chronozones following Mangerud *et al.* (1974) are also demonstrated. Vegetation development at a local level follows both the pollen record and the plant macrofossils. Terrestrial plants are a combination of pollen (line) and macrofossils (histogram; dark grey = *Pinus*, *Picea* and *Abies*; light grey = *Betula*). Synchronization of Late Pleistocene glaciation is based on ^{10}Be exposure ages: Bohemian Forest – Laka Lake (Laka1 and 2; Mentlík *et al.* 2013); Prášilské Lake (Pras1, 2 and 3; Mentlík *et al.* 2013); Kleiner Arbersee valley (KA WIII and IV; Reuther 2007; Mentlík *et al.* 2013); Krkonoše Mts (K-IV–VII; Engel *et al.* 2014); the Alps (Ivy-Ochs *et al.* 2008, 2009). Synchronization of regional environmental changes in the Bohemian Forest is based on studies by Svobodová *et al.* (2002) and Mentlík *et al.* (2010). Supraregional Holocene environmental changes (Central Europe) are based on studies by Krkonoše Mts (Engel *et al.* 2010), small glacier extent – periods of relatively small glacier extent in the Swiss Alps (Koch & Clague 2006), cold (humid) periods (Haas *et al.* 1998), higher lake levels (Magny *et al.* 2007), human impact (Dotterweich 2008). WG = Weichselian Glacial; BØ = Bølling; AL = Allerød; YD = Younger Dryas; PB = Preboreal; BO = Boreal; AT = Atlantic; SB = Subboreal; SA = Subatlantic; RP = Roman Period; MT = Modern Times.

the Lateglacial. Nevertheless, the oldest local presence of birch (*Betula nana*, *Betula pendula*/*pubescens* macrofossils, Fig. 6) at the study site is evidence that solitary trees grew on favourable sites long before the onset of the Holocene (15.4–13.4 cal. ka BP). These findings corroborate the pollen-based inference that a birch park tundra existed up to 1000 m a.s.l. in the Central European mid-mountains at the end of the Late Pleistocene (Jankovská 2006; Lang 2006). The local presence of conifer trees has been documented in low and mid-altitudes of the central Alps from 13.8 cal. ka BP (Ammann *et al.* 2014).

The short cold episode of the Older Dryas (GI-1d *sensu* Blockley *et al.* 2012) marked by glacier re-advances in some areas of the Bohemian Forest (Mentlík *et al.* 2013) and other Hercynian mountains (Engel *et al.* 2014) could not be distinguished either in the pollen spectra of the study area or elsewhere in the region (Pokorný 2002; Hošek *et al.* 2014). It is possible that this short cooling event may have caused only a delay in the vegetation expansion to higher elevations. Furthermore, the temporal resolution of the pollen and macrofossil analysis may have been unable to distinguish this short-term climate shift.

The Younger Dryas chronozone and the Pleistocene/Holocene transition

Proxy data of local conditions (sparse macrofossils, low sedimentation rate) point to a cold severe climate at the study site at the end of Lateglacial and during the Lateglacial/Holocene transition (Figs 3, 6). Similarly, the pollen record showed a short-term decline in tree pollen, and a slight increase in herb pollen (Gramineae) and light-demanding taxa (*Artemisia*) in the region between 12.2 and 11.1 cal. ka BP (Fig. 5). These changes reflect climate deterioration and accord with the response of the vegetation to Younger Dryas cooling (YD/GS-1, 12.9–11.7 ka BP, Lowe *et al.* 2008) noted across Europe (Theuerkauf & Joosten 2012; Hošek *et al.* 2014). However, the vegetation shift was weakly marked in our study area. Similarly, the less pronounced forest opening during the YD has been described, for example, in Poland, Germany and the Alps (Lotter *et al.* 2000; Ralska-Jasiewiczowa *et al.* 2004; de Klerk 2008). We assume that the Bohemian Forest, as a mid-altitude mountain range and relatively remote from the Atlantic region, has been less affected by the southward expansion of the Atlantic sea ice and a strong westerly circulation than the North Atlantic region and higher altitude areas (Wick 2000; Theuerkauf & Joosten 2012). This hypothesis is also supported by the fact that no glacier re-advances dated to the YD have been recorded in the Bohemian Forest (Fig. 7). However, they are apparent in higher altitude or latitude mountain ranges (Ivy-Ochs *et al.* 2009; Makos *et al.* 2013; Engel *et al.* 2014).

The sparse vegetation cover at the end of the Late Pleistocene is also coincident with a distinct decrease in the sedimentation rate (Fig. 7) reflecting the cessation of sedimentary input at the coring site over the time-span of 14.2–11.3 cal. ka BP. A limnic environment disappeared as a consequence of a dry continental climate during the YD and early Holocene. Evidence for drying up could be the thin intercalation of fine sediment with increased organic content dated to 11.7–11.4 cal. ka BP. This thin layer was found also in the Kleiner Arbersee area and was assigned to the YD age (Raab 1999). We assume that soil water was frozen for longer periods of time during the YD, reducing plant decomposition. Low water levels often correspond to sedimentation of peat and organic detritus in close-to-shore areas, whereas episodes of high water levels in lakes are characterized by accumulation of more minerogenic sediments (Magny *et al.* 2007). Sedimentary hiatuses, or lower sedimentation rates, attributed to low lake level episodes have been recorded also in other parts of Central Europe during the YD and early Holocene (Pražáková *et al.* 2006; Karasiewicz *et al.* 2013; Hošek *et al.* 2014).

The onset of the Holocene (11.3–10.8 cal. ka BP) was characterized by the re-establishment of a lacustrine ecosystem, a rise in sedimentation and tree expansion to higher altitudes of the Bohemian Forest (Fig. 7). These high-energy processes point to a local and regional increase in temperature and rainfall at the beginning of the early Holocene, which is in accordance with a global climate shift (Björck *et al.* 1998).

Synchronization of Holocene forest development

An expansion of primary forest to higher altitudes started in the southern parts of Central Europe during the Bølling-Allerød (GI-1) but was disrupted by the Younger Dryas cooling event (Lotter *et al.* 2000; Ammann *et al.* 2014).

Increases in birch pollen abundance, in combination with the regular occurrence of birch macrofossils, high pine pollen amounts, isolated fragments of pine macrofossils and pine stomata in the pollen record (Figs 5, 6) clearly indicate the local population expansion of a primary birch-pine forest in our study area between 11.1 and 10.1 cal. ka BP (Figs 5, 6). This coincides with the start of the reforestation in Central European mountain areas (Haas *et al.* 1998; Lang 2006). The increasing forest density and gradual closing of the canopy, together with significant changes in the sedimentary record (e.g. a decline in minerogenic input), were a response to both regional and global abrupt climate warming at the beginning of the Holocene (Lotter *et al.* 2000). These early Holocene climate changes had a variable response across the Bohemian Forest. The start of the fine-detritus gyttja and peat sedimentation (this study; Raab 1999; Pražáková *et al.* 2006), tree pollen expansion (Svobodová *et al.* 2002; Jankovská 2006), and disappearance of psychrophile plant species (Mentlík *et al.* 2010) have been recorded.

An undisturbed forest development during the second half of the early and middle Holocene favoured late-successional tree species such as *Picea abies*, *Abies alba* and *Fagus*. Both *Picea* pollen and macrofossils appeared in the record 10.1–9.7 cal. ka BP and suggest the rapid spread of *Picea* to higher altitudes, primarily in favourable (humid) habitats (Fig. 7). These findings support the findings of other authors (Svobodová *et al.* 2002; Jankovská 2006), indicating the Boreal presence of spruce in the Bohemian Forest. This change in vegetation very closely coincides with changes in the geochemical logs between 10.1–9.3 cal. ka BP (GLZ4 in Fig. 3). However, a pronounced turning point in forest development occurred around 9.5 cal. ka BP. The *Picea abies* population expansion affected both the structure and density of the early Holocene forest throughout the Bohemian Forest (Svobodová *et al.* 2002; Jankovská 2006; Mentlík *et al.* 2010). Spruce started to dominate the arboreal spectrum around 8.2 cal. ka BP, which is consistent with pollen records from other parts of Central Europe (Tinner & Lotter 2006; Engel *et al.* 2010) and points to a regional (climate-driven) change. On the contrary, spruce appeared later in the Black Forest, where fir became the dominant tree species during most of the Holocene period (Rösch 2000). Tinner & Lotter (2006) supposed that spruce might have profited from higher humidity during the cold phases 8.2–7.3 cal. ka BP following a particular dry period recorded in the Swiss Alps between 9.5–8.6 cal. ka BP (Roos-Barraclough *et al.* 2004). Abrupt changes in the geochemical record could point to both the intensification of chemical weathering under the humid conditions (Al/Si increase) and a decline in erosional inputs (Zr/Ti and Rb decrease) because of the stabilization of slopes by the vegetation cover.

The expansion of deciduous forest communities (*Quercetum mixtum*) reflects climate stabilization in Central Europe during the middle Holocene (Roos-Barraclough *et al.* 2004; Voigt *et al.* 2008; Litt *et al.* 2009; Veron *et al.* 2014).

The migration of climax tree species to the higher altitudes of the Bohemian Forest started at the beginning of the middle Holocene. *Fagus* pollen are documented (8.2–8.1 cal. ka BP) not only at the study site, but also in the central part of the mountain range (Svobodová *et al.* 2002) (Fig. 7). This is relatively early compared with other Hercynian mountain ranges where *Fagus* expanded in the second half of the middle Holocene (Rösch 2000; Voigt *et al.* 2008; Litt *et al.* 2009; Engel *et al.* 2010; Veron *et al.* 2014). This can be explained by the geographical proximity of probable *Fagus* refugia in the Danube river basin (Magri *et al.* 2006) and/or more favourable (humid) climate conditions in the Bohemian Forest. *Fagus* expansion was primarily triggered by a shift to a more humid climate around 8.2 cal. ka BP. Asynchronous expansion across Central Europe was connected with orographic precipitation gradients (Tinner & Lotter 2006). The expansion of *Fagus* marked the beginning of the formation of the region's present podzols. *Fagus* was not present in the macrofossil record from the study site, but a ~20% occurrence in the pollen record suggests an apparent local presence of the taxon (Ammann *et al.* 2014).

Abies alba was the second most abundant tree species that invaded the mid-Holocene forest of Central Europe. *Abies alba* pollen started to appear in our record during the middle Holocene 6.1–6.0 cal. ka BP (Fig. 5), which is comparable to regional records (Svobodová *et al.* 2002; Jankovská 2006; Mentlík *et al.* 2010; Pidek *et al.* 2013). Fir macrofossils and a first pollen maximum point to the local expansion of this tree at our study site 4.9–4.3 cal. ka BP (Figs 5, 6). The macrofossil findings support earlier palynological research that identified local fir presence in mid-mountains of Central Europe during the middle Holocene (Pidek *et al.* 2013). The findings from southern Central Europe indicates that *Abies* was more important in the upper montane belt than in the lowlands (Tinner & Lotter 2006). *Abies* occurrence is also connected with an increase of moisture availability during the middle Holocene (Tinner & Lotter 2006). In the Bohemian Forest, *Abies alba* pollen appeared later than *Fagus* pollen. This is inconsistent with some records from the northern Alpine Foreland (Tinner & Lotter 2006), Krkonoše Mts (Engel *et al.* 2010) and the Black Forest (Rösch 2000). This discrepancy is probably related to local differences in temperature and precipitation.

The period of the middle Holocene climatic optimum and the beginning of the Late Holocene brought a massive aggradation of organic matter, leading to the gradual infilling of small water bodies, or lake-level fluctuations, in the broader region (Haas *et al.* 1998; Raab 1999; Engel *et al.* 2010; Mentlík *et al.* 2010).

The appearance of anthropogenic indicators in the pollen record (*Secale cereale*, *Plantago lanceolata*, *Sambucus nigra*, *Rumex acetosella*-type, *Urtica*) reflects the German colonization of the foothills of the region during the 13th century AD (Veselý 1998). A decline in the forest and changes in tree composition mark the start of intensive forest management between the 16th and 18th centuries AD and reflect the development of the glass and timber industries in the Bohemian Forest (Veselý 2000).

Conclusions

A multi-proxy-based reconstruction provided evidence of a shift from glacial to temperate climate conditions in a mid-altitude mountain range throughout the Late Weichselian and entire Holocene. Most of the environmental changes during the Lateglacial and early Holocene were sudden compared with the more gradual changes during the middle and late Holocene. Both global and local disturbances were observed in our record.

- The sedimentological record at the coring site covers the terminal stages of the local Late Weichselian cirque glaciation. The distinct changes in the record coincide not only with the regional, but also with the global (Alpine) glacial chronology. Nevertheless, the Lateglacial chronology of the study area matches more closely the chronology of glaciation in the larger cirques of the range (the Kleiner Arbersee and the Plešné Lake valleys) than in the smaller ones (the Prášilské Lake and Laka Lake valleys).

- The short-term climate shifts such as the Older and Younger Dryas (YD), or 8.2 ka cold event affected the environmental record at the study site less than in other localities in the Alps or NW Europe. The YD was primarily a dry episode without glacier re-advances and a low lake level event occurred at our study site. The paucity of precipitation was probably a more limiting factor than temperature during the YD, and at the beginning of the early Holocene, in the southern part of the Bohemian Massif.
- Forest development proceeded to a natural climax vegetation, substantially undisturbed by human activities, until the 10th century AD. At the end of the Lateglacial, vegetation patterns became spatially differentiated by both regional (climate change) and local factors (e.g. soil moisture, morphology). Later, during the Holocene, the environmental (vegetation) changes in our study area were more a response to the climate conditions in the region than a process of succession phases or local disturbances.
- Primary succession shows a close similarity to the forest development in Central Europe. A combination of pollen and macrofossil analysis demonstrated that trees had already colonized favourable localities at altitudes above 1000 m a.s.l. during the Lateglacial (15.4–13.4 cal. ka BP). However, the local tree line exceeded the altitude of the study site (1028 m a.s.l.) by 10.5 cal. ka BP.
- Human impact on the local vegetation was observed from the Middle Ages to the present. Both the structure and extent of the forest were affected by settlement activities and forest management. Unfortunately, the resolution of this record is insufficient for a detailed regional comparison of human impact in the last 500 years.

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