BOREAS An international journal of Quaternary research

Buried Late Weichselian thermokarst landscape discovered in the Czech Republic, central Europe

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BOREAS

Hošek, J., Prach, J., Křížek, M., Šída, P., Moska, P. & Pokorný, P. 2019 (October): Buried Late Weichselian thermokarst landscape discovered in the Czech Republic, central Europe. *Boreas*, Vol. 48, pp. 988–1005. https://doi.org/10.1111/bor.12404. ISSN 0300-9483.

Pronounced climatic warming associated with the Late Weichselian Pleniglacial-to-Lateglacial transition caused considerable environmental changes throughout the former periglacial zones (in Europe ~53°–46°N). During permafrost degradation and subsequent ground subsidence (i.e. thermokarst processes), the landscape changed rapidly. In this study we investigated a flat mid-altitude area in south Bohemia, Czech Republic, lying close to the southern limit of the Weichselian permafrost. We discovered palaeo-lake basins with sedimentary infillings up to 11 m in depth. According to radiocarbon and palynostratigraphical dating, these basins were formed at the onset of the Late Pleniglacial-to-Lateglacial transition, whereas the smaller depressions were formed later. We suggest that the basins resulted from thermal and fluvio-thermal erosion of the former permafrost and represent remnants of discontinuous gullies and possibly collapsed frost mounds (pingo/lithalsa scars). The formation of this a fossil thermokarst landscape was climatically driven and multiple phased, with the major phase during the climatic warming and wetting at the onset of GI-1e (Bølling) and the minor phase during GI-1c (Allerød). This study enhances knowledge of the palaeogeography of the former European periglacial zone by showing that Late Pleistocene thermokarst activity could have had a significant impact on the evolution of the landscape of at least some regions of central Europe along the southern limit of the continuous permafrost zone. The research also points to a similar history for the physical transformation of the landscape of the former European periglacial zone and current thermokarst landscapes and could be a valuable source of information with respect to the future transformation of the Arctic under conditions of ongoing global warming.

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In recent permafrost environments, thermokarst encompasses the whole range of geomorphological landforms affecting the landscapes of the Arctic and the Antarctic (Jorgenson 2013; Kokelj & Jorgenson 2013; Farquharson *et al.* 2016). Thermokarst is understood in terms of processes associated with the thawing of ice-rich permafrost that lead to local or widespread ground collapse, erosion, and surface instability. Resulting landscapes are characterized by pits, basins, and irregular depressions that lack surrounding ramparts (French 2017). Thermokarst (thaw) lakes are the most ubiquitous of these landforms (Jones *et al.* 2011; Morgenstern *et al.* 2011, 2013; Farquharson *et al.* 2016), usually initiated by complete subsurface ice degradation, ground collapse and the subsequent accumulation of water in the closed depression (Van Everdingen 1988; French 2017). The sizes, shapes and morphologies of thermokarst lakes and depressions can vary enormously amongst and even within various regions (Grosse *et al.* 2013), depending mostly on the local relief resulting from geological structure (e.g. fault lines), the topography associated with fluvial patterns (e.g. basins related to beaded streams; Short & Wright 1974; Merck *et al.* 2012; Jorgenson 2013), or the post-formation history of erosion and deposition. Widespread thermokarst initiation appears to have coincided with the onset of the Holocene as a result of warmer and wetter conditions relative to the Pleistocene (Czudek & Demek 1970; Rampton 1988; Walter *et al.* 2007; Morgenstern *et al.* 2011; Biskaborn *et al.* 2013; Lenz *et al.* 2016). Observations indicate that over the past several decades, geomorphic processes in permafrost regions have been intensifying (Biskaborn *et al.* 2019), affecting ecological and biological systems, and destabilizing arctic infrastructure (e.g. Rowland *et al.* 2010). Some projections indicate accelerated modifications to permafrost in the near future as a system-wide response to ongoing global warming (Hinzman *et al.* 2005). Studying relict landforms of past periglacial landscapes may provide useful information on how modern periglacial landscapes will respond to ongoing warming at high latitudes.

Throughout the Weichselian Pleniglacial–Lateglacial transition (~18–15 ka BP), rapid and pronounced climatic oscillations caused distinct environmental changes (Roberts 2014) and induced large-scale physical landscape transformation throughout the former European peri-

DOI 10.1111/bor.12404

glacial zone (Isarin 1997; Huijzer & Vandenberghe 1998). Some structures such as gullies, pits or involutions have been interpreted as relict thermokarst features resulting from the decay of former Pleistocene permafrost (Vandenberghe & Pissart 1993). Of various types of thermokarst depressions distinguished within recent thermokarst landforms (Jorgenson 2013), collapsed open-system pingos and lithalsas are the most frequent kind, documented from numerous sites throughout the lowlands of north, northwestern, and western Europe (Svensson 1964; Hoek 1997; Pissart 2000). Both types of depressions are typically circular or elongated and rimmed by a distinct rampart, which formed by the action of mass wasting down the sides of a former mound that enclosed a central depression where the ice-core had melted (French 2017; Harris *et al.* 2018). These depressions are usually filled by colluvial sediments, peat and sometimes lacustrine sediments. In contrast to pingo and lithalsa scars, evidence of landforms representing Pleistocene non-ramparted thermokarst lakes is very limited. This could be due to their low potential for preservation in the fossil record (French 2017) once the permafrost had thawed, such thawing reducing the terrain to the level of former depression floor (Ballantyne 2018). In Europe, non-ramparted thermokarst depressions filled by lacustrine deposits have so far been described from several sites in the Netherlands and eastern Germany (Bohncke *et al.* 1993; Van Huissteden & Kasse 2001), northern Poland (Dylik 1963), southern England (Berry 1979; Banks *et al.* 2015), and northern France (Van Vliet-Lanoë *et al.* 2017; Bertran *et al.* 2018). In contrast to N and NW Europe, knowledge on thermokarst processes and their importance in the genesis of the Late Pleistocene landscapes of central Europe remains poor (Czudek 1986, 2005; Vandenberghe 2001; Žák *et al.* 2012).

In light of these considerations, the Třeboň region in south Bohemia (Czech Republic) could be a key area with respect to reconstructing the Late Pleistocene environment of central Europe. Even though this landscape had been extensively remodelled during the Early Modern Age (~AD 1500–1600) construction of fishponds, large non-ramparted palaeo-lake basins have been discovered in recent years by drilling (Šída & Pokorný 2011; Hošek *et al.* 2013, 2016). High-resolution, up to 11-m-thick lacustrine sequences of the largest palaeo-lake basins have provided detailed information on supra-regional environmental transformation and dynamics throughout the Late Pleistocene–Holocene transition (Pokorný & Jankovská 2000; Pokorný 2002; Pokorný *et al.* 2010; Hošek *et al.* 2014, 2017). However, the origin of these palaeo-lakes and depressions is so far unknown. Here, we describe these rare landforms in their geological and palaeoenvironmental setting and examine their mechanisms of formation in the context of the Late Pleistocene landscape transformation of the former periglacial zone. Knowledge of past landscape and environmental dynamics could provide valuable information on the interaction between permafrost and climate during the last deglaciation (e.g. Köhler *et al.* 2014), as well as insight into current permafrost deformation, the mechanisms behind which are still not sufficiently understood.

Regional settings

Geology and geomorphology

The study area is situated in South Bohemia, Czech Republic (latitude 49°03′N, longitude 14°43′E, altitude 400–430 m a.s.l.; Fig. 1), in the northern part of the Třeboň Basin, which consists of an area of generally flat terrain, with elevations only 25–30 m in height. The Třeboň Basin is filled by Cretaceous clastic sediments consisting of sandstones, conglomerates and mudstones.

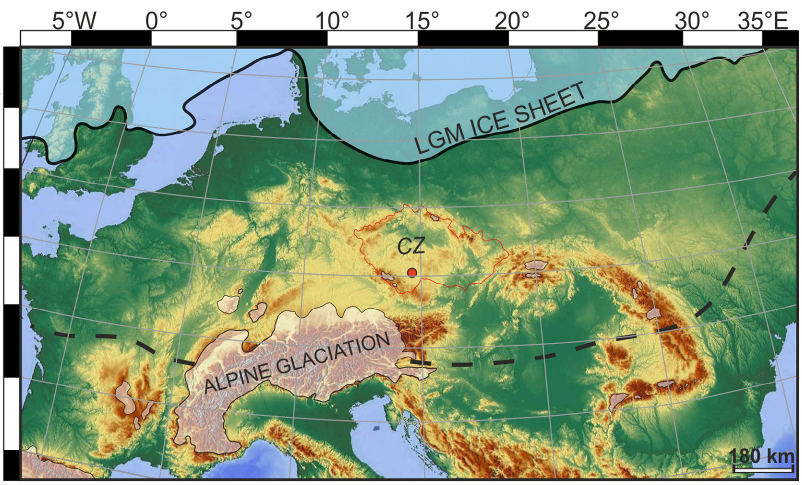

Fig. 1. Map showing the location of the study area (red dot) within the Czech Republic (CZ) together with the maximum extent of the continuous permafrost (dashed line), Scandinavian Ice Sheet and Alpine glaciation during the Last Glacial Maximum, ~20 ka ago (after Vandenberghe *et al.* 2014 and Ehlers & Gibbard 2004). [Colour figure can be viewed at www.boreas.dk].

These Cretaceous sediments are partially covered by a layer of Miocene fluvio-lacustrine sediments up to 60 m in thickness (Malecha *et al.* 1991). All the studied thermokarst depressions are situated on the upper part of the Miocene sequence (Fig. 2), which consists of layers of fine-sandy clays, sandy gravel, diatomite, and

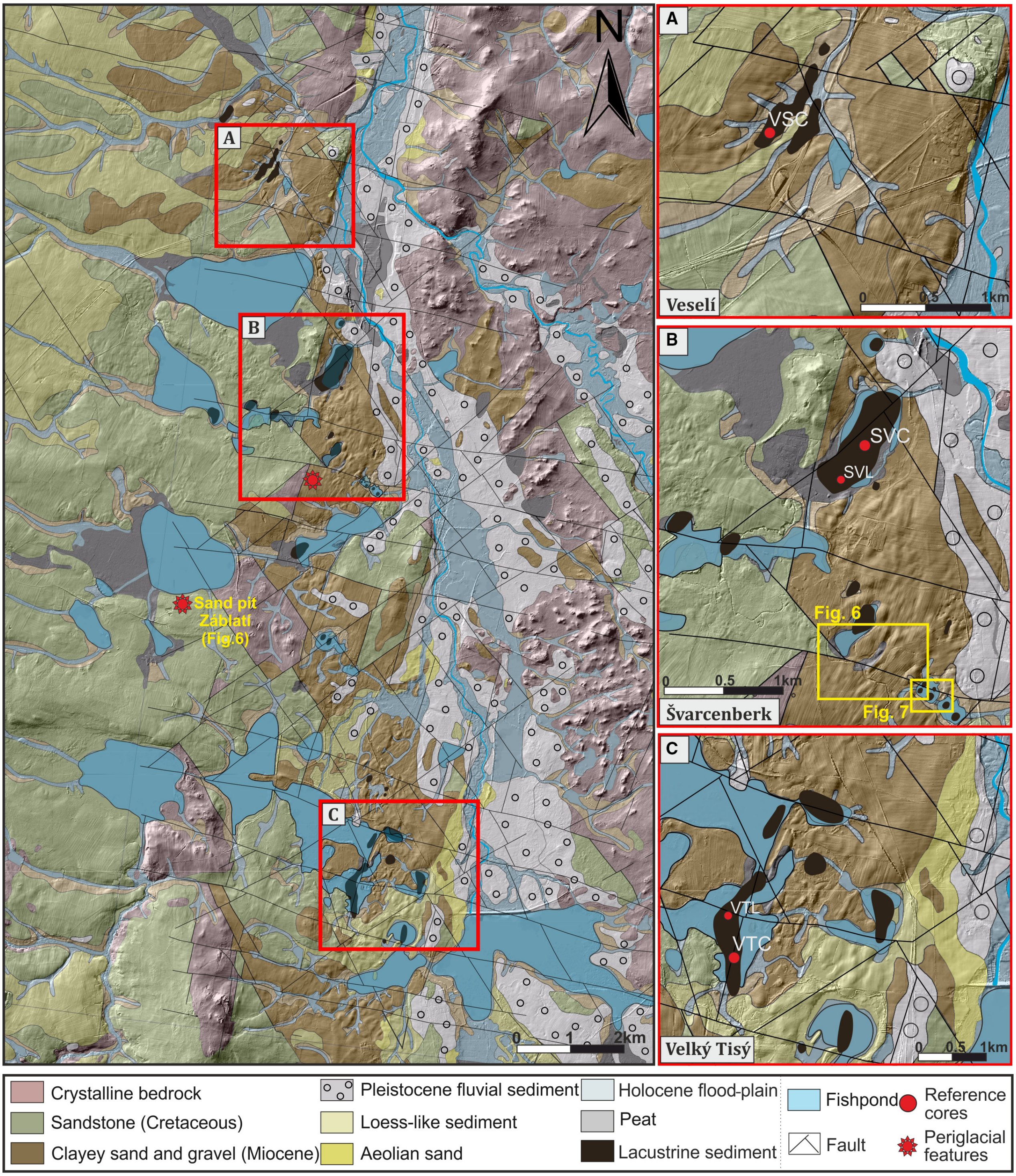

Fig. 2. Geological map of the study area (based on Dornič *et al.* 1977) and the spatial distribution of Late Pleistocene lacustrine sediments. The most investigated areas in the surroundings of the Veselí (A), Švarcenberk fishpond (B) and Velký Tisý (C) fishpond are shown in detail together with locations of sampling cores SVC (Švarcenberk Central Core), SVL (Švarcenberk Littoral Core), VTC (Velký Tisý Central), VTL (Velký Tisý Littoral) and VSC (Veselí Central). [Colour figure can be viewed at www.boreas.dk].

lignite. Miocene sediments fill the NNW–SSE graben, which is a dominant tectonic and geomorphological structure in the area. The boundary between Cretaceous and Miocene sediments is characterized by a system of faults perpendicular to the main tectonic structure. The graben constitutes the shallow depression, up to 2 km in width, in the generally flat terrain. The surface of this zone is characterized by undulating terrain formed by isolated elevations up to several metres in height and depressions between them. The predominant orientation of these features is NE–SW, i.e. in concordance with the zone's current surface drainage system.

Periglacial deposits include loess-like sediments and stratified slope deposits. The area of loess deposits is nowadays restricted to the NW part of the study area. These deposits are 1–6 m thick, slightly sandy and completely decalcified. Within the low-lying water-saturated terrain along the Lužnice River, loess-like sediments were preserved only in isolated islands, due to intensive decalcification and consequent erosion during the Early Holocene (Hošek *et al.* 2017). Middle and Upper Pleistocene fluvial sandy gravels are preserved discontinuously along the Lužnice River as alluvial terraces with surfaces 5 and 8 m, respectively, above the Holocene flood-plain (Chábera & Vojtěch 1972). Pleistocene fluvial sediments are partially covered by numerous aeolian sand dunes formed here during the Younger Dryas (Pokorný & Růžičková 2000).

Hydrogeology

Groundwater in the northern part of the Třeboň Basin currently flows through Cretaceous sediments from the highlands lying southeastern of this area (Krásný *et al.* 2012). Along the contact between Miocene sediments and crystalline bedrock, the groundwater flows upward to the surface along faults. Artesian springs are localized in these zones if the uppermost part of the Miocene sequence consists of sufficiently thick clayey sediment (aquitard; Kadlecová *et al.* 2016). Generally, these fine-grained sediments and a low topographic gradient both contribute to poor surface hydrological drainage across the area and promote the existence of extensive and thick Holocene peat bogs (Pokorný *et al.* 2010). These periodically or permanently waterlogged depressions were also used for the construction of large fishponds during the Early Modern Age – today, artificial ponds are an omnipresent feature of the local landscape.

Periglacial features

During the Last Glacial Maximum (LGM; ~23–19 ka, Mix *et al.* 2001) the study area was located ~110 km north of the Alpine piedmont glaciers and ~400 km from the southern edge of the North European continental ice sheet (Fig. 1). It was also deep below the LGM-equilibrium line altitude of the glaciation of the Bohemian Forest, which was about 1050–1150 m a.s.l. (Křížek *et al.* 2012; Vočadlová *et al.* 2015). Pseudomorphs of thermal-contraction-cracking features clustered into polygonal nets previously documented in the south of the Czech Republic (Kunský 1946; Chábera & Mach 1977) suggest that this region underwent permafrost evolution long enough to allow the growth of thick ground ice bodies. Thermokarst features include soft-sediment deformations (thermokarst involution), abundantly present in the poorly consolidated Cretaceous and Miocene clayey sand as well as in the Upper Pleistocene alluvial sediment. Thermokarst sediments accumulated mostly along the foothills of asymmetrical valleys with steeper slopes (Chábera & Mach 1977).

Material and methods

Fieldwork and imagery

The presence of lacustrine deposits at selected sites was detected using more than 500 individual boreholes performed within terrain depressions, almost all of which are currently flooded by artificial fishpond bodies. On non-flooded sites we also used electrical resistivity tomography for detailed investigation of subsurface geology (for technical details, see Hošek *et al.* 2016). The extent of lacustrine deposits and the morphology of basins were mapped using hand-operated corers (25 mm in diameter) in several transects with 20- to 100-m grids across the basins. Lake sediments covered by fishponds were cored from a boat in summer and from ice during winter seasons. Due to their potential with respect to high-resolution palaeoenvironmental reconstruction, the largest lake basins – Velký Tisý, Švarcenberk and Veselí – were studied in greater detail (220 boreholes in 42 transects) and, thus, a substantial part of the findings relating to morphology and lithostratigraphy discussed below arises from observations made at these sites. Reference cores VTC, SVC and VSC were taken from the central parts of these lakes using a pneumatic hammer-operated piston-corer (tube 50 mm in diameter) and the subsampled material (bulk gyttja and plant macro-remains) was used for radiocarbon dating.

Our field interpretations were consolidated by the analysis of aerial photographs (www.mapy.cz), and the use of a high-resolution digital elevation model (DEM; the Czech State Administration of Land Surveying and Cadastre – CUZK, 1-m grid), which allowed the identification of inherited periglacial patterns at the scale of the region. As the study area has been influenced significantly by modern agricultural management and fishpond building over the last 50 years, we also used historical topographic maps and aerial photographs from the 1950s (provided by the Office of Military Geography and Hydrometeorology of the Ministry of Defence of the Czech Republic), which were produced before agriculture and fishpond management intensified and in which the shapes of several former shallow depressions in the landscape were evident. For expression of the shape of lake basins (elongated, semi-circular, circular) elongation index was calculated. The elongation index (major axis/minor axis) refers to the axes of a best-approximated ellipse with an area equal to that of the object being analysed (Morgenstern *et al.* 2011).

Radiocarbon and OSL dating

The radiocarbon dating of plant remains and bulk lacustrine sediment was performed in order to obtain detailed stratigraphical information on the initiation and evolution of palaeo-lakes. Sediment was sampled from the profundal parts of palaeo-lakes to eliminate the effect of possible redeposition. Overall, 21 radiocarbon ages are presented in this study, some of them already published (Pokorný 2002; Hošek *et al.* 2014, 2017; Table 1). Samples were prepared for ^{14}C accelerated mass spectrometry (AMS) and dated at the Poznań Radiocarbon Laboratory in Poland (abbr. Poz-), at the Center for Applied Isotope Studies, University of Georgia, USA (abbr. UGAMS-) and at the Radiocarbon Dating Laboratory, Department of Quaternary Geology, Lund, Sweden (abbr. LuA-; Table 1). All radiocarbon dates are presented as calibrated (ka BP) against the IntCal13 curve using OxCal v4.2 (Reimer *et al.* 2013).

Two samples for OSL dating were taken from the sedimentary infill of a pseudomorph of thermal-contraction-crack exposed in the wall at the Záblatí sand pit (Zablati_1 and Zablati_2) and processed at the OSL laboratory at the University of Gliwice (Poland). Details on the method of pretreatment and the measurements of samples are provided in Data S1 and Fig. S1.

Comparison of studied sections with modern thermokarst forms – criteria selection

The interpretive syllogism of the study is based substantially on comparison of our observations with known recent thermokarst landforms and structures. Nevertheless, the studied structures represent past (palaeo) features in the recent temperate region, and hence the diagnostic criteria for periglacial processes were blurred by Holocene surface re-shaping. Furthermore, almost all the studied palaeo-lakes are buried by recent fishponds, which make them unavailable for the detailed evaluation of some characteristic features and structures linked with thermokarst processes. Consequently, comparison of the studied palaeo-lakes with modern ones is based on characteristics that could be obtained by borehole investigations. These characteristics include (i) basin

Table 1. Results of radiocarbon dating from the Velký Tisý, Švarcenbek and Veselí palaeo-lakes.

Lab. code	Profile, depth (cm)	Type of material	^{14}C age (a BP)	Calibrated age range (cal. a BP)	Reference
LuA-4590	SVC, 390-393	Woody stem fragment	9640±115	10 801–11 147 (68%)	Pokorný (2002)
LuA-4591	SVC, 520-523	Bulk gyttja sample	10 780±115	12 654–12 877 (68%)	Pokorný (2002)
LuA-4738	SVC, 680-683	Bulk gyttja sample	11 750±120	13 464–13 813 (68%)	Pokorný (2002)
LuA-4737	SVC, 985-995	*Salix* twigs	12 800±120	14 943–15 617(68%)	Hošek *et al.* (2014)
Poz-71857	VTC, 50-52	Terrestrial plant seeds	960±30	796–886 (64.8%) 891–929 (30%)	This study
Poz-72025	VTC, 92.5	Bulk gyttja sample	3230±35	3380–3512 (84.2%) 3527–3558 (10.8%)	This study
Poz-71858	VTC, 240-242	Bulk gyttja sample	7550±50	8209–8261 (7.8%) 8294–8428 (87.1%)	This study
Poz-71859	VTC, 330-335	Bulk gyttja sample	8630±70	9487–9788 (94.1%) 9850–9861 (0.6%) 9878–9883 (0.3%)	This study
Poz-72027	VTC, 422-423	Bulk gyttja sample	9670±60	11 061–11 214 (50.7%) 10 786–10 981(39.2%) 10 986–11 033 (5.1%)	Hošek *et al.* (2017)
Poz-72212	VTC, 487-488	Bulk gyttja sample	10 840±60	12 672–12 823 (95%)	Hošek *et al.* (2017)
Poz-72071	VTC, 536-537	Bulk gyttja sample	11 250±60	13 019–13 249 (95%)	Hošek *et al.* (2017)
UGAMS-25537	VTC, 590	Bulk gyttja sample	11 400±30	13 152–13 306 (95%)	Hošek *et al.* (2017)
Poz-72028	VTC, 617-618	Bulk gyttja sample	11 730±70	13 448–13 717 (95%)	Hošek *et al.* (2017)
Poz-71860	VTC, 678-679	*Betula* (seeds)	12 000±60	13 729–14 037 (95%)	Hošek *et al.* (2017)
Poz-71861	VTC, 730-735	Woody fragment	12 240±60	13 960–14 449 (95%)	Hošek *et al.* (2017)
UGAMS-17379	VTL, 66	Plant frag.	4400±30	4867–5046 (94.1%) 5205–5210 (0.8%)	This study
UGAMS-17380	VTL, 430	Plant frag.	13 090±35	15 496–15 909 (95%)	This study
UGAMS-25536	VSC, 282.5	Bulk gyttja sample	11 890±35	13 580–13 776 (95%)	Hošek *et al.* (2017)
UGAMS-23611	VSC, 355-360	Bulk gyttja sample	11 830±70	13 534–13 772 (89.8%) 13 483–13 527 (5.2%)	Hošek *et al.* (2017)
UGAMS-23612	VSC, 420-422	*Salix*/*Populus* (wood fragment)	12 140±30	13 905–14 152 (94.7%) 13 880–13 884 (0.3%)	Hošek *et al.* (2017)
UGAMS-30901	VS, lake bottom	Wood	11 640±30	13 401–13 658 (95%)	This study

Table 2. Morphometric characteristics and ages of basal deposits of Velký Tisý, Švarcenbek and Veselí palaeo-lakes.

Site	Number of cores	Width × length × maximum depth (m)	Surface of lake sediment (km^2)	Perimeter of former shoreline (km)	Radiocarbon age of basal deposits (cal. ka BP)
Velký Tisý_1	31	970×370×12	0.2	0.23	14.3; 15.8
Velký Tisý_2	5	142×562×6.8	0.1	1.3	–
Švarcenberk	149	450×1280×10	0.44	3.1	15.3; 13.7
Veselí_1	45	130×640×6	0.061	1.6	14.1
Veselí_2	35	154×420×6	0.049	1.02	13.5

morphology and morphometry, (ii) lithostratigraphy, and (iii) the palaeoenvironmental context derived from the sedimentary record.

Results and interpretation

Spatial distribution and morphology of palaeo-lakes

Overall, 31 sedimentary basins were documented in the study area (Fig. 2). They were found solely on Miocene bedrock (sand/clayey sand) within poorly drained (waterlogged) low-lying areas determined mostly by bedrock faults (Fig. 2). All of the basins are enclosed and non-ramparted.

The shapes of most basins are rather irregular, elongated or trough-shaped (n = 16). Nevertheless semi-circular (n = 9) or circular (n = 6) shapes were also mapped. The length of the longer axis of the lake basins ranged from several metres to several hundred metres. The predominant orientation of the longer axis of most of the basins is SW–NE, in concordance with the tectonic fault system as well as with the current surface drainage system (Fig. 2). The minimum lake depth was found to be 1 m, and the maximum 11 m, while the surface area of the current sediment of the former lakes ranged from 0.01 to 0.44 km^2.

On the basis of size and morphometric/morphological characterization, the studied lake basins can be divided into two groups. The first group is represented by basins with an obvious elongated or trough shape, a longer axis greater than 120 m, and a depth of between 6 and 11 m (Table 2). All of these basins were found within short shallow valley-form depressions with low gradients going from slightly elevated areas of SW slopes toward the erosion base of the area, i.e. Lužnice River floodplain (Fig. 2). The orientation of the longer axes of the basins is usually parallel to the axes of the short valleys. In addition, a system of elongated elevations of Miocene bedrock and depressions parallel to the directions of the basin axes is typical for surfaces in the vicinity of the palaeo-lakes and denotes past fluvial activity in these zones (Fig. 2B, C).

The typical morphology and bottom bathymetry of these basins are shown in Figs 3, 4 for the examples of the Švarcenberk (SV), Velký Tisý (VT) and Veselí (VS) palaeo-lakes. The basins are characterized by an asymmetrical profile with steep slopes and a cone-like shaped bottom (see the longitudinal profiles through SV and VT palaeo-lakes). The basins can be partially divided by internal ridges into semi-separate individual depressions. This is most striking in the case of the SV palaeo-lake, where ridges up to 3.5 m in height were found. Cross-sections reveal V-shaped slopes with an internal valley in the central part running parallel with the longer axis and making a step-like profile (Fig. 3). Taking into account the location of the palaeo-lakes within short shallow valley-form depressions, these basins could be remnants of past tributaries of the Lužnice River. However, all basins were found to be entirely enclosed and, consequently, no connection between the sedimentary sequences of the palaeo-lakes and the Lužnice River valley was found. Therefore, this possibility can be rejected (see also discussion below).

The second group of palaeo-lake basins is characterized by a generally circular or semi-circular shape with a diameter of less than 120 m and a maximum depth of 6 m. In comparison with basins of the first group, these are located farther from the downvalley axis. Cross-sections revealed rather gentler slopes and pan-like shaped bottoms (Fig. 7B).

Lithostratigraphy of lacustrine sediments

Although the dating of thermokarst lake sediments has been repeatedly reported as problematic (e.g. Gaglioti *et al.* 2014), several sites from the circumpolar Arctic/Subarctic were shown to provide useful palaeoenvironmental archives (Bouchard *et al.* 2017). In our study the radiocarbon ages obtained from the plant macro-remains and bulk gyttja sediment of the largest and deepest palaeo-lakes (Table 1, Fig. 5) are in stratigraphical order and reveal continuous sedimentation throughout the Lateglacial and the Holocene. On the basis of these data and lithological characterizations, sedimentary records of the largest palaeo-lakes can be divided into three main zones (A-B-C), corresponding to major environmental changes in the study area (Fig. 5).

Zone A consists of two units: (i) minerogenic sediments (clayed sand/gravel and calcareous silt) and (ii) clayey sand with layers of minero-organic sediment (gyttja). Both units have a massive structure and rather low contents of organic matter. The maximum thicknesses (up to 3 m) of these strata were found in the central parts of basins, while the thickness was reduced or even null

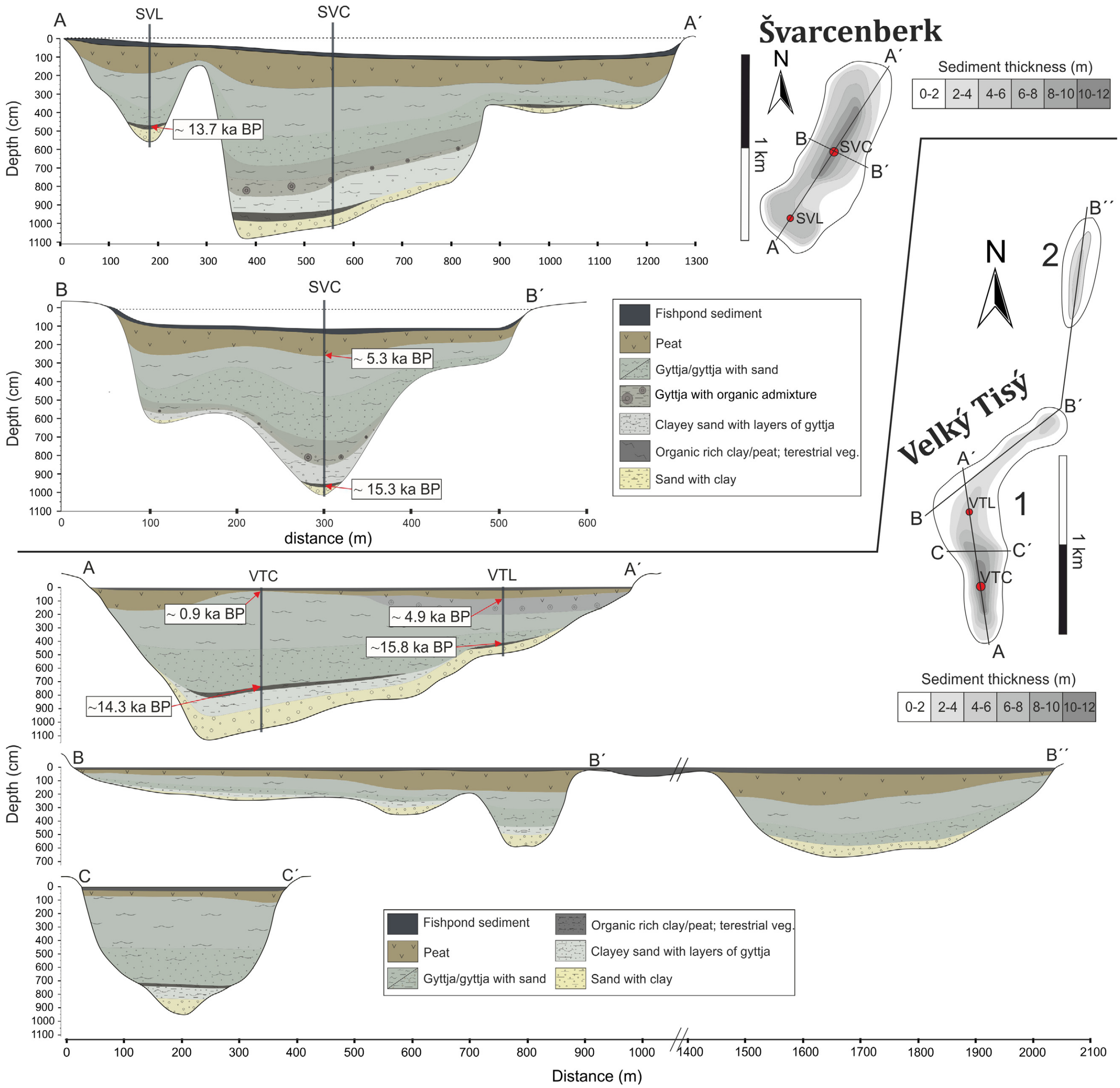

Fig. 3. Bathymetry and stratigraphical cross-sections of the Švarcenberk and Velký Tisý palaeo-lake basins together with the locations of sampling cores and the calibrated radiocarbon ages. [Colour figure can be viewed at www.boreas.dk].

toward the littoral zones (Fig. 3). A distinct layer of clayey peat with the remains of terrestrial vegetation was often found in impure sand within or at the surface of this sequence. It contained the remains of herbs, twigs of arctic dwarf shrubs (*Salix*, *Betula nana* in the case of the Švarcenberk palaeo-lake), and pine trunks (Veselí palaeo-lake). The radiocarbon dates of these remains of the terrestrial vegetation (Table 1) together with palynostratigraphical investigations (Pokorný 2002) revealed that zone A accumulated throughout the late Pleniglacial/Lateglacial transition (~16–15 cal. ka BP). Zone A represents the initial phase of the lake infill. Diamict sediments were relocated into the lake basin by surface erosion and slope processes. They also could have originated from retrogressive slumps of the thawing sides of the lake and can be considered as thermokarst sediments, which are colluvial in nature and consist of a range of locally redeposited and heterogeneous materials, or diamictons, which often incorporate clumps of organic material (see also Murton 1996). The source of allogenic components consisted primarily of exposed Miocene and Cretaceous sediments in the catchment. An additional source was probably loess washed from watersheds, as indicated by the high concentration of

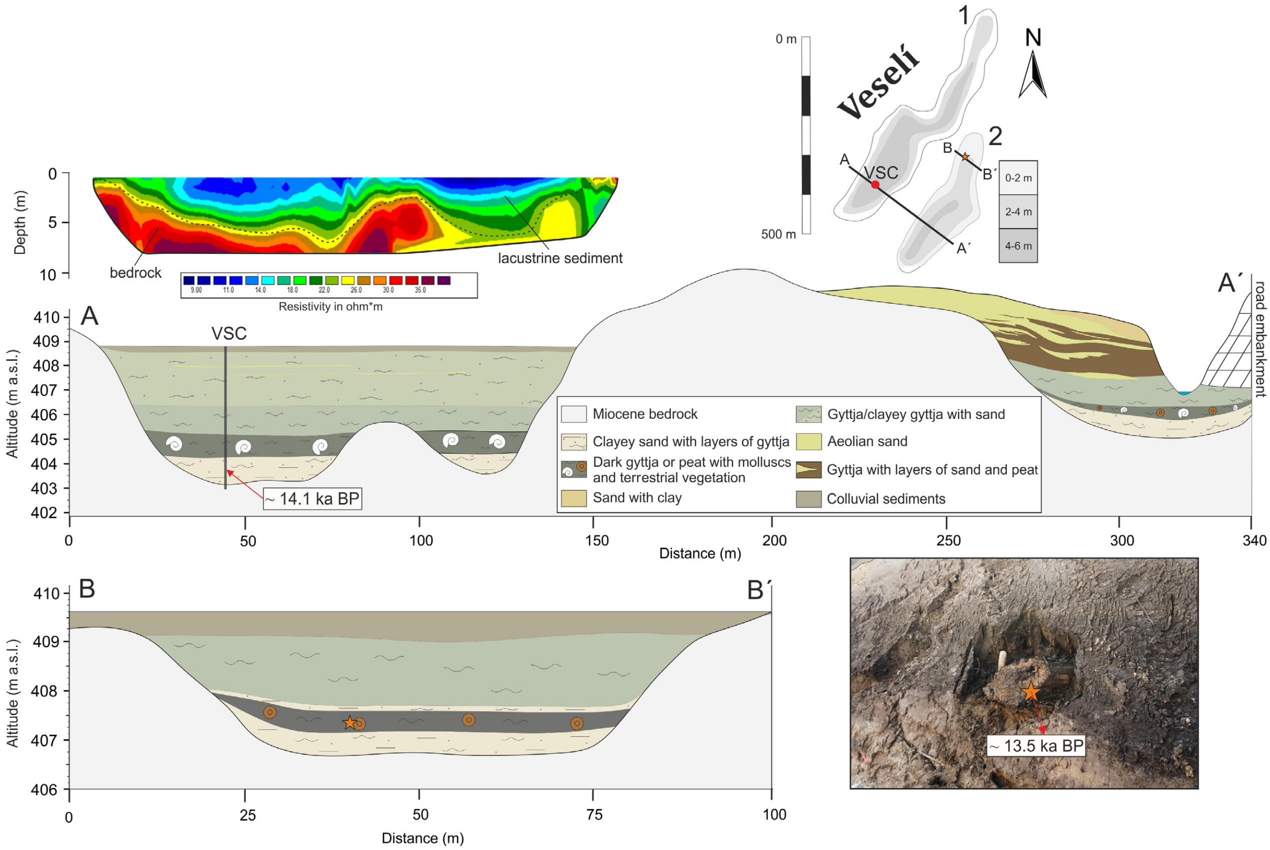

Fig. 4. Bathymetry and stratigraphical cross-sections of the Veselí_1 and Veselí_2 palaeo-lake basins together with the results of electrical resistivity tomography (adopted from Hošek *et al.* 2017), the location of the VSC sampling core and the calibrated radiocarbon ages. The orange star refers to the location of the pine branch within the lacustrine sediment exposed in a temporary artificial outcrop (the photograph's bottom right). [Colour figure can be viewed at www.boreas.dk].

medium/coarse silt and the substantially elevated concentration of calcium in these sedimentary strata (Hošek *et al.* 2017).

Zone B consists of a sequence of organo-mineral deposits (fine-detritus gyttja), up to 8 m in thickness. In the lower part of this zone, an increased input of allochthonous material (fine-grained sand and silt) mixed with the remains of terrestrial vegetation was usually found (subzone B_1), whereas in the upper part the strata are characterized by quiet lacustrine sedimentation (subzone B_2). On the basis of radiocarbon dates obtained from plant macro-remains and bulk gyttja sediment, zone B corresponds to the Lateglacial.

The above-lying zone C corresponds to the Holocene. The lithology of this zone is characterized by the presence of coarse-detritus gyttja with high contents of organic matter and low allochthonous input. In most cases, the lacustrine sediments are overlain by a layer of ligno-herbaceous peat 1–3 m in thickness (Fig. 5). This lithological switch points to a change in depositional conditions, from lacustrine to terrestrial, which occurred in the Middle Holocene (~4.9 cal. ka BP according to radiocarbon dating).

The palaeo-lakes from the second group exhibited similar lithostratigraphy to the largest palaeo-lakes. However, the thickness of the lacustrine/thematic sediment (zone B) was reduced (usually <1 m) and most of the infill was formed by peat (zone C).

Overall, the lithostratigraphy of the studied lakes shows a similar pattern to the sedimentary sequences of most thermokarst lakes. Sediments of recent thermokarst lakes can usually be divided into two general formations (Czudek & Demek 1970; Farquharson *et al.* 2016): (i) basal high-energy colluvial sediment with a massive structure dominated by upland material from bank thaw and collapse events (correlated with zone A), and (ii) an above-lying low-energy central basin environment dominated by lacustrine sediment and peat (zones B and C).

Interpretation and dating of periglacial features

A 153-cm-high and 120-cm-wide structure exposed in the wall of the Záblatí sand pit (Fig. 6C) was interpreted as pseudomorph of thermal-contraction crack. The host material was unconsolidated sand and gravel of Cretaceous sediment. The pseudomorph infill consisted of sandy silt with larger clasts (up to 2 cm in diameter), which were mostly vertically aligned along the walls of

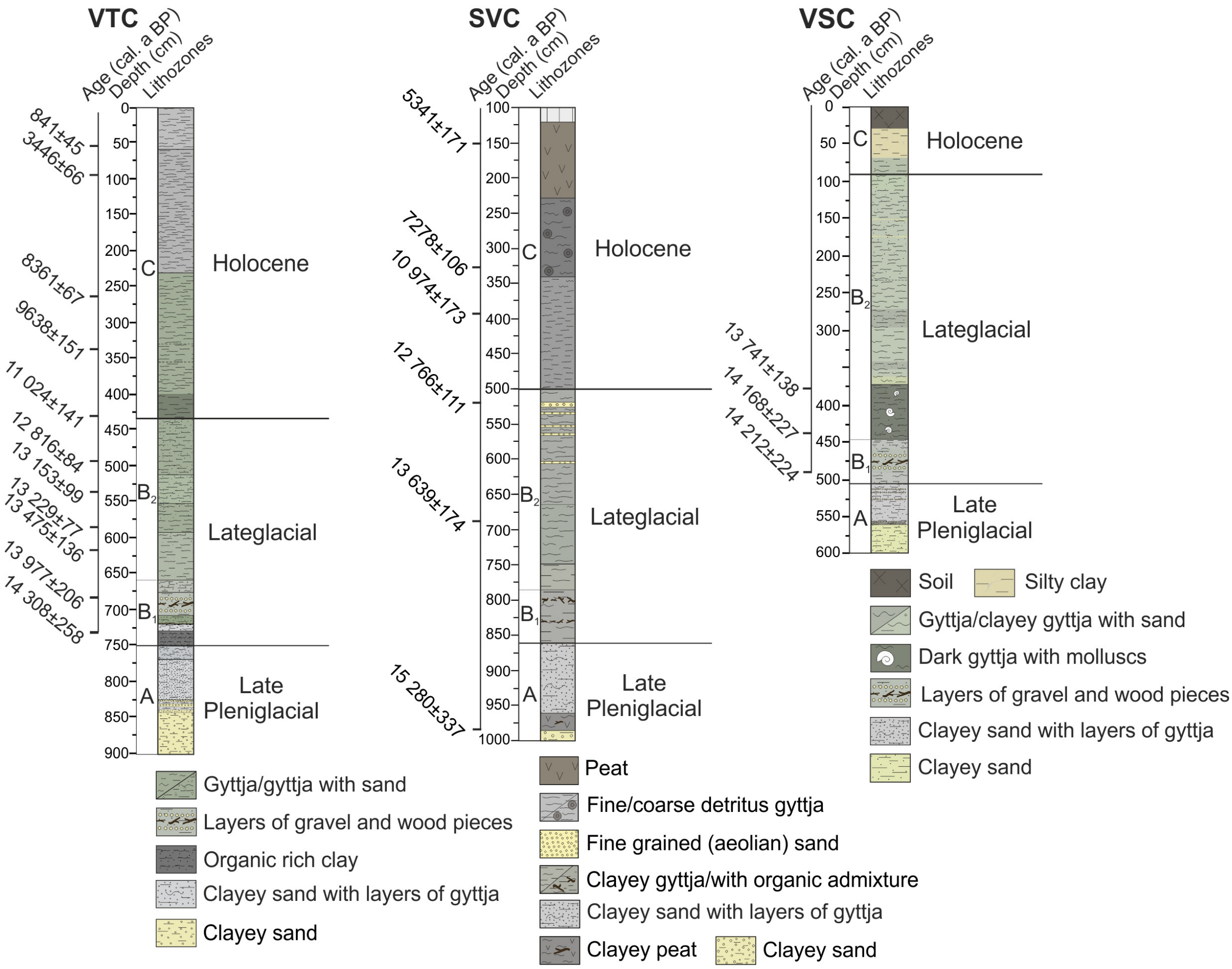

Fig. 5. Lithology and radiocarbon ages of references cores VTC, SVC and VSC. [Colour figure can be viewed at www.boreas.dk].

the pseudomorph. The infilling material was loess, which had been (re)deposited in the wedge together with surrounding sand and gravel by both aeolian and colluvial processes. Two OSL samples obtained from the sediment infilling (Fig. 6C) yielded ages of 53.3±2.8 and 58.3±2.5 ka (Table 3), dating the formation of the pseudomorph of thermal-contraction crack to the Early/Middle Pleniglacial (MIS 4/3). The OSL age of the pseudomorph corresponds to the one period of permafrost formation (~60 ka) in northern France described by Bertran *et al.* (2014). Although no direct evidence of the existence of permafrost during the Late Weichselian (MIS 2) was obtained, its presence in the study area was very likely, as, in central Europe, MIS 2 is reported to have been a significantly colder phase of the Weichselian glacial than MIS 4 (Huijzer & Vandenberghe 1998).

Hexagonal thermal-contraction-cracking features (10–25 m in diameter), visible in fields in aerial photographs (Fig. 6A), were interpreted as having a polygonal pattern (Liljedahl *et al.* 2016; Kanevskiy *et al.* 2017). Most of the observed polygons had sharp edges, which, in aerial photographs, appeared darker than the surrounding land. However, some polygons had more rounded outlines and were delimited by wide depressions or furrows, which may correspond to former thermal-contraction-cracking features that underwent thermokarstic degradation (Bertran *et al.* 2014; Andrieux *et al.* 2018). Larger terrain depressions often appeared irregularly covered with subcircular or elongated dark places, a few metres to 100 m in length (Fig. 6A). This geomorphologically determined distinction is clearly visible in historical maps and photographs, as the wet sites, interpreted as thermokarst depressions, were used as meadows, while arable fields were limited to the elevated and thus drier areas (Fig. S2). On the basis of borehole investigations, dark spots up to 3 m in depth corresponded to wet organic-rich fine-grained sediment or peat with minero-clastic diamicton deposits at the base, whereas light spots indicated the coarser well-drained sediment of bedrock. These structures could be remnants of 'sediment-filled pots' (Conant *et al.* 1976; French *et al.* 2003), which presumably formed at the intersection

Fig. 6. A. Aerial photograph (source: mapy.cz, year 2015) showing distinct structures visible on the agricultural field (49.12°N, 14.7°E) between thermokarst basins (TB) interpreted as permafrost-related features. The structures include hexagonal polygonal nets and asymmetrical permanently wet depressions filled by organic-rich fine-grained sediment or peat. B. An outcrop in the former sand pit near Záblatí (49.1°N, 14.67°E) exposing the Cretaceous conglomerate and an upper layer of unconsolidated sandy gravel with silt. The unconformity between these units was interpreted as the base of the palaeo-active layer; accordingly, the sediment deformations visible in the upper part of the outcrop probably occurred during the deepening of the active layer and were interpreted as thermokarst involutions. C. The pseudomorph of thermal-contraction crack, 1.5 m deep and 1.2 m wide, filled by sandy silt (redeposited loess) dated by OSL at ~55 ka. [Colour figure can be viewed at www.boreas.dk].

Table 3. Dose rate, equivalent dose data and OSL ages of the ice-wedge pseudomorph infill exposed at former sand pit Záblatí. H_2O% = measured water content (water mass over dry sediment mass); U = uranium; Th = thorium; K = potassium.

Lab. code	Sample ID	Sampling depth (cm)	H_2O (%)	U (Bq kg^{-1})	Th (Bq kg^{-1})	K (Bq kg^{-1})	Dose rate (Gy ka^{-1})	OSL age (ka)
GdTL-3531	Zablati_1	110	15±5	30.1±0.5	53.2±0.8	384±10	2.54±0.1	58.3±2.5
GdTL-3532	Zablati_2	130	15±5	30.1±0.5	53.2±0.8	384±10	2.51±0.1	53.3±2.8

of two or more wedges by a combination of thermal erosion and the mixing, slumping and redeposition of material from both the wedges and the enclosing sediments. The modern permafrost analogue is the 'thaw sink' (Hopkins 1949; French 2017).

The mound-like topography observed in the surroundings of some palaeo-lakes can also be interpreted as the remnants of degraded thermal-contraction-cracking features (probably ice wedges) (badland thermokarst reliefs; Kokelj & Jorgenson 2013; Steedman *et al.* 2016), and the shallow valleys between these reliefs are likely to be meltwater channels (Fortier *et al.* 2007).

In the upper part of the exposed wall at the Záblatí sand pit, distinct large deformation structures occurred in unconsolidated diamicton (grey sandy gravel with silt) above the compact, white sandstone/conglomerate (Fig. 6B). They included ball-and-pillow structures of sand and silt, ~0.6 m high and 0.5 m wide, round-topped diapirs of melt-out diamicton up to 1.2 m high and 1 m wide, and other types of cryoturbations in the uppermost part of the outcrop. We interpreted these structures as thermokarst involutions, formed by loading and liquefaction in the permafrost active layer.

Discussion

The remnants of thermal-contraction-cracking features, pitted and undulating topography, or structures interpreted as thermokarst involution (Fig. 6A, B) indicate the previous existence of ice-rich permafrost in the study area as well as past thermokarst landforms resulting from its thawing. Irregular, non-ramparted depressions are the most ubiquitous forms resulting from local thermokarst processes. In a broad sense, thermokarst forms originate from climate-induced and site-specific causes (Toniolo *et al.* 2009). With regard to climate change, the main factor is an increase in ground surface temperature that alters the thermal balance. In mid-latitudes of Europe the onset of the Lateglacial was accompanied by a significant increase in temperature as well as precipitation (Walker 1995; Huijzer & Vandenberghe 1998) and subsequently by permafrost degradation within the former periglacial zones (see Vandenberghe *et al.* 2014 and references therein), with the local development of thermokarst features including shallow depressions filled by alluvial and/or colluvial sediments (Bertran *et al.* 2014). We propose that the amelioration (overall warming) of the climate was, similarly to in recent thermokarst regions, the fundamental trigger of intensive thermokarst processes and thermokarst lake development in the study area.

Site-specific conditions influence the patterns and amount of thermokarst settlement or the loss of surficial material. These processes are related mostly to the quantity and type of ground ice (Shur & Osterkamp 2007; Wolfe *et al.* 2014), local hydrology and terrain configuration (Jorgenson 2013). Therefore, to understand the thermokarst processes in the Třeboň Basin, we need to take into account the geological, hydrogeological and geomorphological contexts of the study area as well as the palaeoenvironmental conditions throughout the Late Pleniglacial – Lateglacial transition.

Massive ground ice formation

Due to a lack of information on cryostructures and ground icing in the study area, the type of ground ice can be only estimated on the basis of current hydrological and geological conditions. All the studied palaeo-lakes, as well as most of the periglacial features identified from aerial photographs, are located within poorly drained low-lying areas. These water-saturated zones are derived mostly from bedrock faults with structural controls on groundwater upwelling, in some cases artesian. We assume that during the cold conditions of the Late Pleniglacial, subsurface ice had its highest occurrence along these zones. All basins were formed in Miocene sediments that consist of layers of sandy/silty clays, clayey sands and sandy gravels with the thickness of particular lithologies varying from several decimetres to several metres. In this sequence, frost-susceptible fine-grained sediments (i.e. layers of silty clay and clayey sand) were particularly prompt in impelling unfrozen water to the freezing front (Wu *et al.* 2012). This action could have induced the formation of discrete bodies of segregation ice (Rampton 1988) and/or intrusive ice, when groundwater was under (artesian) pressure (Mackay & Dallimore 1992; Mackay 1998). Observations from current permafrost areas (e.g. Moorman *et al.* 1998) imply that such geohydrological conditions could promote the formation of ice lenses up to several metres in thickness and eventually heterogeneous tabular and/or folded massive ice bodies parallel to the ground and subsurface structures. In contrast to the deepest and largest basins formed in the central parts of palaeo-valleys, thermokarst lakes located farther from the downvalley axis tend to be rather shallow, probably because of near-surface ice segregation and shallow ice ground.

Formation of palaeo-thermokarst depressions

Pingo and lithalsa scars. – Keeping in mind the assumed hydrological and climatic conditions of the region, the formation of perennial frost mounds, including both open-system (hydraulic) pingos and mineral palsas (lithalsas), can be expected.

Collapsed forms of these structures have the greatest potential for preservation in the fossil record (French 2017) and have previously been described from numerous sites in the past permafrost zone of north and north-western Europe, for example in Wales (Watson 1971; Ross *et al.* 2011), England (Watson & Watson 1972), Scandinavia (Svensson 1971; Seppälä 1972), Denmark (Svensson 1971), Belgium (Pissart 2000, Pissart 2002), Poland (Dylik 1963), northern France (Van Vliet-Lanoë *et al.* 2017) and the Netherlands (Hoek & Joosten 1995). Both structures usually comprise circular or oval-shaped depressions with a flat floor. They are usually surrounded by a rampart, although this need not be necessarily present due to either deposition in the scar depression or erosion of the rampart (Flemal 1976). Diameter ranges from several tens (lithalsa) to several hundreds of metres (pingos) (Áhman 1976; Harris 1993; Mackay 1998), depending on the size of the ice-core and the amount of material that is relocated to the margins through mass wasting (Wolfe *et al.* 2014).

From this point of view, basins of the second group show some morphological similarities to typical lithalsa or pingo scars, as they are obviously circular with a pan-like shaped bottom (Fig. 7). A possible explanation for the absence of distinct ramparts in the surroundings of the investigated lakes could be human action, which completely disturbed the original geomorphology of the sites during the construction of the fishponds and over six centuries of intensive agriculture practices. This was previously documented in areas of cultivation, for instance from England (Watson 1972) or Paris Basin in France (Pissart 2002), where ramparts were lowered or completely destroyed and the overall micro-relief strongly blurred. Another explanation for lacking ramparts may be removal by natural processes such as slumping into the depression or lateral erosion by wave activity, a mechanism described from current Arctic areas (e.g. Müller 1962; Wünnemann *et al.* 2008). The impure sand and gravel of the basal sediments (zone A) could partially originate from the original rampart rims destroyed during the later phase of the thermokarst activity in the region (see also discussion below). Relicts of potential ramparts could be preserved at the Blatný site. When the water level of the fishpond is low, distinct crescent-shaped sandy bars are visible (Fig. 7A). These bars separate several circular depressions up to 3 m in depth, which are filled by lacustrine sediments and peat (Fig. 7B).

However, neither the morphometry nor the morphology of the largest investigated basins (the first group) match the typical remnants of pingo/lithalsa scars, as these basins tend to be rather elongated and irregular in shape, with a V-shaped profile (Figs 3, 4). These findings point to the action of another thermokarst formation process as well as a different post-formation history of erosion and deposition. Given that all these basins are associated with shallow valley-form depressions (Fig. 2), it is possible they could have been influenced by processes of fluvio-thermal erosion. The conceptual model of the formation of such palaeo-lakes is presented in Fig. 8 for the example of the Švarcenberk palaeo-lake.

Fluvio-thermal erosion. – Obviously elongated asymmetrical basins of the first group are located within linear shallow depressions, going from slightly elevated areas of SW slopes toward the axial (Lužnice) river flood-plain (Fig. 2). These structures were presumably formed during the Late Pleniglacial, and could be the remnants of short palaeo-tributaries of the Lužnice River braided plain (Chábera & Vojtěch 1972). The drainage of slopes probably occurred preferentially along the zones with ice-rich ground (Fig. 8A). This is a readily identifiable feature of arctic lowland terrain resulting in the common thermokarst landform known as beaded streams (Merck *et al.* 2012; Jorgenson 2013; Arp *et al.* 2015). Beaded streams are generally associated with ice-wedge polygons and locally with massive ground ice and thaw lakes (Washburn 1973). When streams pass over networks of ice wedges or massive ice, the thermal properties of the flowing water cause complete ground ice degradation, producing elliptical or irregularly shaped pools and thaw pits often connected by long runs (Oswood *et al.* 1989; Arp *et al.* 2015). The highest intensity of thermal erosion and thus the deepest ground ice degradation occurs within low-gradient parts of channels.

The melting of ice and thereby ground subsidence could have been intensified at the beginning of the Lateglacial (Fig. 8B), during periods of climatic amelioration, when surface water discharges were increasing and permafrost was degrading. Increased flow through the valleys was probably connected with lateral and vertical erosion (scour) and the coalescence of separated pools, permafrost scouring usually resulting in the formation of irregular depressions often three to five times deeper than the confluent channels (Rice *et al.* 2008). The strength of bedrock deposits along zones of thawing ground was reduced due to elevated pore pressures, rendering them vulnerable to erosion along channel forms, whereas permafrost zones with low contents of ground ice provided cohesion for bed sediments. This heterogeneous fluvio-thermal erosion could have resulted in the formation of discontinuous gullies. It might also explain the elongated (up to 1 km in length) enclosed morphology of the studied basins. Similar thermokarst processes and landforms were observed, for instance, on Bylot Island in northern Canada (Godin & Fortier 2012) and are suggested to be the driving mechanism for the

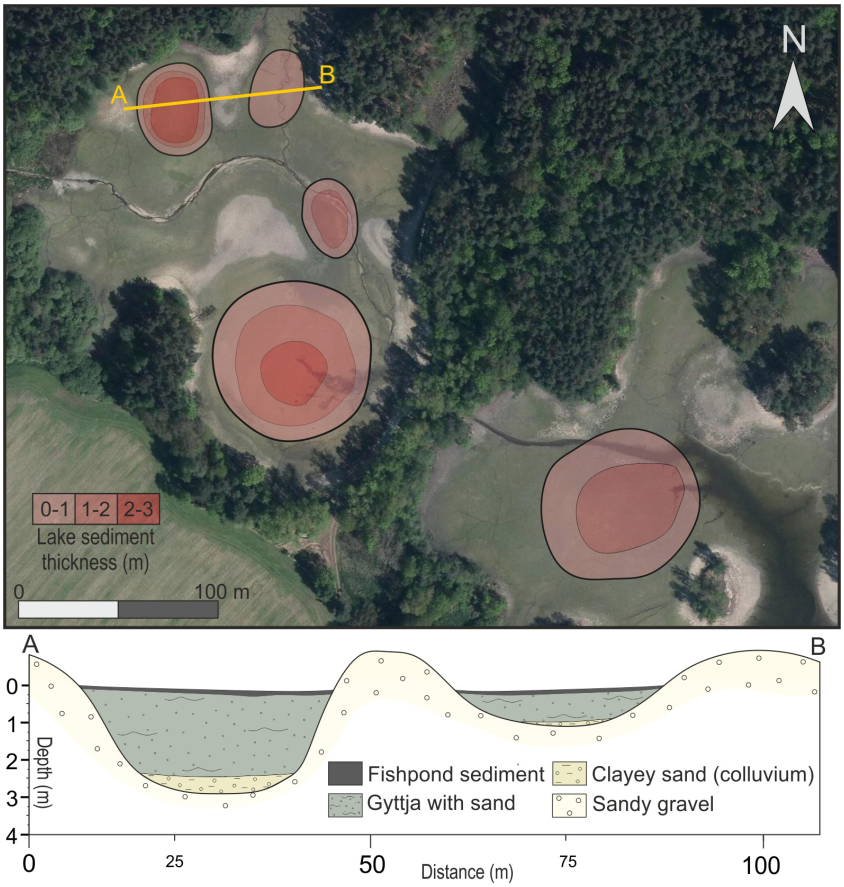

Fig. 7. Aerial photograph (source: CUZK, year 2013) showing the Blatný fishpond during the low water table stage. Several circular, up to 3 m depth palaeo-lake basins were mapped between distinct crescent-shaped sandy bars. Stratigraphical cross-sections of two palaeo-lake basins at the Blatný site (yellow line) are shown below. [Colour figure can be viewed at www.boreas.dk].

formation of non-ramparted, up to 15 m deep, elongated depressions ('hollows') described from the former periglacial zone of England (Berry 1979; Banks *et al.* 2015).

Surface subsidence in zones of ice-rich permafrost together with the incision of the Lužnice River at the transition from the cold Pleniglacial to the warmer Lateglacial (Chábera & Vojtěch 1972) led to the disconnection of former streams from the Lužnice flood-plain and the sudden change in the hypsometric curve of the stream. The shift of the erosion base toward SW slopes was probably accompanied by backward erosion (Fig. 8B) within developed basins resulting in the formation of the steep north-facing slopes revealed at the SV and VT palaeo-lakes (Fig. 3). Water flowing into the depressions was able to amplify the deepening and longitudinal extension of some basins and to cut downward into their beds. The remnants of this process could be internal valleys in the central part running parallel with the longer basin axis (Figs 4, 5).

The central parts of basins were filled with relocated terrigenous sediments (in some cases, with admixtures of terrigenous plant remains), originating from the watershed of the channel and thaw slumps on adjoining thermokarst slopes. The sedimentation of basal deposits was probably followed by the accumulation of water in initial depressions, as indicated by the presence of aquatic plant macrofossils or cladocerans (Pokorný 2002). The formation of a perennial water body in the depressions could have significantly intensified thermokarst processes as a result of its asymmetrical heat exchange during warm and cold seasons, resulting in heat accumulation under the water and the development of taliks under the deepening lakes.

Evolution of lakes in the context of Lateglacial environmental change

The possible mechanism of the formation of palaeo-lake basins, derived mostly from their morphology, was outlined above. The following section provides a chronological framework for their evolution obtained from their sedimentary record.

The initial phase of thermokarst activity in the Třeboň region (Fig. 8B) occurred shortly before ~16 ka, as indicated by palynostratigraphy of the basal sediment of

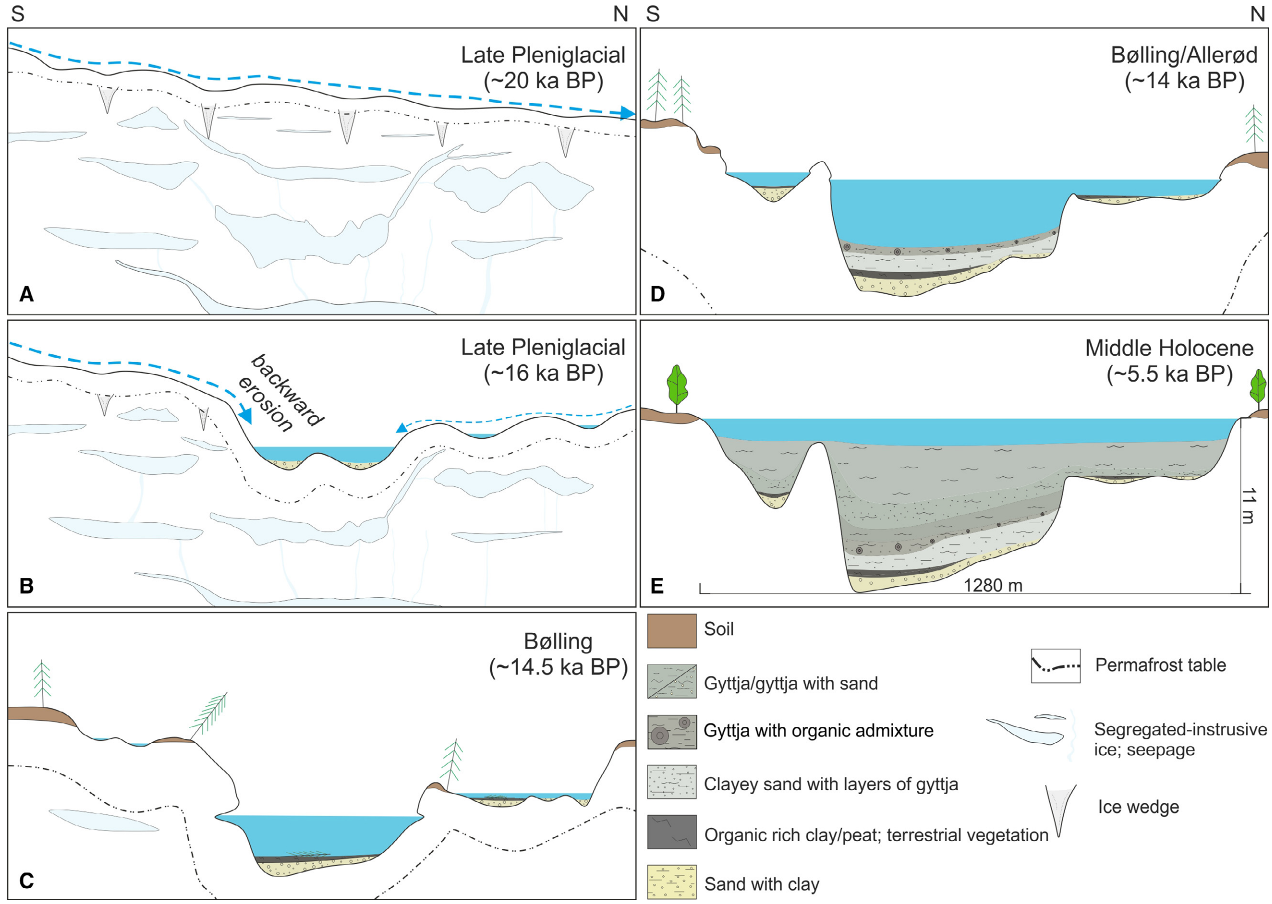

Fig. 8. Conceptual model of Švarcenberk palaeo-lake formation and evolution; see text for explanation. [Colour figure can be viewed at www.boreas.dk].

the Švarcenberk palaeo-lake (Pokorný 2002). This can be correlated to the Weichselian Pleniglacial–Lateglacial transition dated in central Europe to around 15 ka (Willis *et al.* 2000). A sudden increase in air temperatures and precipitation, datable to the onset of the Bølling interstadial (~14.6 cal. ka BP; GI-1e in NGRIP; Björck *et al.* 1998), promoted the rapid deepening of depressions (Fig. 8C). Thermokarst basin subsidence and increasing water depth facilitated the accumulation of lacustrine sediment (fine/coarse detritus gyttja). In many of the studied lacustrine sedimentary records, autochthonous lacustrine sediment alternates with distinct layers of a sand/terrestrial vegetation admixture, which points to a fluctuating lake level and/or the ongoing erosion of lake banks. It also indirectly indicates that the soil surface in the research area was rather unconsolidated and thus vulnerable to erosion.

A decrease in autochthonous components together with the high content of aquatic plants found in the B_1 subzone (Pokorný 2002; Hošek *et al.* 2017; P. Žáčková, unpublished data) indicate lacustrine sedimentation with a minimum input of slope material. This distinct change in lacustrine sedimentation corresponds to the onset of the Allerød interstadial and suggests that the main phase of the development of the largest lake basins was established shortly after ~14 cal. ka BP. Consequently, the initial phase of thermokarst subsidence and lake growth must have occurred rapidly during less than 1000 years. This is in concordance with many observations from recent thermokarst regions, where the active phase of thermokarst subsidence is assumed to have been a short-term catastrophic event occurring over a few centuries or even decades (e.g. Ballantyne 2018).

Although the deepest parts of the largest thermokarst lakes were formed before the Allerød, thermokarst activity in the study area probably continued also during later phases of the Lateglacial. As indicated by varied palaeoenvironmental records from the study area (Pokorný 2002; Pokorný *et al.* 2010; Hošek *et al.* 2014, 2017), the Allerød interstadial (~13.8–12.7 cal. ka BP; GI-1c) was warmer and significantly wetter compared to the preceding periods. This climatic amelioration probably promoted further permafrost degradation and caused the second (minor) phase of thermokarst activity in the study area. In central Europe, a discontinuous/sporadic permafrost table is assumed to have existed during the Lateglacial (Isarin 1997; Huijzer & Vandenberghe 1998). In this environment, reshaping of the existing lake basins occurred and lithalsa scars could form, as indicated by the results of the relative dating of the basal lacustrine sediment of some lake basins of the second group, which suggest Lateglacial (Allerød?) or even Early Holocene age (Hošek *et al.* 2013). Furthermore, the radiocarbon date of ~13.7 cal. ka BP (wood) from the interface between gyttja and basal sands in the lake-shore sediments of the Švarcenberk site (Fig. 3, Table 1) suggests that this part of the lake, semi-separated from the main basin by a distinct ridge (Fig. 3), had developed by the end of the Bølling or at the very beginning of the Allerød (Fig. 8D). Consequently, the final shape of the Švarcenberk palaeo-lake was probably established after this date by the coalescence of two basins during a sudden increase in the water table. An increase in lake level correlating with the Allerød was documented in many boreholes on the basis of changes in sediment lithology and composition (e.g. the dominance of fine detritus gyttja and the algal record; Pokorný 2002; Hošek *et al.* 2016, 2017b). At the Veselí_2 palaeo-lake (Fig. 4), the rise in lake level at the onset of the Allerød was accompanied by the lateral expansion of the lake surface and subsequently by the flooding of adjacent banks and their intensive erosion. This is indicated by the distinct layer of trunks and large branches of pine found within colluvial sediment and dated to ~13.5 cal. ka BP (Fig. 4). It is reminiscent of observations from recent permafrost regions, where the early development of thermokarst depressions was usually accompanied by the submergence of nearby standing trees (Fig. 8C; Czudek & Demek 1970; Vitt *et al.* 1994). During the lateral expansion of the lake surface and reshaping of the basins, destruction of potential ramparts of some basins could occurred.

With the advent of the Younger Dryas stadial (~12.7 cal. ka BP; GS-1), rapid cooling accompanied by a decrease in precipitation occurred throughout central Europe (Roberts 2014). In the study area, climatic deterioration had a significant impact on both biotic and abiotic processes (Pokorný 2002; Hošek *et al.* 2014), resulting in sparser vegetation cover, and consequently an increase in the input of allogenic material to lake basins (Hošek *et al.* 2017), as manifested in the high silt content and/or intermittent-to-common silt laminae within lacustrine sediments (Fig. 5). Overall, colluvial and aeolian sedimentation together with physical weathering processes prevailed. The surface was intensively remodelled by cryoturbation, as documented in the area of archaeological excavation at the former shore of the Švarcenberk palaeo-lake (Šída 2013). Wedge structures and cryoturbation phenomena observed throughout the Bohemian Massif (Czudek 2005) suggest the occurrence of at least sporadic permafrost or deep seasonal frost during the Younger Dryas, although permafrost aggradation is rather unexpected at these altitudes during this stadial (Isarin 1997). Some small-size enclosed depressions and hollows abundant throughout the study area could have resulted in intensive landscape remodelling and the final retreat of permafrost (or seasonally frozen ground), which culminated throughout the Pleistocene–Holocene transition (~11.7 cal. ka BP). These small depressions or thermokarst bogs were filled by colluvial sediment and later, during the Early/Middle Holocene, by peat.

Conclusions

Dozens of large basins and enclosed depressions filled by colluvial deposits, lacustrine sediments and peat were discovered at the southern limit of the former European permafrost zone. We assume that formation of these basins is the result of a complex of several interdependent thermokarst processes that occurred throughout the Weichselian Pleniglacial–Lateglacial transition and during the Lateglacial. These processes include the thermal and fluvio-thermal erosion of ice-rich permafrost zones and the consequent formation of discontinuous thermokarst gullies and possibly pingo or lithalsa scars. The development of these rare post-thermokarst landforms was possibly the result of the specific regional geological and hydrogeological conditions. The formation and subsequent stabilization of the lakes was climatically driven and had two phases, with the major phase at the onset of Pleniglacial/Lateglacial warming and rise in precipitation (~16–15 cal. ka BP) and the minor phase during the Lateglacial climatic oscillations (~14.7–11.7 cal. ka BP). This study contributes to the knowledge on the palaeogeography of the former European periglacial zone by showing that Late Pleistocene thermokarst activity could have had a significant impact on the landscape evolution of some regions of central Europe along the southern limit of the continuous permafrost zone. Such findings also point to the involvement of similar processes of physical landscape transformation with respect to the former European periglacial zone and current thermokarst landscapes of the Arctic.

Acknowledgements. – This research was supported by the Czech Science Foundation Grantová Agentura České Republiky, projects no. 17-21612S and no. 17-07851S, Charles University Research Centre program no. 204069 and an internal project of the Czech Geological Survey (no. 322500). We are grateful to Jiří Bumerl, Petra Houfková, Barbora Koutská, Martin Prach, Oto Rauch and Daniel Vondrák for their help during fieldwork and Pavla Žáčková for providing us with her preliminary results of plant macro-remain analysis. Matthew Nicholls is acknowledged for improving the English. This manuscript benefitted from the thoughtful reviews of Josefine Lenz and an anonymous reviewer. Special thanks go to J. A. Piotrowski for his careful revision of the manuscript.

Author contributions. – JH and PP designed the study; JH, JP, MK, PŠ and PP performed fieldwork; PM performed the OSL analyses; JH wrote the paper and made the figures; all the authors commented on the manuscript.

References

Áhman, R. 1976: The structure and morphology of minerogenic palsas in Northern Norway. *Biuletyn Peryglacjalny 26*, 25–31.

Andrieux, E., Bateman, M. D. & Bertran, P. 2018: The chronology of Late Pleistocene thermal contraction cracking derived from sand wedge OSL dating in central and southern France. *Global and Planetary Change 162*, 84–100.

Arp, C. D., Whitman, M. S., Jones, B. M., Grosse, G., Gaglioti, B. V. & Heim, K. C. 2015: Distribution and biophysical processes of beaded streams in Arctic permafrost landscapes. *Biogeosciences 12*, 1–19.

Ballantyne, C. K. 2018: *Periglacial Geomorphology.* 472 pp. John Wiley & Sons, New Jersey.

Banks, V. J., Bricker, S. H., Royse, K. R. & Collins, P. E. F. 2015: Anomalous buried hollows in London: development of a hazard susceptibility map. *Quarterly Journal of Engineering Geology and Hydrogeology 48*, 55–70.

Berry, F. G. 1979: Late Quaternary scour-hollows and related features in central London. *Quarterly Journal of Engineering Geology and Hydrogeology 12*, 9–29.

Bertran, P., Andrieux, E., Antoine, P., Coutard, S., Deschodt, L., Gardère, P., Hernandez, M., Legentil, C., Lenoble, A., Liard, M., Mercier, N., Moine, O., Sitzia, L. & Van Vliet-Lanoë, B. 2014: Distribution and chronology of Pleistocene permafrost features in France: database and first results. *Boreas 43*, 699–711.

Bertran, P., Andrieux, E., Bateman, M., Font, M., Manchuel, K. & Sicilia, D. 2018: Features caused by ground ice growth and decay in Late Pleistocene fluvial deposits, Paris Basin, France. *Geomorphology 310*, 84–101.

Biskaborn, B. K., Herzschuh, U., Bolshiyanov, D. Y., Schwamborn, G. & Diekmann, B. 2013: Thermokarst processes and depositional events in a tundra lake, Northeastern Siberia. *Permafrost and Periglacial Processes 24*, 160–174.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M. & Lantuit, H. 2019: Permafrost is warming at a global scale. *Nature Communications 10*, 264, https://doi.org/10.1038/s41467-018-08240-4.

Björck, S., Walker, M. J. C., Cwynar, L. C., Johnsen, S., Knudsen, K. L., Lowe, J. J., Wohlfarth, B. & INTIMATE Members 1998: An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. *Journal of Quaternary Science 13*, 283–292.

Bohncke, S., Vandenberghe, J. & Huijzer, A. 1993: Periglacial environments during the Weichselian Lateglacial in the Maas valley *Netherlands Journal of Geosciences – Geologie en Mijnbouw 72*, 193–210.

Bouchard, F., MacDonald, L. A., Turner, K. W., Thienpont, J. R., Medeiros, A. S., Biskaborn, B. K., Korosi, J., Hall, R. I., Pienitz, R. & Wolfe, B. B. 2017: Palaeolimnology of thermokarst lakes: a window into permafrost landscape evolution. *Arctic Science 3*, 91–117.

Chábera, S. & Mach, V. 1977: Mrazové hrnce a klíny severně od Plané n. Lužnicí. *Sborník Jihočeského muzea v Českých Budějovicích, přírodní vědy 17*, 3–9.

Chábera, S. & Vojtěch, S. 1972: Terasy řeky Lužnice. I. Terasy Lužnice v kotlině Třeboňské. *Sborník Jihočeského muzea v Českých Budějovicích, Přírodní vědy XII*, 1–10.

Conant, L. C., Black, R. F. & Hosterman, J. W. 1976: Sediment-filled pots in upland gravels of Maryland and Virginia. *Journal of Research, United States Geological Survey 4*, 353–358.

Czudek, T. 1986: Pleistocenní permafrost na území Československa. *Geografický Časopis 38*, 245–252.

Czudek, T. 2005: *Vývoj reliéfu krajiny České republiky v kvartéru*. 238 pp. Moravské zemské muzeum, Brno.

Czudek, T. & Demek, J. 1970: Thermokarst in Siberia and its influence on the development of lowland relief. *Quaternary Research 1*, 103–120.

Dornič, J., Suk, M., Zikmund, J. & Holásek, O. 1977: *Geological map 1:25 000, sheet 23-333 (Horusice)*. Ústřední ústav geologický. Praha.

Dylik, J. 1963: Traces of thermokarst in the Pleistocene sediments of Poland. *Bulletin de la Société des Sciences et des Lettres de Łódź 14*, 1–16.

Ehlers, J. & Gibbard, P. L. 2004: *Quaternary Glaciations – Extent and Chronology. Part 1. Europe.* 450 pp. Elsevier, Amsterdam.

Farquharson, L., Anthony, K. W., Bigelow, N., Edwards, M. & Grosse, G. 2016: Facies analysis of yedoma thermokarst lakes on the northern Seward Peninsula, Alaska. *Sedimentary Geology 340*, 25–37.

Flemal, R. C. 1976: Pingos and pingo scars: their characteristics, distribution, and utility in reconstructing former permafrost environments. *Quaternary Research 6*, 37–53.

Fortier, D., Allard, M. & Shur, Y. 2007: Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago. *Permafrost and Periglacial Processes 18*, 229–243.

French, H. M. 2017: *The Periglacial Environment*. 533 pp. Wiley, Chichester.

French, H. M., Demitroff, M. & Forman, S. L. 2003: Evidence for Late-Pleistocene thermokarst in the New Jersey Pine Barrens (latitude 39° N), Eastern USA. *Permafrost and Periglacial Processes 16*, 173–186.

Gaglioti, B. V., Mann, D. H., Jones, B. M., Pohlman, J. W., Kunz, M. L. & Wooller, M. J. 2014: Radiocarbon age-offsets in an arctic lake reveal the long-term response of permafrost carbon to climate change. *Journal of Geophysical Research, Biogeosciences 119*, 1630–1651.

Godin, E. & Fortier, D. 2012: Geomorphology of a thermo-erosion gully, Bylot Island, Nunavut, Canada. *Canadian Journal of Earth Sciences 49*, 979–986.

Grosse, G., Jones, B. & Arp, C. 2013: Thermokarst lakes, drainage, and drained basins. *In* French, H. & Harbor, J. (eds.): *Treatise on Geomorphology Glacial and Periglacial Geomorphology 8*, 325–353. Academic Press, San Diego.

Harris, S. A. 1993: Palsa-like mounds developed in a mineral substrate, Fox Lake, Yukon territory. Proceedings, Sixth international conference on permafrost. 5–9 July 1993. Beijing, China, Wushan Guangzhan, China. *South China University of Technology Press 1*, 238–243.

Harris, S. A., Brouchkov, A. & Guodong, C. 2018: *Geocryology: Characteristics and Use of Frozen Ground and Permafrost Landforms.* 765 pp. Taylor & Francis, London.

Hinzman, L. D. and 35 others. 2005: Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climate Change 72*, 251–298.

Hoek, W. 1997: Palaeogeography of Lateglacial vegetations. Aspects of Lateglacial and Early Holocene vegetation, abiotic landscape, and climate in The Netherlands. *Netherlandse Geografische Studies 230*, 1–147.

Hoek, W. Z. & Joosten, J. H. J. 1995: Pingo-ruïnes en kalkgyttja in het Weerterbos. *Natuur Historisch Maandblad 84*, 234–241.

Hopkins, D. M. 1949: Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. *Journal of Geology 57*, 119–131.

Hošek, J., Pokorný, P., Kubovčík, V., Horáček, I., Žáčková, P., Kadlec, J., Rojik, F., Lisá, L. & Bučkuliaková, S. 2014: Lateglacial climatic and environmental changes in Eastern-Central Europe: correlation of multiple biotic and abiotic proxies from the Lake Švarcenberk, Czech Republic. *Palaeogeography, Palaeoclimatology, Palaeoecology 396*, 155–172.

Hošek, J., Pokorný, P., Prach, J., Lisá, L., Grygar, T. M., Knésl, I. & Trubač, J. J. C. 2017: Lateglacial erosion and pedogenesis dynamics: evidence from high-resolution lacustrine archives and palaeosols in south Bohemia (Czech Republic). *Catena 150*, 261–278.

Hošek, J., Pokorný, P., Šída, P. & Prach, J. 2013: Newly discovered Lateglacial lakes in Třeboň region. *Geoscience Research Reports 46*, 126–131 (in Czech with English summary).

Hošek, J., Prach, J., Šída, P., Houfková, P., Vondrák, D., Lisá, L., Pokorný, P., Chvojka, O. & Dohnal, J. 2016: Sedimentary development of the Lateglacial lakes near Veselí nad Lužnicí South Bohemia. *Geoscience Research Reports 49*, 157–164 (in Czech with English summary).

Huijzer, B. & Vandenberghe, J. 1998: Climatic reconstruction of the Weichselian Pleniglacial in northwestern and central Europe. *Journal of Quaternary Science 13*, 391–417.

Isarin, R. F. B. 1997: Permafrost distribution and temperatures in Europe during the Younger Dryas. *Permafrost and Periglacial Processes 8*, 313–333.
Jones, B. M., Grosse, G., Arp, C. D., Jones, M. C., Walter Anthony, K. & Romanovsky, V. E. 2011: Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research 116*, G00M03, https://doi.org/10.1029/2011jg001666.
Jorgenson, M. T. 2013: Thermokarst terrains. *In* Shroder, J. F., Giardino, R. & Harbor, J. (eds.): *Treatise on Geomorphology, Vol. 8, Glacial and Periglacial Geomorphology*, 313–324. Academic Press, San Diego.
Kadlecová, R., Burda, J., Bruthans, J., Bůzek, F., Grundloch, J., Hroch, T., Kondrová, L., Kůrková, I., Navrátilová, V., Nol, O., Šíma, J., Homolka, M., Daněk, A., Kašpárek, L., Beran, A., Datel, J. V., Hanel, M., Hrdinka, T., Peláková, M., Polák, M., Milický, M., Zeman, O., Gvoždík, L., Uhlík, J., Chaloupková, M., Patzelt, Z., Melichar, V., Hrkal, Z. & Ambrozek, L. 2016: *Hydrogeologický rajon 2151 – Třeboňská pánev – severní část. Stanovení zásob podzemních vod, závěrečná zpráva*. 150 pp. MS Geofond, Praha.
Kanevskiy, M., Shur, Y., Jorgenson, T., Brown, D. R., Moskalenko, N., Brown, J., Walker, D. A., Raynolds, M. K. & Buchhorn, M. 2017: Degradation and stabilization of ice wedges: implications for assessing risk of thermokarst in northern Alaska. *Geomorphology 297*, 20–42.
Köhler, P., Knorr, G. & Bard, E. 2014: Permafrost thawing as a possible source of abrupt carbon release at the onset of the Bølling/Allerød. *Nature Communications 5*, 5520, https://doi.org/10.1038/ncomms6520.
Kokelj, S. V. & Jorgenson, M. T. 2013: Advances in thermokarst research. *Permafrost and Periglacial Processes 24*, 108–119.
Krásný, J., Císlerová, M., Čurda, S., Datel, J. V., Dvořák, J., Grmela, A., Hrkal, Z., Kříţ, H., Marszałek, H., Šantrůček, J. & Šilar, J. 2012: *Podzemní vody České Republiky. Regionální hydrogeologie prostých a minerálních vod*. 1144 pp. Czech Geological Survey, Praha.
Křížek, M., Vočadlová, K. & Engel, Z. 2012: Cirque overdeepening and their relationship to morphometry. *Geomorphology 139–140*, 495–505.
Kunský, J. 1946: Mrazové klíny v jižních Čechách. *Sborník ČSSZ 50*, 25–27.
Lenz, J., Wetterich, S., Jones, B. M., Meyer, H., Bobrov, A. & Grosse, G. 2016: Evidence of multiple thermokarst lake generations from an 11 800-year-old permafrost core on the northern Seward Peninsula, Alaska. *Boreas 45*, 584–603.
Liljedahl, A. K., Boike, J., Daanen, R. P., Fedorov, A. N., Frost, G. V., Grosse, G., Hinzman, L. D., Iijma, Y., Jorgenson, J. C., Matveyeva, N., Necsoiu, M., Raynolds, M. K., Romanovsky, V. E., Schulla, J., Tape, K. D., Walker, D. A., Wilson, C. J., Yabuki, H. & Zona, D. 2016: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience 9*, 312–318.
Mackay, J. R. 1998: Pingo growth and collapse, Tuktoyaktuk Peninsula area, western Arctic coast, Canada: a long-term field study. *Géographie physique et Quaternaire 52*, 271–323.
Mackay, J. R. & Dallimore, S. R. 1992: Massive ice of the Tuktoyaktuk area, western Arctic coast, Canada. *Canadian Journal of Earth Sciences 29*, 1235–1249.
Malecha, A., Holásek, O. & Maštera, J. 1991: *Explanatory notes for the geological map 1:55 000, sheet 23-33 (Veselí n Lužnicí)*. Ústřední ústav geologický, Praha.
Merck, M. F., Neilson, B. T., Cory, R. M. & Kling, G. W. 2012: Variability of in-stream and riparian storage in a beaded arctic stream. *Hydrological Processes. 26*, 2938–2950.
Mix, A. C., Bard, E. & Schneider, R. 2001: Environmental processes of the ice age: land, ocean, glaciers (EPILOG). *Quaternary Science Reviews 20*, 627–657.
Moorman, B. J., Michel, F. A. & Wilson, A. T. 1998: The development of tabular massive ground ice at Peninsula Point, NWT, Canada. *In* Lewkowicz, A. G. & Allard, M. (eds.): *Permafrost, Proceedings of the Seventh International Conference on Permafrost, Yellowknife, Canada*, 23–27 June, 757–761. Centre d'études nordiques, Université Laval, Québec.
Morgenstern, A., Grosse, G., Günther, F., Fedorova, I. & Schirrmeister, L. 2011: Spatial analyses of thermokarst lakes and basins in Yedoma landscapes of the Lena Delta. *Cryosphere 5*, 849–867.
Morgenstern, A., Ulrich, M., Günther, F., Roessler, S., Fedorova, I. V., Rudaya, N. A., Wetterich, S., Boike, J. & Schirrmeister, L. 2013: Evolution of thermokarst in East Siberian ice-rich permafrost: a case study. *Geomorphology 201*, 363–379.
Müller, F. 1962: Analysis of some stratigraphic observations and radiocarbon dates from two pingos in the Mackenzie Delta Area, N.W.T. *Arctic 15*, 278–288.
Murton, J. B. 1996: Thermokarst lake basin sediments, Tuktoyaktuk Coastlands, western arctic Canada. *Sedimentology 43*, 737–760.
Oswood, M. W., Everett, K. R. & Schell, D. M. 1989: Some physical and chemical characteristics of an arctic beaded stream. *Holarctic Ecology 12*, 290–295.
Pissart, A. 2000: Remnants of lithalsas of the Hautes Fagnes, Belgium: a summary of present-day knowledge. *Permafrost and Periglacial Processes 11*, 327–355.
Pissart, A. 2002: Palsas, lithalsas and remnants of these periglacial mounds: a progress report. *Progress in Physical Geography 26*, 605–621.
Pokorný, P. 2002: A high-resolution record of Late-Glacial and Early-Holocene climatic and environmental change in Czech Republic. *Quaternary International 91*, 101–122.
Pokorný, P. & Jankovská, V. 2000: Long-term vegetation dynamics and the infilling process of a former lake Švarcenberk, Czech Republic. *Folia Geographica 35*, 433–457.
Pokorný, P. & Růžičková, E. 2000: Changing environments during the younger dryas climatic deterioration: correlation of aeolian deposits in Southern Czech Republic. *Geolines 11*, 89–92.
Pokorný, P., Šída, P., Chvojka, O., Žáčková, P., Kuneš, P., Světlík, I. & Veselý, J. 2010: Palaeoenvironmental research of the Schwarzenberg Lake, southern Bohemia, and exploratory excavations of this key Mesolithic archaeological area. *Památky archeologické 101*, 5–38.
Rampton, V. N. 1988: Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories. *Geological Survey of Canada, Memoir 423*, p. 98.
Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M. & van der Plicht, J. 2013: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon 55*, 1869–1887.
Rice, S. P., Roy, A. G. & Rhoads, B. L. 2008: *River Confluences, Tributaries and the Fluvial Network*. 461 pp. Wiley-Blackwell, Chichester.
Roberts, N. 2014: *The Holocene. An Environmental History.* 316 pp. John Willey & Sons, Chichester.
Ross, N., Harris, C., Brabham, P. J. & Sheppard, T. H. 2011: Internal structure and geological context of ramparted depressions, Llanpumsaint, Wales. *Permafrost and Periglacial Processes 22*, 291–305.
Rowland, J. C., Jones, C. E., Altmann, G., Bryan, R., Crosby, B. T., Geernaert, G. L., Hinzman, L. D., Kane, D. L., Lawrence, D. M., Mancino, A., Marsh, P., McNamara, J. P., Romanovsky, V. E., Toniolo, H., Travis, B. J., Trochim, E. & Wilson, C. J. 2010: Arctic landscapes in transition: responses to thawing permafrost. *Eos, Transactions, American Geophysical Union 91*, 229–230, https://doi.org/10.1029/2010eo260001.
Seppälä, M. 1972: Pingo-like remnants in the Peltojärvi area of Finnish Lapland. *Geografiska Annaler 54. Series A*, 37–45.
Short, A. D. & Wright, L. D. 1974: Lineaments and coastal geomorphic patterns in the Alaskan Arctic. *Geological Society of America Bulletin 85*, 931–936.
Shur, Y. & Osterkamp, T. 2007: *Thermokarst. Report INE 06.11*. 50 pp. University of Alaska Fair-Banks, Institute of Northern Engineering, Fairbanks.
Šída, P. 2013: Evidence of the Lateglacial surface remodeling on Lake Švarcenberk shore. *Geoscience Research Reports 46*, 159–163 (in Czech with English summary).

Šída, P. & Pokorný, P. 2011: Zjišťování archeologického potenciálu krajiny pomocí kvartérně geologického mapování na příkladu Třeboňska. *Archeologické Rozhledy LXIII* 485–500.

Steedman, A. E., Lantz, T. C. & Kokelj, S. V. 2016: Spatio-temporal variation in high-centre polygons and ice-wedge melt ponds, Tuktoyaktuk Coastlands. *Northwest Territories. Permafrost and Periglacial Processes 6*, 66–68, https://doi.org/doi: 10.1002/ppp.1880.

Svensson, H. 1964: Traces of pingo-like frost mounds. *Svensk Geografisk Årsbok 40*, 93–106.

Svensson, H. 1971: Pingos i ytre delen av Adventdalen. *Norwegian Polar Institute's 1969 yearbook*, 168–174.

Toniolo, H., Kodial, P., Hinzman, L. D. & Yoshikawa, K. 2009: Spatio-temporal evolution of a thermokarst in Interior Alaska. *Cold Regions Science and Technology. 56*, 39–49.

Van Everdingen, R. O. 1988: *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms. National Snow and Ice Data Center/World Data Center for Glaciology, Boulder*. Available at: http://globalcryospherewatch.org/reference/glossary_docs/Glossary_of_Permafrost_and_Ground-Ice_IPA_2005.pdf.

Van Huissteden, J. & Kasse, C. 2001: Detection of rapid climate change in Last Glacial fluvial successions in The Netherlands. *Global and Planetary Change 28*, 319–339.

Van Vliet-Lanoë, B., Brulhet, J., Combes, P., Duvail, C., Ego, F., Baize, S. & Cojan, I. 2017: Quaternary thermokarst and thermal erosion features in northern France: origin and palaeoenvironments. *Boreas 46*, 442–461.

Vandenberghe, J. 2001: Permafrost during the Pleistocene in North West and central Europe. *In* Paepe, R., Melnikov, V., van Overloop, E. & Gorokhov V. D. (eds.): *Permafrost Response on Economic Development, Environmental Security and Natural Resources*, 185–194. Springer, Dordrecht.

Vandenberghe, J. & Pissart, A. 1993: Permafrost changes in Europe during the last glacial. *Permafrost and Periglacial Processes 4*, 121–135.

Vandenberghe, J., French, H. M., Gorbunov, A., Marchenko, S., Velichko, A. A., Jin, H., Cui, Z., Zhang, T. & Wan, X. 2014: The Last Permafrost Maximum (LPM) map of the Northern Hemisphere: permafrost extent and mean annual air temperatures, 25–17 ka BP. *Boreas 43*, 652–666.

Vitt, D. H., Halsey, L. A. & Zoltai, S. C. 1994: The Bog landforms of continental western Canada in relation to climate and permafrost patterns. *Arctic, Antarctic, and Alpine Research 26*, 1–13.

Vočadlová, K., Petr, L., Žáčková, P., Křížek, M., Křížová, L., Hutchinson, S. M. & Šobr, M. 2015: The Lateglacial and Holocene in Central Europe: a multi-proxy environmental record from the Bohemian Forest, Czech Republic. *Boreas 44*, 769–784.

Walker, M. J. C. 1995: Climatic changes in Europe during the last glacial/interglacial transition. *Quaternary International 28*, 63–76.

Walter, K. M., Edwards, M. E., Grosse, G. S., Zimov, A. & Chapin, F. S. 2007: Thermokarst lakes as a source of atmospheric CH_4 during the last deglaciation. *Science 318*, 633–636.

Washburn, A. L. 1973: *Periglacial Processes and Environment*. 320 pp. St Martin's Press, New York.

Watson, E. 1971: Remains of pingos in Wales and the Isle of Man. *Geological Journal 7*, 381–392.

Watson, E. 1972: Pingos of Cardiganshire and the latest ice limit. *Nature 236*, 343–344.

Watson, E. & Watson, S. 1972: Investigation of some pingo basins near Aberystwyth, Wales *Report of the 24th International Geological Congress (Montreal) 12*, 212–233.

Willis, K. J., Rudner, E. & Sümegi, P. 2000: The full-glacial forests of central and southeastern Europe. *Quaternary Research 53*, 203–213.

Wolfe, S. A., Stevens, C. W., Gaanderse, A. J. & Oldenborger, G. A. 2014: Lithalsa distribution, morphology and landscape associations in the Great Slave Lowland, Northwest Territories, Canada. *Geomorphology 204*, 302–313.

Wu, Q., Zhang, T. & Liu, Y. 2012: Thermal state of the active layer and permafrost along the Qinghai-Xizang (Tibet) Railway from 2006 to 2010. *The Cryosphere 6*, 607–612.

Wünnemann, B., Reinhardt, C., Kotlia, B. S. & Riedel, F. 2008: Observations on the relationship between lake formation, permafrost activity and lithalsa development during the last 20 000 years in the Tso Kar basin, Ladakh, India. *Permafrost and Periglacial Processes 19*, 341–358.

Žák, K., Richter, D. K., Filippi, M., Živor, R., Deininger, M., Mangini, A. & Scholz, D. 2012: Coarsely crystalline cryogenic cave carbonate - a new archive to estimate the Last Glacial minimum permafrost depth in Central Europe. *Climate of the Past 8*, 1821–1837.

Supporting Information

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

Fig. S1. Relative probability density functions for samples from Záblatí.

Fig. S2. Approximate extent of the lake sediments (red line) determined by hand boring.

Data S1. Optically stimulated luminescence dating.