The impact of postglacial palaeoenvironmental changes on the properties of sediments in the kettle hole at Jurki (NE Poland)

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This research is focused on a small kettle hole located within the Morąg moraines (Iława Lake District, NE Poland). The study objective was to determine the impact of palaeoenvironmental changes on properties of sediments filling the bottom of the kettle hole. Sedimentological, geochemical, and palaeobotanical studies enabled us to distinguish several development phases of the kettle hole, and cluster analysis performed on physicochemical data yielded seven local geochemical zones ($Ju_{I/I}$ to $Ju_{I/VII}$). The beginning of biogenic sedimentation in the conditions of a small water body, functioning in the Late Glacial period (4.20–4.10 m), was determined on the basis of palaeobotanical research. Sediments deposited in the lake during its further evolution were rich in microelements such as Ca, Na, Mg, and K, and to a smaller extent – Fe and Mn ($Ju_{I/I–III}$ local geochemical zones). The Late Glacial lacustrine period ended with the accumulation of very silty, pollen-free gyttja, with a stratigraphic hiatus ($Ju_{I/IV}$, 3.40–3.20 m). The sediments were enriched with SiO_{2ter}, which indicates an increased rate of slope erosion, and concretions of Fe-Mn occurring below this layer (Ju_{III}) provide evidence for lowering of the water level and even desiccation. In the Holocene, the lacustrine period ended with the accumulation of coarse detrital gyttja (3.20–2.60 m). Palaeobotanical data indicate that the next group of sediments were deposited in the Late Subboreal and Subatlantic periods (2.60–0.0 cm, $Ju_{I/V–VII}$; sedge peat). Their properties were varied and related to hydrologic conditions, limited denudation, and vegetation succession. There was also a significant change in the trophic conditions of the water and consequently in the sediments of the kettle hole, which changed during the lacustrine period from basic to acid, and strongly acid in the surface layer. This reaction may be related to a change in the water regime as well as to human impact in the environment, which led to the colonization of the peat bog by *Sphagnum* moss.

Key words: young glacial landscape, kettle hole, end moraines, geochemical analysis, biogenic deposits.

INTRODUCTION

Kettle holes are a common feature of a young glacial landscape. They are defined as small, shallow, depressional wetlands of glacial origin with water supply coming from closed catchments (Kalettka and Rudat, 2006). As isolated depressions with vertical water fluctuation, they are usually very sensitive to both natural and anthropogenic environmental changes (e.g., Küster et al., 2011). Therefore, analysis of sediments deposited at their bottoms is often a key element in the reconstruction of e.g., palaeoclimatic, palaeohydrological, palaeobotanical and sometimes archaeological conditions.

The functioning of these landforms may be strongly linked to regional or local settings and therefore large-scale changes associated with climate and hydrological conditions may affect their ecological integrity (Drexler et al., 1999; Fraser et al., 2001). The most important effects of such changes may include changes in the deposition/sedentation of sediments, fluctuations in water levels and increased peat decomposition (Gorham and Rochefort, 2003; Lamentowicz et al., 2008; Karasiewicz et al., 2014b; Forysiak, 2015).

Kettle holes are typically located in agricultural areas (Kochanowska et al., 1998; Karasiewicz et al., 2014a; Kleeberg et al., 2015). According to Kalletka and Rudat (2006), there are two main hydrogeomorphic types of these forms: fen type (with growing fen) and open-water type (permanently or temporarily flooded, filled with peat and non-peat sediments).

Many authors (e.g., Frielinghaus and Vahrson, 1998; Podlasiński, 2013; Świtoniak, 2014; Karasiewicz et al., 2014b) stress that, due to long-term agricultural use, the catchment area is prone to accelerated soil erosion by runoff. Consequently, kettle holes may receive abundant terrigenous material

from adjacent slopes, which may lead to their disappearance and levelling of the land relief. Their sediments can act as sinks for nutrients (N, P and K), pesticides, and heavy metals, and consequently as a geochemical barrier which reduces the spread of pollutants (Cooper and Knight, 1990; Bilotta et al., 2007; Podlasińska, 2012).

Kettle holes in Poland are still relatively rarely included in palaeoenvironmental studies. This is due to the widespread belief that their sediments reflect only local changes in the environment, and hence the obtained results might be of limited use. The examples presented below, however, prove the contrary. Comprehensive palaeogeographic studies involving geochemical analyses were conducted by Borówka (1992) on sediments collected from small kettle holes in Western Pomerania. Similar studies carried out by Major (2009) concern the functioning of kettle holes in the drainage basin of the upper Parsęta River. Szwarczewski (2008) and Szwarczewski and Kupryjanowicz (2008) described the development stages of kettle holes in the Eastern Suwałki Lake District near the town of Sejny based on the properties of their sediments. Interdisciplinary studies of sediments of single landforms were conducted in the Brodnica Lake District (Karasiewicz et al., 2012, 2014b; Mendyk et al., 2015), and in the neighbourhood of Łódź (Lamentowicz et al., 2009; Twardy et al., 2010). There are also examples of research on geomorphological processes connected with environmental changes during the Late Pleistocene and the Holocene in the mountain areas (e.g., Jäger et al., 2015; Malkiewicz et al., 2016). A common objective of these studies was to reconstruct the palaeoenvironmental conditions recorded in sediments, which were treated as archives and carriers of information. The authors obtained good correlations between local and regional palaeogeographic changes. An example of a different approach was studies in the field of palaeoecology that analyse the man-induced transformations of the environment in the Tuchola Forest (Lamentowicz et al., 2007, 2008). The research on kettle holes may also be helpful in determining the chronostratigraphy of geomorphological events in river valleys. The results obtained by Krześlak et al. (2014) link the beginning of lacustrine sedimentation in the kettle hole located within terrace V of the Vistula Valley (Toruń Basin) with the formation of lower terraces in the Late Glacial period.

The research presented in this paper focuses on the kettle hole functioning in the agricultural landscape of the Iława Lake District in the area of Morąg moraines (Jurki site, NE Poland). This study aims to analyse the effect of palaeoenvironmental changes on the sedimentological and geochemical properties of kettle hole sediments. Based on the results obtained, combined with palaeobotanical and radiocarbon data, the local palaeoenvironment and the human impact on some of the landscape components were determined. This is a continuation of the multi-proxy studies focusing on kettle holes of different genesis and different land use, located near the main stagnation lines of the Vistulian ice sheet (Karasiewicz et al., 2014a, b).

STUDY AREA

The kettle hole studied in the Jurki village is of a small form (bottom – 40 x 60 m, the direct catchment area – 4.6 ha). It is located ca. 4 km north of Morąg (53°58'N and 19°58'E; the Iława Lake District, NE Poland; Fig. 1). The site is located at the southern side (distal part) of the recessional end moraines from the Pomeranian Phase of the Vistulian Glaciation, the height of which locally exceeds 200 m a.s.l. (Roszkówna, 1955; Karasiewicz, 2006a, b). The moraines form a belt extending from east to west with a width ranging from 2 to 4.5 km. Roszkówna (1955) distinguished three zones within the belt: the internal (till) zone, the central zone (built of glacial sand and fluvioglacial deposits), and the outer (pushed) zone. The interior of the frontal moraines is built up of pushed fluvioglacial deposits, locally with till on the surface. The research by Karasiewicz (2006a, b) revealed that the internal structure of the Morąg moraines is glaciotectonically disturbed, and the arrangement of moraine belts is connected with lobal-oscillatory disappearance of the continental ice sheet in this zone. It is difficult to determine the southern (outer) range of the Morąg moraines, which often smoothly turn into a hilly moraine plateau (Karasiewicz, 2006a, b).

The origin of the kettle hole studied is most likely connected with the melting of a dead-ice block in moraine deposits, hence the surroundings and substratum of this landform is dominated by deposits of sand, gravel, and boulders of end moraines. Colluvial deposits are found in the lower parts of the slopes, while the bottom of the kettle hole is filled with biogenic sediments. In the past, the entire direct catchment of the kettle hole studied was used for agriculture, while at present, land use is varied. Young stands of oak and spruce trees occur along the northern and eastern edges of the depression: arable fields in the south, and meadows and pastures in the west. The bottom of the kettle hole is overgrown with shrubs and birch and willow trees. The groundcover is dominated by *Sphagnum* peat, moss peat and sedges.

METHODS

Sampling. In total, 18 boreholes were drilled within the direct drainage basin and in the bottom of the kettle hole in the Jurki village. Based on the boreholes, 3 cores with an intact structure were collected by a Livingstone's probe modified by Więckowski (1989) in the central (Ju_I), northern (Ju_{II}), and southern (Ju_{III}) parts of the depression (Fig. 1). In addition, 4 soil pits were made on the slopes of the kettle hole. Their location closely corresponded with the two main types of land use in the drainage basin: agricultural (profiles A and B) and forest (profiles C and D). The samples were analysed using the selected sedimentological, geochemical, and palaeobotanical methods described below.

SEDIMENTOLOGICAL AND GEOCHEMICAL ANALYSIS

Grain-size composition. Samples collected from the slope sediments (profiles A–D, 42 samples) were dried and sieved using a set of sieves with diameters ranging from 10 to 0.1 mm. The finer fraction was determined using a *Fritsch* laser particle sizer *Analysette 22*. For each sample, textural parameters such as mean diameter (Mz) and sorting (σ_1) were calculated according to Folk and Ward (1957) – *Gradistat* software (Blott and Pye, 2001).

Geochemistry. Analyses were performed on samples collected from two cores, which reflected the differentiation of the sediment sequence i.e. from the central part of the kettle hole (Ju_I – thickness of 4.20 m; 55 samples) and from its southern peripheries (Ju_{III} – 1.70 m; 33 samples), as well as from two outcrops on the slopes (profile A – 1.50 m; and D – 1.40 m: 22 samples). The following parameters were determined in the biogenic and mineral deposits:

– the content of organic matter loss on ignition at a temperature of 550°C for 3 h;
– reaction (pH) by the potentiometric method;
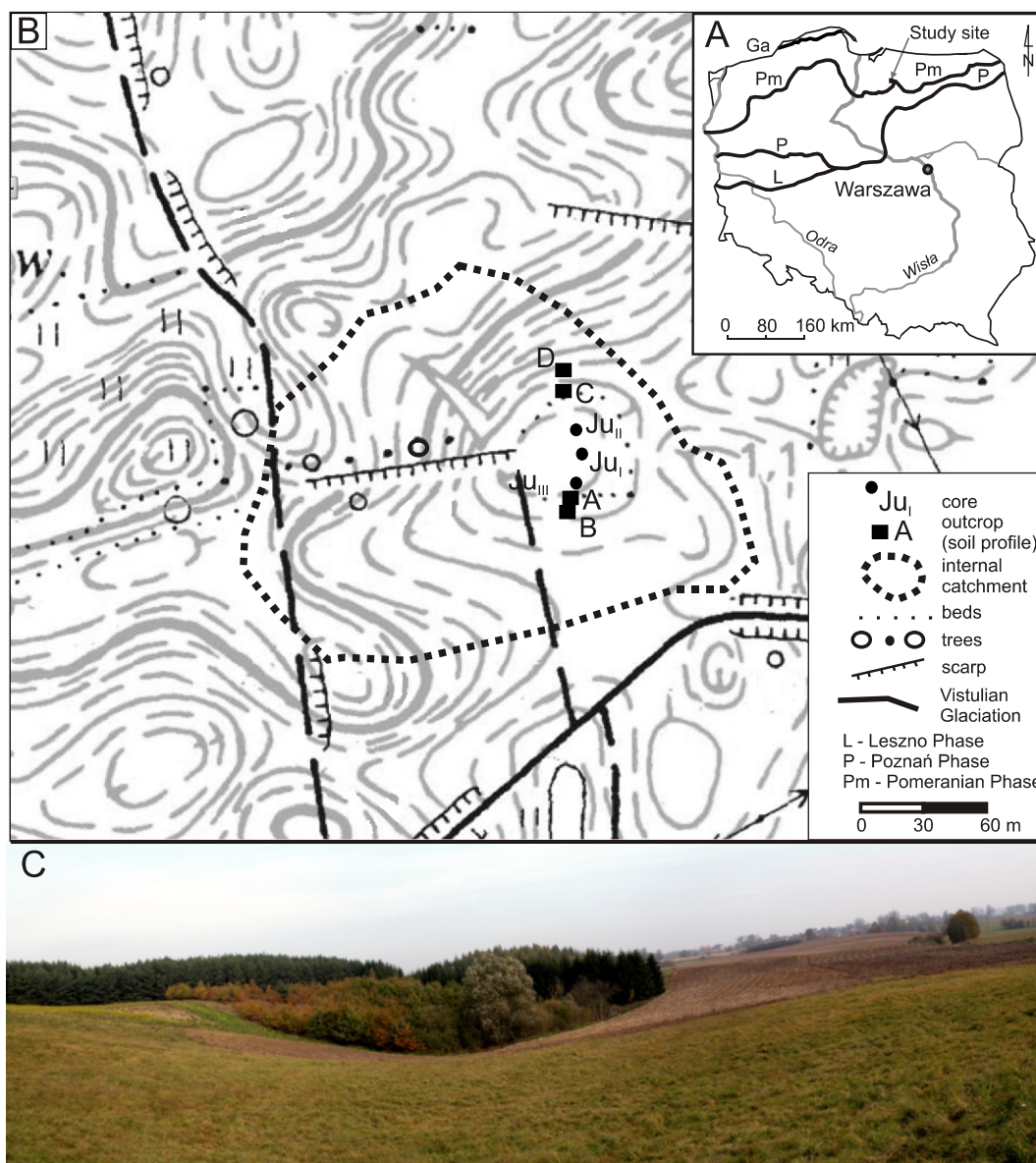– the content of calcium carbonate by Scheibler's method.

Fig. 1. Map of the study area

A – location related to the extent of the Vistula Glaciation, of the Pomeranian Phase in Poland;
B – detailed location on a topographic map; **C** – view of the kettle hole studied from the west

The total content of Ca, Mg, Fe, and Mn was determined by atomic absorption spectrometry (AAS); Na and K content was determined by emission spectrometry (ES) after treatment of samples with $HNO_3 + H_2O_2$ mixture on a sand bath. The content of terrigenous silica was determined in the sediments of core Ju_I and Ju_{III} using a method proposed by Apolinarska et al. (2012) by digestion of samples using aqua regia and NaOH after ignition at 550°C.

Statistical analysis (Ju_I core only). Hierarchical cluster analysis was used to identify the geochemical zones (*Past* software). The software package *Statistica* 9.0 (*Statsoft Inc.*) was used to draw scatter plots between selected parameters of the sediments.

PALAEOBOTANICAL ANALYSES

Pollen analysis. A total of 72 sediment samples (Ju_I – 45 samples and Ju_{III} – 27 samples) of 1 cm^3 volume at a resolution of 5–10 cm were examined palynologically, and based on the standard procedures were treated with 10% HCl, 10% KOH, 40% HF, and Erdtman's acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). A known number of indicator spores of Lycopodium (Stockmarr, 1971) was added to each sample in order to determine pollen concentration. The *Polpal* software for *Windows* (Nalepka and Walanus, 2003) was used to analyse the results.

Macroremain analysis. A total of 43 sediment samples (10 samples from the bottom of the profile did not contain plant macroremains) were collected in close correlation with palynological sampling (Ju$_I$ core). They were taken at the following intervals: every 5 or 10 cm (depending on the lithological characteristics) along the remaining 3.25 m up to the topmost layer. The samples were macerated according to a standard procedure (adopted by e.g., Stachowicz-Rybka, 2011).

Radiocarbon dating. One bulk sample from the Ju$_I$ core (0.25 m b.g.l.) was dated. The analysis was carried out at the Radiocarbon Laboratory, the Silesian University of Technology in Gliwice (Poland). The data were calibrated using the *OxCal v. 4.2.2* software (Bronk Ramesy, 2009).

RESULTS

Lithology and chronology. Based on the field research conducted on the sediments of the direct catchment of the kettle hole studied, it was found that sand, gravel, and boulders of end moraines dominate in the substrate, often interbedded with flow till of a small thickness. On the other hand, the thickness of colluvial deposits and tillage diamicton (agricultural colluvia) increased towards the bottom of the depression. Those were mainly sand deposits, with an addition of ca. 10% of silt. The fraction of gravel and clay accounted for a total of up to 10%. The median (Mz) for deposits of profile A ranged from 1.53 to 4.08 phi; the mean was 2.35 (Figs. 2 and 3). Similar results were obtained for other profiles (Mz from 2 to 3 phi). The sediments analysed were poorly sorted (σ_1 1.42–2.94) and differed

from each other in colour and enrichment with organic matter. Buried soil horizons were identified in profile A at depths of 0.80–0.90 m and 1.10–1.20 m (Fig. 3). The thickness of colluvial deposits in the profiles analysed (A–D, Fig. 2) was >0.80 m, and the maximum was 1.30 m. In the case of slopes with northern (profile A) and southern (profile C) exposure, the deposits are easily identified because they cover the biogenic sediments (peat). Despite the fact that all soils represented by profiles A–D were developed from slope sediments, their properties differed markedly. Therefore, they were classified into various soil units according to WRB system (IUSS Working Group WRB, 2015), i.e.: acidic soils having a umbric horizon (profiles A and C) as Haplic Umbrisols (Colluvic), soils more rich in base cations with mollic horizon (profile B) as Haplic Phaeozems (Colluvic), and others (profile D) as Colluvic Regosols (Figs. 2 and 3).

Mineral-organic gyttja was found at the floor (bottom) of the kettle hole, covered with sedge and moss peat (Dystric Histosols; Fig. 2). The maximum thickness of organic sediments was determined in the central part of the kettle hole – 4.15 m (Ju$_I$). In the second core (Ju$_{II}$), located several metres away from the first one to the south-east, biogenic sediments had a thickness of 3.56 m. Biogenic sediments in the third core (Ju$_{III}$; located at the southern edge of the bottom) had a thickness of only 1.20 m and occurred in the form of peat with a high content of mineral matter (Fig. 2).

The stratigraphy of the sediment sequence in the kettle hole studied was based on the palynological analysis performed in the Ju$_I$ core. Moreover, the Ju$_{III}$ core comprised Early Holocene deposits (Fig. 4). The seven local pollen zones were distinguished (L PAZ – local pollen assemblage zones; Fig. 4). They related to the development of vegetation in north-central Poland
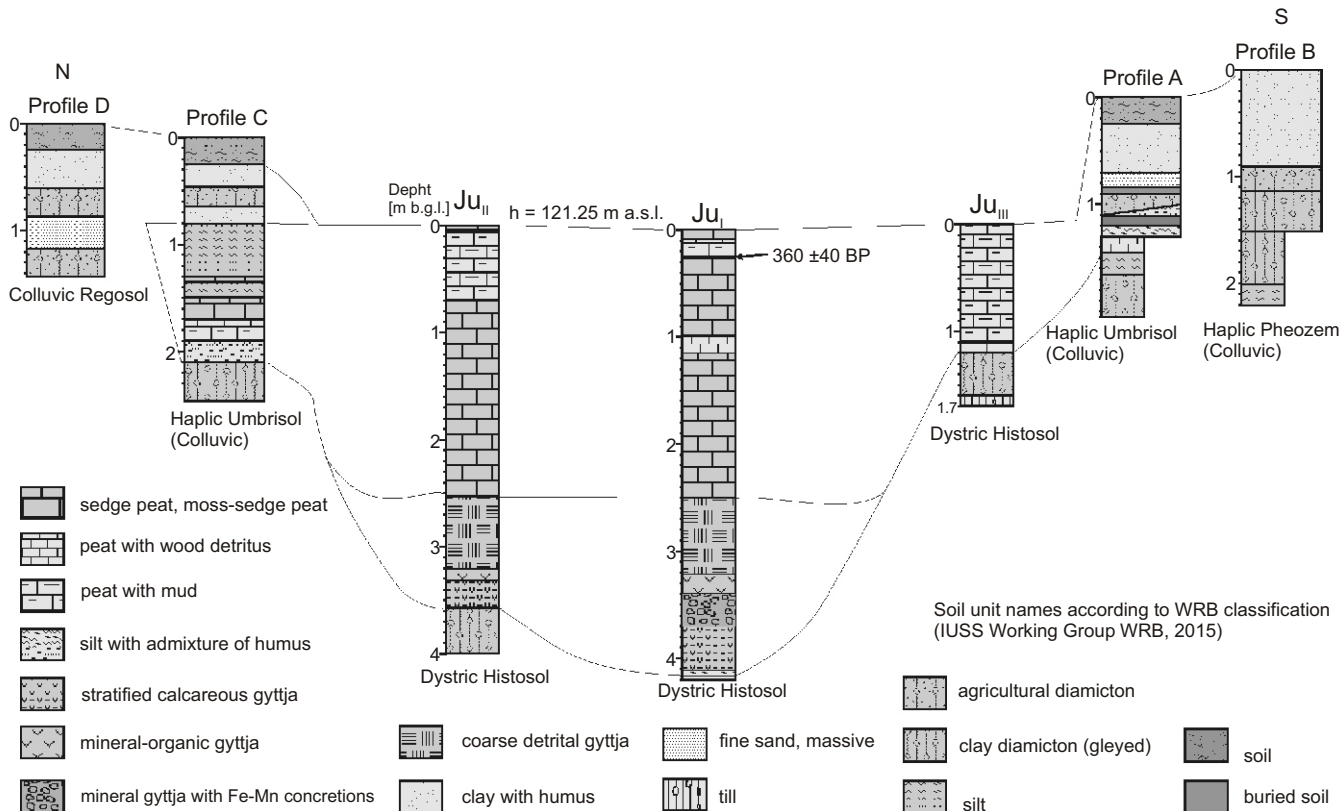

Fig. 2. The geological structure of the slopes and bottom of the kettle hole

(Noryśkiewicz, 1987, 2013; Ralska-Jasiewiczowa et al., 1998). Moreover, the history of local vegetation was completed with the results of macroremains analysis (in total, 6 local macrofossil assemblage zones – L MAZ; Fig. 5). A synthetic description of the stratigraphy and lithology of the deposits studied correlated with L PAZ and L MAZ is presented in Figure 6. The following chronozones were distinguished: 3.40–4.20 m – the Late Glacial (the top sediment sample was characterized by mixed taxa of the Late Glacial and the Holocene; Fig. 4);

3.20–3.40 m – a hiatus from the Preboreal, Boreal and Early Atlantic periods; 2.90–3.20 m – the Late Atlantic; 0.0–2.80 m – the Subboreal and Subatlantic.

In addition to well-preserved sporomorphs, the Late Glacial deposits (3.40–4.20 m) in the Ju$_I$ profile contained reworked material (*Ilex, Sequoia, Hystrix*). On the other hand, the overlying segment 3.20–3.40 m comprised pollen-free deposits with corroded fern spores and fragments of broken Fe-Mn concretions. The upper part of the remaining sediment was character-
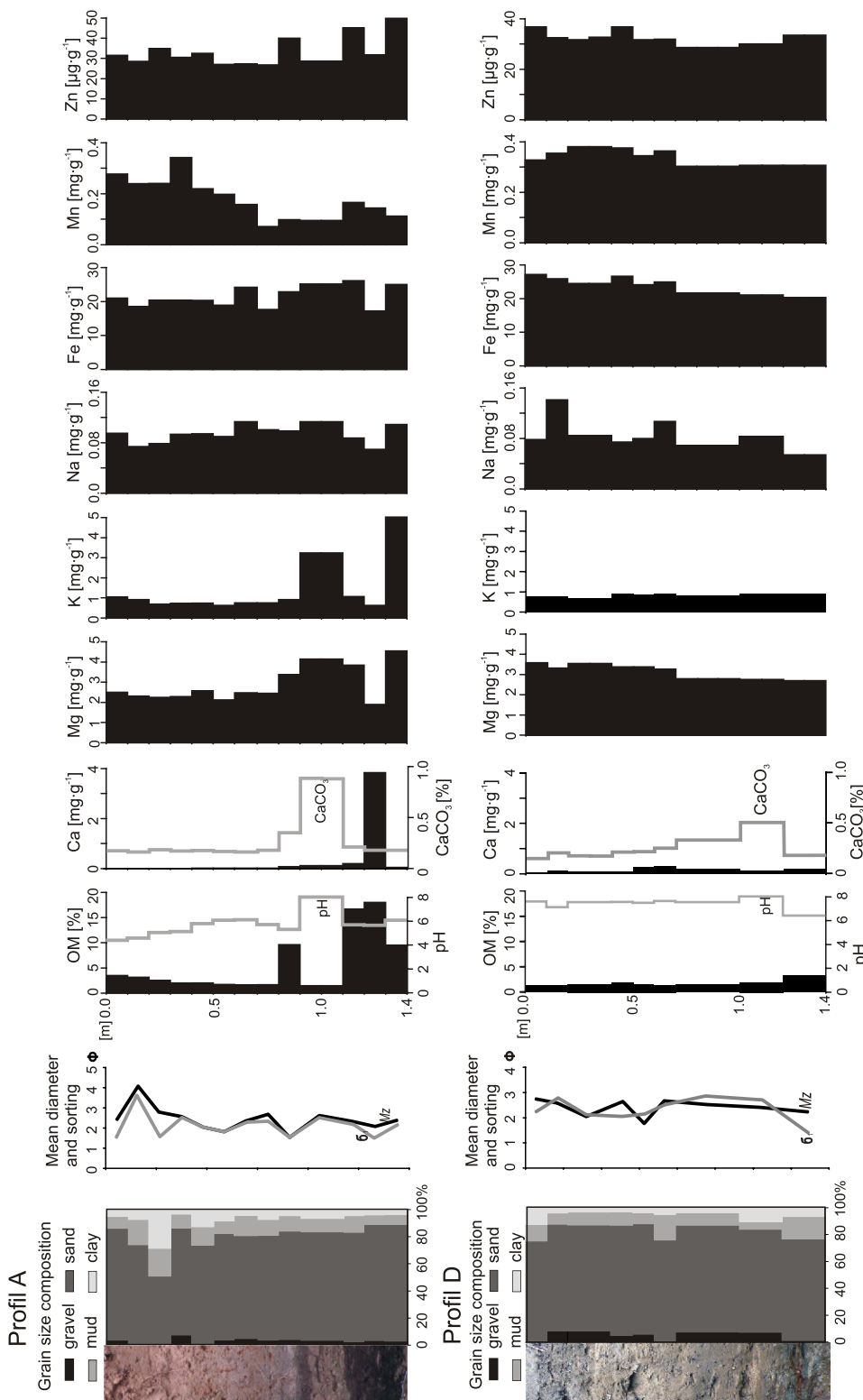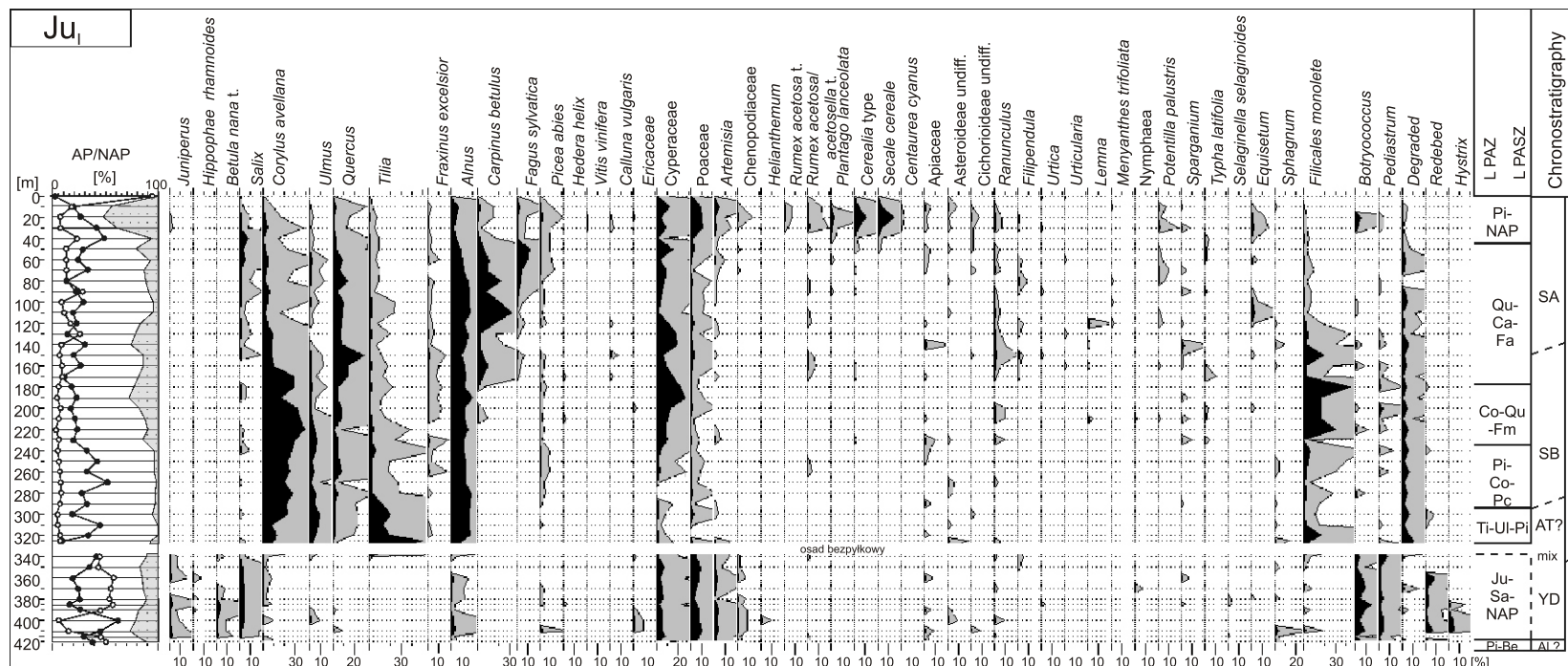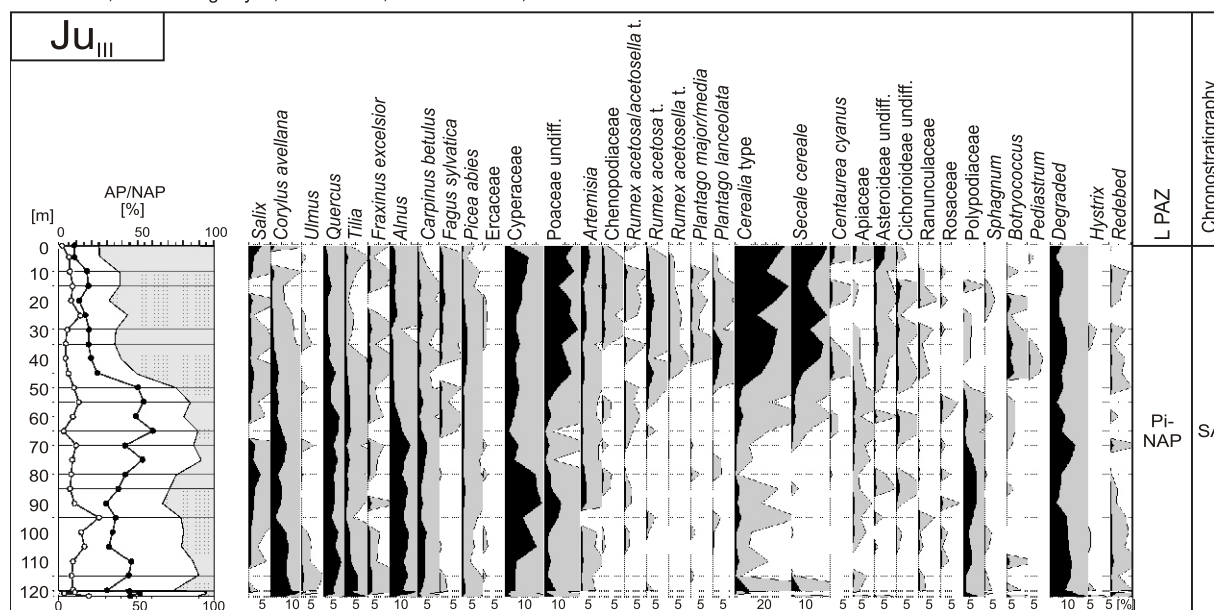

Fig. 3. Diagrams showing the geochemical sediment properties of profiles A and D

Al - Allerod; YD - Young Dryas, AT - Atlantic; SB - Subboreal; SA - Subatlantic

analysed by A.M. Noryśkiewicz

analysed by W.W. Gamrat

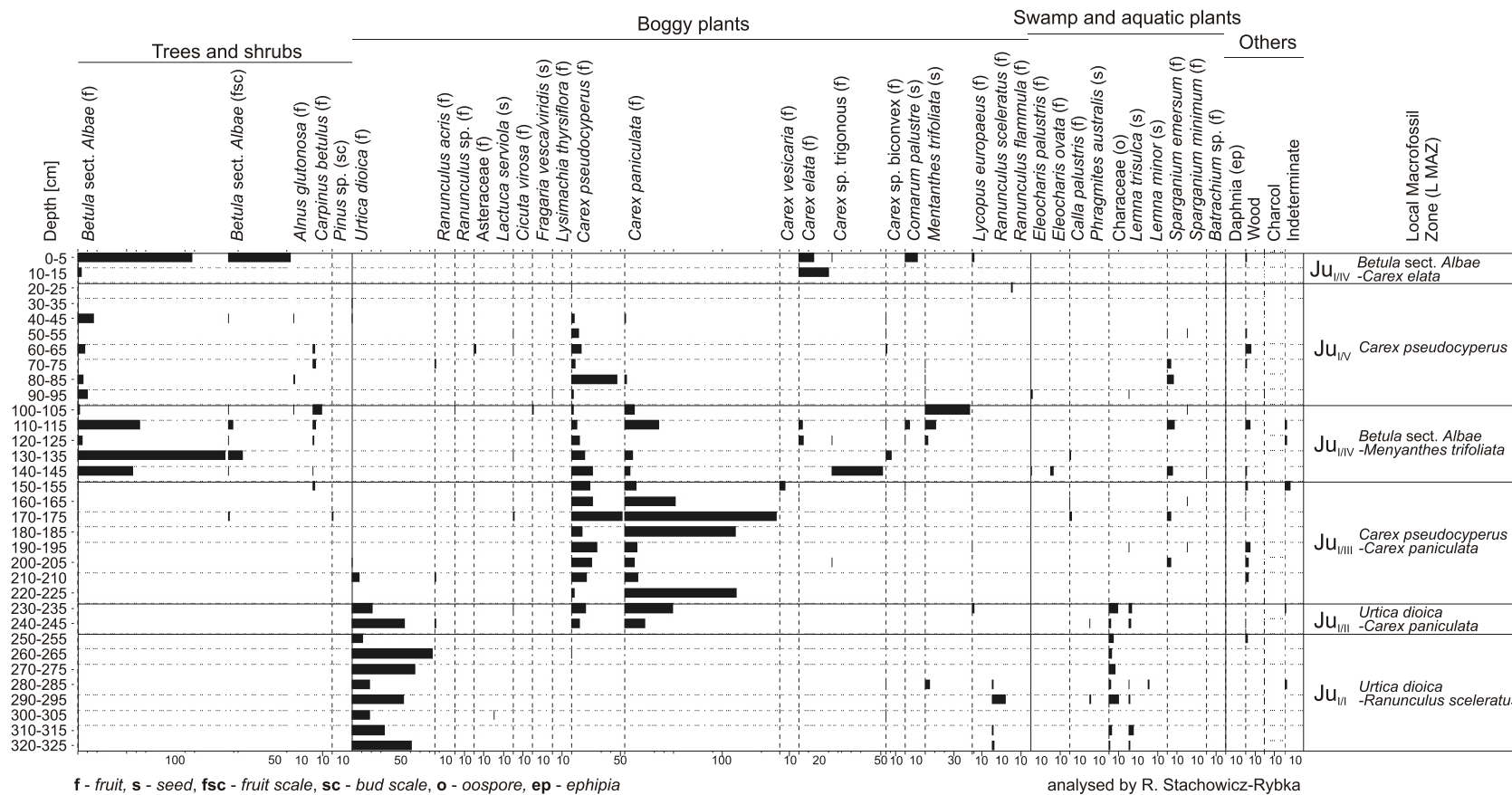**Fig. 4. Percentage pollen diagrams for the Ju$_I$ and Ju$_{III}$ cores**

Fig. 5. Macroremains diagram for the Ju$_I$ core

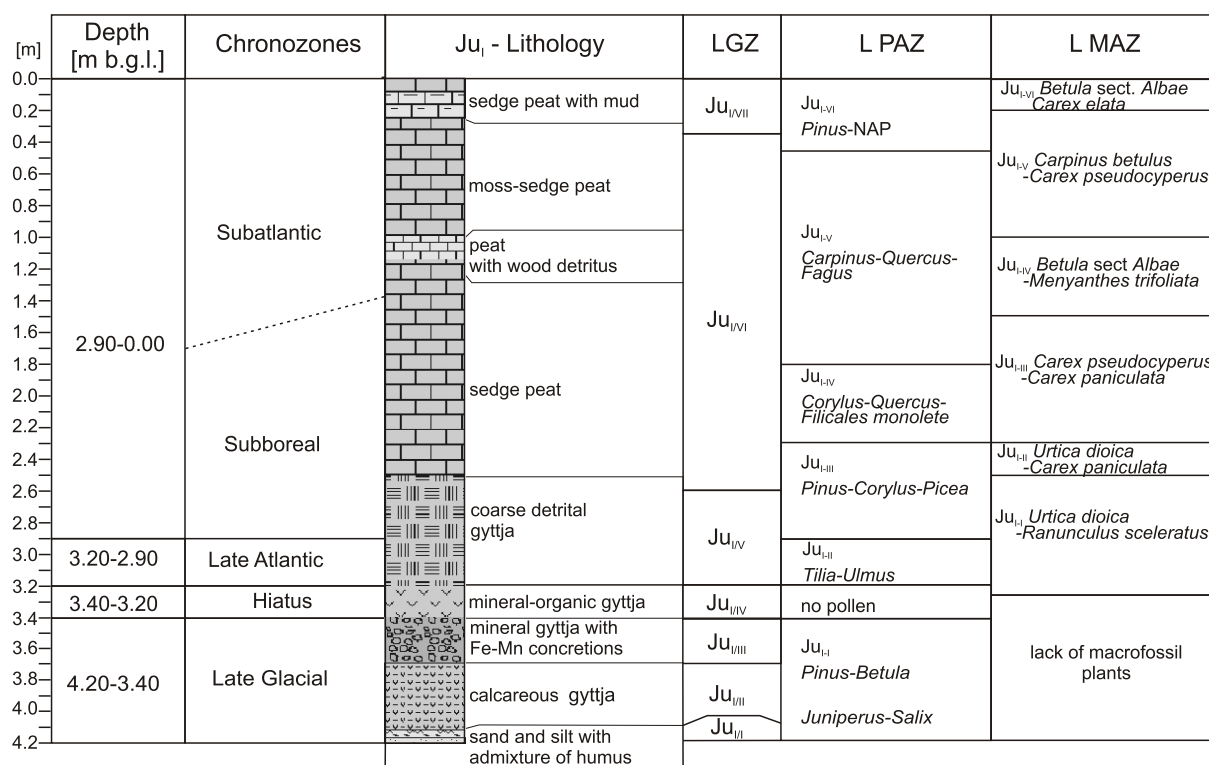| Depth [m]	Depth [m b.g.l.]	Chronozones	Ju_I - Lithology	LGZ	L PAZ	L MAZ
0.0–4.2						Ju_{I-VI} *Betula* sect. *Albae* *Carex elata*
		Subatlantic	sedge peat with mud	$Ju_{I/VII}$	Ju_{I-VI} *Pinus*-NAP	
			moss-sedge peat			Ju_{I-V} *Carpinus betulus* -*Carex pseudocyperus*
	2.90–0.00		peat with wood detritus		Ju_{I-V} *Carpinus-Quercus-Fagus*	Ju_{I-IV} *Betula* sect *Albae* -*Menyanthes trifoliata*
				$Ju_{I/VI}$		Ju_{I-III} *Carex pseudocyperus* -*Carex paniculata*
		Subboreal	sedge peat		Ju_{I-IV} *Corylus-Quercus-Filicales monolete*	Ju_{I-II} *Urtica dioica* -*Carex paniculata*
			coarse detrital gyttja		Ju_{I-III} *Pinus-Corylus-Picea*	Ju_{I-I} *Urtica dioica* -*Ranunculus sceleratus*
	3.20–2.90	Late Atlantic		$Ju_{I/V}$	Ju_{I-II} *Tilia-Ulmus*	
	3.40–3.20	Hiatus	mineral-organic gyttja	$Ju_{I/IV}$	no pollen	
			mineral gyttja with Fe-Mn concretions	$Ju_{I/III}$	Ju_{I-I} *Pinus-Betula*	lack of macrofossil plants
	4.20–3.40	Late Glacial	calcareous gyttja	$Ju_{I/II}$	*Juniperus-Salix*	
			sand and silt with admixture of humus	$Ju_{I/I}$		

Fig. 6. Chronozones marked in the Ju_I sediment core

Lithological description as on Figure 2

ized by a high content of sporomorphs, corroded to a lesser or greater extent (e.g., the degraded curve – Fig. 4). Therefore, the results of pollen analysis for profiles Ju_I and Ju_{III} are difficult to interpret.

GEOCHEMISTRY

Slope sediments. Sediments of profiles A and D are distinguished by a varying content of organic matter (A – 1.5–18.0%; D – 1.4–3.3%) and a low content of Ca (0.01–3.84 mg·g^{-1} and 0.06–0.31 mg·g^{-1}, respectively; Fig. 3). The highest content of OM was determined in the buried soil horizons (profile A; 0.80–0.90 m and 1.10–1.20 m). The content of potassium (up to 5.3 mg·g^{-1}) and magnesium (up to 4.6 mg·g^{-1}) was higher in the sediments of profile A compared to profile D (accumulation in the deeper mineral sediment layer). On the other hand, sediments of the latter profile were characterized by a higher content of such metals as Mg, Fe, Mn, and Zn (Fig. 7). The range of pH values varied greatly (profile A – 4.2–7.7; profile D – 6.4–8.1). The lowest pH values were recorded in colluvial sediments of profile A, and the highest in the levels containing CaCO$_3$ (up to 0.8%; Fig. 3).

Bottom sediments. Properties of the bottom sediments of the kettle hole studied were described based on the samples collected from two cores at sites Ju_I and Ju_{III}. The attention was focused mainly on the former due to its location in the central part of the bottom and a complete sequence of bottom sediments.

The seven geochemical zones (from $Ju_{I/I}$ to $Ju_{I/VII}$) were identified in the Ju_I core by hierarchical cluster analysis (Fig. 7). As shown in Table 1, the zones differ significantly in their chemical properties. The most important features of these zones are described below.

The $Ju_{I/I}$ zone (4.10–4.20 m; sand, organic silt), which represents the bottom layer of the sediment sequence, was characterized by a slightly alkaline reaction (pH 7.3–7.9) and by considerable enrichment with organic matter (OM 4.6–14.3%). The content of OM was determined as a loss on ignition and therefore the values obtained may be somewhat overstated (as in $Ju_{I/II}$) due to the very high concentration of carbonates. The zone was distinguished by the maximum (in relation to the whole profile) Fe (274 mg·g^{-1}) and Mn content (10.2 mg·g^{-1}) as well as a very high content of SiO$_{2ter}$ (up to 64.2%), Ca (up to 212 mg·g^{-1}), and CaCO$_3$ (up to 30%) (Fig. 7). Low values of geochemical indicators, i.e. Na:K (0.10–0.12), Ca:Fe (0.1–3.5) and Fe:Mn (28–68) were determined. A relatively high ratio of Ca:Mg (7–36) may be connected with a high content of carbonates.

The $Ju_{I/II}$ zone (3.70–4.10 m; mineral gyttja) had a lower content of OM (minimum for the whole profile – 2.5%) and a higher content of SiO$_{2ter}$ compared to $Ju_{I/I}$ (up to 67.3%). The maximum values for the whole profile were recorded for Ca (up to 249 mg·g^{-1}), CaCO$_3$ (46.5%), K (3.3 mg·g^{-1}), Mg (7.2 mg·g^{-1}), Na (0.22 mg·g^{-1}), and pH (8.2). Furthermore, a significant reduction in the content of Fe and Mn was determined. The indicators Ca:Mg and Fe:Mn significantly increased (up to 43 and 120, respectively), and the Ca:Fe ratio had the maximum value throughout the profile (15.8). Values of the Na:K ratio were similar to $Ju_{I/I}$.

Sediments in the $Ju_{I/III}$ zone (3.40–3.70 m; mineral gyttja with Fe-Mn concretions) were moderately rich in organic matter (OM 6.9–17.0%). Compared to $Ju_{I/II}$, a decrease in pH values and in the content of SiO$_{2ter}$, Ca, CaCO$_3$, K, Mg, and Na was determined, along with a very large increase in the content of Fe (up to 245 mg·g^{-1}), Mn (up to 8.6 mg·g^{-1}), and Zn (up to 129 mg·g^{-1}). In this zone, a significant decrease in the values of Ca:Fe (min.

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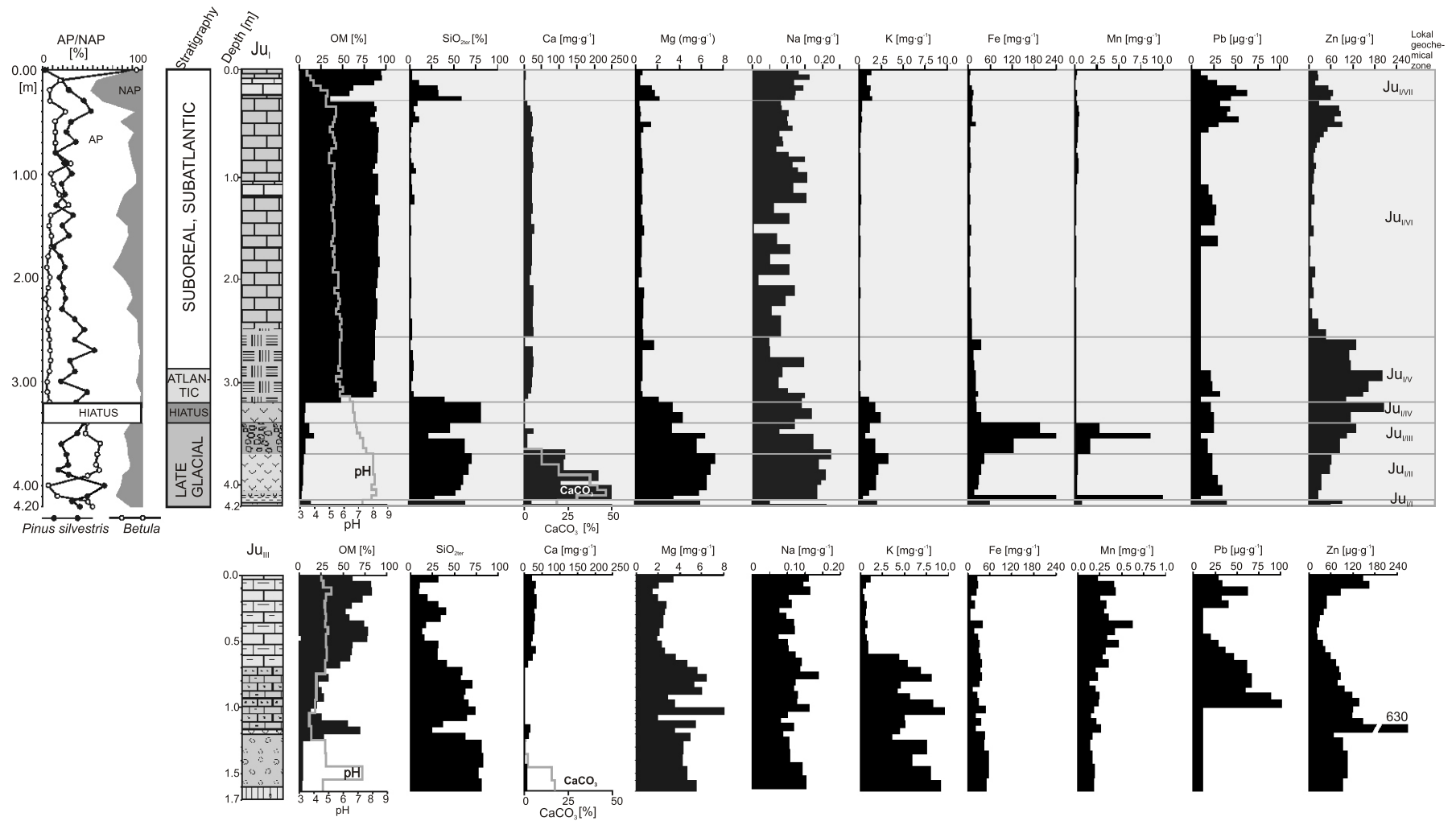**Fig. 7. Geochemical properties of the Ju$_I$ and Ju$_{III}$ core sediments**

Lithological description as for Figure 2

Statistical measures of the analysed sediment parameters (mean ± standard deviation, range), Ju$_I$ core

Parameter	Local geochemical zones						
	I (n = 2)	II (n = 5)	III (n = 5)	IV (n = 5)	V (n = 11)	VI (n = 29)	VII (n = 7)
OM [%]	9.5 ±6.8 (4.6–14.3)	3.7 ±0.9 (2.5–4.9)	9.4 ±5.1 (6.9–17.0)	9.7 ±23.7 (5.8–47.6)	87.1 ±1.4 (85.8–89.1)	90.2 ±5.7 (61.6–92.9)	70.5 ±22.6 (35.4–95.0)
SiO$_{2ter}$ [%]	46.1 ±25.7 (27.9–64.2)	63.0 ±6.4 (52.1–67.3)	46.8 ±20.7 (21.0–62.1)	70.1 ±23.9 (39.5–80.9)	2.7 ±1.3 (1.3–4.5)	1.4 ±2.4 (0.1–11.0)	12.5 ±20.8 (2.7–59.1)
CaCO$_3$ [%]	24.6 ±7.7 (19.2–30.0)	32.5 ±13.4 (16.7–46.5)	4.0 ±2.4 (1.4–6.2)	0.48 ±0.56 (0.11–1.12)	–	–	–
Ca [mg·g^{-1}]	117 ±133 (23.0–212)	145 ±67.0 (104–249)	4.4 ±13.2 (0.5–26.7)	0.6 ±6.5 (0.2–11.5)	15.2 ±9.6 (1.6–27.4)	23.8 ±2.7 (16.3–28.2)	1.9 ±3.1 (0.1–8.3)
Mg [mg·g^{-1}]	4.7 ±1.7 (3.5–5.9)	6.6 ±0.5 (5.8–7.2)	4.8 ±1.6 (3.3–6.3)	3.4 ±1.1 (2.2–4.3)	0.7 ±0.5 (0.5–1.7)	0.6 ±0.2 (0.3–1.4)	0.8 ±0.8 (0.4–2.2)
K [mg·g^{-1}]	1.3 ±1.2 (0.4–2.1)	2.1 ±0.8 (1.1–3.3)	1.3 ±0.6 (0.7–1.8)	1.8 ±0.7 (1.1–2.4)	0.1 ±<0.1 (0.07–0.12)	0.1 ±0.1 (0.05–0.31)	1.0 ±0.4 (0.3–1.5)
Na [mg·g^{-1}]	0.1 ±0.1 (0.05–0.21)	0.2 ±<0.1 (0.19–0.22)	0.1 ±0.1 (0.08–0.17)	0.2 ±<0.1 (0.14–0.17)	0.1 ±<0.1 (0.05–0.15)	0.1 ±<0.1 (0.01–0.16)	0.1 ±0.0 (0.08–0.16)
Fe [mg·g^{-1}]	167 ±151 (60.3–274)	30.6 ±10.2 (15.8–43.5)	166 ±61.5 (122–245)	26.2 ±8.6 (20.0–35.8)	20.7 ±7.5 (14.4–35.2)	5.7 ±3.4 (3.5–20.3)	6.1 ±4.3 (2.7–13.1)
Mn [mg·g^{-1}]	5.5 ±6.5 (0.9–10.2)	0.3 ±0.1 (0.2–0.4)	2.7 ±3.7 (1.7–8.6)	0.1 ±<0.1 (0.11–0.17)	0.2 ±<0.1 (0.16–0.20)	0.2 ±0.1 (0.08–0.51)	0.1 ±0.1 (0.06–0.27)
Pb [µg·mg^{-1}]	25.0 ±21.3 (10.0–40.1)	26.9 ±6.0 (22.7–26.3)	17.9 ±7.3 (10.0–24.5)	19.5 ±7.8 (10.0–25.1)	14.9 ±9.1 (10.0–23.2)	14.1 ±11.9 (10.0–52.9)	30.2 ±18.4 (10.0–62.5)
Zn [µg·mg^{-1}]	76.2 ±21.1 (61.3–91.1)	43.6 ±15.2 (26.3–60.8)	101 ±21.9 (85.1–129)	141 ±56.2 (102–205)	140 ±34.4 (109–200)	12.5 ±26.4 (2.0–90.3)	34.3 ±19.8 (16.3–66.3)
pH	7.6 ±0.4 (7.3–7.9)	8.0 ±0.1 (7.9–8.2)	7.1 ±0.6 (6.8–6.3)	6.6 ±0.2 (6.4–6.7)	5.7 ±<0.1 (5.7–5.8)	5.4 ±0.2 (5.1–5.8)	4.5 ±0.5 (3.8–5.0)
Na:K	0.1 ±<0.1 (0.10–0.12)	0.1 ±<0.1 (0.07–0.17)	0.1 ±<0.1 (0.09–0.12)	0.1 ±<0.1 (0.07–0.13)	0.8 ±0.2 (0.6–1.2)	0.7 ±0.3 (0.1–1.3)	0.1 ±0.1 (0.1–0.3)
Fe:Mn	48 ±29 (28–68)	105 ±21 (69–120)	56 ±24 (28–71)	183 ±39 (138–210)	123 ±38 (85–179)	33 ±17 (14–68)	51 ±27 (14–86)
Ca:Mg	21 ±21 (7–36)	25 ±12 (16–43)	2 ±2 (<1–4)	2 ±3 (<1–5)	34 ±17 (1–46)	40 ±7 (19–53)	8 ±8 (<1–23)
Ca:Fe	1.8 ±2.4 (0.1–3.5)	6.6 ±5.6 (2.7–15.8)	0.1 ±0.1 (<0.1–0.1)	0.2 ±0.3 (<0.1–0.6)	1.1 ±0.6 (0.1–1.7)	4.3 ±1.3 (1.3–6.5)	0.9 ±0.9 (<0.1–2.1)

<0.1), Fe:Mn (28–71) and Ca:Mg (min. <1) was recorded. Values of the Na:K ratio were similarly low as in older horizons.

The Ju$_{I/IV}$ zone (3.20–3.40 m; mineral-organic gyttja) was distinguished by the presence of slightly acid deposits (pH 6.4–6.7) with a highly varied content of organic matter and terrigenous silica, i.e. 6 and 81% (the profile's maximum) in the floor and 48 and 40% in the top, respectively. Compared to Ju$_{I/III}$, a significant decrease in the content of Ca (up to 0.2 mg·g^{-1}), Mn (up to 0.1 mg·g^{-1}), and Mg (up to 3.3 mg·g^{-1}) was determined in this zone, and there was a major increase in the content of Zn (maximum for the profile – 205 µg·g^{-1}). Furthermore, the maximum values of the Fe:Mn ratio (210) were determined and there was a considerable decrease in the values of Fe:Ca, Na:K, and Ca:Mg ratios, which were equally low as in the Ju$_{I/III}$ zone.

The Ju$_{I/V}$ zone (2.60–3.20 m; coarse detrital gyttja) was distinguished by a sudden increase in the organic matter content (OM 86–89%), with a simultaneous major decrease in the content of terrigenous silica (SiO$_{2ter}$ 1.3–4.5%), K (0.07–0.12 mg·g^{-1}), and Mg (0.3–1.4 mg·g^{-1}). The content of Zn remained at a level above 100 µg·g^{-1} (Fig. 7). The pH values ranged from 5.7 to 5.8, which indicated acidification of the environment. Contrary to the Fe:Mn ratio (85–179), values of Na:K (0.6–1.2), Ca:Mg (1–46) and Ca:Fe (0.1–1.7) ratios increased.

The Ju$_{I/VI}$ zone (0.35–2.60 m; coarse detrital gyttja at the floor, sedge peat and moss-sedge peat at the top) was distinguished by a very high content of organic matter and a small content of terrigenous silica (the minimum value of 0.1%). These parameters varied, however, to a larger extent compared to Ju$_{I/V}$ (OM 62–93%, SiO$_{2ter}$ 0.1–11%). The sediments were acidic (pH 5.1–5.8) with particularly poor concentrations of potassium and magnesium, which occurred with the minimum values in this zone (K 0.05 mg·g^{-1}, Mg 0.3 mg·g^{-1}). In the uppermost layer of the zone, the concentrations of Pb (up to 52.9 µg·g^{-1}) and Zn (up to 90.3 µg·g^{-1}) significantly increased. Furthermore, a small increase in the values of Ca:Fe (1.3–6.5), Ca:Mg (19–53), and Na:K (up to 1.3 – the maximum value in the profile) and a considerable decline in values of the Fe:Mn ratio (14–68) was observed.

The Ju$_{I/VII}$ zone (0.0–0.35 m; peat) was characterized by a wide range of organic matter content (35–95%). With respect to Ju$_{I/VI}$, a significant increase in the content of SiO$_{2ter}$ (up to 59.1%), Mg (0.4–2.2 mg·g^{-1}), and K (0.3–1.5 mg·g^{-1}) was determined. Fe and Mn reached their profile minima (2.7 and 0.06 mg·g^{-1}, respectively). The content of lead and zinc largely varied (Pb 10.0–62.5 µg·g^{-1}; Zn 16.3–66.3 µg·g^{-1}) and significantly dropped in the last 10 cm of the roof. A large decrease in pH values towards the roof of sediments was observed, which

were very acidic at the surface (pH 3.8). Values of geochemical indices, except for Fe:Mn (14–86), were much lower compared to Ju$_{I/VI}$.

Figure 8 presents scatter plots between the content of terrigenous silica (SiO$_{2ter}$) and the content of organic matter (OM) and selected metals in the whole Ju$_I$ profile. A highly significant negative correlation between SiO$_{2ter}$ and OM was recorded (r value –0.944, p = 0.000), whereas a significant positive correlation was found only for Na, K, Mg, Fe, Pb, Zn – elements closely connected with lithological conditions of the drainage basin. K and Mg demonstrated the strongest correlation with SiO$_{2ter}$ (r values 0.922 and 0.859, respectively; p = 0.000). These metals are generally more strongly sorbed by sediments and therefore subject to passive migration together with mineral and organic colloids (Borówka, 1992; Franz et al., 2006).

The bottom part of profile Ju$_{III}$ was built of mineral deposits (loam), which are rich in CaCO$_3$ (ca. 16%, pH 7.6–8.0) and all the metals analysed (Fig. 7). Paludal sediments of Ju$_{III}$ (1.20–0.0 m) were distinguished by a significant heterogeneity of all the parameters analysed. A considerable enrichment in organic matter (up to 83%), Ca (up to 32 mg·g^{-1}), Mn (up to 3.4 mg·g^{-1}), Zn (up to 163 µg·g^{-1}), and Pb (up to 61 µg·g^{-1}) was observed from the depth of 0.65 m towards the upper part of profile, with the content of terrigenous silica <40%. Compared to surface layers within the range of 0.65–1.2 m, the content of OM (12–69%), Ca (0.1–15.8 mg·g^{-1}), Mn (0.1–0.3 mg·g^{-1}) decreased, while the content of SiO$_{2ter}$ increased (up to 73%), Mg (1.9–8.3 mg·g^{-1}), K (4.1–9.5 mg·g^{-1}), and Fe (10.1–47.2 mg·g^{-1}) (Fig. 7).

DISCUSSION

The origin of the kettle hole studied is connected with the melting of a dead-ice block and the disappearance of long-term permafrost. According to van Loon et al. (2012), the permafrost mostly developed in the ice-free zone that appeared after the recession of the ice sheet. Consistent with the views of Błaszkiewicz (2008, 2011), it was likely that the melting of a buried dead-ice block proceeded relatively quickly in the absence of water runoff from the kettle hole studied and the presence of thermokarst processes. Sediment accumulation of the first local geochemical zone Ju$_{I/I}$ probably still occurred in the periglacial conditions of the initial cold lake, which may be shown by e.g., a low concentration of Ca (Fig. 7). Then the permafrost underwent a gradual degradation, which resulted in a significant intensification of chemical and mechanical denudation processes in the drainage basin (the maximum content of Ca, CaCO$_3$, K, Mg, and Na) in Ju$_{I/II}$ (Table 1, Figs. 7 and 8). A layer of mineral gyttja was located at a depth of 3.70–3.40 m, which testifies to the further evolution of the small lake (Ju$_{I/III}$). The layer was characterized by a significant enrichment in terrigenous silica, the lack of carbonates, and the presence of ferruginous-manganese concretions. The presence of the latter can probably be associated with post-sedimentation processes, i.e. diagenesis of deposits in the conditions of partial dehydration and/or water-level fluctuations. This suggestion was also supported by the presence of a hiatus above the analysed layer, and the material containing mixed Late
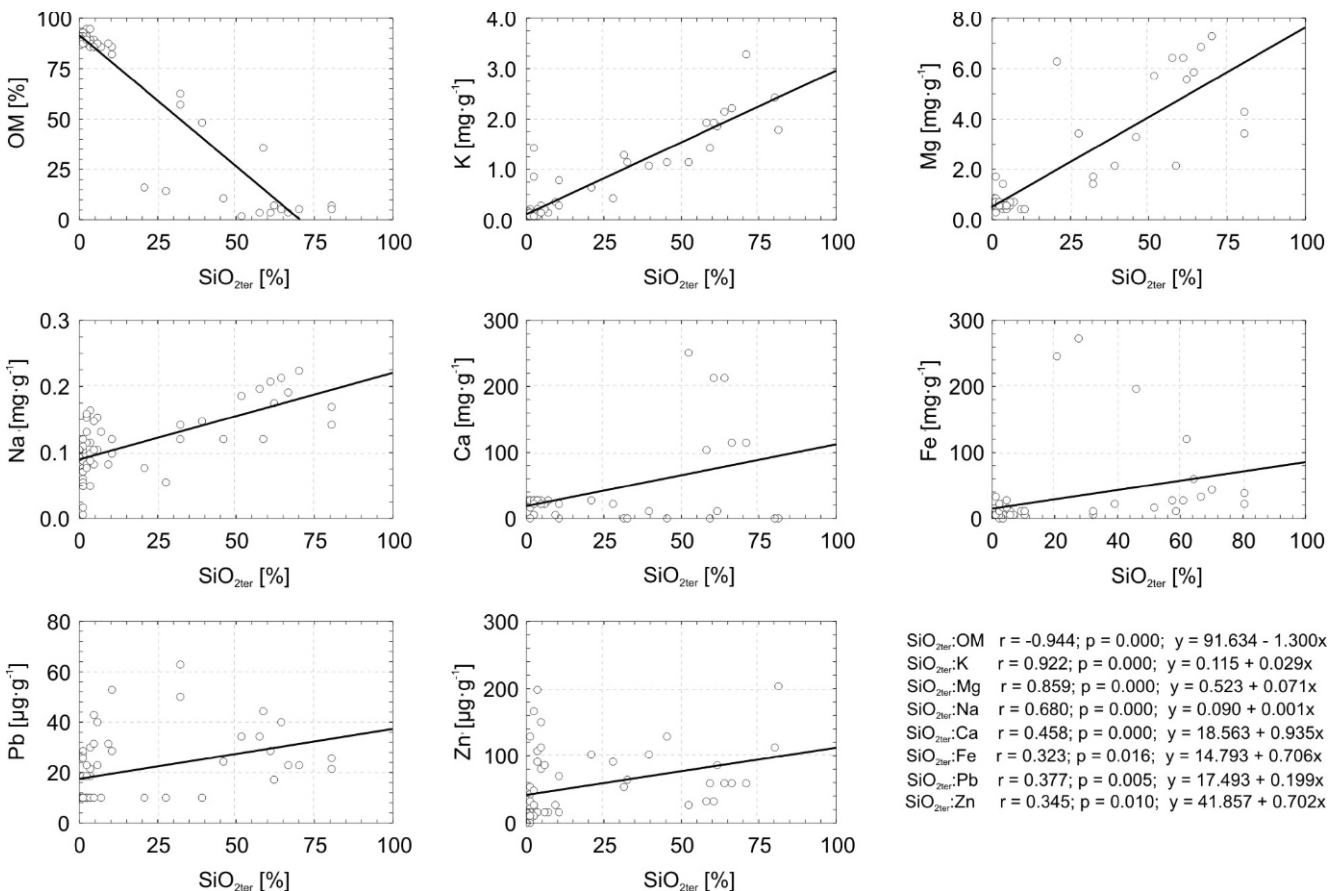

SiO$_{2ter}$:OM   r = -0.944; p = 0.000; y = 91.634 - 1.300x
SiO$_{2ter}$:K   r = 0.922; p = 0.000; y = 0.115 + 0.029x
SiO$_{2ter}$:Mg   r = 0.859; p = 0.000; y = 0.523 + 0.071x
SiO$_{2ter}$:Na   r = 0.680; p = 0.000; y = 0.090 + 0.001x
SiO$_{2ter}$:Ca   r = 0.458; p = 0.000; y = 18.563 + 0.935x
SiO$_{2ter}$:Fe   r = 0.323; p = 0.016; y = 14.793 + 0.706x
SiO$_{2ter}$:Pb   r = 0.377; p = 0.005; y = 17.493 + 0.199x
SiO$_{2ter}$:Zn   r = 0.345; p = 0.010; y = 41.857 + 0.702x

Fig. 8. Scatter plots of the terrigenous silica (SiO$_{2ter}$) content *versus* the content of organic matter (OM) and selected metals (Ju$_I$ core)

Glacial and Holocene taxa (depth 3.40 m; Fig. 4). Mineral-organic gyttja at a depth of 3.20–3.40 m did not contain pollen. A stratigraphical gap occurred during the Preboreal, Boreal, and Early Atlantic periods. Perhaps the reservoir was not completely sealed and in the Early Holocene was drained along with lowering the groundwater level? It is possible in this time that the basin was dry. The likely reason for the presence of sediments with no pollen and macroremains was the desiccation of the depression's bottom, which could contribute to the wind deflation of deposits, and consequently the destruction of pollen grains. Therefore, the interpretation of geochemical indicators for $Ju_{I/IV}$, which is characterized by e.g., profile maxima for Zn and the Fe:Mn ratio (Table 1 and Fig. 7), was in this case very limited. A similar case was described by Mendyk et al. (2015) based on research conducted in the drainage basin of Lake Sumowskie (Brodnica Lake District, north-central Poland). If it is assumed that the accumulation of sediments with a hiatus began in the Preboreal, the water-level lowering in the kettle hole analysed can also be related to similar trends reported from other regions of Poland (e.g., Niewiarowski, 1989, 1995; Starkel et al., 1998; Twardy et al., 2010; Hirsch et al., 2015).

As shown by the palynological analysis, the bottom layer of sediments from the profile Ju_I, covering the geochemical levels I, II, and III, should be related to the relatively cold Late Glacial period (Fig. 4). At that time, trees were represented only by pine (*Pinus*) and birch (*Betula*), and they were accompanied by heliophilous shrubs and low shrubs (*Juniperus, Salix, Betula nana* t. and occasionally *Hippophae rhamnoides*). In addition, plant indicators of cold glacial periods occurred (*Dryas octopetala*, *Selaginella selaginoides* and *Helianthemum*). The redeposited taxa (of Quaternary origin and Neogene, and fragments of dinoflagellates – *Hystrix*) were also present in relatively large numbers. They probably came from the eluviation of older deposits derived from the drainage basin of the kettle hole, which was possible because of a rather loose vegetation cover. Macroremains have not been preserved in the sediments of these zones.

The presence of coarse detrital gyttja deposits $Ju_{I/V}$ (the Late Atlantic and Early Subboreal) indicated a change in the sedimentation process and the prevailing telmatic conditions in the depression. However, due to the presence of the above-mentioned hiatus, it was not possible to determine the beginning of the coarse detrital gyttja accumulation. A low content of terrigenous silica and high values of Na:K, Ca:Mg, and Ca:Fe indices may indicate the dominance of chemical denudation processes in the drainage basin over mechanical denudation (Table 1 and Fig. 7). In such conditions, a wide range of Fe:Mn values may reflect the variable redox potential associated with water-level fluctuations (Borówka, 1992; Cohen, 2003). Similarly to $Ju_{I/IV}$, the geochemical zones analysed were distinguished by a high content of Zn (up to 200 $\mu g \cdot g^{-1}$), caused by bottom-up post-sedimentation migration in the acidic environment (including groundwaters). Taking into account the results obtained by Karasiewicz et al. (2014b), despite the lack of a clear record in the diagrams of pollen and macroremains, one cannot exclude the effect of Zn bioaccumulation.

Analysis of plant remains from a depth of 3.00–3.25 m (L MAZ Ju_{I-1}; Fig. 5) showed that in the process of shallowing, the surface of the water body was covered with a Lemnatea pleuston community, the main component of which was *Lemna trisulca*. The presence of rare fruits of *Lemna trisulca* in the top part of the zone suggests increased trophy and calcium carbonate content in the water reservoir (Szoszkiewicz et al., 2010), but in the deposit there was no $CaCO_3$. This could have occurred when the environmental conditions did not favour the precipitation of calcium carbonate. *Urtica dioica* occurred along

the shores in nitrogen-rich waterlogged places. Periodically emerged, highly eutrophic places were overgrown with *Ranunculus sceleratus*. A lack of tree remains and the presence of *Lactuca serriola* – a species occurring in dry and sunlit habitats – may indicate the supply of material from places located farther from the shores of the water body. This corresponded to L PAZ Ju_{I-3} (Ti-Ul 2.70–3.20 m; Fig. 4) where pollen grains have traces of intensive corrosion and pollen spectra are distinguished by a large number of *Tilia* pollen, which is rather unusual in the study area (Kupryjanowicz et al., 2004; Bałaga and Chodorowski, 2006). Linden produces rather large amounts of pollen, but the grains are relatively large and heavy (Dyakowska, 1959), hence the genus is rather underrepresented in "pollen rain" (Środoń, 1991). Nevertheless, sporoderm of linden pollen is relatively resistant to the destruction, which means that they can be identified even when they are heavily damaged; this could explain their over-representation in the sediment (Bałaga and Chodorowski, 2006). In the same segment of sediment, there were sporomorphs and NPP (non pollen palynomorphs) coming from the pre-Quaternary sediments (including, e.g., sequoias, Neogene spores, and dinoflagellates *Hystrix* – marine organisms – Ju_{III}; Fig. 4), which showed the transport of older material from the drainage basin surrounding the peat bog.

The Late Subboreal and the Early Subatlantic were represented by genetically diverse sediments of $Ju_{I/VI}$, i.e. coarse detrital gyttja at the bottom part and sedge peat in the top (Fig. 6). Based on the analysis of geochemical indicators (Na:K, Ca:Mg, Fe:Mn), it can be concluded that sedimentation of these deposits occurred in varying denudation conditions of the drainage basin (Table 1; Figs. 7 and 8) and with considerable water-level fluctuations. The water-level rise in the Early Subatlantic is generally recorded in lacustrine and peat-bog sediments of the young glacial area in Poland (Kowalewski, 2014). Similar changes were documented in the pollen and macroremain diagram created for profile Ju_I (Figs. 4 and 5). They were particularly well-visible for L PAZ J_{I-6} (Qu-Ca-Fa), L MAZ J_{I-2} (*Urtica dioica-Carex paniculata*), and J_{I-3} (*Carex pseudocyperus-Carex paniculata*). A high content of Cyperaceae at a depth of 1.40 m and *Filicales monolete* at a depth of 1.50 m was determined in the pollen spectra obtained. The increase in sedge pollen and the re-occurrence of *Sparganium* and *Lemna* may be correlated with a water-level rise, and the previous fern content of several dozen percentage with peat desiccation. A very high contribution of *Carex paniculata* and *C. pseudocyperus* fruits was determined in L MAZ J_{I-2} and J_{I-3} (Fig. 5). They suggest a developed telmatic zone. This situation could be accounted for by favourable habitat conditions. In the conditions of a more humid habitat (depth of 1.90 m), large amounts of *Carex nutlets* (depth 2.20 and 1.70–1.80 m) and Cyperaceae pollen were produced (Fig. 4). It can be assumed that an increase in the quantity of sedge nutlets in the macroremain material was affected by diagenetic processes (draining of sediment, partial decomposition of organic matter) which led to peat compaction. A similar phenomenon, triggered by a water-level fall and documented by a sudden increase in the contribution of *Filicales monolete*, was recorded in sediments at many sites (e.g., Noryśkiewicz, 2006; Wysota and Noryśkiewicz, 2011; Gamrat et al., 2014).

Zone $Ju_{I/VII}$ consisted of deposits accumulated in the Late Subatlantic, the properties of which largely reflected a strong human impact. The high intensity of the catchment denudation may be proven by a higher content of terrigenous silica, Na, K, and Mg as compared to $Ju_{I/VI}$ (Table 1; Figs. 7 and 8). For comparison, the surface organic sediment occurring in the marginal parts of the kettle hole (profile Ju_{III}), with the strongest effect of slope denudation, had a significantly higher content of

terrigenous silica, K, Mg, Pb, and Zn (Fig. 3). For this relatively thin (0.35 m) layer of sediments, a considerable reduction in pH values (to <4) towards the top uppermost layer was observed, which together with the presence of *Sphagnum* (particularly on the surface of the peat bog in its marginal part; Fig. 4) can indicate a transition towards ombrotrophy. It can be assumed that the likely cause of this phenomenon could be the exposure of the ground around the kettle hole (probably through deforestation), which intensified the water erosion in the drainage basin and resulted in an increased supply of acidic soil organic matter. No supply of groundwater and a relatively large inflow of matter from the catchment area obviously contribute to changes in the ecological conditions of the kettle hole. It should be noted, however, that a small area and location in the agricultural landscape prevent the development into a typical raised bog (Timmerman and Succow, 2001; Tobolski, 2003). Certain corresponding events were documented in the sediments of a peat bog in Tuchola Forest by Lamentowicz et al. (2007). According to the results of palynological analysis, the beginning of intensive agricultural land-use in the catchment area was recorded in sediments of Ju$_I$ and Ju$_{III}$ at a depth of ca. 0.30 and 0.50 m, respectively (Fig. 4). Pollen grains of synanthropic plants were found in the pollen spectra, i.e. cereals including *Cerealia* type and *Secale cereale* as well as *Centaurea cyanus, Plantago lanceolata, Rumex, Artemisia* and Chenopodiaceae. Sediments collected from the middle part of the depth range of L PAZ Ju$_{I-6}$ (0.25 m) were AMS radiocarbon dated at 360 ±40 BP; GDA-2400. After calibration, performed in the *OxCal 4.2* application, the averaged date was determined as 1543 yr AD. At that time, those were arable lands, first controlled by the Teutonic Order, and then governed by the administration of the Ducal and East Prussia. The comparison of profiles Ju$_I$ and Ju$_{III}$ with other data from northeastern Poland (Wacnik, 2009, 2012) showed that profile Ju$_I$ did not present a complete picture of the economic changes in this area. Most likely, a hiatus occurred in the Subatlantic record at a depth of 0.30 m. The pollen record in the roof part of the surface sample was characterized by local encroachment of birch on the present-day area of the kettle hole studied.

The analysis of macroremains in the upper part of the sediments (0.0–0.10 m) of profile Ju$_I$ showed the presence of numerous achenes of *Betula* sc. *Albae* and *Carex elata* as well as seeds of *Comarum palustre* (Fig. 5). This corresponded to a contemporarily developed tall-sedge community (*Caricion elatae*) with numerous birch trees in the vicinity. A very similar record is found in the uppermost layer from profile Ju$_I$, where *Betula* pollen represents over 90% of all sporomorphs, while herbaceous plants were represented mostly by sedges (Cyperaceae pollen). It should be noted, however, that the analysis of macroremains was conducted only in the sediments from the central part of the peat bog (Ju$_I$), where *Sphagnum* succession has not yet been observed.

It appears that slope processes occurring in the drainage basin resulted in the formation of colluvial deposits (agricultural diamicton – Sinkiewicz, 1998; Frielinghaus and Vahrson, 1998), which are up to several dozen centimetres thick and cover a sequence of biogenic sediments (fossil soils; profiles A and C, Figs. 2 and 3). This showed the existence of a larger (compared to its current size) water body, transformed mostly by anthropogenic denudation.

The extent and intensity of the catchment land use was also reflected in the pH of colluvial deposits (Fig. 3). In the case of long-term agricultural use (profile A), the acid reaction of the deposits can be attributed to the properties of initial surface soil horizons formed before the slope processes were activated within the top uppermost parts of the slopes (Smolska, 2005; Podlasiński, 2013; Karasiewicz et al., 2014a; Świtoniak, 2015). Significant accumulation of organic matter may act as the second factor responsible for acidification (Markiewicz et al., 2015). Neutral and slightly alkaline reactions (profile D) can be accounted for by the inflow of material from the zone with the most severe erosion processes, where carbonate-rich, parent rock soils are exposed (Świtoniak, 2014; Świtoniak et al., 2016). The effect of soil liming associated with afforestation of this part of the drainage basin also cannot be excluded.

CONCLUSIONS

Vertical diversification of the sedimentological and geochemical properties of the deposits in the kettle hole studied largely corresponded to environmental changes reconstructed through palaeobotanical studies. The geochemical record has been preserved in the bottom and slope sediments of the kettle hole as a result of both natural (e.g., climate changes, hydrographic conditions, vegetation cover) and anthropogenic processes (land use) occurring over the last several thousand years. This study showed that despite the small size of the kettle hole, its deposits have archived local and supralocal palaeoenvironmental changes.

Based on the results obtained it was possible to identify several postglacial stages reflecting the history of palaeoenvironmental changes in the kettle hole and the surrounding area. The first important stage consisted in the melting of a dead-ice block in permafrost conditions, followed by the stage of a small, late glacial lake, the sediments of which were deposited beneath the pollen-free layer. The presence of this layer provides evidence for the changing hydrological conditions, which resulted in a stratigraphic gap covering several thousand years (from the Preboreal to the Middle Atlantic), and consequently a temporary disappearance of the water body. In the subsequent stage, limnic conditions dominated again (mineral-organic gyttja), followed by telmatic conditions after the lake basin was filled with sediments (coarse detrital gyttja). This led to the development of a peat bog (sedge and sedge-moss peat deposits). These deposits contain a record of water-level fluctuations during the Subboreal and Subatlantic wet periods, and from the Middle Ages – a strong human impact. In this context, the reduction in the bottom surface of the kettle hole studied as a result of natural and anthropogenic denudation, as well as the strong acidification of the habitat, which resulted in *Sphagnum* succession, appear particularly important.

The authors hope that their research will contribute to a comprehensive reconstruction of the postglacial development of the Polish Lowland, and the results may be used in comparative studies.

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