Holocene vegetation history and soil development reflected in the lake sediments of the Karkonosze Mountains (Poland)

Malkiewicz, Malgorzata ; Waroszewski, Jaroslaw ; Bojko, Oskar ; Egli, Markus ; Kabala, Cezary

DOI: https://doi.org/10.1177/0959683615622546

Originally published at:
Malkiewicz, Malgorzata; Waroszewski, Jaroslaw; Bojko, Oskar; Egli, Markus; Kabala, Cezary (2016). Holocene vegetation history and soil development reflected in the lake sediments of the Karkonosze Mountains (Poland). The Holocene, 26(6):890-905.
DOI: https://doi.org/10.1177/0959683615622546

Holocene vegetation history and soil development reflected in the lake sediments of the Karkonosze Mountains (Poland)

Małgorzata Malkiewicz[1*], Jarosław Waroszewski[2], Oskar Bojko[2], Markus Egli[3], Cezary Kabala[2]

[1]Laboratory of Paleobotany, Department of Stratigraphical Geology, University of Wroclaw, Plac Maxa Borna 1, 50-205 Wroclaw, Poland

[2]Institute of Soil Science and Environmental Protection, Wroclaw University of Environmental and Life Sciences, Grunwaldzka 53, 50-357 Wroclaw, Poland

[3]Department of Geography, University of Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland

* corresponding author: Tel.: +48 71 375 95 28; fax: +48 71 375 93 71

Email address: malgorzata.malkiewicz@ing.uni.wroc.pl

Abstract

A 11 m-long lake sediment core of a mountain lake situated at 1225 m a.s.l. in the Karkonosze Mountains (Poland) provided a unique, multi-proxy archive to reconstruct natural and human-induced environmental changes over the entire Holocene period. Pollen analyses allowed for the local and regional reconstruction of vegetation history. The chemical composition of the core and the determination of amorphous Fe and Al phases enabled to trace back soil formation in the surrounding catchment. About 11 ka ago, birch-pine and pine-birch communities started to develop in the Preboreal chronozone. Subsequently, the vegetation cover changed to *Corylus* - *Picea* – *Abies+Fagus* in the higher and middle mountain zones, and to *Ulmus* – *Quercus* – *Carpinus* in the mountain foreland and footslopes. The decline of forests that started in the 11th century due to clearing was accompanied by the expansion of grasses, both as pastures in the mountains and cereal crops in the foreland. At the same time, the mining and smelting gave rise to environmental pollution with heavy metals (Pb, Cu and Zn) at a regional scale. Combined geochemical and palynological data indicated a relationships between vegetation type, sediment texture and its elemental composition. This relationship seemed to be linked to climatic conditions and surface erosion intensity. A first progressive soil-forming phase occurred between 10.9 until about 8.4 ka cal BP. Rapid and strong soil erosion (regressive phase), related to rapid climate deterioration, occurred at about 8.4 ka cal BP. Thereafter, continuous soil formation (progressive phase) and podzolisation in the Boreal and Atlantic continued until about 1 ka BP when strong human impact (deforestation) led again to a regressive soil evolution.

Keywords

vegetation history, pollen analysis, human impact, soil development, mountain lake, Holocene, Poland

Introduction

Paleoenvironmental reconstructions of the Holocene in mountain areas of Central Europe are often based on the analysis of mires (Dudova et al., 2010; Jankovska, 2001; Madeyska, 2005; Speranza et al., 2000; Treml et al., 2008). Although mountain mires are in most cases relatively shallow (Bogacz et al. 2012; Glina and Bogacz, 2013) and involve only fragmentary data sequences (Baranowska-Kącka, 2003; Dudova et al., 2012; Kuszell, 1988; Muszer, 1989; Novak et al., 2010; Popowski, 2005), some peat profiles provide a complete overview of the Holocene vegetation development (Madeyska, 2005; Marek, 1998). Mires may also reflect regional air contamination (Karczewska and Kabala, 2001).

To extend the knowledge in landscape processes to the late Pleistocene period, lacustrine sediments have been more and more taken into account (Engel et al., 2010; Jankovska, 2006; Więckowski, 2009). Although the sporomorphs may be poorly preserved and replaced or mixed to a certain extent, lake sediments may provide more extended information than peat-bogs, including evidences of climate oscillations (Haas et al., 1998), changes in vegetation (Birks, 1986; Wacnik et al., 2011), weathering dynamics and local erosion (Arnaud et al., 2012; Chmal and Traczyk, 1998; Hosek et al., 2014), advances in adjacent soil development (Brisset et al., 2013; Favili et al. 2008; Mourier et al., 2010; Wicik, 1986), changes in land-use practice (Röpke et al., 2010), and environmental contamination (Kabala and Bojko, 2014; Rzetala et al., 2013). Therefore, lake sediments are considered as excellent archives of environmental changes (Birks, 1986; Engel et al. 2010).

Compared to other mountain areas in Europe, particularly the Alps (Arnaud et al. 2012; Böhlert et al., 2011; Giguet-Covex et al., 2011; Mourier et al., 2010; Oris et al., 2013) and the southern Carpathians (Buczko et al., 2009, 2013; Magyari et al., 2009), suitable lake sediments are often lacking in the northern Carpathians and Sudeten Mountains (Engel et al., 2010; Kotarba, 1996; Wicik, 1984a, 1984b). This is due to the low number of mountain lakes in these areas (Więckowski, 2009). Holistic approaches of soil and landscape reconstruction for the entire Holocene using the history of lakes and their catchments are rather rarely undertaken (Brisset et al., 2013; Dreibrodt and Wiethold, 2015; Mendyk et al., 2015; Mourier et al., 2010).

This paper attempts to fill this gap for the environmental history of the Sudeten Mountains for the Holocene period. In several parts of the European Alps, a major human impact can be recognized around 5 to 6 ka BP and particularly since 2 ka BP (Egli and Poulenard, 2015). In addition, cold events (or climatic shifts) at around 4.2 and 8.2 ka BP are known to have occurred (Magny, 2004; Berger and Guilaine, 2009; Brisset et al., 2013). Consequently, we try to find out if imprints of these climatic events and human impact can be manifested for this part of the Sudeten. One major aim of this paper is to improve the reconstruction of environmental changes in the Sudeten over the Holocene having a special focus on (1) the sedimentary environment and geochemistry, (2) the vegetation history on a local and regional scales, and (3) early human influences.

Study area

Wielki Staw (Figure 1) is the largest of the few postglacial ponds in the Karkonosze Mountains, the highest north-western range of the Sudeten. The lake is situated at 1225 m a.s.l. in a glacial cirque sealed with a moraine embankment (Migoń et al., 2013). The lake comprises two units, a larger oval basin, and a smaller bay elongated at the W-E axis. Currently, the water body is (on average) 646 m in length and 138 m in width and its area is 8.32 hectares. The maximum water depth is 24.4 meters in the main basin and only 7.5 m in the elongated bay (Komar, 1978). The catchment is only about 165 hectares including the main plateau, the cirque walls and glacial moraines. Wielki Staw is supplied mainly by rainwater and snowmelt; four small permanent and several periodic creeks deliver water and suspended solids during spring and the rainy season. The area directly surrounding the lake has never been permanently inhabited (excluding some seasonal shepherds on the plateau); thus, there is no direct or indirect inflow of human-affected waters.

The Karkonosze Mountains have a sub-oceanic climate. Mean annual air temperature in the lake area, interpolated from the nearest meteorological stations (Mt. Śnieżka, Mt. Szrenica, and Polana stations) is about 2.5°C. Mean air temperatures of the warmest months vary between 8.5 and 12.4°C (Polana station at 1077 m asl and Mt. Śnieżka station at 1602 m asl), and of the coldest months between -4.0° and -7.0°C. Mean annual precipitation (MAP) at 1250 m a.s.l. is about 1350 mm, and mean annual snow cover duration is 170 days. Prevailing winds come from the SW-W direction (Sobik et al., 2013).

The geology of the cirque and the adjacent surfaces is dominated by homogeneous granite of the Carboniferous age (Aleksandrowski et al., 2013). The 130 m-high north-east-facing walls of the cirque are covered with a thin stony or loamy regolith having Lithic Leptosols (in the upper part), Hyperskeletic Leptosols or Lithic Cambisols (in the lower slope; Kabala et al., 2013). The thick sandy-loamy regolith of the plateau provides the parent material for Albic and Histic Podzols that show often skeletal and cryoturbated features. These soils therefore have Hyperskeletic or Relictiturbic characteristics, according to FAO-WRB classification (IUSS working group WRB, 2015)

Today, five climate-induced vertical vegetation zones are recognizable in the Karkonosze Mountains; however, forest management has strongly influenced the species composition at the lower altitudes. Natural broadleaf forests in the sub-mountain zone (<500 m a.s.l.), presumably *Galio-Carpinetum* and *Luzulo-Quercetum* communities, are preserved fragmentarily due to common agricultural land use at this altitude or forest conversion to spruce stands (Danielewicz et al., 2013). The lower mountain forest zone (500-1,000 m a.s.l.), potentially a habitat of *Luzulo-Fagetum* and *Abieti-Piceetum* communities, is covered mainly by human-introduced mono-species Norway spruce stands. The upper mountain forest zone (1000-1250 m a.s.l.) is, due to its climate, naturally dominated by a *Calamagrostio villosae-Piceetum* community with Norway spruce as the prevailing species. The sub-alpine zone (1250 – 1450 m a.s.l.) is a mosaic of phytocenoses having shrubs of mountain pine (*Pinetum mugo sudeticum*) and matgrass-meadows (*Carici-Nardetum*), with several unique communities on the bogs and in the glacial cirques (Żołnierz and Wojtuń, 2013). The alpine zone (1450 – 1603 m a.s.l.) in the Karkonosze Mts covers only small areas around the highest peaks and is represented by herbaceous communities such as "sparse meadows" with mountain rush (*Carici-Festucetum airoidis*).

Wielki Staw is situated in the sub-alpine zone, just above the timberline. Only single trees of Norway spruce are present within the mountain pine shrubs and matgrass-meadows. The cirque walls are colonised by specific plant communities (usually Pleistocene relics), including (Żołnierz and Wojtuń, 2013): *Salicetum lapponum (Salix lapponum, Salix silesiaca, Calamagrostis villosa, Polygonum bistorta), Pado-Sorbetum (Sorbus aucuparia subsp. glabrata, Padus petraea, Ribes petraeum), Adenostyletum alliariae (Adenostyles alliariae, Cicerbita alpine, Epilobium alpestre, Aconitum plicatum, Valeriana sambucifolia),* and *Empetro-Vaccinietum (Calluna vulgaris, Vaccinum myrtillus, V.vitis-idaea, Empetrum nigrum, Cetraria islandica)*.

Methods

Sediment sampling

Bathymetric testing and sediment sampling was performed from the ice surface by Więckowski and team in winter 1983 (Więckowski, 2009). Sediment thickness varies in the range from 3 to 11 m. Three sediment cores were taken using a geological probe, but only the longest one, reaching the granite regolith under the lake sediments was selected for laboratory analyses. The core was 11 m long, taken at 18.5 m below the water table. The core was divided into 20 cm-long sections (55 samples) which were dried and stored in double polyethylene bags, packed together in an additional polyethylene bag and cardboard box. The core was macroscopically classified and characterized (Więckowski, 2009). The drying procedure after sampling is unfortunately unknown; however, mean weight loss at 105^{o}C that was done in 2012 was less than 1% indicating careful and complete drying before storage. This guaranteed a good preservation of the samples (in terms of structure, color, etc.). The sediment samples were provided by Dr B. Wicik, University of Warsaw, Poland.

Laboratory analyses

Particle-size distribution, pH, and total organic carbon analyses were done in previous investigations (Kabala and Bojko, 2014). Here, some of these data (clay/silt/sand content and pH) have been used for the general characterisation of sediments and statistical calculations of the relationships between palynological, geochemical and textural data.

The total concentration of elements (Si, Al, Ti, Fe, Ca, Mg, Na, K, P, S, Cl, V, Ba, Rb, Zr, Pb, Zn, and Cu) was measured using X-ray fluorescence (ED-XRF, SPECTRO X-LAB 2000, SPECTRO Analytical Instruments). The quality of the analyses was checked using a soil reference material (sample ID SO-4, Canada Centre for Mineral and Energy Technology) with XRF-certified total element concentrations. Element recovery and detection limits are given in Table 1.

The concentration of macro-elements (as oxides) is presented in two ways: (i) based on the total sample weight, and (ii) calculated on the basis of the inorganic fraction, i.e. by omitting the organic matter content (LOI). The concentration for the latter version was calculated using the following formula: $C_{in} = C_m$ x 100/(100-LOI), where C_m is the measured concentration of the element, C_{in} is the concentration that refers to the inorganic part of the investigated material and LOI is the loss-on-ignition (%).

The sediments were carbonate-free. The approximate content of organic matter was determined as loss-on-ignition (LOI) at 550^{o}C (Bojko and Kabala, 2014). In addition to total contents, the oxalate-extractable iron (Fe_{ox}) and aluminium (Al_{ox}) cocentration, as an indication of pedogenic processes in the lake watershed (Mourier et al., 2008; Wicik, 1986), was determined using the Tamm method with the Schwertmann modification (Van Reeuwijk, 2002). The concentrations of Fe and Al in the extracts were measured using ICP-AES (Thermo Scientific iCAP 7400).

Three samples, taken at a depth of 1.2 – 1.4 m, 8.4 - 8.6 m (macrofossils) and 10.8 - 11.0 m (bulk gyttja sample), were dated at the Poznań Radiocarbon Laboratory (Poland) using Accelerator Mass Spectrometry (AMS). Calendar ages were obtained using the OxCal 4.2 calibration program (Bronk Ramsey, 2001, 2009) based on the IntCal 13 calibration curve (Reimer et al., 2013). Calibrated ages are given in the 2σ range, minimum and maximum value for each (Table 2).

The palynological analysis was performed in 33 sediment samples only, as some of the samples were too small (the volume remained after geochemical analysis that was made first) for extracting a reliable sporomorph amount. Samples of detritus gyttja were treated with 15% hydrogen peroxide (H_2O_2) and samples of mineral gyttja - with concentrated hydrofluoric acid for 24 hours. Then, the material was macerated using Erdtman's acetolysis. The pollen appeared to be very well preserved and rich in taxa. Pollen spectra were counted using two or three preparations. A total of 800 – 1000 sporomorphs were found in each sample. The percentage calculations are based on the total sum of arboreal and non-arboreal species (AP + NAP) which include trees, shrubs (AP) and herbaceous plants (NAP). Aquatic, swampy plants and spore plants were excluded from the sum and are presented separately. The pollen diagram (Figure 2) was plotted using POLPAL for Windows (Nalepka and Walanus, 2003). Eleven biostratigraphic units were distinguished with a characteristic content of sporomorphs in individual profile sections (L PAZ – local pollen assemblage zones), thus illustrating the process of changes occurring in the vegetation cover. The biostratigraphic units were assigned to the Mangerud's chronozones and were calibrated according to Walanus and Nalepka (2010). Due to the low number of ^{14}C dates, it was impossible to draw a detailed depth-age model. Thus, the chronozone boundaries, in particular these of the Atlanticum/Subboreal and the Subboreal/Subatlanticum, were assigned based on comparison of the pollen associations to isopollen maps for species succession in Poland (Berglund and Ralska-Jasiewiczowa, 1986; Obidowicz et al., 2004; Ralska-Jasiewiczowa et al., 2004; Zachowicz et al., 2004) and the reports providing numerous ^{14}C dates from the Sudeten Mountains (Baranowska-Kącka, 2003; Dudova et al., 2010, 2012; Engel et al., 2010; Hosek et al., 2014; Jankovska, 2001). The chronozone names are consequently used with the necessary caution.

Statistical analyses

Basic statistical analyses and Pearson's correlations are provided to characterize data variability and the relationships between the variables. The geochemical sections were separated in the core based on the lithological and geochemical data ordering using a multiple cluster analysis (k-means method). The differences between distinguished classes were examined using the Turkeys' post-hoc test (homogeneous groups were indicated, Table 4). Principal component analysis (PCA, after a log-transformation of the data) and canonical correspondence analysis (CCA) were used for displaying and statistical approximating the general relationships between vegetation and sediment texture and geochemistry. All statistical calculations were performed using the Statistica 10 (StatSoft Inc.) software; the pollen assemblage zones were distinguished based on cluster analysis using POLPAL software (by Walanus and Nalepka, Institute of Botany, Polish Academy of Sciences, Cracow, Poland).

Results

Dating and geochemistry

The core from Wielki Staw involves a complete series of sediments that were accumulated during the Holocene period. The calibrated age of the gyttja (bulk) sample collected at the core bottom (depth of 10.8 – 11.0 m) was estimated to be in the range of 10,862 – 11,041 cal BP (Table 2); thus giving the start of lake sedimentation in the Preboreal chronozone.

Mineral sediments prevail in the whole core and were classified as a clay-detritus gyttja (Więckowski, 2009). The sediments are in general relatively rich in organic matter (mean organic carbon content was 7.82%); however, the organic carbon content varies across a wide range from 0.23 to 20% (Kabala and Bojko, 2014). The typical feature of the core is a variable micro-stratification with thin (0.5-2 mm) layers having medium-coarse sand. Through the core, the sandy loam and sandy clay loam texture prevail with an average content of clay and silt of 16% and 23%, respectively. The clay concentration in the upper part of the core (20 – 25%) is higher compared to the middle section (7 – 11% clay; Figure 3). At a depth of 8.6 – 9.2 m, a weakly sorted, grayish sand sediment appears. The sand strata contains single gravels of up to 3 cm in diameter and a silt/clay content of 1 – 4%. In the lower section of the core (9.2 – 11.0 m), the silt and clay fractions increase to 35% and 26%, respectively. The sediments are carbonate-free and acidic throughout. The pH values vary in a relatively narrow range between 4.0 and 5.6 (Kabala and Bojko, 2014).

The chemical composition of the sediments (Table 3) was influenced by the surrounding granitic rocks which is reflected by a dominance of SiO_2 (average 64.4%; average calculated for the organic-free part it is 73.8%) and Al_2O_3 (mean 10.7 as average and 12.3% as average for the organic-free part, respectively), the relatively high levels of potassium and sodium and low amount of iron, calcium and magnesium. This geochemical background is found along the core giving rise to a relatively low variability ratio (the ratio of the standard deviation to the mean), e.g. 8% for SiO_2 and 11 – 23% for other major and minor elements, including Ba, Rb, and Zr. A higher variability (up to more than 30 - 40%) was recorded for the organic matter content (LOI), phosphorus, sulphur and trace elements (Mn, Zn, Cu, Pb, V). Based on the content of major and minor elements, LOI, pH, and particle size fractions (sand, silt, and clay) and using the PCA case-wise data diagnostics protocol, five sections were highlighted in the core. The large section (1.0-7.8 m) in the upper part of the core was additionally subdivided because of a distinct change in texture (at the depth of 4.4 – 4.6 m). Finally, seven geochemical sections could be separated (Figure 3; Table 4).

The oldest sediments (section GW1) have a sandy-silty texture and a very low content of organic matter and phosphorus (Table 4), but a relatively high content of Mg, Fe and trace elements (in particular Cu and Zn; Figure 3). Also the sediments in the section GW2 have a relatively coarse texture (low content of clay and high content of sand fraction), higher percentage of Na and K, whereas, very low content of organic matter, Fe and trace elements. Moreover, the P content is still very low. The following section GW3 exhibits clayey sediments (highest clay content along the core) that are rich in Fe, Mn, and trace elements (in particular Cu and Zn). The LOI reaches 13%, and P content gradually increases, up to 0.4%. The sedimentation of this silty-clayey gyttja was interrupted before 8370 cal BP by a rapid inflow of sandy material (at a depth of 8.6 – 9.2 m) that was very poor in organic matter and major and minor elements (except Si, Na and K, that reached here their maxima; cf. section GW4). The next section GW5 has similar characteristics as GW3 has; in fact, GW3+GW5 may be considered as one section broken with sandy sedimentation in section GW4. The following thick section GW6 has high LOI and P content, relatively high and stable Ca and Fe content, and variable concentration of other major and minor elements . The sections distinctly differ in texture (abrupt change at the depth of 4.6 m): GW6b is more clayey, with nearly twofold higher clay content than GW6b has. Several anomalies were identified in these sections, given by concentration peaks of Na, K and Ca (at 1.8 – 2.0, 6.8 – 7.0, and 7.0 – 7.2 m). At the end of the GW6 zone, the Pb concentration started to increase that was continued in the uppermost GW7 section. The significant increase was also detected for Zn and Cu. The sediments in this section have a distinctly coarser texture (compared to GW6b), a higher percentage of K, Na, and Al, and a significantly lower content of phosphorus (Figure 3). Most major compounds (K, Na, clay, etc.) directly indicate the change in GW7; and if the elemental concentrations are normalised to Ti, then also Si and Al (Table 4) enable a better distinction between GW6 and GW7.

The oxalate-extractable Fe and Al contents were at a low level (ca 0.1%) in the oldest sediments, and Fe_{ox} initially slightly prevailed over Al_{ox}. The ratios Fe_{ox}/Fe_t and Al_{ox}/Al_t were the lowest of the core, <0.10 and <0.02, respectively (Figure 4). The percentage of Fe_{ox} and Al_{ox} and their ratios to total Fe and Al started to increase as early as in the Preboreal period. The rate of increase was initially similar for both elements; however, at a depth of 9.5-9.8 m the increase in Al_{ox} accelerated. The increases were abruptly interrupted at the depth of 9.2 m and remained at much level up to the depth 8.6 m (i.e. within a sandy layer). Following the further increase, the Fe_{ox} and Al_{ox} concentrations reached a more or less steady level (0.26 and 0.6%, respectively) starting at the depth of 8.5 (Fe_{ox}) and 6.3 m (Al_{ox}). Similarly, the Fe_{ox}/Fe_t and Al_{ox}/Al_t ratios have stabilized at the level of 0.22-0.27 and 0.10-0.12 for iron and aluminium, respectively. A distinct decrease in Fe_{ox} and Al_{ox} concentrations was recorded in the uppermost 1 m-thick sediment layer, in particular of Fe_{ox} that fell to the level noted in the Preboreal period. The decrease in Fe_{ox}/Fe_t and Al_{ox}/Al_t ratios was less distinct.

Palynology

Based on the percentage of identified pollen of the arboreal (AP) and non-arboreal (NAP) species, six local pollen assemblage zones (L PAZ) were distinguished (Table 5).

The oldest sediments start with very high AP values (>92%), in particular for *Betula* and *Pinus* (PW1 *Betula –Pinus* L PAZ*)*. Birch, characterised by low edaphic requirements and a fast growth as pioneer species, reacted first to the postglacial climate warming and, as a consequence, the highest percentage (throughout the core) with up to 50%,is recorded. Also the pine showed a high abundance with about 40% (Figure 2). The low contribution of other tree species (*Salix, Ulmus*, and *Corylus*) testifies their transport from a more distant area. Based on the species composition and the ^{14}C date (Table 2), the assemblage can be allocated to the Preboreal chronozone. The *Pinus* proportion gradually increased during the Preboreal and reached its maximum (nearly 60%) in the next section (PW2 *Pinus* L PAZ), when a pine-birch forest was formed with a birch admixture of less than 30% (Figure 2). The high density of stands was the cause for the very low percentage of NAP species (ca. 5%). The increasing percentage of *Corylus* and *Ulmus* pollen (Table 5) testifies their successive invasion into the Sudeten Mountains during this period. The pollen assemblages in the section PW3, having *Corylus* and *Ulmus,* indicated a fast and strong transformation of the forest stands that happened in the early Boreal period. Initially (PW3-a *Corylus-Ulmus* L PAZ), the *Corylus* percentage rapidly increased while *Pinus* and *Betula* decreased. At the same time, the proportion of *Ulmus* and *Quercus* started to increase. *Corylus* was dominant (with a maximum of 67%) during the relatively long next phase PW3-b *Corylus-Ulmus* (Late Boreal period, indicated by the ^{14}C date at the depth 8.4 – 8.6 m; Table 2). In this period, *Ulmus* reached a maximum of about 9% and *Alnus* increased significantly (up to 14%) that was correlated with the first larger occurrence of *Picea* pollen. The *Quercus* percentage was still high during PW3-b. The low frequency of *Tilia* and *Fraxinus* indicated a pollen delivery from more distant areas rather than from the direct vicinity of the lake. Further climate warming, presumably during the Atlantic period, was indicated by the presence of *Hedera helix* and *Viscum album* pollens and led to the next significant transformation in the tree-species composition. The PW4-a assemblage with *Corylus-Picea* L PAZ was characterised by a high (but successively decreasing) percentage of *Corylus* and *Alnus*. However, most spectacular was the increase in *Picea* pollen. Climate warming at the lower altitudes led to a spread of broadleaf stands consisting of thermophilous species, such as *Tilia, Ulmus, Acer, Quercus, Carpinus* and *Fagus*, presumably together with *Corylus* in the lower tree layer. Moist and wet sites were colonised by stands dominated by *Alnus, Salix, Fraxinus,* and *Humulus* in the understory. The subsequent pollen assemblage (PW4-b Corylus-Picea L PAZ) is featured the same species; however, *Corylus* rapidly decreased (down to 26%) whereas *Picea* increased to 11% (its highest value). Also *Abies, Fagus* and *Carpinus* pollen rapidly increased. Thermophilous taxa reached their maximum values during this period. After this, a long-lasting pollen section started (PW5-a *Fagus–Abies* local pollen assemblage zone (L PAZ)), characterised by a decrease in the proportion of *Corylus* and an increase in *Fagus* and *Abies*. High-altitude stands were still dominated by *Picea*. During the following, presumably the Subatlantic period (cf. sample 1.2-1.4 m, Table 2), the tree species' composition was relatively stable (PW5-b, c *Fagus–Abies* L PAZ). However, two parallel trends can be observed: a continuous decrease in the *Corylus* percentage and a continuous increase in non-arboreal pollen, in particular *Poaceae* (Figure 2). In the uppermost and youngest section of the pollen diagram (PW6 *NAP-Pinus* L PAZ), a rapid and distinct decrease in many tree species occurred, in particular for *Fagus, Abies* and *Carpinus.* The percentage of *Quercus, Corylus* and *Alnus* was relatively stable and only the proportion of *Pinus* rose. However, most spectacular was the increase in non-arboreal species, mainly *Poaceae* (up to 40%). The forest decline and grassland spread at the higher altitudes was accompanied by the appearance of species that are typically related to human settlement and agriculture (at the lower altitudes, not in the close proximity of the lake), including *Rumex, Plantago lanceolata, Centaurea cyanus, Polygonum aviculare, Urtica, Chenopodiaceae, Cerealia* (undifferentiated), *Secale,* and *Fagopyrum*. The human influence was also detectable in the geochemistry of the sediments due to a continuous increase in the lead, zinc, and copper concentrations (section GW7).

Discussion

Vegetation history

Although the dating of the bottom gyttja sample (collected at the depth of 10.8 – 11.0 m) was performed using a bulk sediment sample that may involve some addition of the older organic matter inherited from the Pleistocene period (Engel et al., 2010; Wicik, 1986), it is very likely that the dating has reliably indicated the start of sediment formation in the Preboreal chronozone. This is confirmed by the composition of the pollen assemblage (PW1 *Betula-Pinus* L PAZ) with a predominance of *Betula* accompanied by *Pinus* and the lack or very low percentage of thermophilous species, typical for warmer periods of the Holocene (Ralska-Jasiewiczowa et al., 2004). This would be congruent with investigations of mires. Most of the deep mires in the Sudeten (Poland, Czech Republic, Germany) and Carpathian (Poland, Czech Republic, Slovakia, Ukraine, Hungary, Romania) Mountains started to develop at the beginning of Holocene, i.e. after local mountain glacier retreat and the stabilization of tundra vegetation (Chmal and Traczyk, 1998; Traczyk and Migoń, 2003).

Successive warming during the Preboreal period led to the establishment of birch-pine stands into pine-birch forests (PW2 Pinus L PAZ). *Pinus* became the dominant tree species and the higher density of forests limited the abundance of heliophilous *Betula*. The presence of *Corylus, Ulmus* and *Alnus* in the oldest sediments testifies the gradual migration of mesotrophic species. Although *Corylus* was present in the pollen diagram from its bottom, the percentage was lower than 1% and indicates a long-distance transport rather than a local occurrence. Huntley and Birks (1983) demonstrated that a minimum a 2% share is needed for a local occurrence of the species. *Ulmus* started to spread from the south-east at the beginning of the Holocene period and in the late Preboreal period it was present across all Poland (Zachowicz et al., 2004). Taking into account the high rate of *Ulmus* migration (Huntley and Birks, 1983), it is very likely that this species was present at the foothills of the Karkonosze Mountains in the early Preboreal period (Malkiewicz and Maj, 2010).

The rapid spread of *Corylus avellana* recorded in the sediment samples from a depth of 10.4 – 10.6 m (PW3-a *Corylus-Ulmus* L PAZ) indicates a further climate warming. A fast hazel expansion similar to that described by Huntley and Birks (1983) was possible due to its moderate light requirements and a lack of competition from other broadleaf species (Birks 1986). Furthermore, increasing hazel occurrence reduced the light penetration to the forest bottom and worsened the growth conditions for birch and pine seedlings. These species then were gradually eliminated, in particular at sites having fertile soils (Iversen 1960). The maximum proportion of *Corylus* in Wielki Staw was recorded at a depth of 9.8 – 10.0 m, identified as the mid-Boreal period (PW3-b *Corylus-Ulmus*). This agrees well with findings of Madeyska (2005), who confirmed maximum of *Corylus* already in Boreal period. Also on the southern side of the Sudeten ridge, a hazel maximum was recorded at 9500 BP (Dudova et al., 2010) or even at the beginning of the Atlantic period at about 8200 BP (Engel et al., 2010). The *Ulmus* abundance in the forest stands increased significantly during the Boreal period. The percentage of this species reached its maximum in the younger Boreal period and clearly indicates the presence of more fertile soils at lower altitudes. In parallel to *Coryllus* and *Ulmus*, but with some time shift, *Quercus* and *Alnus* started to spread. In contrast, *Tilia* and *Fraxinus* were represented by a low percentage that confirms their absence in close vicinity to the lake. *Picea* started to spread during the Boreal period (Latalowa and Knaap, 2006); however, its abundance was initially low (<5%). According to Markgraf (1980), Huntley and Birks (1983), and Lisitsyna et al. (2011), at least a 5% share is needed to confirm the local occurrence of this species, whereas Björkman (1996) concluded that *Picea* pollen at the 1% level already may indicate the local occurrence of single trees.

During the Atlantic the climate was in general warmer and moister ('climatic optimum') than today (Starkel et al., 2013) which caused the next significant change in the forest composition (PW4-a *Corylus-Picea* L PAZ). At higher altitudes and in close vicinity to the lake, a rapid increase of *Picea* was noted in the samples overlying the horizon where macrofossils were dated with 8370 cal BP. *Picea abies* started its Holocene succession in Poland about 11 ka cal BP from the south-west Carpathian Mountains (Obidowicz et al., 2004) and reached the mountain range in the early Atlantic period (Madeyska, 2005). However, on the southern side of the Sudeten mountains, *Picea* reached a 10% level as early as at 9 ka cal BP (Engel et al., 2010) or even 9.5 ka BP (Dudova et al., 2010). This has been explained by its fast preferential advance from the west Carpathians (Rybníček and Rybníčková, 2002). A widespread occurrence of spruce forest during the Atlantic period has been documented for the Sudeten Mts using deep peat sections (Baranowska-Kącka, 2003; Marek, 1998). The percentage of *Picea abies* in the pollen diagram of Wielki Staw is much lower compared to other sites, presumably due to the high altitude and the vicinity to the upper limit of Norway spruce occurrence. As reported by Więckowski (2010), the dating of a thick spruce trunk (diameter 15 cm) that was sampled during the coring in the Wielki Staw gave an age of 5.4 ka BP (conventional dating, no calibration available). Assuming a $\delta^{13}C$ of -25‰ (a realistic value for wood) and a typical error range of ±50 years, then the calibration of this wood would result in a calibrated age (2σ-range) of about 6000 – 6300 cal BP. Consequently, the timberline above Wielki Staw may be confirmed in the younger Atlantic period (or older Subboreal period) only.

At lower altitudes, climate warming during the Atlantic period led to the spread of broadleaf and mixed stands with termophilous species. Forests consisting of *Tilia, Ulmus, Acer* and *Corylus* in the understory developed on more fertile soils which are common at the northern mountain footslopes and in the foreland (Kabala, 2015). Less fertile and drier sites were presumably colonised by mixed *Pinus-Quercus* stands, with *Betula* and *Sorbus aucuparia* in the understory. Wet sites, seasonally flooded, had forests consisting of *Alnus, Fraxinus* and *Salix*, with *Humulus* in the understory. At the same time, *Hedera helix* and *Viscum album* appeared, thus confirming mild climatic conditions. The presence of *Hedera helix* indicates moderately high summer temperatures and relatively mild winters, with a mean temperature of the coldest month not much lower than –1.5°C (Iversen, 1944). The concurrent presence of *Viscum album* pollen indicates mean air temperatures in the summer months of up to 18ºC (Iversen, 1944).

During the next period, *Picea, Pinus* and *Alnus* were still abundant or locally dominant in the forest stands; however, the expansion of *Fagus, Abies,* and *Carpinus* had already started (PW4-b *Corylus-Picea* L PAZ). As recorded in the Wielki Staw sediments, Norway spruce dominated the forests at the higher altitudes, whereas mixed beech-fir stands covered the slopes at the lower altitudes displacing oak and other broadleaf species. The rapid spread and domination of beech-fir stands in this period is documented for large parts of the Sudeten Mts and correlates with the Subboreal chronozone (Dudova et al., 2010, 2012; Engel et al., 2010; Madeyska, 2005; Muszer, 1989; Marek, 1998). The beech-fir forests in the Izerskie Mts (the western part of the Sudeten) were less widespread than in the central and eastern Sudeten Mts (Baranowska-Kącka, 2003). Locally and under favourable conditions at the lower altitudes, as recorded in the Polanica profile of the Bystrzyckie Mts, *Tilia* has preserved its position (Kuszell, 1988). In the foreland forests, *Carpinus* became an important species during the Subboreal period. Ralska-Jasiewiczowa et al. (1998) concluded that *Carpinus* started its spread before 6 ka BP, but its migration was relatively slow. Thus, this species became an important component of the stands in Poland not earlier than in the Subboreal chronozone. The low contribution of *Carpinus* to the pollen diagram of Wielki Staw indicates that this species was absent in the near vicinity (due to the lake's location at high altitude) and the pollen was transported from the foothills or close foreland, as suggested by Dudova et al. (2010, 2012) for bogs on Mt Hruby Jesenik.

Significant changes in the contribution of *Sphagnum, Filicales* and *Isoetes* in assemblages PW4-b, PW5-a, and PW5-b may indicate a moist climate phase followed by a much drier one. In particular, the maxima of *Filicales* and *Isoetes* in the sample at 4.6 – 4.8 m accompanied by the rapid decrease in *Corylus* may correlate with the '4.2 ka climate shift' — reflected by a sudden aridification at lower latitudes and cooler and wetter conditions in the northern hemisphere (Magny, 2004). Unfortunately, the lack of dating for this section makes a clear correlation impossible. However, directly after this event, the succession of *Abies, Fagus*, and *Carpinus* accelerated. The expansion of *Fagus* and *Abies* started in the south Karkonosze Mts at about 4200 cal BP (Engel et al., 2010) and in the eastern Sudeten mountains at about 3950 cal BP (Dudova et al., 2012).

The forest tree species that started to prevail during the PW-4 phase maintained their dominance during the next period (PW5 *Fagus –Abies* L PAZ) that is assigned to the Subatlantic chronozone (Engel et al., 2010; Speranza et al., 2000b). The upper mountain forest zone mostly had spruce forests, the lower mountain zone beech-fir stands and the foreland and footslopes/foreland broadleafed or mixed forests with *Carpinus, Quercus* and *Pinus* (Figure 2). In contrast to the previous periods, the contribution of tree pollen was lower during the Subatlantic period and rapidly decreased in the last phase (PW6 *NAP-Pinus* L PAZ). During the PW5 this was connected to the *Corylus* replacement with *Poaceae*, whereas during PW6 it was related to the clearing of broadleafed forests on fertile soils in the Sudeten foreland (with a subsequent decrease in *Carpinus* and *Ulmus* pollen) and the extinction of beech-fir stands in the lower mountain zone (causing a decrease in *Abies* and *Fagus* pollen). The significant increase in non-arboreal pollen (mainly grasses; initially up to 10% and then up to 40%) confirms this large-scale deforestation. Simultaneously, there is a significantly increased contribution of species directly connected to human impact (*Artemisia, Urtica, Chenopodiaceae*), including agriculture (*Rumex, Plantago lanceolata, Centaurea cyanus, Polygonum aviculare, Fagopyrum, Cerealia,* and *Secale*). This indicates a strong human impact in the mountain foreland, but not in the vicinity of the mountain lake. A distinct decrease in tree species and a concurrent increase in grass pollens started at 915 – 1004 cal BP (= 946 – 1035 cal AD), as indicated by macrofossil dating (obtained from a depth of 1.2 – 1.4 m, Table 2). The given age probably indicates an influence from the southern Bohemian foreland of the Sudeten that was colonized earlier than the northern Silesian foreland (Curta, 2006). The dates of 946-1035 cal AD are somewhat earlier than findings of Speranza et al. (2000a) who reported a rapid decrease in beech and fir pollen in the Karkonosze Mts at around 1130 cal AD. Dudova et al. (2010) suggested a much later decrease of beech and fir forests of the east Sudeten. According to them, this has happened in the 13th century and was also confirmed by dating of human-induced fires (Novak et al., 2015). This discrepancy can at the moment not fully be explained.

The uppermost section of the pollen diagram reflects local vegetation changes in the immediate vicinity of Wielki Staw. The extraordinary increase in the *Poaceae* contribution — that was detected on a similar scale only by Jankovska (2001) and Speranza et al. (2000a) – reflects the clearing of spruce stands (at the timberline) and mountain pine (*Pinus mugo)* shrubs (on the plains above the timberline) for the creation of mountain pastures (Novak et al., 2010). The increase in other heliophilous and nitrophilous species (*Artemisia, Urtica, Chenopodiaceae, Cyperaceae*) points to a spread of open spaces and shepherding (Figure 2). Although the first human-induced fires in the sub-alpine zone of the Sudeten Mts started in the early Medieval epoch and increased in the 12th and 13th century (Novak et al., 2010), it is likely that strong human pressure on the highest altitude zone of the Karkonosze Mts started during the Thirty Year's War in the 16th century, when the large overpopulation and migration of the sub-mountain villages led to the construction of numerous mountain colonies and single seasonal buildings surrounded by pastures (Staffa, 2005). At the beginning of the 19th century, the number of shepherd houses in the Karkonosze Mts was about 2000, inhabited by 14,000 people, which placed the Karkonosze to the most densely populated mountain regions (Staffa, 2005). Large mountain meadows (pasturing ended in the 1970s) are preserved in most places; however, the former pastures are subject of reforestation (with spruce or mountain pine) at many sites, both at the timberline and in the subalpine zone (Żołnierz and Wojtuń, 2013). This is evident in the pollen diagram of Wielki Staw (Figure 2) and the bogs of the Czech side of the Karkonosze Mts (Jankovska, 2001). The relatively short-term existence of widespread pastures/meadows in the subalpine zone is also reflected in the preservation of podzolization features in soil profiles (Kabala et al., 2013; Waroszewski et al., 2013). Also, the rapid spruce stands decay in the western Sudeten Mountains in the 1970s/80s, known as the 'ecological disaster in the Black Triangle' (Danielewicz et al., 2013), may be responsible for the extraordinary contribution of NAP pollen and the detectable amounts of *Sorbus*.

Sediment geochemistry

Little diversified granite rocks in the lake watershed (Aleksandrowski et al., 2013) provide a relatively uniform sedimentary material. However, a varying intensity of weathering, soil formation and surface erosion, that are due to climate and vegetation changes, are responsible for the differences in sediment texture and elemental composition.

The date 8315 – 8422 cal BP directly above the thick sand layer (Table 2) correlate with the rapid climate shift that is documented in many lakes and mires throughout Europe (Berger and Guilaine, 2009). The term '8.2 ka cold event', used for this phenomenon, called after the sudden drainage of glacial lakes Agassiz and Ojibway into the Hudson Bay, merges various climatic phenomena that occurred in the Northern hemisphere between 8.5 and 8.0 ka BP (Alley et al., 1977). Well-sorted sand-textured sediments correlated with a series of cold and wet events were also identified in lake sediments of northern Poland (Ralska-Jasiewiczowa et al., 1998) and sediments of high-energy floods that occurred in the Wisła (Vistula) basin between 8.4 – 7.8 ka BP (Starkel et al., 1996). In the Sudeten, thick sand layers were found in mires of the Izera valley (Baranowska-Kącka 2003) at the Boreal to early Atlantic transition. As stated above, numerous sand layers were described in the generally fine-textured gyttja sediments of the Wielki Staw, indicating many short wet events associated with intense soil erosion (Wieckowski, 2009). The well-sorted sand strata are in most cases very thin, below 0.5 cm, rarely up to 1 cm thick, and in one case even 60 cm-thick. We cannot exclude other geomorphic phenomena that may have contributed to the formation of these mineral sediments such as floods (Baranowska-Kącka, 2003) or landslides (Chmal and Traczyk, 1998). Nonetheless, the thickness and sorting (purity) of the sand-textured sediments in the Wielki Staw confirm a moister climate and rapid acceleration of erosion in the lake's watershed, terminated at 8315 – 8422 cal BP.

In general, the element concentrations do not reflect a 'one-direction' trend over the core (Figure 3) with the exception of SiO_2 and Fe_2O_3 (a decreasing trend from the bottom to the top) as well as Al_2O_3 and Na_2O (an increasing trend). These weak trends are confirmed to some extent by differences between mean values in distinguished sections (Table 4). The concentration of some elements (Al, K, Fe, and Mg) in the oldest sediments was unexpectedly high suggesting intense rock weathering. Wicik (1986) believed that such high concentrations might be the result of delayed erosion and sedimentation and thus reflect a specific 'asynchronicity' in weathering, pedogenesis, erosion and sedimentation processes. The phenomenon is in particular visible in the case of copper (Figure 3), where the concentration in older sediments was 4 times higher than in younger ones. The element lability in the sediments was not tested in this study, but the abrupt changes between the single layers at various depths and the prominent accumulation of metals in the uppermost section demonstrate the lithogenic origin of elements and their low solubility or strong binding to organic matter (Karczewska and Kabala 2001). Trace metal lability in lake sediments was reported only under specific conditions, in particular under seasonal drying (change in redox conditions) or in the case of intense faunal mixing in the benthic zone (Boyle, 2001). We have no data to consider significance of these mechanisms in the Wielki Staw.

Some general relationships can be derived from a correlation analysis (Table 6). Although the content of organic matter significantly decreased in the more sandy sediments, it does not correlate with the clay fraction. SiO_2 and Al_2O_3 do not significantly correlate with any grain-size fraction. This may indicate an initial stage of weathering and weak separation of quartz from other alumino-silicates in the sand and silt fractions (Waroszewski et al., 2013; 2015b). In contrast, the sand fraction correlates positively with K_2O and Na_2O, and negatively with CaO and Fe_2O_3. K_2O and Na_2O derive from feldspar and Na-plagioclase (while Ca-plagioclase and biotite seem to be depleted in the sand fraction). The sand fraction negatively correlated to most microelements, phosphorus and sulphur. In contrast, the clay fraction correlates positively with Fe, Ti, and P. Moreover, trace elements (excluding Mn) in sediments do not correlate with organic matter, but correlate with iron content. This is in contrast to soils of the Karkonosze Mountains, where correlation between trace elements and organic carbon is often reported (Karczewska et al., 2006; Szopka et al., 2011; 2013; Waroszewski et al., 2009). This may be explained by primary enrichment of micaceous minerals with trace elements and iron (that are released together during weathering), or by sorption of trace elements on iron oxides (Table 6; Kabala and Szerszen, 2002). The Ti-normalized element concentrations, that are often used to estimate elemental enrichment or depletion (Mourier et al., 2008, 2010), lead to the same conclusions (Table 4). The Ti-normalized concentrations have spectacularly highlighted the distinctness of the GW4 section (in particular in a case of Si and Al); however, this was due to unevenly low Ti concentration rather than increase of Si and Al content in these sediments (Table 4).

Vegetation and sediment features

The seven sections (Table 4) distinguished in the core are based on their particle-size distribution, organic matter content, and the concentration of major and microelements. These sections coincided to some extent with the local pollen assemblages (Figure 3). Thus, an attempt was made to combine the quantitative data on pollen contribution and sediment properties using statistical methods. The analyses were done for the local vegetation (existing in the vicinity of the Wielki Staw) with a presumably direct relation to sediments (Figure 5, Table 7).

The first three components derived by PCA explain 70.7% of the variability of geochemical and pollen data. The two most indicative components of the variability are the sediment texture (component 1) and the mineral/organic character of the sediments (component 2) which count for 28.9% and 26.2% of the variability, respectively (Figure 5A). The canonical correspondence analysis showed that the sand fraction is the most influential single variable for the geochemical data and explains of about 40% of the variation. For combined, geochemical and pollen data, CCA has indicated two significant canonical roots (factors) that may be closely linked to the first two components of PCA (Table 7). The first canonical root (related to component 2), associated with organic matter content (as LOI), indicates strong influence on the Ca and P content, as well as relation to *Alnus*, *Picea*, *Filicales*, and *Quercus*. The second canonical root (related to component 1), strongly associated with sand content, indicates influence on the Na and K content, as well as *Poaceae*. Fine-textured sediments (rich in clay fraction) are enriched in Fe, Ti, Ca and P, but are not specifically enriched in any arboreal or arboreal pollen. The CCA supports the general findings from PCA: coarse lake sediments that are enriched in

Na and K (group PCA-A) are not directly connected to any single type of vegetation. Sediments having coarse but almost organic matter-free material (PCA-B) correlate with the *Pinus-Betula* stands, while coarse materials, moderately rich in organic matter (PCA-C) are better related to the grassland vegetation, which is also confirmed in the group PCA-I (Figure 5B). The fine-textured (clayey) gyttja contains more Fe and Mn (PCA-D), and is related to a high forest density in general and a higher *Corylus* proportion in particular. Most organic sediments are enriched in P, S and Ca (PCA-E). Their sedimentation is not simply connected with one type of vegetation; however, they closely correlate to *Picea/Alnus* stands that are accompanied by *Filicales* and *Sphagnum* (PCA-F).

The nature of the third component of the PCA analysis, responsible for 15.6% of variability (Figure 5B), is less clear. Probably, it is related to climate; humidity rather than temperature. The variability encompasses *Pinus-Betula-Cyperaceae* (PCA-G) and *Picea-Filicales-Alnus* (PCA-H) groups of species, indicating drier and moister climate phases, respectively. The sediment texture and the content of organic matter are very weak related to this factor. This may indicate that the short-range factors, e.g. rapid climate shifts, may be responsible for the specific character of sediments.

Sedimentation of coarser material that is rich in Na and K seemed to prevail under *Betula-Pinus* stands in the early Holocene and under grasslands that developed after forest clearing in the late Holocene. The fine sediments are enriched in iron and manganese and indicate a complete afforestation of the watershed. Denudation under spruce forests was rather fine-textured (silt dominated) and had organic colloids that were enriched in phosphorous, sulphur, and calcium (Figure 5A). The prevailing texture and composition of sediments is poorly and indirectly related to the climate (Figure 5B). The sandy layers present in the core result from a short-term climate deterioration and rapid erosion events that are poorly reflected by a dominant vegetation pattern.

Soil development and sediment geochemistry

Progressive (soil profile deepening) and regressive (soil shallowing) phases can be distinguished (Johnson and Watson-Stegner, 1987). A first progressive phase seems to have occurred between 10.9 until shortly before 8.4 ka cal BP. About 8.4 ka cal BP, strong soil erosion processes are recognizable. After this event, soil formation seems to be continuous until about 1 ka cal BP when a strong human impact led to a regressive soil evolution. The relationships between sediment elemental composition, particle-size distribution and vegetation (to some extent related to climate conditions) illustrate the intensity of surface soil erosion rather than pedogenesis (Böhlert et al., 2011; Chmal and Traczyk, 1998; Engel et al., 2010; Hosek et al., 2014; Jäger et al., 2015; Magyari et al., 2010). However, the waving content of the oxalate-extractable iron and aluminium, as well as their ratios to total Fe and Al indicate the changes in intensity of weathering and pedogenetic processes (Kabala, 2006; Lundström, 2000; Mourier et al., 2008; Waroszewski et al., 2015a). Initial low content of Al_{ox} and Fe_{ox} as well as the low Fe_{ox}/Fe_t and Al_{ox}/Al_t ratios are close to these reported in weakly weathered (physically rather than chemically) granite regoliths (Kabala, 2005).

The synchronous increase in Fe_{ox} and Al_{ox} concentrations and the low values of Al_{ox}/Fe_{ox} ratio (much below 1, common in *cambic* horizons [Galka et al., 2013]), indicates an early stage of Cambisols development under the still cold and rather dry climate during the early Holocene (Figure 4). The fast increase in Al_{ox} and broadening of the Al_{ox}/Al_t ratio started at the depth of 9.5-9.8 m, at the same time when alder and spruce appeared in the pollen spectrum. Both, a more humid climate and coniferous forests (and shrubs) are factors that highly promote podzolization (Lundström et al., 2000). A rapid broadening of the Al_{ox}/Fe_{ox} and Al_{ox}/Al_t ratios in the sediments indicates the production of active aluminium and its mobility in soils (Fitze, 1982). Both indices confirm the rapid advance of podzolization in the Wielki Staw watershed during the late Boreal and Atlantic periods. This is in agreement with findings of Podzols and Podzol-like strongly bleached soils (Kabala et al., 2010), which were fossilized under the thin peats during the Atlantic period (Baranowska-Kącka, 2003; Novak et al., 2010; Speranza et al., 2000a). All the indices (including the Al_{ox}/Fe_{ox}, Fe_{ox}/Fe_t, Al_{ox}/Al_t) stabilised since late Atlantic for a long time indicating stable Podzols prevalence in the watershed.

A rapid decrease of the Fe_{ox} and Al_{ox} concentrations and their contribution in total Fe and Al in the uppermost sediments is correlated with a decrease in spruce pollen and an increase in grasses. The human-induced decline of spruce forests and mountain pine shrubs impeded podzolization, while the grass cover stabilized the topsoil and soil surface and reduced the leaching of mobile forms of elements. Therefore, the Podzols in the subalpine zone of the Karkonosze Mts must be considered as relic soils (conserved rather than still developing) under the present-day grass vegetation (Kabala et al., 2013).

Human impact on sediment properties

The earliest human presence in the Sudetes Mts (probably Neolithic [Novak et al., 2015]) is documented in pollen diagram only (*Cerealia* and synanthropic species above the depth of 400 cm), without any geochemical imprint (Figure 3). Whereas, the medieval and more recent human influences are manifested by both a change in vegetation and heavy metals input into the lake Wielki Staw (Figure 3). A rapid increase in the Pb and Zn concentrations is detectable shortly after the start of the beech-fir stand clearing phase. This process is obviously related to the earliest documented mining and smelting activities, i.e. not later than the 13^{th} century (Staffa, 2005). Although iron ore was the most important raw material for the smelting industry in this region, the Fe concentration in the sediments did not increase (Figure 3). Similar “paradox” is known from other iron-smelting areas (Schulin et al., 2007) and may be related to high native Fe content in parent rocks and soils that masks the anthropogenic input. Whereas, Zn and Cu at least doubled and Pb tripled their concentration in the sediments. The hydrothermal and metamorphic ores exploited since the medieval period often had a multi-mineral composition resulting in multi-metal industrial emissions (Staffa, 2005). Moreover, glass smelting was greatly developed on both sides of the Karkonosze Mts (Staffa, 2005), which may also be responsible for the historic contamination with Pb and Zn. The increase in Zn and Cu in the uppermost sediment layers may additionally be explained by a long-distance aerosol transport from the large copper mining and smelting industries in southwestern Poland that started to develop after World War II (Medynska et al., 2009; Medynska-Juraszek and Kabala, 2012). Despite an evident contamination, the upper sediments of Wielki Staw contain a lower concentration of heavy metals than the soils and peats in the western Sudeten (Glina and Bogacz, 2012; Kabala and Szerszen, 2002; Karczewska et al., 2006; Szopka et al., 2013; Waroszewski et al., 2009).

Conclusions

The 11 m-thick sediments from Lake Wielki Staw provides a complete record of environmental changes during the entire Holocene period. Both the local and regional history of vegetation can be traced, starting with birch-pine and pine-birch communities in the Preboreal and changing subsequently to a *Corylus* - *Picea* – *Abies+Fagus* community at the higher to middle mountain zones, and *Ulmus* – *Quercus* – *Carpinus* community in the mountain foreland. The decline of forests, accompanied by the expansion of grasses, was initiated during the 11th century (the depth 1.2-1.4 m). This is in line with the hypothesis of Bal et al. (2015) about the anthropogenic origin of the grassland in the subalpine zone of many European mountain ranges, including the Sudeten (Novak et al., 2010; 2015). A strong human impact followed by sediment contamination with Pb and Cu (and to a lesser extent Zn) started in the area under study at the same time, indicating a close relationship between mountains’ colonization, mining-smelting development and environmental pollution on a regional scale.

The texture, organic matter content and the total concentration of the major elements in the sediments changed periodically in line with local vegetation variations. Sediments having coarser (more sandy) texture were rich in Na, K, and Ba, and were related to a vegetation dominated by *Pinus* and *Betula* (as at the depth of 10.6-10.8 m), or NAP-*Poaceae-Artemisia* (in the uppermost 0.8 m). Medium textured (silty) materials were enriched in organic matter, Ca, P, and S, and were related to species such as *Spruce, Alnus, Filicales, Sphagnum*, and indicated moister periods. The fine-textured sediments were enriched in Fe and Mn and could be related to periods with the highest afforestation in general, and with *Corylus* in particular. These relationships indicate phases with varying intensities of surface soil erosion and the delivery of primary minerals from granite weathering.

In addition, distinct progressive and regressive soil development phases could be detected. The rise in oxalate-extractable Al and Fe indicate progressive pedogenetic processes during the Boreal when Cambisols started to develop. A rapid climate deterioration at around 8315 – 8422 cal BP was recorded as a thick, pure sand layer that is poor in organic matter. The deposition of this material may be used as a time-marker for similar inclusions in other lake sediments and mires. Soil development showed a clear regressive phase during this event. Thereafter, a more humid climate, relatively stable conditions and spruce forest in the Atlantic chronozone rapidly accelerated weathering and the formation of Podzols. This was recorded with a strong increase of the oxalate-extractable Al and Fe, and their ratio to total content of Al and Fe. The stable measures of Al and Fe since the Atlantic until the late Subatlantic period confirmed the dominance of Podzols and the active podzolization process that typically occurs under dense spruce stands and mountain pine shrubs. The rapid decrease in the amorphous Fe and Al content since the 11^{th} century is again related to regressive soil processes that were due to deforestation and grass succession which was recorded in the pollen diagram.

In contrast to several sites of the European Alps, a human impact during the Neolithic and Early Bronze Age is weakly manifested by discontinuous presence of *Plantago laceolata*, *Urtica* and *Cerealia* pollen at the depths between 2.5 and 4 m. Also, during Roman times, this part of the Sudeten Mountains seemed to remain weakly affected. Clear and significant anthropogenic disturbances could be registered since the 11^{th} century. They are manifested both in rapidly increasing trace metal concentrations, an enhanced proportion of cereal and weed sporomorphs and a rapid disappearance of beech and fir forests.

Acknowledgement

The research was financed in part (physicochemical analysis and ^{14}C dating) by the National Science Centre (Poland), grant number N N309 281737, and in part (palynological analyses) by the Ministry of Science and Higher Education (Poland), Wroclaw University grant number 1017/S/ING/14. Financial support for geochemical analysis was provided by the Scientific Exchange Programme/Swiss Contribution (Sciex-NMS.ch), grant code 12.264. The authors are indebted to MSc Dorota Iwanuś for her help in sample preparation for the palynological analyses. Finally, the authors would like to thank Dr Bogumil Wicik (University of Warsaw, Poland) who provided the complete sediment core.

References

Aleksandrowski P, Slaby E, Szuszkiewicz A, Galbarczyk-Gasiorowska L, Madej S and Szeleg E (2013) Geological structure. In: Knapik R and Raj A (eds) *Nature of Karkonosze Mts National Park*. Jelenia Góra: Karkonoski Park Narodowy, pp. 7-46. (in Polish)

Alley RB, Mayewski PA, Sowers T, Stuiver M, Taylor KC, Clark PU (1997) Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25(6): 483-486.

Arnaud F, Révillon S, Debret M, Revel M, Chapron E, Jacob J and Magny M (2012) Lake Bourget regional erosion patterns reconstruction reveals Holocene NW European Alps soil evolution and paleohydrology. *Quaternary Science Reviews* 51: 81-92.

Bal MC, Allée P and Liard M (2015) The origins of a *Nardus stricta* grassland through soil charcoal analyses: Reconstructing the history of a mountain cultural landscape (Mont Lozère, France) since the Neolithic. *Quaternary International 366:* 3-14.

Baranowska-Kącka A (2003) *Holocene history of the vegetation in the Izerskie Mountains*. PhD thesis, University of Wrocław, Poland (in Polish).

Berger JF and Guilaine J (2009) The 8200 cal BP abrupt environmental change and the Neolithic transition: A Mediterranean perspective. *Quaternary international* 200: 31-49.

Berglund BE and Ralska-Jasiewiczowa M (1986) Pollen analysis and pollen diagrams. In: Berglund BE (ed.) *Handbook of Holocene palaeoecology and palaeohydrology*. Chichester, Toronto: Wiley, pp. 455-484.

Birks HJB (1986) Late-Quaternary biotic changes in terrestial and lacustrine environments, with particular reference to north-west Europe. In: Berglund BE (ed.) *Handbook of Holocene palaeoecology and palaeohydrology*. Chichester, Toronto: Wiley, pp. 3-65.

Björkman L (1996) *The Late Holocene history of beech Fagus sylvatica and Norway spruce Picea abies at stand-scale in southern Sweden*. Lundqua Thesis 39, Lund University, Sveden.

Bogacz A, Dzieciol D, Glina B and Gersztyn L (2012) Peat soil in the restoration Niknąca Łąka peatland in the Stołowe Mountains National Park. *Soil Science Annual* 63(2): 3-8.

Böhlert R, Mirabella A, Plötze M and Egli M (2011) Landscape evolution in Val Mulix, eastern Swiss Alps – Soil chemical and mineralogical analyses as age proxies. *Catena* 87: 313-325.

Bojko O, Kabala C (2015) Loss-on-ignition as an estimate of total organic carbon in the mountain soils. *Polish Journal of Soil Science* 47 (2): 71-79.

Boyle JF (2001) Inorganic geochemical methods in palaeolimnology. In: Last WM and Smol JP (eds) *Tracking environmental change using lake sediments*. Springer, Netherlands, pp. 83-141.

Brisset E, Miramont C, Guiter F, Anthony E, Tachikawa K, Poulenard J, Arnaud F, Delhon F, Meunier JD, Bard

E and Sumera F (2013) Non-reversible geosystem destabilisation at 4200 cal BP: sedimentological, geochemical and botanical markers of soil erosion recorded in a Mediterranean Alpine Lake. *The Holocene* 23: 1863-1874.

Bronk Ramsey C (2001) Development of the radiocarbon calibration program. *Radiocarbon* 43: 355-363.

Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51: 337-360.

Buczkó K, Magyari EK, Bitušík P and Wacnik A (2009) Review of dated Late Quaternary palaeolimnological records in the Carpathian Region, east-central Europe. *Developments in Hydrobiology* 208: 3-28.

Buczkó K, Magyari EK, Braun M and Bálint M (2013) Diatom-inferred lateglacial and Holocene climatic variability in the South Carpathian Mountains (Romania). *Quaternary International* 293: 123-135.

Chmal H and Traczyk A (1998) Postglacial development of the Karkonosze Mountains and Izerskie Mountains relief in the basis of the analysis of fluvial, lacustrine and slope sediments. In: Sarosiek J and Štursa J (eds) *Geoecological problems of the Karkonosze Mountains*. Poznan: Acarus, pp. 81-87. (in Polish)

Curta F (2006) *Southeastern Europe in the Middle Ages, 500-1250*. Cambridge University Press.

Danielewicz W, Raj A and Zientarski J (2013) Forest ecosystems. In: Knapik R and Raj A (eds) *Nature of Karkonosze Mts National Park*. Jelenia Góra: Karkonoski Park Narodowy, pp. 279-302. (in Polish)

Dreibrodt S and Wiethold J (2015) Lake Belau and its catchment (northern Germany): A key archive of environmental history in northern central Europe since the onset of agriculture. *The Holocene* 25: 296-322.

Dudová L, Hájek M and Hájková P (2010) The origin and vegetation development of the Rejvíz pine bog and the history of the surrounding landscape during the Holocene. *Preslia* 82: 223-246.

Dudova L, Hajkova P, Buchtova H and Opravilova V (2012) Formation, succession and landscape history of Central-European summit raised bogs: A multiproxy study from the Hruby Jesenik Mountains. *Holocene* 23(2): 230-242.

Egli M and Poulenard J (2015) Soils of Mountainous Landscapes. In: Richardson D (ed.) *The International Encyclopedia of Geography*. Wiley-Blackwell, accepted.

Engel Z, Nývlt D, Křížek M, Treml V, Jankovská V and Lisá L (2010) Sedimentary evidence of landscape and climate history since the end of MIS 3 in the Krkonoše Mountains, Czech Republic. *Quaternary Science Reviews* 29(7): 913-927.

Favilli F, Egli M, Cherubini P, Sartori G, Haeberli W and Delbos E (2008) Comparison of different methods of obtaining a resilient organic matter fraction in Alpine soils. *Geoderma* 145(3): 355-369.

Fitze P (1982) Zur Relativdatierung von Moränen aus Sicht der Bodenentwicklung in den kristallinen Zentralalpen. *Catena* 9: 265-306.

Galka B, Podlaska M, Kabala C (2013) Forest habitats on Dystric Cambisols developed from granite in the Stolowe Mountains. *Sylwan* 157, 5: 385-394.

Giguet-Covex C, Arnaud F, Poulenard J, Disnar JR, Delhon C, Francus P and Delannoy JJ (2011) Changes in erosion patterns during the Holocene in a currently treeless subalpine catchment inferred from lake sediment geochemistry (Lake Anterne, 2063 m asl, NW French Alps): the role of climate and human activities. *The Holocene* 21(4): 651-665.

Glina B and Bogacz A (2013) Concentration and pools of trace elements in organic soils in the Izera Mountains. *Journal of Elementology* 18(2): 199-209.

Haas JN, Richoz I and Tinner W (1998) Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. *The Holocene* 8: 301–309.

Hosek J, Pokorny P, Kubovcik V, Horacek I, Zackova P, Kadlec J, Rojik F, Lisa L and Backuliakova S (2014) Late glacial climatic and environmental changes in eastern-central Europe: Correlation of multiple biotic and abiotic proxies from the Lake Svarcenberk, Czech Republic. *Palaeogeography, palaeoclimatology, palaeoecology* 396: 155-172.

Huntley H and Birks HJB (1983) *An atlas of past and present pollen maps for Europe: 0-13000 years ago*. Cambridge University Press.

IUSS Working Group WRB (2015) *World Reference Base for Soil Resources 2014, update 2015*. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports 106. Rome: FAO.

Iversen J (1944) *Viscum, Hedera* and *Ilex* as climate indicators. A contribution to the study of Post-Glacial temperature climate. *Geologiska Foreningens Stockholm Forhandlingar* 666 (3): 464-483.

Iversen J (1960) *Problems of the early post-glacial forest development in Denmark*. Kobenhavn: Geological Survey of Denmark IV (3).

Jankovská V (2001) Vegetation development in the western part of the Giant Mts. during the Holocene. *Opera Corcontica* 38: 11-19.

Jankovská V (2006) Late Glacial and Holocene history of Plešné Lake and its surrounding landscape based on pollen and palaeoalgological analyses. *Biologia* 61(20): S371-S385.

Jäger H, Achermann M, Waroszewski J, Kabala C, Malkiewicz M, Gärtner H, Dahms D, Krebs R and Egli M (2015). Pre-alpine mire sediments as a mirror of erosion, soil formation and landscape evolution during the last 45 ka. *Catena* 128: 63-79.

Johnson DL and Watson-Stegner D (1987) Evolution model of pedogenesis. *Soil Science* 143: 349–366.

Kabała C (2006) Diagnostic spodic horizons in Podzols of the Sudety Mountains. *Polish Journal of Soil Science* 39(2): 175-183.

Kabala C (ed.) (2015) *Soils of Lower Silesia: origins, diversity and protection*. PTG, PTSH. Wroclaw, Poland. dx.doi.org/10.13140/RG.2.1.2070.9603

Kabala C, Bogacz A, Labaz B, Szopka K and Waroszewski J (2013) Diversity, dynamics and threats for soils. In: Knapik R and Raj A (eds) *Nature of Karkonosze Mts National Park*. Jelenia Góra: Karkonoski Park Narodowy, pp. 91–126.

Kabala C and Bojko O (2014) Trends in trace elements concentrations in Holocene bottom sediments of a Lake Wielki Staw in the Karkonosze Mountains. *Polish Journal of Environmental Studies* 23, 2: 357-362.

Kabala C and Szerszen L (2002) Profile distributions of lead, zinc, and copper in Dystric Cambisols developed from granite and gneiss of the Sudetes Mountains, Poland. *Water Air and Soil Pollution* 138(1-4): 307-317.

Kabala C, Waroszewski J, Szopka K and Bogacz A (2010) Origin, properties and occurrence of Stagnopodzols in the Sudeten Mountains. *Roczniki Gleboznawcze - Soil Science Annual* 61(4): 1-15.

Karczewska A and Kabała C (2001). Natural and anthropogenic bioaccumulation of heavy metals in selected high moor peats of Lower Silesia (Poland). In: *9th international conference of IHSS: Understanding and managing organic matter in soils, sediments and waters (*eds Swift RS and Spark KM). Australia, University of Adelaide, pp. 533-540.

Karczewska A, Szopka K, Kabala C and Bogacz A (2006). Zinc and lead in forest soils of Karkonosze National Park – data for assessment of environmental pollution and soil monitoring. *Polish Journal of Environmental Studies* 15(2a): 336-342.

Komar T (1978) Morphometry of Mały Staw and Wielki Staw in the Karkonosze Mountains. *Acta Universitatis Wratislaviensis* 340: 15-26.

Kotarba A (1996) Lacustrine sediments as indicators of environmental changes in the High Tatra. *Dokumentacja Geograficzna* 4: 33-48.

Kuszell T (1988) The site of Young Holocene peat from Polanica-Zdrój, Central Sudetes. *Geologia Sudetica* 23 (2): 191-206.

Latalowa M, Van der Knaap W O (2006) Late Quaternary expansion of Norway spruce Picea abies (L.) Karst. in Europe according to pollen data. *Quaternary Science Reviews* 25: 2780-2805.

Lisitsyna O V, Giesecke T, Hicks S (2011) Exploring pollen percentage threshold values as an indication for the regional presence of major European trees. *Review of Palaeobotany and Palynology* 166: 311-324.

Lundström US, van Breemen N and Bain D (2000) The podzolization process. A review. *Geoderma* 94(2): 91-107.

Madeyska E (2005) The history of the Zieleniec mire and the surrounding areas based on the palynological research. *Monographiae Botanicae* 94: 145-157.

Magny M (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International* 113(1): 65-79.

Magyari E, Buczkó K, Jakab G, Braun M, Pál Z, Karátson D and Pap I (2009) Palaeolimnology of the last crater lake in the Eastern Carpathian Mountains: a multiproxy study of Holocene hydrological changes. *Hydrobiologia* 631(1): 29-63.

Malkiewicz M and Maj J (2010) The local Holocene history near Tomislaw (Lower Silesian Forests, Poland) in the light of pollen analysis. *Acta Palaeobotanica* 50(1): 55-63.

Marek S (1998) Development of Wielkie Torfowisko Batorowskie mire deciphered by biostratigraphic study. *Szczeliniec* 2, 49-88.

Markgraf V (1980) Pollen dispersal in a mountain area. *Grana* 19: 127-146.

Medynska A, Kabala C, Chodak T, Jezierski P (2009). Concentration of copper, zinc, lead and cadmium in plants cultivated in the surroundings of Zelazny Most copper ore tailings impoundment. *Journal of Elementology* 14: 729-736.

Medynska-Juraszek A and Kabala C (2012) Heavy metal pollution of forest soils affected by the copper industry. *Journal of Elementology* 17: 441-451.

Mendyk L, Świtoniak M, Bednarek R, Falkowski A (2015) Genesis and classification of the soils developed from the sediments of the former Oleszek mill pond basin (the Chełmińskie Lakeland, N Poland). *Soil Science Annual* 66(1): 29-35. dx.doi.org/10.1515/ssa-2015-0016

Migoń P, Kasprzak M and Traczyk A (2013) How high-resolution DEM based on airborne LiDAR helped to reinterpret landforms: examples from the Sudetes, SW Poland. *Landform Analysis* 22: 89-101.

Mourier B, Poulenard J, Carcaillet C and Williamson D (2010) Soil evolution and subalpine ecosystem changes in the French Alps inferred from geochemical analysis of lacustrine sediments. *Journal of Paleolimnology* 44(2): 571-587.

Mourier B, Poulenard J, Chauvel C, Faivre P, and Carcaillet C (2008) Distinguishing subalpine soil types using extractible Al and Fe fractions and REE geochemistry. *Geoderma* 145(1): 107-120.

Muszer J (1989) Age of the Olszyny mire (Sudety Srodkowe Mountains) as reflected in the palynological investigation. *Acta Universitatis Wratislaviensis* 15: 91-104.

Nalepka D and Walanus A (2003) Data processing in pollen analysis. *Acta Palaeobotanica* 43 (1): 125-134.

Novák J, Petr L and Treml V (2010) Late-Holocene human-induced changes to the extent of alpine areas in the East Sudetes, Central Europe. *The Holocene* 20(6): 895-905.

Novák J, Svoboda J, Šída P, Prostředník J, Pokorný P (2015) A charcoal record of Holocene woodland succession from sandstone rock shelters of North Bohemia (Czech Republic). *Quaternary International* 366: 25-36.

Obidowicz A, Ralska-Jasiewiczowa M and Kupryanowicz M (2004) *Picea abies* (L.) H. Karst. – Spruce. In: Ralska-Jasiewiczowa M, Latałowa M, Wasylikowa K, Madeyska E, Wright HE and Turner C (Eds) *Late Glacial and Holocene history of vegetation based on isopollen maps*. Kraków: Szafer Institute of Botany, pp. 147-157.

Oris F, Lamentowicz M, Genries A, Mourier B, Blarquez O, Ali AA and Carcaillet C (2013) Holocene changes in climate and land use drove shifts in the diversity of testate amoebae in a subalpine pond. *Journal of Paleolimnology* 49(4): 633-646.

Popowski B (2005) Results of a palynological analysis of peat sediments from Izerskie Bagno (Izerskie Mts.). *Acta Botanica Silesiaca* 2: 95-106.

Ralska-Jasiewiczowa M, van Geel B and Demske D (1998) Holocene regional vegetation history recorded in the Lake Gosciąż sediments. In: Ralska-Jasiewiczowa M, Goslar T, Madeyska T, Starkel L (eds) *Lake Gościąż (central Poland), a monographic study*. Kraków: Szafer Institute of Botany, pp. 202-219.

Ralska-Jasiewiczowa M, Wacnik A, Mamakowa K and Nalepka D (2004) *Betula* L. – Birch. In: Ralska-Jasiewiczowa M, Latałowa M, Wasylikowa K, Madeyska E, Wright HE and Turner C (Eds) *Late Glacial and Holocene history of vegetation based on isopollen maps*. Kraków: Szafer Institute of Botany, pp. 57-68.

Reimer PJ, Bard E, Bayliss A et al. (2013) IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP. *Radiocarbon* 55(4): 1869-1887.

Röpke A, Stobbe A, Oeggl K, Kalis AJ and Tinner W (2011) Late-Holocene land-use history and environmental changes at the high altitudes of St Antönien (Switzerland, Northern Alps): combined evidence from pollen, soil and tree-ring analyses. *The Holocene* 21(3): 485-498.

Rybníček K and Rybníčková E (2002). Vegetation of the Upper Orava region (NW Slovakia) in the last 11,000 years. *Acta Paleobotanica* 42: 153–170.

Rzetala M, Jagus A, Rahmonov O, Rahmonov M and Khak V (2013) Variations in the chemical composition of bottom deposits in anthropogenic lakes. *Polish Journal of Environmental Studies* 22(6): 1799-1805.

Schulin R., Curchod F., Mondeshka M., Daskalova A., Keller A. 2007. Heavy metal contamination along a soil transect in the vicinity of the iron smelter of Kremikovtzi (Bulgaria). *Geoderma* 140: 52-61.

Sobik M, Błaś M, Migała K, Godek M and Nasiółkowski T (2013) Climate. In: Knapik R and Raj A (Eds) *Nature of Karkonosze Mts National Park*. Jelenia Góra: Karkonoski Park Narodowy, pp. 147-187. (in Polish)

Speranza A, Hanke J, van Geel B and Fanta J (2000a) Late-Holocene human impact and peat development in the Černá Hora bog, Krkonoše Mountains, Czech Republic. *The Holocene* 10(5): 575-585.

Speranza A, van der Plicht J, van Geel B (2000b) Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by 14C wiggle-matching. *Quaternary Science Reviews* 19(16): 1589-1604.

Staffa M (2005) History of the settlement in the Karkonosze Mountains. In: Mierzejewski PM (ed.) *Karkonosze. Przyroda nieożywiona i człowiek*. Wrocław: Wydawnictwo Uniwersytetu Wrocławskiego, pp. 23-50. (in Polish)

Starkel L, Michczyńska DJ, Krąpiec M, Margielewski W, Nalepka D and Pazdur A (2013) Progress in the Holocene chrono-climatostratigraphy of Polish territory. *Geochronometria* 40: 1-21.

Starkel L, Pazdur A, Pazdur M F, Wicik B and Wieckowski K (1996) Lake-level and groundwater-level changes in the Lake Gosciąż area, Poland: palaeoclimatic implications. *The Holocene* 6(2): 213-224.

Szopka K, Karczewska A, Jezierski P and Kabala C (2013) Spatial distribution of lead in the surface layers of mountain forest soils, an example from the Karkonosze National Park, Poland. *Geoderma 1*92: 259-268.

Szopka K, Karczewska A and Kabala C (2011) Mercury accumulation in the surface layers of mountain soils: A case study from the Karkonosze Mountains, Poland. *Chemosphere* 83, 11: 1507–1512.

Treml V, Jankovská V and Petr L (2008) Holocene dynamics of the alpine timberline in the High Sudetes. *Biologia* 63(1): 73-80.

Traczyk A and Migoń P (2003) Cold-climate landform patterns in the Sudetes. Effects of lithology, relief and glacial history. *Acta Universitatis Carolinae, Geographica* 35: 185-210.

Wacnik A, Ralska-Jasiewiczowa M and Madeyska EW (2011) Late Glacial and Holocene history of vegetation in Gostynin area, central Poland. *Acta Palaeobotanica* 51(2): 249-278.

Walanus A, Nalepka D (2010) Calibration of Mangerud's boundaries. *Radiocarbon* 52(4): 1639.

Waroszewski J, Kabala C, Jezierski P (2015a) Relief-induced soil differentiation at the sandstone-mudstone contact in the Stołowe Mountains, SW Poland. *Zeitschrift für Geomorphologie* 59, *Supplementary Issue* 1: 209 – 224.

Waroszewski J., Kabala C and Szopka K (2009) Trace elements in soils of upper zone of spruce forest on Szrenica Mount and the Kowarski Grzbiet Range in the Karkonosze Mountains. *Journal of Elementology* 14(4): 805-814.

Waroszewski J, Kalinski K, Malkiewicz M, Mazurek R, Kozlowski G and Kabala C (2013) Pleistocene–Holocene cover-beds on granite regolith as parent material for Podzols—An example from the Sudeten Mountains. *Catena* 104: 161-173.

Waroszewski J, Malkiewicz M, Mazurek R, Labaz B, Jezierski P and Kabala C (2015b) Lithological discontinuities in Podzols developed from sandstone cover beds in the Stolowe Mountains (Poland). *Catena* 126: 11-19.

Wicik B (1984a) Tatra lakes sediments and their accumulation stages. *Prace Studia Geograficzne* 5: 55-69. (in Polish)

Wicik B (1984b) Bottom sediments of Mały Staw lake. *Przeglad Geologiczny* 10: 549-551. (in Polish)

Wicik B (1986) Asynchrony of weathering and sedimentation processes in the lakes of the Tatra Mountains and the Karkonosze Mountains in the postglacial. *Przeglad Geograficzny* 58(4): 809-823. (in Polish)

Więckowski K (2009) Origin, age and evolution of lakes in various Polish regions in the basis of their bottom sediments studies. *Studia Limnologica et Telmatologica, Supplement* 1: 29 - 72 (in Polish)

Van Reeuwijk LP (2002) *Procedures for soil analysis*. ISRIC, Wageningen, Netherlands.

Zachowicz J, Ralska-Jasiewiczowa M, Miotk-Szpiganowicz G and Nalepka D (2004) *Ulmus* L. – Elm. In: Ralska-Jasiewiczowa M, Latałowa M, Wasylikowa K, Madeyska E, Wright HE and Turner C (Eds) *Late Glacial and Holocene history of vegetation based on isopollen maps*. Kraków: Szafer Institute of Botany, pp. 225-235.

Żołnierz L and Wojtuń B (2013) Subalpine and alpine vegetation. In: Knapik R and Raj A (Eds) *Nature of Karkonosze Mts National Park*. Jelenia Góra: Karkonoski Park Narodowy, pp. 241–279. (in Polish)

Table 1. Detection limits and accuracy of the geochemical analyses (Reference Soil Sample CCRMP SO-4)

Element	Detection limit	Recommended value ± 95% confidence interval	Mean measured value	Element	Detection limit	Recommended value ± 95% confidence interval	Mean measured value
	%				mg kg^{-1}		
Si	0.010	31.95 ± 0.24	30.5	Mn	0.7	600 ± 20	610
Al	0.004	5.46 ± 0.15	5.16	Sr	1.0	170 ± 18	154
Fe	<0.001	2.37 ± 0.07	2.34	Zn	0.3	94 ± 3	89
K	0.001	1.73 ± 0.03	1.70	V	1.5	90 ± 11	83
Ca	0.001	1.11 ± 0.05	1.13	Cr	0.5	61 ± 6	65
Na	0.01	1.00 ± 0.02	0.95	Ni	1.3	26 ± 3	23
Mg	0.003	0.56 ± 0.04	0.64	Cu	0.6	22 ± 1	19
Ti	<0.001	0.34 ± 0.02	0.34	Pb	0.3	16 ± 3	14
P	0.001	0.090 ± 0.007	0.093	Co	0.3	11 ± 1	10

Table 2. Radiocarbon dates from the lake Wielki Staw in the Karkonosze Mountains

Depth (cm)	Code	Type of material	Radiocarbon age (^{14}C yr BP)	Calibrated age (^{14}C cal BP, 95.4%)
120-140	Poz-53653	Plant tissue	1130 ± 35	915 - 1004
840-860	Poz-53654	Plant tissue	7620 ± 50	8315 - 8422
1080-1100	Poz-53655	Bulk gyttja sample	9630 ± 50	10,862 - 11,041

Table 3. Statistical measures of element concentrations in the sediments (n=55).

Element	Minimum	Maximum	Mean	Standard deviation	Variability index	Mean inorganic*
LOI [%]	0.57	29.98	15.36	5.61	36	0
SiO_2 [%]	48.8	74.6	64.4	5.11	8	73.8
Al_2O_3 [%]	8.5	13.7	10.7	1.16	11	12.3
Fe_2O_3 [%]	0.47	2.05	1.47	0.27	18	1.70
K_2O [%]	2.14	5.15	2.96	0.68	23	3.38
Na_2O [%]	1.50	2.99	1.97	0.35	18	2.26
MgO [%]	0.44	1.09	0.75	0.11	15	0.86
CaO [%]	0.30	0.93	0.55	0.09	16	0.64
TiO_2 [%]	0.095	0.437	0.328	0.066	20	0.38
MnO [%]	0.015	0.068	0.048	0.015	31	0.052
P_2O_5 [%]	0.001	0.491	0.341	0.124	36	0.40
SO_3 [%]	0.029	0.960	0.506	0.164	33	0.59
Cl [%]	0.002	0.024	0.011	0.005	43	0.013
V [mg kg^{-1}]	<0.4	31.6	15.1	5.9	39	n.c.
Ba [mg kg^{-1}]	76	127	105	9	9	n.c.
Rb [mg kg^{-1}]	187	310	230	28	12	n.c.
Zr [mg kg^{-1}]	43	178	136	27	20	n.c.
Zn [mg kg^{-1}]	11.7	55.0	29.0	8.6	30	n.c.
Cu [mg kg^{-1}]	3.4	19.1	8.7	4.0	46	n.c.
Pb [mg kg^{-1}]	4.9	75.0	37.2	13.1	35	n.c.

* Mean element content on an inorganic base calculated using the following formula: $C_{in} = C_m \times 100/(100\text{-LOI})$, where C_m is a measured concentration of the element, C_{in} is the concentration related to inorganic base, LOI – loss-on-ignition (%); n.c. – not calculated.

Table 4. Core sections distinguished based on element concentrations, particle size distribution and loss-on-ignition. The mean concentrations normalised to Ti are given in brackets. Homogeneous groups of GW sections, for each element separately, are calculated using Tukey post-hoc test and are highlighted with figures in superscripts.

Section	Depth	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	CaO	TiO_2	P_2O_5	LOI	sand	silt	clay	Zn	Cu	Pb
	m	%													mg kg^{-1}		
GW7	0.0-1.0	64^{ab} (189)	13.2^{c} (39)	1.37^{b} (4.0)	3.59^{b} (11)	2.58^{c} (7.7)	0.81^{c} (2.4)	0.56^{b} (1.6)	0.35^{b}	0.26^{c} (0.7)	14.1^{d}	71^{c}	19^{b}	10^{ab}	33.3^{bc} (0.017)	8.3^{c} (0.002)	56.9^{d} (0.009)
GW6b	1.0-4.6	62^{a} (178)	10.9^{b} (31)	1.46^{c} (4.2)	2.73^{a} (7.8)	1.98^{b} (5.7)	0.72^{b} (2.1)	0.56^{b} (1.6)	0.35^{b}	0.40^{d} (1.2)	17.6^{e}	57^{ab}	22^{b}	21^{b}	29.4^{b} (0.010)	6.1^{b} (0.002)	23.7^{b} (0.007)
GW6a	4.6-7.4	62^{a} (196)	10.7^{b} (33)	1.49^{c} (4.7)	2.68^{a} (8.5)	1.96^{b} (6.2)	0.72^{b} (2.3)	0.60^{c} (1.9)	0.38^{bc}	0.38^{d} (1.2)	19.7^{e}	60^{ab}	29^{c}	10^{ab}	28.5^{b} (0.013)	7.3^{b} (0.002)	40.4^{c} (0.009)
GW5	7.4-8.6	66^{bc} (201)	9.8^{a} (30)	1.56^{c} (4.8)	2.68^{a} (8.2)	1.69^{a} (5.2)	0.76^{b} (2.3)	0.56^{bc} (1.7)	0.41^{c}	0.35^{d} (1.3)	15.8^{de}	52^{a}	27^{c}	20^{b}	37.3^{d} (0.013)	11.6^{cd} (0.004)	41.2^{c} (0.011)
GW4	8.6-9.2	74^{c} (729)	10.1^{ab} (99)	0.54^{a} (5.3)	5.08^{c} (50)	2.54^{c} (25)	0.50^{a} (5)	0.31^{a} (3)	0.10^{a}	$<0.01^{a}$ (0.04)	0.73^{a}	94^{d}	2^{a}	4^{a}	12.3^{a} (0.006)	3.5^{a} (0.004)	6.4^{a} (0.012)
GW3	9.2-10.6	68^{bc} (192)	9.8^{a} (28)	1.71^{d} (4.8)	2.83^{a} (8.0)	1.62^{a} (4.6)	0.82^{c} (2.3)	0.54^{b} (1.6)	0.35^{b}	0.35^{d} (1.5)	12.3^{d}	52^{a}	24^{b}	24^{c}	40.4^{d} (0.011)	15.3^{d} (0.004)	37.9^{bc} (0.011)
GW2	10.6-10.8	70^{bc} (217)	11.3^{bc} (35)	1.48^{c} (4.6)	3.88^{b} (12)	2.16^{bc} (6.8)	0.95^{d} (3.0)	0.48^{ab} (1.5)	0.32^{b}	0.06^{b} (0.9)	3.6^{b}	75^{c}	18^{b}	7^{ab}	21.7^{b} (0.007)	9.3^{c} (0.003)	22.9^{b} (0.007)
GW1	10.8-11.0	71^{bc} (170)	11.4^{bc} (27)	2.05^{d} (4.9)	3.50^{b} (8.4)	1.74^{a} (4.2)	1.09^{e} (2.6)	0.48^{ab} (1.2)	0.42^{c}	0.06^{b} (0.8)	6.0^{c}	58^{ab}	35^{c}	7^{ab}	37.3^{d} (0.009)	18.1^{e} (0.004)	36.9^{bc} (0.009)

Table 5. Local pollen assemblage zones (L PAZ)

L PAZ	Depth [cm]	Zone description
WS-1 **_Betula-Pinus_**	1100-1080	*Betula* (ca. 50%) and *Pinus* (ca. 39%) dominate; presence of *Salix, Alnus, Ulmus* and *Coryuls avellana*; low proportion of NAP (ca. 7.5%). The upper boundary: decrease of *Betula*; increase of *Corylus avellana* and *Ulmus*.
WS-2 **_Pinus_**	1080-1050	Increases of *Pinus* (ca. 59%) and *Corylus avellana* (ca. 3%); decrease of *Betula* (ca. 27%); very low frequency of *Salix, Alnus, Quercus* and *Picea abies*; rather low proportion of NAP (ca. 5%). The upper boundary: decrease of *Pinus* and *Betula*; increase of *Corylus avellana* and *Ulmus*.
WS-3 **_Corylus-Ulmus_**	1050-830	Domination of *Corylus avellana* and *Ulmus*, rise in *Quercus, Tilia* and *Alnus*. The upper boundary: decrease of *Corylus avellana*; increase of *Picea abies*.
WS-3a **_Corylus-Ulmus_** **(_Ulmus_)**	1050-1010	Gradual rise in *Ulmus* (up to ca. 5%); high values of *Corylus avellana* (up to ca. 47%); first pollen grains of *Tilia, Alnus* and *Fraxinus excelsior*; rather low proportion of NAP (ca. 4%).
WS-3b **_Corylus-Ulmus_** **(_Corylus_)**	1010-830	Absolute maximum for *Corylus avellana* (to 67%) and *Ulmus* (ca. 9%) ; increases of *Quercus* (ca. 5%), *Alnus* (ca. 14%) and *Picea abies* (ca. 2%); low frequency of *Tilia, Fraxinus excelsior*; first pollen grains of *Carpinus betulus, Fagus sylvatica, Sorbus aucuparia, Hedera helix* and *Humulus lupulus*; NAP still low (ca. 5%).
WS-4 **_Corylus-Picea_**	830-460	The highest values of *Picea abies* and high contribution of *Corylus avellana;* fall in *Carpinus betulus* and *Fagus sylvatica*; increase in *Alnus, Quercus, Tilia* and *Fraxinus excelsior*. The upper boundary: decrease of *Corylus avellana*; increase of *Carpinus betulus* and *Fagus sylvatica*.
WS-4a **_Corylus-Picea_** **(_Quercus_)**	830-590	Rise in *Quercus* (ca. 9%); fall in *Alnus* (ca. 15%) and *Picea abies* (ca. 8%); high contribution of *Corylus avellana* (ca. 37%); *Ulmus, Tilia* and *Fraxinus excelsior* still high; presence of *Carpinus betulus, Fagus sylvatica, Sorbus aucuparia, Hedera helix* and *Humulus lupulus*; first pollen grains of *Acer* and *Viscum*.
WS-4b	590-460	Highest value of *Picea abies* (to 11%); *Alnus* and *Quercus* still high (to 16%

***Corylus-Picea* (*Picea*)**		and 9%); fall in *Corylus avellana* (to 26%) and *Ulmus* (ca. 4%); increase of *Carpinus betulus* (up to 7%) and *Fagus sylvatica* (up to 6%); decrease of *Tilia* (ca. 2%) and *Fraxinus excelsior* (ca. 2%); first pollen grains of *Abies alba*; presence of *Acer*, *Sorbus aucuparia* and *Taxus baccata.*
WS-5 *Fagus-Abies*	460-100	The highest values of *Fagus sylvatica, Carpinus betulus* and *Abies alba*; *Picea abies* and *Alnus* still high; decrease of *Corylus avellana, Quercus, Tilia* and *Fraxinus excelsior*. The upper boundary: decrease of *Carpinus betulus, Fagus sylvatica, Abies abies* and *Picea abies*.
WS-5a *Fagus-Abies* (*Carpinus*)	460-420	Rise in *Carpinus betulus* (ca.7.5%); increase of *Fagus sylvatica* (to 11%) and *Abies alba* (to 7%); decrease of *Corylus* (ca. 14%), *Quercus* (ca. 5%), *Picea* (ca. 7%) and *Ulmus* (ca. 3%); *Tilia* and *Fraxinus* still low.
WS-5b *Fagus-Abies* (*Fagus*)	420-200	The highest contribution of *Fagus sylvatica* (to 14%); fall in *Alnus* (to 17%) and *Abies alba* (to 8%); decrease of *Picea abies* (up to 5%) *Carpinus betulus* (up to 3%); *Corylus avellana, Quercus, Ulmus, Tilia* and *Fraxinus excelsior* still low.
WS-5c *Fagus-Abies* (*Abies*)	200-100	Domination of *Abies alba* (ca. 8%) and rise in *Carpinus betulus* (ca.8%) and *Picea abies* (ca.8%)*; Fagus sylvatica* still high (up to13%); decrease of *Alnus* (ca. 11%); *Corylus avellana* and *Quercus* still low.
WS-6 *NAP-Pinus*	100-20	Decrease of *Carpinus betulus* (ca. 2%), *Fagus sylvatica* (ca. 4%), *Abies alba* (ca. 3%) and *Picea abies* (ca. 6%); increase of *Pinus* (ca. 20%), *Betula* (ca. 11%), *Alnus* (ca. 18%) and *Corylus avellana* (ca. 11%); *Tilia* increases slightly; very low frequency of *Quercus* and *Ulmus*; NAP pollen rises up to 39%.

Table 6. Pearson correlation coefficient between elemental composition of the lake sediments and particle-size fractions and organic matter content (as loss-on-ignition, LOI). Statistically significant correlations at $p<0.05$ are indicated (*).

Element (total content)	LOI	clay	silt	sand	Ca (total)	Fe (total)
Si	-0.73*	-0.14	-0.31	0.32	-0.63*	-0.21
Al	-0.04	-0,25	-0,09	0,23	0,08	-0,05
Fe	0,35	0,47*	0,64*	-0,79*	0,50*	-
K	-0,77*	-0,44*	-0,64*	0,77*	-0,63*	-0,67*
Na	-0,24	-0,46*	-0,46*	0,64*	-0,21	-0,60*
Mg	-0,08	0,20	0,31	-0,37	0,27	0,74*
Ca	0,78*	0,24	0,53*	-0,55*	-	0,50*
Ti	0,37	0,43*	0,53*	-0,68*	0,41*	0,85*
Mn	0,45*	0,28	0,71*	-0,71*	0,63*	0,82*
P	0,79*	0,45*	0,48*	-0,65*	0,62*	0,45*
S	0,84*	0,32	0,63*	-0,67*	0,82*	0,57*
Zn	0,37	0,01	0,43*	-0,31	0,39	0,44*
Cu	-0,25	0,31	0,30	-0,43*	0,00	0,67*
Pb	0,02	0,33	0,48*	-0,58*	0,17	0,71*
LOI	-	0,21	0,59*	-0,57*	0,78*	0,35

Table 7. Summary of the canonical correspondence analysis for basic lithological parameters of the sediments versus geochemical and pollen data.

Variable	Canonical weights	
	Canonical root 1	Canonical root 2
Independent variables		
LOI (organic matter)	-0.89	0.44
sand fraction	0.23	-0.97
clay fraction	0.21	0.82
Dependent variables		
Si	0.61	-0.11
Al	-0.15	-0.47
K	0.46	-0.67
Na	-0.07	-0.74
Fe	0.12	0.78
Mg	0.47	0.31
Ca	-0.53	0.55
Ti	-0.08	0.57
P	-0.62	0.55
Pinus	0.50	0.03
Betula	0.62	-0.12
Corylus	0.28	0.33
Alnus	-0.80	-0.22
Quercus	-0.76	-0.07
Picea	-0.86	-0.17
Poaceae	-0.18	-0.43
Artemisia	-0.12	-0.26
Filicales	-0.77	0.01
AP	0.18	0.45

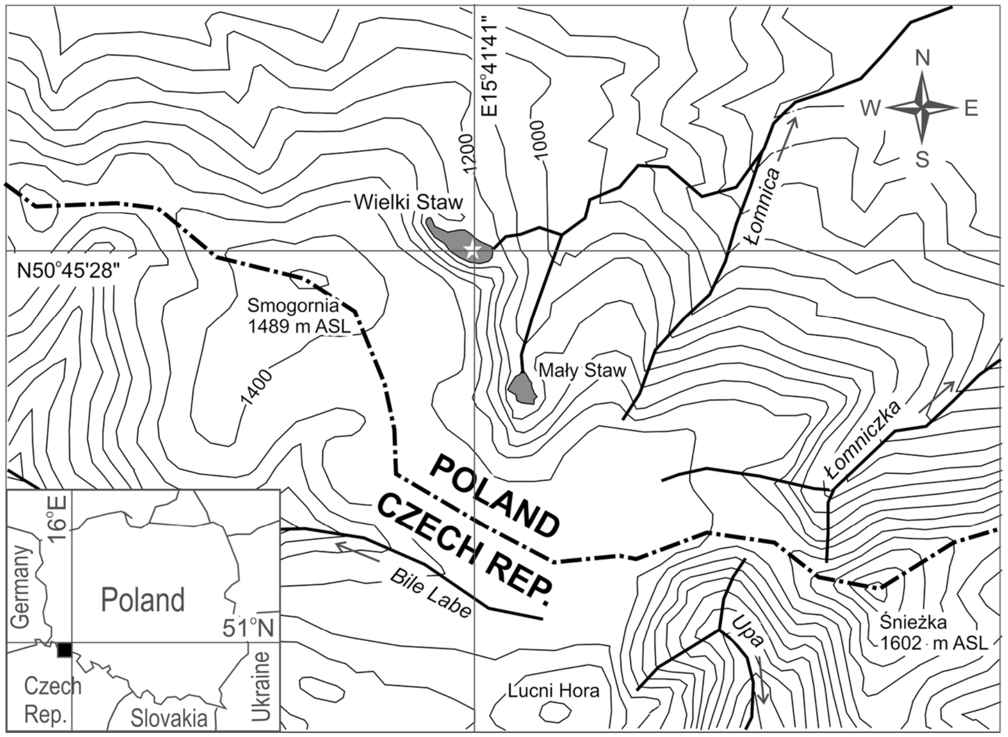

Figure 1. Localisation of the lake Wielki Staw and the sampling site (a white star).
121x88mm (300 x 300 DPI)

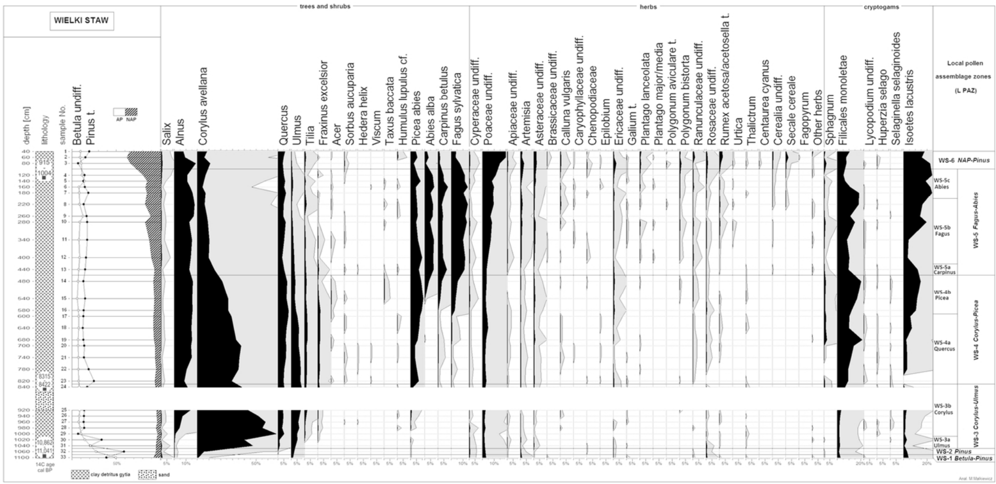

Figure 2. Pollen diagram. Percentage of cryptogam sporomorphs was counted separately (not included in the sum of arboreal and non-arboreal species). SA – Subatlantic, SB – Subboreal, AT –Atlantic, BO – Boreal, PB – Preboreal chronozone. All other abbreviations are explained in the text.
136x66mm (300 x 300 DPI)

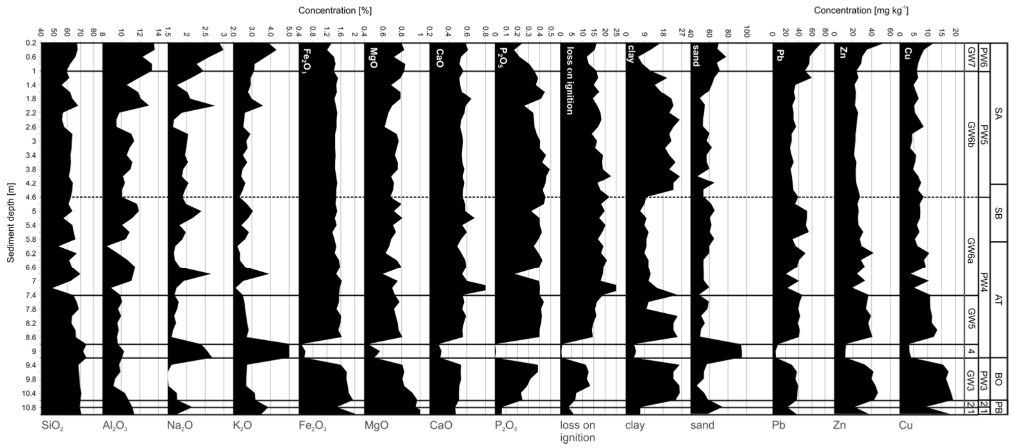

Figure 3. Element concentration, particle-size distribution (clay and sand fractions) and organic matter content (as loss-on-ignition) through the sediment core.
First columns from the right: chronozones (based on pollen recognition; explanation in Figure 2). Second column: local pollen assemblage zones (explanation in text and table 5). Third column: geochemical/lithological core sections (explanation in text and table 4). Clay and sand content drawn based on Kabala and Bojko (2014).

167x73mm (300 x 300 DPI)

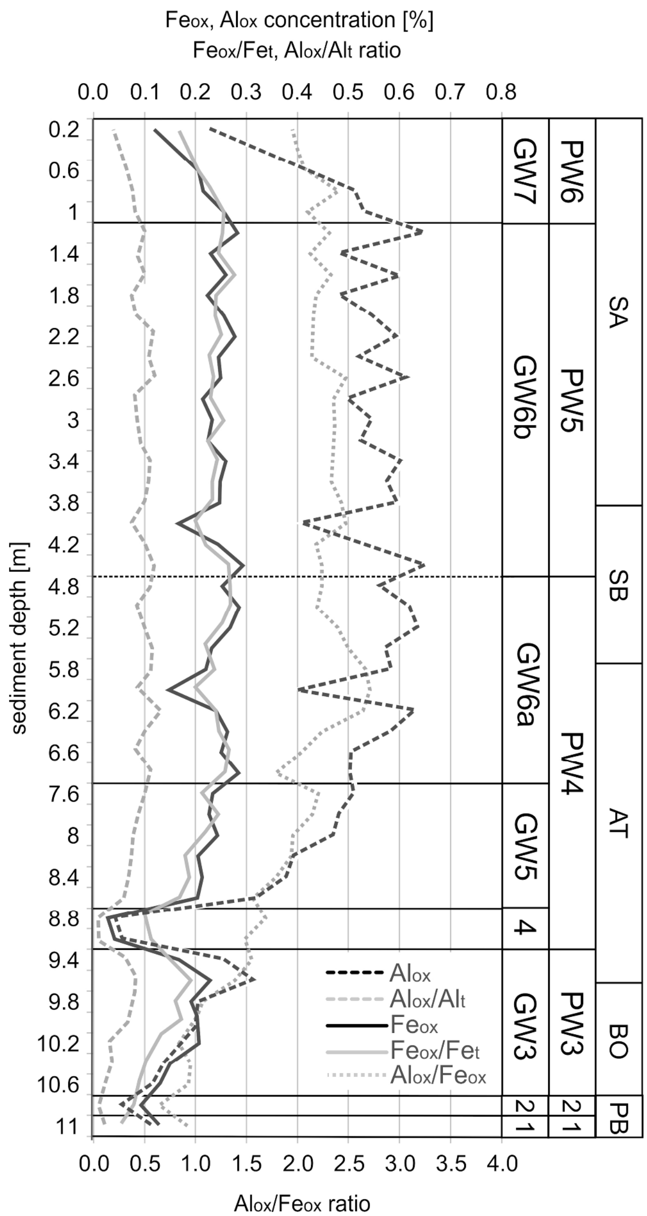

Figure 4. Total and oxalate-extractable Fe and Al through the sediment core.
Explanation: Feox, Alox – oxalate-extractable iron and aluminium; Fet, Alt – total iron and aluminium. All other abbreviations are explained in Figure 3.

168x317mm (300 x 300 DPI)

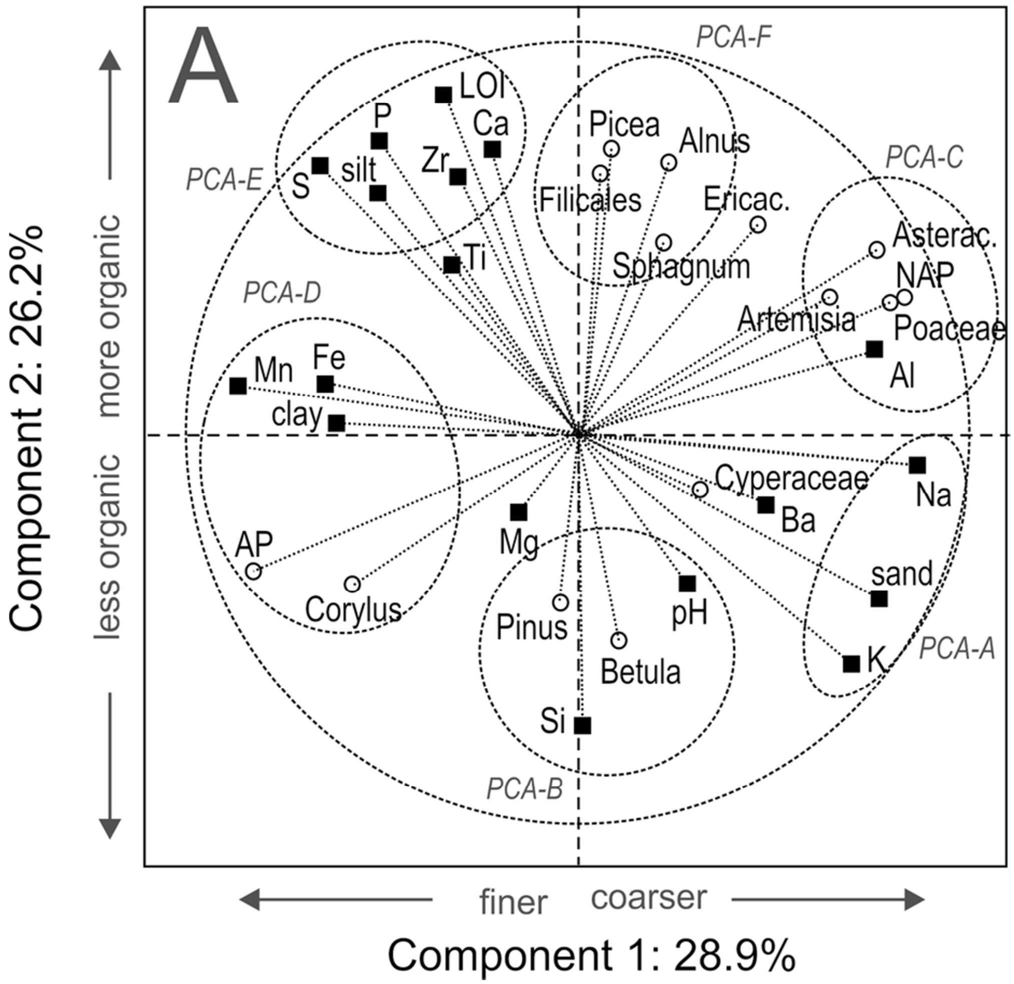

Figure 5. Principal component analysis for the geochemical data and the local vegetation: (A) components 1 and 2, (B) components 1 and 3.
78x76mm (300 x 300 DPI)

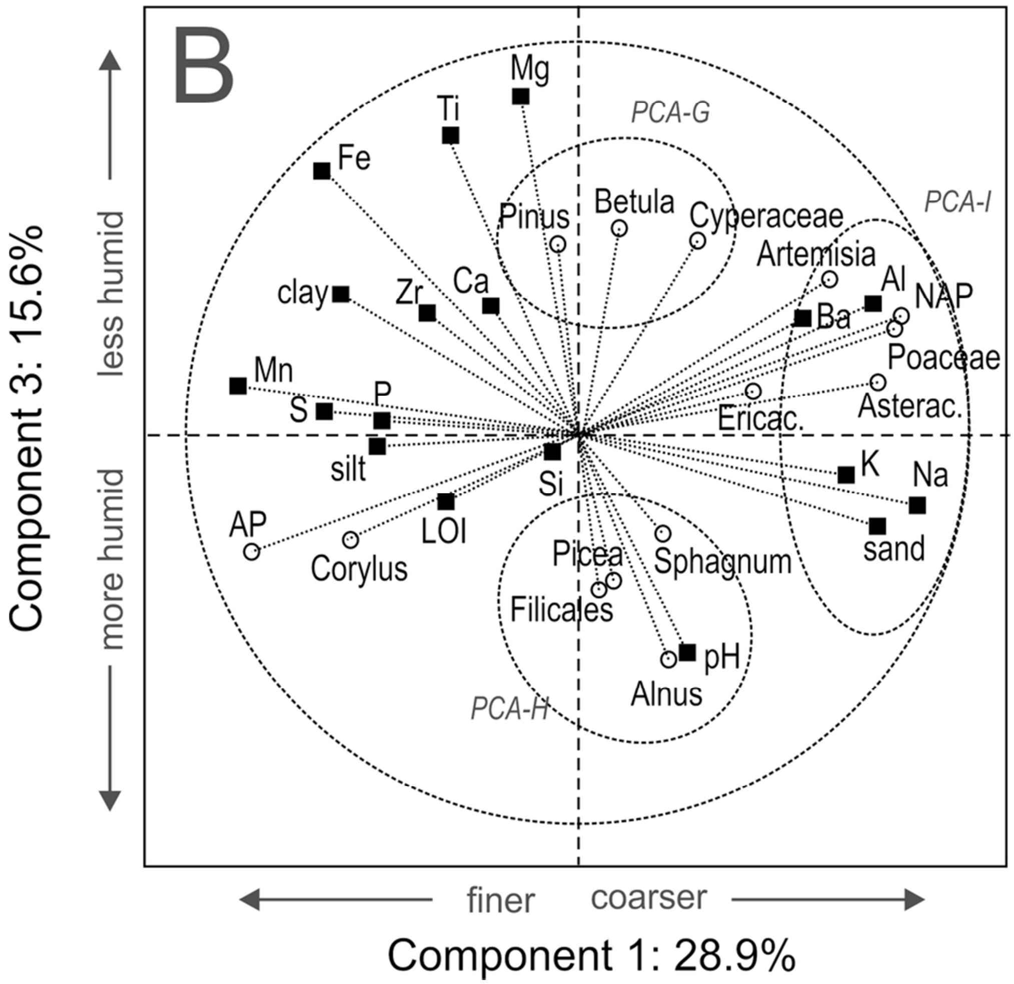

Fig. 5B
78x76mm (300 x 300 DPI)