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A DEPOSITIONAL RECORD OF TEMPERATE WOODLAND EXPANSION DURING HOLOCENE IN THE INTERDUNE LAKE INFILL (VIENNA BASIN)

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A depositional record of temperate woodland expansion during Holocene in the interdune lake infill (Vienna Basin)

Open temperate woodlands were recorded in Central Europe during the Holocene, where Early Holocene lowland pine-forest areas were succeeded by a spread of temperate trees dominated by the oak species. These then prevailed later in the Slovak Northeast Vienna Basin at 4 000 yrs cal BP compared to those on the Danubian Lowland which were dated to 10 390 – 7 500 yrs cal BP. Further changes in the development of vegetation in the region were explored by a multi-proxy approach of radiocarbon dating and palynological, macrofossil, sedimentary, and microprobe chemical analysis. The lithological changes, magnetic susceptibility, and loss-on ignition all suggest a sedimentary hiatus in the peat profile, and results identified that regional vegetation cover during the Late Glacial/Early Holocene comprised an open steppe area with several forest stands. While Pinus taxa dominated during this time, there was also increased temperate woodland species with Quercus at 6 275 – 5 916 yrs cal BP and Corylus, and Fagus in the Middle/Late Holocene. Later record of vegetation development from pollen and macrofossil analysis proves the transition into overgrowing mires from ~ 5 000 – 6 000 yrs cal BP. Open temperate woodland species (especially Quercus) were recorded during this time within natural pine forests stabilizing the dunes. Two fire events were noted and first one happened around 5 000 – 6 000 yrs cal BP and the second with a larger amount of microcharcoals with Frangula alnus and Pteridium spores ~1 000 yrs cal BP. The secondary indicators of possible human influence Plantago lanceolata, Rumex acetosa type and Centaurea jacea type, Chenopodiacea, Rumex acetosa type were present throughout the profile but increased only over the last 1 000 yrs cal BP and continued with further presence of Cerealia undiff.

Key words: radiocarbon dating, palynological analysis, magnetic susceptibility, loss-on ignition, Vienna Basin, Slovakia

INTRODUCTION

The inland dune fields system in the NE Vienna Basin region is currently stabilised by vegetation cover, but it was active throughout the Pleistocene (Kadlec et al. 2015). With warming of the climate during the Holocene and vegetation overgrow it was gradually stabilised. This evolution is similar throughout the great plains within the temperate zone in the sand dune / interdune lake system (Forman et al. 2001 and Mason et al. 2004). In this environment it is quite a difficult task to identify the key factors of the landscape changes throughout the Holocene (Jamrichová et al. 2019), because local changes such as human influence (cattle grazing, deforestation, reforestation, etc.) could have caused regional disturbances by destabilising the sand-dunes as well as possible climate changes (Forman et al. 2001, Mason et al. 2004 and Bábek et al. 2018).

The Morava River, the left tributary to the Danube River formed Pleistocene sand-dune system. Data from study of Kadlec et al. (2015) suggest the valley lake formation during the Last Glacial Maximum (LGM) with downstream damming by the dune complex with undercutting and slumping of dune accumulations with the rise of lake levels. Further research of interdune peat sediments in this area referred to several hiatuses in the sedimentological profiles (Svobodová 1997 and Jamrichová et al. 2019). Kalivodová et al. (2008) added that the Záhorská nížina lowland (Slovak part of NE Vienna Basin) sandy substrate has increased temperature, less ability to hold water, and the highly siliceous component is very poor in nutrients. The sand dune landscape was dominated by the aeolian system during MIS2 and the LGM (Kadlec et al. 2015 and Sümegi et al. 2015). Bábek et al. (2018) pointed out that Morava River had previously an anastomosing character forming several main channels with consequent fluvial accumulation on the Záhorská nížina lowland. The reasons behind this evolution were caused more by the climatic changes and vegetation overgrowth during warmer times than the accelerated basin subsidence. The Pleistocene/Holocene transition was marked with an increase in short-term aggradation rates (Bábek et al. 2018). Inter-dune depressions formed numerous mires with accumulated organic sediment which originated as deflation lakes. Further development until the present was directed into transitional mires with a gradual overgrow by a hydro-series succession of hygrophilous vegetation (Krippel 1988).

Even though the dune environment formation is connected mostly to the Pleistocene, further inter-dune lakes infill formations took place mostly during the Holocene. Interdune sedimentary records provide information about vegetation development, landscape development, even about human influence and possibly major climate changes. That is also very important in understanding the dune system movements and its conservation by vegetation cover (Mason et al. 2004, Petr and Novák 2014 and Jamrichová et al. 2019).

In the postglacial period several warmer/colder fluctuations of the climate occurred. The last warmer period was between 13 971 – 12 910 yrs. cal. BP with warm and wet climatic conditions with the occurrence of deciduous trees. Between 12 910 – 11 482 yrs. cal. BP the climate in the Moravian region became colder and it was the last return of the periglacial conditions before the onset of Holocene warming. During the Early Holocene, the vegetation cover within the lowlands changed from tundra to taiga and became warmer than today's climatic conditions (Moravcová 2010). During the Middle Holocene, other temperate trees adjoined the vegetation cover and climate warming continued. The Holocene climatic optimum with the warmest climate was dated to 6 000 – 5 000 yrs cal BP (Moravcová 2010). The climate changes in the Záhorská nížina lowland on the Middle/Late Holocene boundary are not precisely determined. In Western Europe, the Middle/ Late Holocene boundary was characterised by larger amounts of rainfall in the Alps (Furlanetto et al. 2018). The conditions in Central Europe of the adjacent lowlands such as the Danubian Lowland in the south and otherparts of the Pannonian

Basin suggest a rather warmer climate with early occurrence of temperate trees (Magyari et al. 2010 and Jamrichová et al. 2019).

Forested areas in the Central European lowlands during the Early Holocene contained pine forests, and they were followed by a spread of temperate woodlands dominated by oak in this era (Jamrichová et al. 2013, 2017 and 2019, Petr et al. 2013, Potůčková et al. 2018 and Šolcová et al. 2018). While their cover in the Slovak Northeast Vienna Basin spread in 4 000 yrs cal BP (Jamrichová et al. 2019), a higher occurrence of oak was recorded between 10 390 and 7 500 yrs cal BP in the Danubian Lowland. (Petr et al. 2013 and Jamrichová et al. 2014 and 2017). Kuneš et al. (2015) suggest that this late spread of oak species and other temperate trees in the Northern Vienna Basin in the Moravian region was due to local arid climatic conditions. The short review of the temperate trees occurrence in the Vienna Basin and surroundings is in Tab. 1. A multi-proxy reconstruction from the Vienna Basin in the location of Hanšpile near the Malé Karpaty Mts. recorded only a late glacial period (Hájková et al. 2015) although the forest situated on open sand dunes was quite uniform and dominated by Pinus species (Hájková et al. 2015).

Tab. 1. Known prevailing pollen types of temperate trees during the Holocene in the Vienna Basin and surroundings

Temperate tree taxa	Spread in pollen profiles (~years calBP)	Published by	Locality	Geomorphological unit
Pine dominated with oak	from ~4000	Jamrichová et al. (2019)	Studienka (SK) Holbičky (SK)	Vienna basin
Oak with hazel	7 500	Jamrichová et al. (2017)	Nová Vieska (SK), Hodonín (CZ)	Danubian Lowland Vienna basin
Oak	8 500	Petr et al. (2020)	Viničky (SK)	Zemplínske Hills
Pine dominated with birch and hazel	8 450	Kuneš et al. (2015)	Vracov (CZ)	Vienna basin
Oak	8 850	Petr et al. (2013)	Šúr (SK)	Danubian Lowland
Oak	9 880	Šolcová et al. (2018)	Santovka (SK)	Danubian lowland
Oak Hazel	10 390 7 300	Jamrichová et al. (2014)	Parížske močiare (SK)	Danubian lowland
Oak, hazel, elm	10 500	Gálová et al. (2016)	Nad Šenkárkou (SK)	Malé Karpaty Mts.

Human influence could be prevalent in the northern half of the Záhorská nížina lowland from the Eneolithic and later in the Neolithic as Linear Pottery Culture farmers found its soils to be the most suitable for agriculture (Drahošová 2005). Furthermore, Katkinová (1994) and Mellnerová-Šuteková (2015) suggest that the number of archaeological components significantly decreased in the Late Eneolithic and increased again only in the Late Bronze Age. Kuneš et al. (2015) added that humans most likely contributed to the oak spread and altered hazel and hornbeam dynamics in the Moravian area northwest of the Záhorská nížina lowland.

From the 17th Century pine forests were planted in the Záhorská nížina lowland to stabilise the sand dunes completely (Budke 1981). This suggests that this area was previously deforested or naturally without forest cover (Jamrichová et al. 2019). However, there is now only the Quercus robur and Q. petraea oak species left while the Pinus silvestris L. pine monoculture forest remains (Šomšák et al. 2004). Krippel (1965) and Budke (1981) supported this by reporting that oak was planted in the Záhorská nížina lowland in the last centuries, together with pine and a smaller proportion of other tree species.

The objectives of this study are to prospect the Holocene sedimentary infill of the mire in the inter-dune depression with a possible connection of found hiatus to climatic or hydrological events and to reconstruct Holocene vegetation development and find out more about local vegetation changes, and possible human impacts to provide further knowledge in the context of the whole region.

STUDY AREA

Previously peat mining was planned in the area of Zelienka mire (Fig. 1, part B), and the construction of draining channels caused the water level to fall more than 50 cm below the mire surface (Krippel 1988). However, in 1964 it became a national protected area and current restoration has reversed this trend as the water level has increased back to its original depth (ŠOP SR 2010), so that the *Alnus glutinosa* trees are now noticeable and the mire is more open with a rich overgrowth of sedges and hygrophilous grassland vegetation. The previous overgrowth of *Alnus glutinosae* implies that the mire was higher in the forested area before.

The surrounding lowland area with sand dunes, and regional vegetation consisting of the mono-specific *Quercetum* oak stands with the *Pineto-Quercetum* forests. Currently, there is a *Robinietum* locust forest prevalence in the numerous forest stands, and some areas have steppe grasslands on the aeolian sands dominated by *Festuca dominii*, *Dianthus serotinus*, *Corynephorus canescens* and *Thymus angustifolius*.

The pine forests of *Saliceto-Populetum* and *Fraxino-Ulmetum* are also widespread along the Záhorská nížina lowland rivers and streams. Therefore, the soils are constantly water-logged and vegetation on the organic sediments is characterised by alder forests with *Betuleto-Alnetum* birch and *Betuleto-Alnetum* oak forests with birch (Krippel 1965 and Kalivodová et al. 2008). The protected *Hydrocotyle vulgaris*, *Juncus bulbosus*, *Peucedanum palustre*, *Veronica scutellata* and *Viola palustris* flora species have been recorded in the Zelienka National Protection area, which is most important for protected bird-nesting species (ŠOP SR 2010). Today's land use in the surrounding of the mire is mostly dedicated to forest management with monocultures of pine and arable land.

Archaeological evidence of the human impact and settlements in history were recorded during the Neolithic colonization (Department of Acheology, Faculty of Arts, Comenius University, Archeological database processed by Dr. Bača). Only three components were recovered from the first prehistoric settlements during the long Eneolithic era. Therefore, while we presume that human activity around Zelienka was sporadic and generally of low intensity.

The settlement dynamics in this entire region increased significantly only during the Middle/Late Bronze Age and five archaeological components from this epoch were discovered within a 5 km buffer-zone of the Zelienka mire with a possible direct impact.

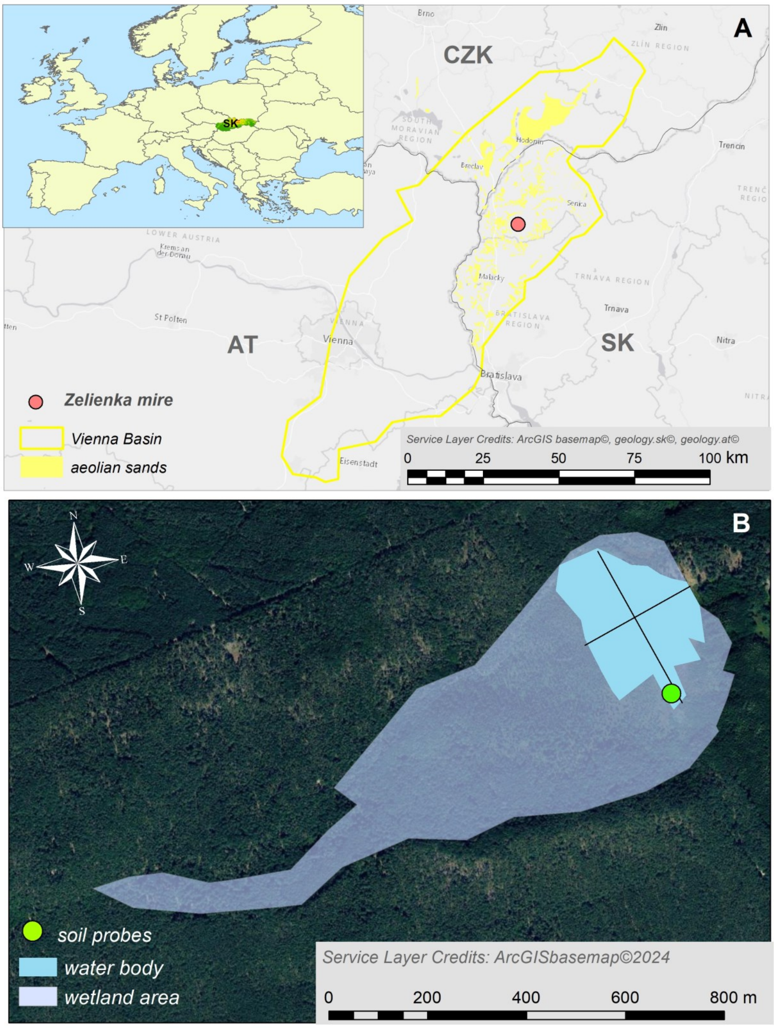

Fig. 1. A – Localisation of the study area in the Vienna Basin,
B – Localisation of the study area as an inter-dune depression of the Zelienka mirelength of water body 350 m and width 244 m and with an area of water body 58 600 m^2, area of the wetland 335 087 m^2

MATERIAL AND METHODS

Field research

Three sediment probes were drilled by an Eijkelkamp peat corer in the Zelienka transitional mire (Probe 1 coordinates 17.167898° E, 48. 602438° N; Probe 2 coordinates 17.167975°E, 48.6022409°N and Probe 3 coordinates 17.168498°E, 48.602278°N). The first and second probes were drilled in November 2015 and the cores were used for palynological analysis, macro-fossil remains analysis, magnetic susceptibility and loss-on ignition measurements. Samples were taken from the probe in 3 – 5 cm gaps until the change of peat sediment into the sandy substrate. In probe 1 there were 47 samples taken (155 cm) and in probe 2 which was a bit deeper (160 cm), there were 49 samples taken. 2 more samples were from the sandy substrate to cover the sedimentary transition in magnetic susceptibility and loss-on ignition. For pollen analysis and macrofossil remain analysis samples were taken from Probe 1. No pollen, spores or macrofossils are in the sandy substrate, so it was not so important to take more samples from the bottom.

The third probe was taken in November 2016 for better prospection of the found clastic layer. This layer was present in at least six cores recovered during reconnaissance research of the area. The sediment colour was identified directly in the field by the 2010 Munsell Colour charts before sampling (Munsell Color 2010).

The sediment stratigraphy and further lithological properties were described following Troels-Smith (1955).

Palynological analysis

Forty-seven samples were collected in 5 ml syringes and sent for processing to the Brno laboratory at the Institute of Botany Vegetation Ecology Department of the Czech Academy of Sciences. The samples were processed by the standard methods of acetylation by potassium hydroxide and hydrofluoric acid (Moore et al. 1991). We then used a Lycopodium marker in 2 tablets per sample in batch number 3862 at the Department of Geology at Lund University before the samples were loaded in glycerine and archived in plastic test tubes for identification.

The prepared peat samples were examined under KAPA 2100s lightning LED in 400x laboratory microscope, and each sample provided at least 500 pollen grains in different taxa, or 300 grains if 500 was not possible. Identification of pollen types followed the key material in Punt (1976, 1980, 1981, 1984, 1988, 1991 and 1995), Moore et al. (1991), Beug (2004) and Reille (1998).

The palaeoecological data is presented in percentages and the total pollen amount was based on terrestrial pollen types with the resultant diagram constructed in the Tilia software environmental version 2.6.1 (Grimm 2011). The wetland and lower plant taxa, macrophytes and other non-pollen palynomorphs were excluded from this analysis.

Macrofossil analysis and radiocarbon dating

The remaining sediment from probe 1 was passed through 0.25 mm EURO SITEX sieves and 3% of peroxide solution was added to the water bath. The macroscopic charcoals and grass macrofossil remains were then examined under a binocular magnifying lens. The plant macrofossils were identified as in Cappers et al. (2006) and Welichkevich and Zastawniak (2008) and compared with the recent flora seeds in the reference collection of the Department of Physical Geography and Geoecology at Comenius University in Bratislava.

The collected seed samples and one wood sample were sent for radiocarbon dating (AMS) to the radiocarbon laboratory at the Adam Mickiewicz University in Poznań in Poland (4 samples) and two samples to the radiocarbon laboratory of

Center of the Applied Isotope Studies at the University of Georgia (USA). The results were calibrated in Oxcal version 4.2 software (Bronk Ramsey 1995) under the IntCal20 calibration curve (Reimer et al. 2020).

Sedimentology analysis

Samples from the second probe were used for organic matter and magnetic susceptibility measurements.

The organic matter percentage or Loss on Ignition (LOI) was measured in the laboratory of the Vegetation Ecology section of the Institute of Botany, Czech Academy of Sciences by drying the samples at 100°C for 12 hours and combustion at 550°C for 3 hours. The weight of the samples was measured before and after combustion, and the organic matter content was calculated by subtracting these values (Heiri et al. 2001).

The magnetic susceptibility was measured in the sedimentology laboratory at the Department of Physical Geography and Geoecology at the University of Ostrava in Czechia. Samples were again dried at 45°C for at least 12 hours and then homogenized in a pestle and added to $10cm^3$ containers. The containers with sediment samples were measured in an Agico s. r. o Brno KLYS-4S stationed kappa susceptibility-bridge with a 3.10^{-8}SI sensibility, $300Am^{-1}$ magnetic field intensity and 920Hz operational frequency. Each sample was measured three times and the results are presented as the mean value of these measurements. Finally, the output of lithology characteristics, organic matter and magnetic susceptibility measurement was processed in Strater Golden Software v4.

Microprobe chemical method

The microprobe chemical method established the mineralogy composition of the clastic marker layer foundin the peat profile. The samples for this analysis were taken from Probe 3. The Dionýz Štúr Institute of Geology Cameca SX 100 microprobe was used for three samples. Samples were collected from the following depths:

63 – 66 cm presented the transition from peat to clastic sediment,

67 – 80 cm yielded the core of the clastic sediment,

80 – 83 cm provided transition from the clastic sediment to the peat sediment with wood remnants.

RESULTS

Chronology and depositional record of sediments

There is the possibility of sample contamination of one sample (dating 137 – 140 in Tab. 2). The dating of the other two samples was in reverse, but after calibration these two samples could be basically around the same age. Therefore, we only used the depth-age model for one of these samples that dated wood, as we find it more reliable. Furthermore, we provide further description of the results of dating and basic lithology.

The bottom part of the profile is formed by the silicious sands with sharp transition to peat. It was dated from ~13 800 yrs cal BP to the Late Glacial Age. The next dating in the depth of 137 – 140 cm was dated as ~1 020 yrs cal BP, possibly suggesting sample contamination from the upper part of the profile. Macrofossil remains of Carex seeds in the depth of 116 – 119 cm were dated as ~51 900 yrs cal BP. Macrofossil remains found in the depth of 104 – 107 cm were dated as ~6 030 yrs cal BP. Further dates followed to the Late Holocene ~3 105 yrs cal BP and ~645 yrs cal BP in the upper 26 – 29 cm sample.

The peat profile consisted of numerous narrow dark organic layers with decomposed peat with parts of decomposing plants, and a higher proportion of wood. However, consistency in the peat sediment was recorded (Fig. 2).The sedimentary changes from peat to clastic sediment layer was only at a depth of 100 – 120 cm possibly from ~4 000 – 6 000 yrs cal BP (Probe 1). During field researchthis layer of clastic sediment in several soil probes was characterised by a different colour according to the Munsell 2010 chart as 3 to 2. 5 Y 5/3.

Tab. 2. Radiocarbon dating of the chosen samples of macrofossils (Probe 1)

Depth [cm] lab code*	AMS date (uncalibrated BP)	AMS date (yrs calibrated BP) (% probability)	Holocene subdivision/ archaeo-logical cultures	Sample type/weight [mgC]
26 – 29 poz-87094	185 ± 30	540 – 750 (99.7%)**	Present	Seeds of Urtica sp., Rannunculus sp./0.2
83 – 86 poz-87095	2 950 ± 70	2 580 – 3 630 (99.7%)	Late Bronze Age Late Holocene	Seeds of Rubus sp./0.05
104 – 107 cais – 35742	5 290 ± 80	5 550 – 6 510 (99.7%)	Late Neolithic/ Early Eneolithic Middle Holocene not used in depth-age model	Seeds of Carex sp., Eupatorium sp. and Poaceae
116 –119 cais – 35743	4 520 ± 20	4 4 650 – 5 730 (99.7%)	Late Neolithic/ Early Eneolithic (Baden culture) Middle Holocene	Seed of Carex, sp. and wood/0.05
137 – 140 poz-87096	210 ± 50	1 020 cal BP (99.7%)	Present, probably sample contamination not used in depth-age model	Seeds of Carex sp./0.05
150 – 155 poz-87097	11 930 ± 70	13 380 – 14 220 (99.7%)	Palaeolithic – Late Glacial	Seeds of Carex sp./0.3

* lab code: poz = Laboratory in Poznań, Poland; cais = Radiocarbon Laboratory in Georgia, USA

** the percentage precision and calibration were calculated separately from each dating using the online program Oxcal (Bronk Ramsey 1995 and 2011) using curve IntCal 20 (Reimer et al. 2020)

The soil type in the prospected probes is Histosol (IUSS Working Group WRB 2015), with more than 70% peat sediment from decomposed plant remains in almost the entire profile. The organic matter decreased only in the deepest part of the sedimentary profile with a sandy sediment presence, with a rapid decrease from 65% at 140 – 145 cm to 7.92% at 160 – 165 cm. Most interestingly, while in the 71 – 98 cm layer organic matter content decreased from 67% to 60%, there was then a sudden increase to 90.57% at 98 – 101cm. Therefore, the layer in between is partially not classified as peat sediment (should be at least ~ 65% in LOI – Dargie et al. 2017). Soft sandy particles were identified in this layer.

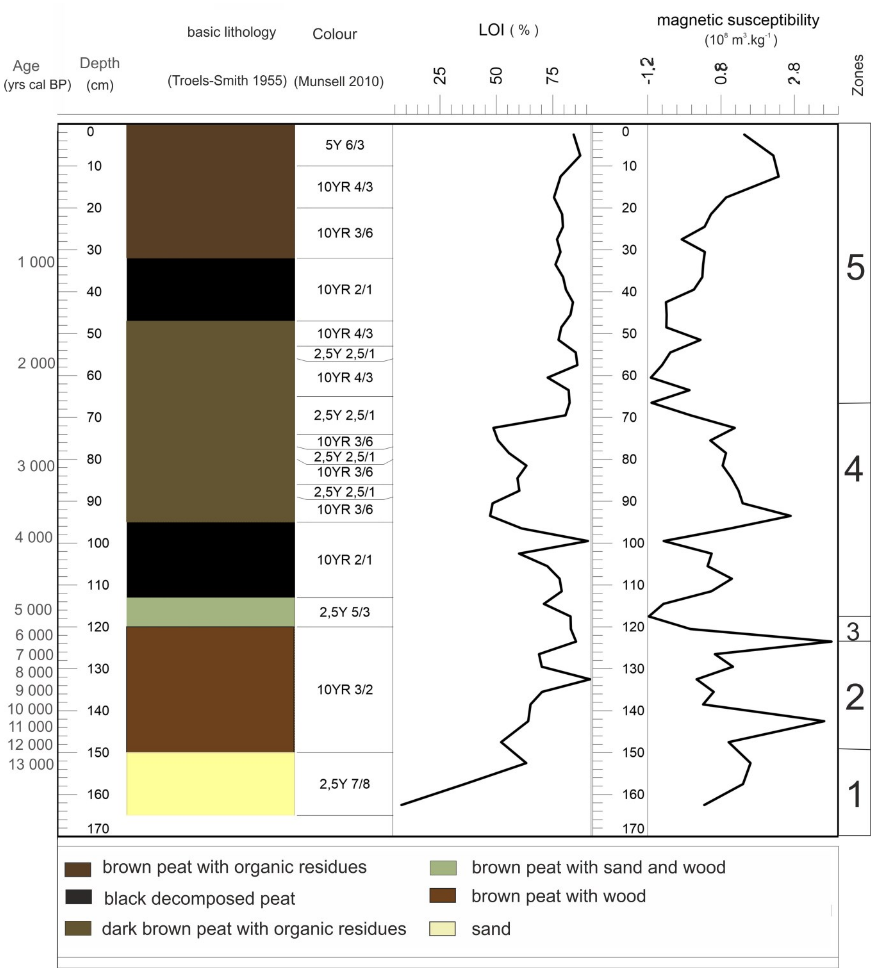

Fig. 2. Lithology profile with LOI and magnetic susceptibility measurements and general division into zones

The magnetic susceptibility (MS) results reflect the organic matter content; with two maxima at 3.61 10^8 $m^3.kg^{-1}$ in ~11 400 – 12 600 yrs cal BP and 3.81 10^8 $m^3.kg^{-1}$ in ~5 900 – 6 600 yrs cal BP. However, the values in the clastic layer above this depth were negative at -0.76 10^8 $m^3.kg^{-1}$ in 4 800 – 5 000 yrs cal BP.

Moreover, we divided the profile according to the Magnetic susceptibility of sediments and LOI into 5 general zones.

Zone 1 consists of sandy sediment below 150 cm and its transition to peat, dated to the Late Glacial, and there was a steep decline in both parameters. Zone 2 in ~ 8 000 – 12 600 yrs cal BP is characterised by two shifts in magnetic susceptibility values with its peak in ~6 000 yrs cal BP and in ~10 400 yrs cal BP. The minimum MS value was reached together with the maximum LOI in ~8 100 yrs cal BP.

Zone 3 in ~4 600 – 5 200 yrs cal BP is a narrow layer with a clastic sediment mentioned already above, that had wood fragments in the peat sediment, and the magnetic susceptibility rises sharply and then declines, suggesting an erosion event, a new sediment influx of other than organic matter etc. LOI values stayed constant around 70% with one sharp drop in ~4 900 yrs cal BP.

Zone 4 appears as a quite warmer period (~ 2 500 – 4 600 yrs cal BP) with only one sharp increase in LOI together with a drop of MS in ~ 4 050 yrs cal BP, which is reflected also in the lithology profile with a peat sediment of higher decomposition. Otherwise the LOI was at the continual decreased values reaching to 50 – 55% mirrored by higher MS values.

Zone 5 is characterised by a stable LOI with higher values around 80% and gradually increasing MS, especially in the upper part of the profile.in the last ~ 500 yrs cal BP.

Regional palaeoenvironmental changes and vegetation development

Regional changes can be interpreted from some pollen type in the diagram and following their changes we divided the development into 4 zones (Fig. 3).

Zone 1 in ~ 11 400 – 13 800 yrs cal BP recorded high percentages of Poaceae grasses and Artemisia Vegetation cover with trees consisted of mainly Betula, Pinus, and locally Alnus.

In Zone 2, contained a high proportion of pine and birch together with other pollen types such as Corylus, Quercus, Carpinus. Slight drop of Artemisia was recorded, but also two major peaks in ~8 500 and ~4 800 yrs cal BP, coinciding with an MS profile In this zone covering ~4 600 – 11 400 yrs cal BP, the tree cover, even fluctuating, stays represented in higher percentage than the herb layer. In zone 4 lies a suggested hiatus where all of the pollen types suddenly dropped in ~ 4 800 yrs cal BP. Therefore, some part of sedimentation between 4 200 – 11 400 is missing or there was no pollen in the surroundings.

Zone 3 covers ~ 4 600 – 1 800 yrs cal BP. Although there was a major decrease in *Pinus*, *Corylus*, *Betula*, *Poaceaee grasses*, the temperate trees percentage increased. The main arboreal pollen types with higher amounts were *Quercus*, *Fagus* and *Carpinus*. *Abies*, *Picea* and *Corylus* reached its peak ~ 3 600 – 3 800 yrs cal BP and then gradually decreased at the end of the zone. The Artemisia pollen type was at very high percentages throughout zone 3 and reached the maximum in ~ 1 700 yrs cal BP. For the herb layer *Chenopodiaceae* and *Rumex acetosa type* were also recorded in considerable numbers. Non-pollen remains recorded were mainly the woody remains and an increased amount of charcoals at the end of this zone.

The zone 4 boundary (0 – 60 cm) representing the last ~1 800 – 2 000 yrs cal BP is rich in human indicators such as *Plantago lanceaolata*, *Ambrosia*, *Cerealia*, and the highest amount of microcharcoals. The most abundant pollen types were *Betula*, *Fagus*, *Quercus*, *Carpinus*, *Abies*, *Fraxinus* and *Poaceae grasses*. *Artemisia* dropped dramatically in this zone, but other herbal pollen appeared such as *Centaurea cyanus*, *Plantago media/major*, *Falcaria* and *Pimpinela major*. The increase in herbal pollen was recorded ~770 yrs cal BP.

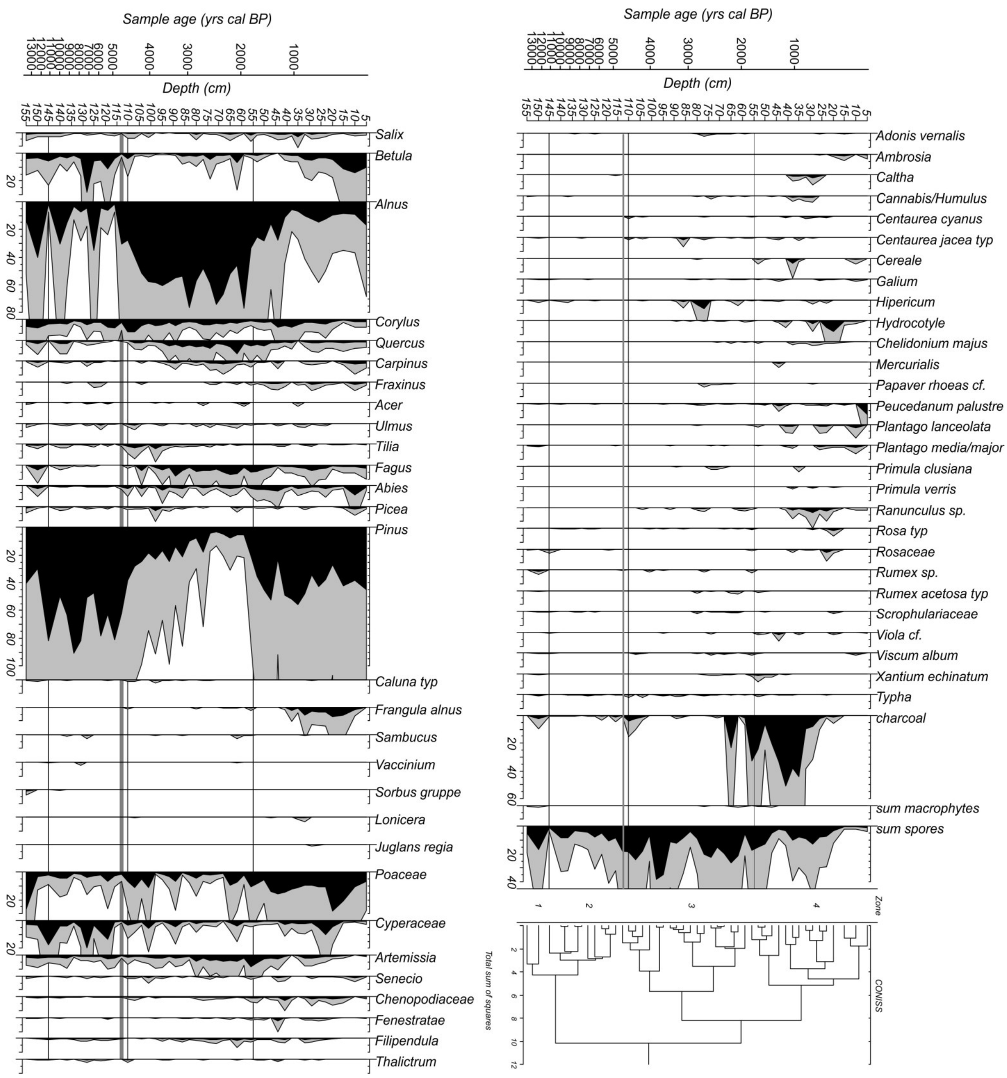

Fig. 3. Percentage pollen diagram of prevalent pollen types in Zelienka

Local vegetation succession and mire changes

Pollen analysis perspective and interpretations

The modern times are represented by an increase of *Cyperaceae* pollen, *Salix*, *Frangula*, *Lonicera* arboreal pollen, and a slight decline in *Alnus*. The water intake was favourable for a general macrophyte increase and also for the wetland and hygrophilous species including *Hydrocotyle*, *Filipendula*, *Thalictrum* and *Fenestratae*. The human impact in the proximity area was recorded by anthropogenic effects which ensured the regular occurrence of *Cerealia undiff*. pollen types and increased microcharcoals, *Calluna* (pyrophyte indicator) and *Rumex acetosa* type, *Plantago lanceolata* and *P. media/major* pasture indicators.

Macrofossil analysis perspective and interpretations

To complete the local landscape development and to compare with the pollen data proxy, we integrated macrofossil analysis and divided local changes into 3 generalized profile zones, however, the third zone was divided into 2 subzones. The lack of macrofossils compared to pollen richness was accompanied by this profile and all of macrofossil remains found in the sediment were recorded in Fig. 4.

Zone 1 in ~ 3 500 – 13 800 yrs cal BP contained a very low percentage of plant macrofossils, some preserved macrophytes such as *Batrachium* species in the early sedimentary infill of the inter-dune depressions and systematic *Carex sp*.

The upper part of this zone contained no macro-fossils and more *Alnus* wood remnants, but in the 92cm area increased *Poaceae* grass seeds were recorded.

Zone 2 in ~1 300 – 3 500 was marked with a constant occurrence of *Rubus* cf. *fruticosus/hirtus* taxa in the sediment. This is a photophilic taxon unable to reproduce in the shade, and it was followed by wet grassland species, forest edges and littoral shrubs in the two sediment samples at 86 – 89 cm (~3 100 – 3 300 yrs cal BP). This zone also contained wood remnants and the only finding of the tall *Eupatorium cannabinum* herb which settles rapidly in new habitats.

Zone 3 dates to the last ~450 yrs cal BP and it is differentiated into subzone 3a and 3b. It is characterised by a gradual decrease in *Rubus* cf. *fruticosus/hirtus* seeds and especially those from *Poaceaee* taxa. The grasses were replaced by *Carex* and *Lycopus europaeus* and *Lythrum salicaria* hygrophilous species, and these were accompanied by higher wetland habitat diversity comprising *Galium palustre*, Viola and Potentilla meadow species.

Subzone 3a in ~500 – 1 300 yrs cal BP contained a significant amount of *Urtica dioica* seeds. *Urtica* favours ruderal habitats with *Ranunculus* spp. in open stands which range from hygrophilous grasslands to periodically flooded habitats. Fens and fen meadow presence is indicated by *Carex davalliana* and *Carex hartmanii* sedges.

The 3b subzone in the last ~500 yrs cal BP highlights initial forest stages with Betula pendula and *Hydrocotyle vulgaris* flooded stand species in the pollen profile. *Batrachium* was again identified in this zone and this genus favours varying shallow to mid-depth waters. In contrast, the surface samples had a prevalence of *Alnus glutinosa* common alder and this species prefers a more stable long-term decreased water level. Finally, samples in ~ 50 – 1 000 yrs cal BP contained *Carex* seeds, thus identifying tall grasses with *Carex elata* and *Carex riparia*.

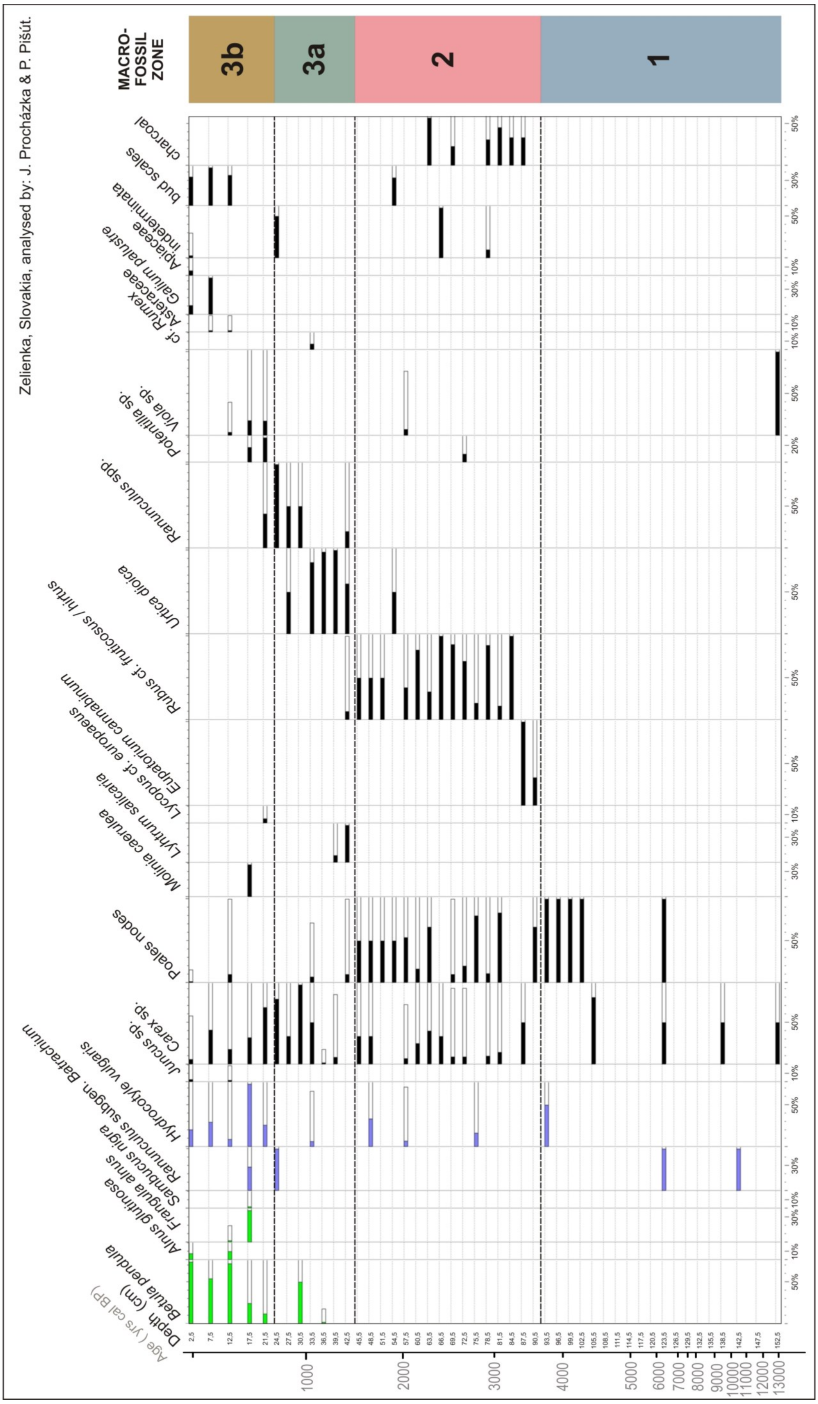

Fig. 4. Percentage plant macro-fossil diagram from Zelienka with macrofossils found in the Probe 1

Microprobe chemical analysis of the clastic layer

Fig. 5 shows specifically samples of the clastic layer of sediment that was well distinguished in Probe 3 dated to ~4 800 – 5 100 yrs cal BP and it records the transition from peat sediment to clastic sediment with sand in the first sample (~older than 5 000 yrs cal BP). Then the second sample is taken directly from this layer (4 800 – 5 000 yrs cal BP) and the last from the transition to the peat sediment from the other side (before 4 800 yrs cal BP) Diatom siliceous shells of lake origin formed most of the clastic layer and these were combined with higher amounts of alder wood.

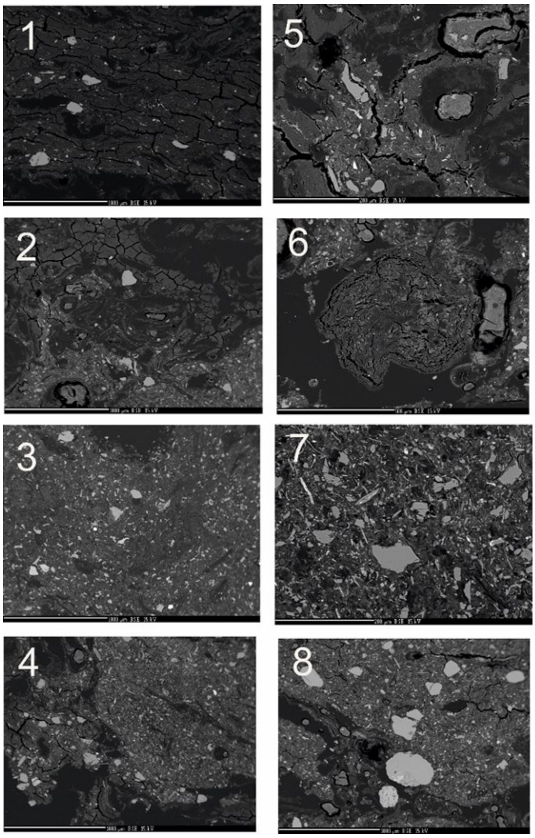

Fig. 5. *Bacillariophycae* – diatom shells in electron micro-analysis view from the clastic layer in Probe 3 during ~ 4 800 – 5 100 yrs cal BP

1 – siliceous sand particles in the peat sediment – possible sand dune material influx from the surrounding, 2 – transition from peat sediment to the diatom shells layer – change of the mire conditions, possible flood or higher moisture with higher water level in ~5 100 yrs cal BP, 3 – diatom shells layer of sediments with sandy particles in ~4 950 yrs cal BP, 4 – transition from diatom shells layer to the peat sediment in ~4 800 yrs cal BP, 5 – peat material mixed with sandy particles and diatom shells layer containing various sandy particles of quartz, barite and monazite 6 – accumulated organic plant material – stem buried in the peat material mixed with sandy particles and diatom shells layer, 7 – diatom shells layer containing various sandy particles made of quartz, barite, monazite, albite, epidote and potassium felspar, 8 – diatom shells layer containing various sandy particles made of very large quartz particles rounded by wind and smaller albite and potassium felspar particles.

DISCUSSION

The upper part of the profile dated approximately to 4 000 – 13 800 yrs cal BP reveals disturbances in the sedimentary profile. It was therefore more difficult to interpret considering the results of dating; especially due to possible hiatus existence as in other profiles within this region during the Early/Middle Holocene (Svobodová 1997, Hájková et al. 2015 and Jamrichová et al. 2019). As the human impact was claimed not to be so intensive near the studied locality until (~3 950 yrs cal BP, the sedimentary record could show possible natural changes like climate changes or floods between the Late glacial (Alleröd 12 000 – 13 971 yrs cal BP in this region) – Moravcová (2010) and Early/Middle Holocene 8.2 event disturbances (Magny et al. 2003). There is little evidence of pollen records from this time in this region (Jamrichová et al. 2019), although other studies claim changes in hydrological situation such as the migration of the anastomosing Morava River further in the north from this area with possible flooding from sand dune blockage during the late Glacial (Kadlec et al. 2015 and Bábek et al. 2018). The natural conditions could be similar in this region with sandy substrate and react accordingly to natural changes in climatic conditions.

In the sand-dune environment of the Elbe River, the first inter-dune lake formation and interstadial deposition of the drift sand dune was dated between 13 946 – 13 464 yrs cal BP in the Hrabanovská Černava (part of the Elbe Rfluvial sands system) – Petr and Novák (2014). At the end of the Alleröd there was a higher aeolian activity due to the temperature drop and vegetation retreat (Petr and Novák 2014). Tolksdorf and Kaiser (2012) report in Northern Europe near the Baltic and Northern Sea that the increased aeolian activity was not only connected to the late Glacial but persisted until ~6500 yrs cal BP with local scale vegetation-free areas, with sparse surface stabilization until the early Subboreal ~5 000 yrs cal BP.

Petr and Novák (2014) also mention the hiatuses and suggest the possibility of fluvial activity with reworked material sedimentation and possible influx of material from the surrounding areas near the Labe River. Further, it was suggested from a macrofossil record that the surrounding landscape was formed by a mosaic of water bodies and scattered terrestrial vegetation during the Late Glacial/Early Holocene (Petr and Novák 2014).

Lakes formation in the late Glacial with a sandy layer sedimentation and persisting higher water level within Šúr Lake during the Early Holocene was also recorded in the Danubian Lowland (Petr et al. 2013 and Potučková et al. 2018). In the Malé Karpaty Mts., Gálová et al. (2016) also claim that sedimentation starts from the end of Alleröd ~12 950 yrs cal BP. Higher hydrological activity probably also occurred in the Vienna Basin and it is quite possible the sand dune environment was not stable. The vegetation possibly played one of the major roles in the landscape transformation and further development of sand-dune environments throughout the Holocene, as human impact prevailed much later (Jansen et al. 2013 and Jamrichová et al. 2019). During the Preboreal and Boreal period the sand-dune system within Záhorská nížina lowland was still active (Krippel 1988 and Svobodová 1997), and during medieval times after deforestation ~1 700 – 360 yrs cal BP, the sand dune activity emerged again. Modern plantations of pine and other species to stabilise the sand dunes in this region began during the Austro-Hungarian Empire, when Maria Theresa and later her son Joseph ordered massive reforestation (Jamrichová et al. 2019).

Our sedimentary results show higher magnetic susceptibility with peaks in measurements during ~ 6 000 – 6 500 yrs cal BP and ~11 400 – 12 600 yrs cal BP which show higher weathering with possibly dryer climatic conditions that were followed by a major drop in MS, suggesting erosion (Ghilardi et al. 2008 and Petr et al. 2013). It is also mirrored by the organic matter content, that increased to 90% in – approximately 3 700 yrs cal BP after mentioned increased fluvial activity. These changes could be influenced also by changing local conditions in the wetland with higher or lower water levels.

To distinguish further the local and regional changes is possible from the proxy of pollen analysis and also macrofossils. Krippel (1988), prospecting this lake without absolute dating claimed it started peat formation during the Subboreal period (~2500 – 5 000 cal BP). In our case it was the boundary with suspected hiatus which is approximately dated to 4 000 – 5 500 yrs cal BP. Later the *Alnus* woodland overgrow shaded the lake area and also the lake became more shallow and the proportion of *Cyperaceae* declined to the Poaceae and other wetland hygrophilous species. Although other grasses (Poaceae, *Artemisia*) suggest a mixed steppe with pine and temperate trees with a higher proportion of *Quercus* in the wider region of the Lowland. Such an amount of *Quercus* in the pollen profile suggests its higher abundance regionally within the Pine forests, which was already documented by Jamrichová et al. (2019) on Záhorská nížina lowland and Potůčková et al. (2018) on the Danubian Lowland. However, in this profile we can date its higher spread to the Middle/Late Holocene transition (~4 200 yrs cal BP), which was not recorded in the surrounding inter-dune depressions due to hiatuses in the study of Jamrichová et al. (2019).

The last ~ 1500 yrs cal BP are specific with major changes that are manifested by the decline of *Pine* at first, later *Alnus*, increasing grasses *Poaceaee* and the occurrence of microcharcoals with some other plant fire indicators (Pokorný et al. 2015). At the start of *Pinus* decline (~4 000 yrs cal BP the pine decline is possibly caused by *Alnus* overgrowing the mire only locally, even though pine was still regionally abundant (Klimeš at al. 2000, Pokorný 2000 and Grindean et al. 2014). Occurrence of fire indicators of the *Calluna* pollen type with *Pteridium* spore was recorded together with microcharcoals at this time ~ 5 000 – 6 000 yrs cal BP. The fire event with a possible connection to hiatus was also mentioned by Gálová et al. (2016) in the Malé Karpaty Mts. ~5 000 cal BP. These fires could be connected to the human settlements from the Eneolithicmore which is more likely than by natural causes (Dietze et al. 2018). Later fire event(s) from ~ 1 400 – 1 000 yrs al BP with a peak in 1 200 yrs cal BP.was recorded with high amount of microcharcoals together with *Frangula* and *Pteridium* spores. Pollen amounts in samples further decreased and this could reflect vegetation absence after this fire event (Wójcicki et al. 2017) and the temperate tree proportions never recovering their previous levels, probably because of the Modern Pine plantations (Budke 1981). The agriculture in the surrounding area is recorded by *Cerealia*.

Pine monocultures admixed with *Picea*, *Abies*, *Quercus*, *Carpinus* and *Fagus* were planted in this area over the last 300 years (Jamrichová et al. 2019). In the last history of 200 – 300 years, we can observe a slight increase in *Pinus* and *Abies* together with *Carpinus*, *Alnus*, and *Betula*, which covers plantations of mainly pine forests from the 18th Century (Jamrichová et al. 2019). Even though the increase is not dramatic, it is supported by the decline of steppe markers (*Poaceae*, *Artemisia*, *Rannunculus* sp.) as well as the occurrence of human indicators and ruderals

(*Ambrosia*, *Cerealia undiff*., *Chenopodiaceae*, *Plantago lanceolata*). Plantations in the 18th Century were supposed to stabilize the sand dunes which was quite successful. The agricultural planting of *Cerealia undiff*. raised as well but never reached its peak around 800 years ago.

In the mid-20th Century drainage channels were constructed to dry the mire surface for mining peat and this decreased water levels by approximately 70 cm (ŠOP SR 2010). A decade later it became protected as a nature reserve, so this activity was ceased. During revitalization of the Záhorská nížina lowland wetlands in 2005 drainage channels were blocked and the groundwater regained its previous level (ŠOP SR 2010).

CONCLUSIONS

The key factors for these landscape changes were also connected to climate events on the Early/Middle (8.2 event) and Middle/Late Holocene (4.2 event) and vegetation's ability to spread over the poor siliceous sandy substrate. Our research revealed missing information in the North-Eastern part of the Vienna Basin about vegetation development during the Middle Holocene, that was not available directly in the surrounding area because of hiatuses. A recorded hiatus in our profile confirms the hypothesis about higher aeolian activity at the end of the Alleröd, but it probably persisted even at the onset of the Early/Middle Holocene until ~5 000 yrs cal BP, when lake the phase shifted into the mire formation. Even though the first inter-dune depression lakes were formed after sudden climate warming during the Late Glacial, the sedimentation was disturbed by higher fluvial activity.

Later changes recorded human impact in the site proximity and within the region duringthe Bronze Age from ~3 950 yrs cal BP and direct impact with deforestation during the Medieval period from ~ 1 400 – 1 000 yrs cal BP with a peak in 1 200 yrs cal BP. Recorded fire events were also noted in the Malé Karpaty Mts. and could be possibly connected to the first settlements in the region. Nevertheless, our results are consistent with other regional interpretations with temperate trees abundance (especially oak) incorporated into the natural pine forests during the Middle Holocene. Persistence of the open land during the Holocene was also prevalent with occurring forest stands even before direct human impact with induced deforestation.

We would like to dedicate this article to the memory of Eduard Krippel, palaeogeographer at the Institute of Geography of the Slovak Academy of Sciences who put a baseline to the prospection of Slovak wetlands and regional vegetation changes throughout the Holocene. This research was supported by the Scientific Grant Agency of the Ministry of Education, Science and Sport of the Slovak Republic (VEGA 2/0052/21, 1/0217/23 a 1/0245/23).

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SEDIMENTÁRNY ZÁZNAM Z VÝPLNE MEDZIDUNOVEJ DEPRESIE S EXPANZIOU TEPLOMILNÝCH DREVÍN POČAS HOLOCÉNU (VIEDENSKÁ PANVA)

Článok sa zaoberá regionálnym a lokálnym vývojom vegetácie Viedenskej panvy na príklade analýzy sedimentárneho profilu z rašeliniska Zelienka na Záhorskej nížine. Venuje sa postglaciálnym až rano-holocénnym zmenám, ktoré sa týkajú formovania riečnej siete a následkov možných povodňových udalostí v nestabilnom prostredí piesočných dún, ale aj lokálneho vývoja a zmien vegetácie v jednej z medzidunových depresií Záhoria. Zároveň ide o jeden zo sedimentárnych záznamov v rámci Viedenskej panvy pokrývajúci časť stredného holocénu, ktorý v sedimentárnych profiloch rašelinísk v tejto oblasti zvyčajne nie je k dispozícii. Autori, ktorí publikovali výskumy o vývoji vegetácie v postglaciálnom období a v holocéne, zistili, že v sedimentárnych záznamoch sa často vyskytuje sedimentačný hiatus – tzv. prerušenie akumulácie sedimentov (Svobodová 1997, Hájková et al. 2015 a Jamrichová et al. 2019). Cieľom prezentovaného článku bolo konfrontovať dôvody vzniku tohto narušenia v sedimentácii v Zelienke s podobnými výsledkami iných autorov. Rovnako bolo dôležité aj prispieť k doterajšej medzere v poznaní rekonštrukciou zmien krajiny multiproxy prístupom k takému rozsiahlemu rašelinisku, akým je Zelienka chránená prírodnou rezerváciou. Ďalším cieľom bolo vytvoriť hypotézu o možnom výskyte hiatusu v regionálnych sedimentárnych záznamoch a nájsť tak spoločnú príčinu. V podobných výskumoch sú taktiež viditeľné aj vplyvy a zásahy človeka do okolitej krajiny, o čom sme sa tiež snažili vytvoriť záznam, ak to bolo možné.

Zmeny a vývoj vegetácie v tejto oblasti boli preskúmané metódami rádiokarbónového datovania a palynologickej analýzy, analýzy makrozvyškov a sedimentárneho profilu (analýza spáleného podielu, magnetická susceptibilita a elektrónová mikroanalýza). Výsledky viedli k identifikácii možných povodňových udalostí počas neskorého glaciálu/raného holocénu. V systéme aktívnych vnútrozemských dunových polí na severovýchode Viedenskej panvy sa počas neskorého glaciálu v poslednom teplom období allerödu (pred 13 971 – 12 910 rokmi) postupne vytvorili deflačné jazerá. Vegetačný kryt do konca tohto obdobia (pred 13 890 rokmi) bol v rámci regiónu len riedky s prevažne borovicovými lesmi. Podľa našich paleoekologických a sedimentárnych výsledkov existovala silná súvislosť medzi medzidunovými deflačnými jazerami počas raného holocénu a vyššou fluviálnou aktivitou. Neskoršie záznamy o vývoji vegetácie z peľovej analýzy a analýzy makrozvyškov dokazujú prechod na zarastajúce rašeliniská od ~ 5 000 – 6 000 rokov do súčasnosti. V tomto období bol v rámci prirodzených borovicových lesov stabilizujúcich piesočné duny zaznamenaný aj zvýšený podiel teplomilných drevín mierneho pásma (najmä *Quercus* – dub). Zvýšený počet uhlíkov v niektorých vrstvách naznačuje dve udalosti spojené s požiarmi, pričom k prvej došlo približne pred 5 000 – 6 000 rokmi a k druhej s väčším množstvom mikrouhlíkov so spórami *Frangula alnus* a *Pteridium* pred ~1 000 rokmi. Sekundárne indikátory možného vplyvu človeka *Plantago lanceolata*, *Rumex acetosa* typ a *Centaurea jacea* typ, *Chenopodiacea*, *Rumex acetosa* typ boli identifikované v rámci celého profilu, ale ich počet sa zvýšil až v priebehu posledných 1 000 rokov a pokračoval ďalšou prítomnosťou *Cerealia undiff*. – obilininami, ktoré naznačujú poľnohospodársku činnosť človeka v okolí. Diskusia o hiatuse, ktorý sa často vyskytuje v sedimentoch v rámci Viedenskej panvy, zostáva otvorená a ďalším výskumom by sa mohlo zisťovať, či odráža regionálne zmeny, keďže datovanie sedimentov zaznamenalo možné nedávne narušenie v profile pravdepodobne pri odvodňovaní rašeliniska v minulom storočí. Táto štúdia je zároveň revalidáciou výskumu E. Krippela, ktorý v roku 1988 publikoval článok v Geografickom časopise o tomto konkrétnom rašelinisku, a teda aj prehľadnou aplikáciou aktuálne dostupných metodík a nových možností pri interpretáciách v oblasti paleogeografie.

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