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Environmental gradients during Late Glacial in Central Europe

Diverzita životního prostředí v pozdním glaciálu ve střední Evropě

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Hereby I declare that I made this thesis independently, using the mentioned references.
I have not submitted or presented any part of this thesis for any other degree or diploma.
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Author contribution statement

I declare that I made substantial part of the thesis papers (manuscripts).

Contribution to each paper is specified below:

1. **Libor Petr Petr L., Žáčková P., Grygar T. M., Píšková A., Křížek M., Treml V. - Šúr – former Lateglacial and Holocene lake on westernmost margin of Carpathians:** Pollen analysis, LOI, MS, paleecological interpretation, linking of analysis, ca 60% of paper text and corrections.
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3. **Petr L., Sádlo J., Žáčková P., Lisá L., Novák J., Rohovec J., Pokorný P. - Late-glacial and Holocene environmental history of an oxbow wetland in the Polabí lowland (Elbe river, Czech Republic); a context dependent interpretation of multi-proxy analysis:** Pollen analysis, LOI, MS, geomorphology, linking of methods, paleoecological interpretation, a part of discussion and entire text corrections.
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5. **Treml V., Jankovská V., Petr L. - Holocene dynamics of the alpine timberline in the High Sudetes:** Pollen analysis of Keprnik and Mezikotli site
6. **Petřík J., Petr L., Šabatová K., Doláková N., Lukšíková H., Hladilová Š., Dohnalová A., Koptíková L. - Human impact on Holocene floodplain development at catchment of Těšetička-Únanovka river, South Moravia - Czech Republic:** Pollen analysis – bore hole SZVNV5, paleoecological interpretation, a part of discussion

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Abstract

The Lateglacial and Early Holocene are key periods with respect to the understanding of the present-day vegetation and environment. An interdisciplinary approach is important for the study of these changes. Only by interlinking biological and geoscience evidence can we obtain a more comprehensive picture of this key period. It is not possible to interpret any pollen spectrum in the sedimentary record without knowledge of the history of the locality and its vicinity.

Rapid climate changes had a crucial effect on the environment and vegetation. Continentality of the climate and a deficit of precipitation amplify the effect of local conditions. Vegetation, as in the case of vertebrates and molluscs, comprises a combination of species of a continental steppe, mountain biotopes and disturbed habitats. This facilitated contact among species and populations that are biogeographically separated at present. Vegetation of the Lateglacial period in the Czech Republic ranges in character from frost barrens in the mountains, through steppe-tundra vegetation at medium altitudes to a continental steppe in the lowlands and pine woodlands constrained to a moist floodplain. The Western Carpathians were covered by a taiga. In the Pannonian Lowland, there were open forests with conifers and broadleaved woody plants.

Only at the beginning of the Holocene does nature attain today's character by migration of forest species and, conversely, a retreat of montane elements. In the Czech Basin, an open birch-pine forest expanded first; in Pannonia, broadleaved species spread immediately. The advent of the Neolithic era is not manifested in the pollen log because vegetation in the lowland was naturally diffuse and the human population was small. The human impact increased gradually until it reached a point when it became the main factor overshadowing natural processes.

Abstrakt

Období pozdního glaciálu a raného holocénu představuje klíčovou periodu ve vývoji současné přírody. Pro studium těchto změn je důležitý mezioborový přístup. Teprve propojením biologického a geovědního záznamu lze získat ucelenější obraz této klíčové periody. Bez znalosti vývoje lokality a jejího okolí nelze interpretovat pylové spektrum obsažené v sedimentárním záznamu.

Rapidní klimatické změny měli zásadní vliv na prostředí a vegetaci. Kontinentalita klimatu a nedostatek srážek zesiluje vliv lokálních podmínek. Vegetaci, stejně jako v případě zvířat a měkkýšů, tvoří kombinace druhů z kontinentální stepy, horského biotopu a druhů narušovaných stanovišť. To umožnilo kontakt druhů a populací dnes biogeograficky oddělených. Vegetace pozdního glaciálu v ČR má charakter od mrazové pustiny na horách, stepotundrové vegetace ve středních polohách až po kontinentální step v nížinách a borové lesy vázané na vlhkou nivu. Západní Karpaty jsou pokryty tajgou, v panonské nížině jsou světlé lesy s jehličnany a širokolistými dřevinami.

Teprve začátkem holocénu migrací lesních dřevin a naopak ústupem horských prvků příroda nabývá dnešní charakter. V České kotlině nejprve expanduje světlí březoborový les, v Panonii se rovnou šíří širokolisté dřeviny. Nástup neolitu se v pylovém záznamu neprojevuje, protože vegetace v nížině je přirozeně rozvolněná a populace lidí je malá. Lidský vliv narůstá pozvolně, až se stane hlavním faktorem, který převažuje nad přírodními procesy.

General Introduction

Regarding the complex questions related to this research, a wide context of the inquiry is necessary for understanding of the changes of the environment on the turn of the Glacial and Holocene periods. A terminological complexity of the quaternary stratigraphy and amount of synonyms for particular periods can serve as examples. Interconnection of various approaches to analysis of the sedimentary importance is limiting for the risk of circular processes in the field and it has to supersede our inability to conduct an experiment in the past. Various types of the record comprise various understanding potential; their comparison is not only a simple sum. I have tried to supplement the palynological record with further proxy-record i.e. interconnection of the biological record to the sedimentary and geomorphological evidence in my paper.

The present vegetation in the Central Europe has gradually been formed under the influence of the periodic climatic changes in the youngest period of the geological past – the Quaternary (Lang 1994). This period has been lasting for approximately 2.5 million years (MIS 103). It consists of the cold (glacials) and warm periods (interglacials) at its lowest level of focusing. See http://www.quaternary.stratigraphy.org.uk/correlation/chart.html for division and stratigraphy of the Quaternary Period (Gibbard and West 2000). The vegetation of Central Europe began to change from the damp and warm subtropics with many from today’s point of view exotic species from the Tertiary period (Pliocene) and the older Pleistocene to the stage as we know it at present (Lang 1994). The periods of the later glacial and the Early Holocene have been important for development of the present environment and vegetation in Central Europe. There occurs recession of the glacial elements of the original steppe-tundra vegetation and there increases migration of the broadleaf trees in this period (Hewitt 1999). This is the last period when the human impact was negligible and the nature was fully influenced by the climatic cycles. A gradual human impact on the environment has been in progress since arrival of the first farmers which is literally global at present (Roberts 1998, Ruddiman 2007)

Last Climatic Cycle

The last interglacial (Eemian) lasted approximately from 128 to 116 ka BP (MIS 5e) (Tzedakis 2003). It is not easy to compare the Eemian glacial and Holocene. The Eemian climate was only by 1 up to 2 ˚C in average warmer (Zagwijn 1996, Kukla et al. 1997). However, it was more balanced. The higher sea levels created so called Eemian Sea in the area of the today´s Baltic Sea which was connected with the North Sea (Tzedakis 2007). This situation was influencing the sea currents and also the oceanic character of the European climate. There were only a few exotic elements in Europe in comparison to the previous interglacials. Those which have been documented were of a rather Atlantic character (like *Ilex*, *Celtis*, *Hedera*) (Tzedakis 2007). The so called *Carpinus*-phase of Eemian is important for the forest vegetation and so called flora of the *Brasenia*-complex in the wetlands (Velichkevich and Zastawniak 2006). The main diversity from the Holocene period was in extent of the species which reached more to the north in the Eemian than today (Velichkevich and Zastawniak 2006).

There is no paleobotanic record in the Czech Republic which can unambiguously be dated to the last interglacial (Svobodová 2002). The travertine mound in Gánovce in Slovakia has provided us with such a record (Kneblová 1960). The entire interglacial from the end of interglacial has been recorded. The profile begins with a pine wood, continues through expansion of the leafy woods up to the end of the warm period and arrival of spruce and fir. Record of the indecidous oak of the *Quercus illex* section also is interesting. According to the malacozoologic evidence, there are no steppe species presented in the high phase of the Eemian interglacial. There prevail woodland species with the diagnostic species of *Drobacia banatica* (Ložek 1973, 1990).

The last ice age (Würm) began after 116 ka BP (MIS 5d) through gradual decrease of temperatures and loosening the vegetation (Dawson 1992). The course of the last glacial was characterized by unstable climate and fast changes in the warm and cold oscillations. MIS 4 is the first glacial maximum (59 to 66 ka BP) and the transition phase (66 to 74 ka BP) (van Andel and Davies 2003). The relatively warm instadials prevailed therefore the overall climate can be characterized as warm and dry with occasional cold oscillations. There were approximately 26 cold oscillations of various intensity and duration during the last glacial (Dawson 1992). Dansgaard-Oeschger oscillations are characteristic for the middle part of the last glacial. There are missing at its end and beginning (Dansgaard et al. 1993). There are 24 oscillations know from the period from 110 to 23 ka BP when the temperatures fluctuated by around 5° up to 8°C. They lasted approximately 500 to 2 000 years on the northern hemisphere. The difference between the cold and the warm phase is up to 7°C. Then there occurred drop of temperature (Johnsen et al. 1992, Dansgaard et al. 1993, GRIP 1993, Grootes et al. 1993). The analogies can be seen in the so called Heinrich events. They are documented in layers of raw material in the sea sediments which were formed during melting of the sea ice. Sudden rise of temperatures on the northern hemisphere followed by drop of temperatures and advance of the icebergs can be perceived as the result (Heinrich 1988, Bond et al. 1993).

The first large expansion of the Scandinavian continental glacier towards the Baltic Sea occurred around 68 ka BP. It was in this period when loess was deposited and biome of the loess steppe-tundra developed (van Andel and Tzedakis 1996). This first maximum of the last glacial did not last long. It got warmer after approximately 8 000 years and the glacier receded. This period was followed by warmer era characterized by wetter unbalanced climate during which the formation of loess dropped (Frechen 2003)**.**

OIS 3 is constituted of several climatically different phases (van Andel 2002). The period from 31 to 23 ka BP is the last warmer and wetter oscillations in terms of OIS 3. It is characterized by the Dansgaard-Oeschger events (DO 5 -3). The cold climatic oscillations are the Heinrich events H3 and H2 (Zicheng and Wright 2000, Ditlevsen et al. 2005). The climate was deteriorating gradually up to the largest drop of temperatures during the last ice age – the Last Glacial Maximum.

The only natural pollen profile of the MIS 3 period from Moravia is on the site Bulhary in the vicinity of Dolní Věstonice (Rybníčková and Rybníček 1991). The 50 cm thick layer of peat is buried under 10 m loess (Havlíček and Zeman 1986). The only C14 date (25 kaBP) dates the sediment to the end of the MIS 3 period. This feature was a shallow water reservoir or a river meander infilling gradually with shallow water and wetland vegetation. The conifers prevail in the pollen specter (*Pinus sylvestris*, *P. cembra*, *Larix* and *Picea*). The mezophilic deciduous trees *Ulmus*, *Corylus*, *Quercus*, *Tilia* and *Acer* are sporadically recorded. This specter is similar to the charcoal assemblages from the Gravettian excavations (Musil 2003). There also prevail the conifers (Beresford-Jones et al. 2010, Beresford-Jones et al. 2011) including *Abies* and *Taxus*. However, mezophilic deciduous woods including *Fagus* have been documented in several contexts (Slavíková – Veselá 1950, Kneblová 1954). These forests most probably were related to the warmer oscillations during the MIS 3 period (van Andel and Tzedakis 1996). Charcoals of the conifers prevail also on other Paleolithic sites in Central Europe (Willis and van Andel 2004) where only tolerant *Betula*, *Salix* and *Alnus* have been documented. The site Praha – Podbaba (former Vltava meander; Janovská and Pokorný 2008) dated 31 – 40 ka BP demonstrates the pollen specter in which the conifers prevail (*Pinus*, *Picea* and *Larix*) which also is recorded in the sediment containing wood of the conifers.

The paleoecological importance of the last glacial (47 to 25 ka BP) from the adjacent Paleolithic site called Dzeravá Cave is remarkable as well (Kaminská et al. 2005). This corresponds with the charcoal assemblages (Hajnalová and Hajnalová 2005) in which *Pinus*, *Betula*, *Salix* and *Picea* prevail, *Larix*, *Corylus*, *Fagus* and *Ulmus* are less frequent but they also contain skeletal material of small forest mammals (Horáček 2005). However, the layers from the high and late glacial contain archaeobotanic material from the Eneolithic period (Hajnalová and Hajnalová 2005) so it is difficult to interpret them as an evidence of the surviving forest biocoenosis in the LGM in Little Carpathians. The preliminary results from the site of Šúr in West Slovakia document prevalence of the conifers in the limnic layers under the Holocene gyttja dated from 45 to 25 ka BP. The evidence has been identified in the pollen record (*Pinus* and *Picea*) and in macroremains (pine bark). The leafy trees are less common, *Betula* prevails; *Alnus* and *Ulmus* are rare.

Last Glacial Maximum (LGM)

The OIS 2 period (27,5 – 18,2 ka BP) represents the last glacial maximum (Rasmussen et al. 2008). A significant drop of temperatures at its beginning is represented by the Heinrich event 2 then there occurs the Dansgaard-Oeschger event. Further, a distinct drop of temperatures occurs. The Heinrich event 1 is at the end of the LGM (Dawson 1992). The Scandinavian glacier advanced to the south across the region of the present Baltic Sea to Poland and Germany up to today´s Berlin (Ehlers et al. 2011). The central European mountain glaciers advanced to the valleys and reached its largest expansion (Engel et al. 2010, Nývlt et al. 2011, Mentlík et al 2013). The region of the Czech Republic was situated in a narrow stripe between the continental glacier in the north and the alpine glacier in the south and it was part of a narrow corridor connecting West and East Europe having a massive impact on the contemporary biota (Ložek 1973). Loess was being intensively formed in Central Europe (Haase 2007). A specific ecosystem, so called loess steppes, was related to it (Ložek 2001). Species *Pupila triplicita, P. loessica, Columella columella* and *Vallonia tenuilabris* were typical for this environment. This environment is generally known as the "loess steppe" (Ložek 1990, 2001). The loess biome has no present analogy and it is the most pronounced characteristic feature of the cold glacial oscillations.

A massive loess accumulation reaching more than 10 m is typical for the LGM in Bohemia. Its thickness and also the number and complexity of the interstadial fossil soils (PK I and PK II) has no analogy in the previous glacial (Frechen et al. 1999). Almost no late-glacial loesses are known from the Czech Republic which is in contrast to West Europe (Frechen et al. 2003). The Holocene soils usually follow the loess layers (Fuchs et al. 2012). The formation of loess is an evidence of extreme climatic conditions during the LGM and it represents a certain turning point in development of the Central European environment.

Lateglacial

A gradual increase of temperatures occurs after the end of the LGM. Evidence for rapid shifts in climate on decadal to millennial timescales during the period of the Late Pleistocene (ca 20 ka BP) and the Early Holocene (ca 11.6 ka BP) comes from Greenland ice cores (GRIP 1993, Bond et al. 1993; Lowe et al. 1994, Walker et al. 1999). But also other records contain lacustrine sediments and peat records from localities in the central and Western Europe (De Beaulieu et Reille 1992, Seret et al. 1992, Pazdur et al. 1995, Goslar et al. 1999, Ammann 2000, Leroy et al. 2000, Litt et al. 2009, Magny et al. 2007) and dendrochronological record in Swiss Alps (Schaub et al. 2008). The following late-glacial interstadial begins around

13 000 BP with a warmer Bölling period. It is separated from the warm Alleröd period by a short cold oscillation Older Dryas (DR 2). No reliable evidence of the Older Dryas oscillation is known from the Czech Republic. The interstadial appears to be only one period according to the pollen record.

The Younger Dryas (YD, DR 3) was the last cold oscillation in the glacial that influenced the entire northern hemisphere. It lasted only a short time, approximately 1 300 ± 70 years. It is also known as the Greenland Stadial 1 (GS 1) (Berger, 1990). Its origins are not clear; they most probably are related to the end of the post-glacial lakes in North America spill-over of which into the Atlantic Ocean influenced the North Atlantic Oscillation (Alley 2000, Broecker et al. 2010). A bizarre theory mentioning impact of a space object has emerged (Pinter et al. 2011). The Late Glacial was characterized by rapid climatic changes with fast transitions during only a few decades (Taylor et al. 1993, Alley et al. 1993, Severinghaus and Brook 1999).

The continental glaciations as well as the mountain glaciers recede. The Central European glaciation of the Hercynien Mountains reflected well the climatic changes of the Upper Pleistocene even though it occurred in a small area only (Beaulieu and Reille 1992). The records from these areas document the changes of the landscape in the medium elevations, i. e. in region above the line of sustainability of the mountain glaciation during the cold periods. The records from the mid-mountains regions complete the idea about the influence of the regional climatic oscillations on the enclaves of the mountain glaciation - the High Sudetes (Chmal et Traczyk 1999, Engel et al. 2010), the Bohemian Forest (Jankovská 2006, Pražáková et al. 2006, Mentlík et al. 2010) and Bavarian Forest (Raab and Völkel 2003, Reuther 2007). Vegetation in the vicinity of the Black Lake was of a more extreme arctic-alpine tundra character (Vočadlová et al. submited). Only the stress-tolerant species (grasses, bent-grass and mosses) were able to survive on the initial soils and rocky surfaces as the species indicating sites damaged by erosion. The lower parts of the Šumava Mountains were covered with the steppe-tundra vegetation during the Younger Dryas. Pollen grains of various species of woods origin in the long-distance transport. The mosaic-like vegetation including several tundra (*Betula nana*) and steppe (*Artemisia*, *Heliantemum*) elements was abundant on the medium elevated sites (Pokorný 2002).

The bottom land of the Labe River constitutes the main factor forming diversity of the environments and vegetation in the Czech lowland. The Central European river bottom land reflects the climatic and environmental changes which are of the crucial influence on the dynamics of the fluvial systems in regions which have not been fully affected by the continental glaciation (Vandenberge 2003, Maddy et al. 2001, Tyráček and Havlíček 2009). The changes of the climate may be observed in formation of the river terraces, changes in the water behavior in a shorter time and sedimentation of the alluvial in the Holocene period.

The site called Chrást (Petr et al. in press) in the middle Labe River stream has yielded evidence of a meanders in the Allerød and Bölling interstadials which were surrounded with open bottom land vegetation with disturbed habitats related to the bar deposits. After the meander was cut off, the site was surrounded by a wood (*Pinus* and *Betula* including rare *Picea*). The sporadic occurrence of the mesophilous woods most probably is the result of the long-distance transport. These woods have not been documented in this part of Central Europe yet (Bittman 2007). The sand was sedimenting in the Younger Dryas which is the evidence of the unbalanced river water regime. The vegetation was influenced by wet conditions in the alluvium during the late glacial therefore the profile reflects mainly the changes in the vegetation mosaic and not of the overall regional development. A completely different pollen profile has been obtained in Hrabanovská Černava (Petr 2005). This is a former small shallow lake outside the Labe River alluvium. The pollen record represents a prevailing open steppe with a massive occurrence of *Artemisia* and *Helianthemum* and minimum amount of trees. This means that the wood vegetation was limited only on the favorable habitats along the river. According to Chytrý et al. (2008), the continental climate increases dependence of the vegetation on the local geomorphologic conditions as it has been shown on the example of the recent vegetation in south Siberia.

In the West Carpathians, palaeobotanical studies reconstructed Glacial boreal forests in middle altitudes with dominant trees such as *Picea abies*, *Pinus cembra*, *Larix decidua* (Jankovská 1988, Jankovská and Pokorný 2008). Presence of coniferous trees during the Full Glacial is confirmed for both the Outer and the Inner Carpathians (Jablůnka and Šafárka sites - Jankovská et al. 2002, Jankovská and Pokorný 2008). At the same sites, pollen of the mesophilous deciduous trees has been found (e.g., *Carpinus*, *Tillia*), but it was interpreted as long-distance pollen dispersal. In 1990s most papers postulated the glacial tree refugia in south European mountains as the Balkan, the Apennines and the Iberian Peninsula (Lang 1994, Taberlet et al. 1998). According to other recent papers (Ložek 2005, Birks and Willis 2008) the glacial refugia of many present-day species of the mesic forests were situated more to the north. The Carpathian mountain arch now appears the most prominent ‘cryptic’ refuge for the cold-tolerant boreal species. Several recent studies, however, also start to bring evidence of glacial survival of some characteristic components of temperate forests. Charcoal and pollen records situated (Magyari et al. 1999, Willis at al. 2000) document broad-leaf trees through LGM near north Hungarian border. Pollen of temperate tree taxa such as *Fagus*, *Carpinus*, *Taxus* and *Coryllus* has been found in the putative LGM layers also directly in the West Carpathians, however, no firm conclusions could be drawn because of missing radiocarbon dating (e.g., Krippel 1986). In two sites in central part of West Carpathians full glacial mollusc assemblages containing strictly temperate forest species has been also recorded (Ložek 2005). In addition, recent phytogeographical study of beech-forest understory species shows low dispersal potential of such taxa and indicates survival of whole beech forest endemic species assemblage in the Carpathian region (Willner et al. 2009). Collectively, the incised valleys of west Carpathians might have hosted in environmentally favourable pockets with suitable conditions for survival of whole temperate forest communities (as suggested by Stewart and Lister 2001, Willis et al. 2000). On the other hand, these preliminary indices have not been already comprehensively supported. In the phylogeographic study of *Fagus*, its survival in Carpathians was only slightly indicated by the isozyme data (its northern refugia were placed to areas further to the west according to the fossil evidence, Magri et al. 2006). Within the studies dealing with fossil material, majority of them have documented temperate forest taxa (mainly trees) only in the relatively mild periods (interstadials) of the glacial but not during the harshest LGM period (e.g., Willis and van Andel 2004). The evidence of a continuous survival even during the LGM is a crucial part in demonstrating the ‘real’ glacial refuge (Sommer and Zachos 2009). For example, the only deciduous tree seriously documented in the macrofossil studies during LGM is the hardy boreal and tundra *Betula* spp. (Willis van Andel 2004). Taken together, further more intensive screening directly in the refugial areas (i.e., West Carpathian valleys and their immediate vicinity) is crucial for assessing the LGM *in situ* survival of the temperate forest components. However, evidence of the mesophilous trees occurring in the Hungarian lowlands during the Full Glacial has been provided recently (Willis and Sümegi 2000). According to the phylogeographical data and biogeographical analyses, such refugia might occur directly in the West Carpathians (see Magri 2008 for *Fagus*; Tollefsrud et al. 2009 for *Picea* and Willner et al. 2009 for understorey species), but direct palaeoecological evidence is rare.

The continental and northern species recede to the north and east. Some of the species characteristic for the last glacial died out. The large mammals (Mammoth, hairy Rhinoceros and the cave bear) can serve as an example (Musil 1997). The fast climatic changes at the end of the Pleistocene period leading to decrease of the population number in combination with the activities of the Paleolithic hunters most probably had the major influence on the process of the species loss (Mithen 2003, Barnosky et al. 2004, Stuart et al. 2004). Herbivore species were characteristic for the glacial mammal groups and it is the evidence of a high production of the plant biomass (so called Mammoth steppe) along the findings regarding the population densities (Walker et al. 2001). Similar drastic changes have been documented in the structure of the vegetation. It still has not been clarified to what extent the species loss occurred in the case of the biomass. Many species (e.g. *Ephedra*, *Pinus cembra and Larix*) receded from their glacial extension which reached from the east up to the region of the Czech Republic (Jankovská and Pokorný 2008). Some of the species which are only scarcely represented today were more frequent (e.g. *Hippophae rhamnoides*) (West 2000). Some relict mosses can serve as another example; it was abundant in the lowland during the last glacial (Hájková et al. 2012). These species had their refuge in the Holocene period and optimum in the glacial conditions.

Early Holocene

Basis of the Holocene is dated to 11 650 cal. BP. The transition is recorded in the glacier bore from the Greenland glacier (GRIP 1993, Alley et al. 1995). A detail record is known from the annually laminated lake sequences from Germany (Litt et al., 2001) or Poland (Ralska-Jasiewiczowa 2003). The increase of temperatures (Mayewski et al. 2004, Rasmussen et al. 2007, Starkel 2011) meant beginning of migration of many thermophillous elements to the present habitats (Lang 1994). The main directions of these migrations lead from the foothills of the Alps and from the West Carpathians or from Balkan (Hewitt 1999). It is key change of character of the entire Central European nature occurred on the turn of the Late Glacial and the Holocene.

The turn of the glacial and Holocene epochs is visible in medium elevations on many sites in the Czech Republic (Rybníčková and Rybníček 1996, Kuneš et al. 2009). Třeboň Basin (Rybníčková 1982, Jankovská 1987 Pokorný 2002) and Českomoravská Highlands (Rybníčková and Rybníček 1988) belong to the pallynologically well-surveyed regions. The rates of the birch and pine pollens increase whereas NAP decreases. *Ulmus* appears to be the first one of the leafy woods then other woods begin to spread (Chytrý 2012). The biostratigraphic division of the Holocene is based on the chronology of expansion of the leafy woods in Central Europe (Firbas 1949).

The Central European mountain ranges already are without ice and vegetation starts to spread to higher elevations and move the upper forest limit. This process has been documented in the vicinity of the Černé jezero in paleobotanic and sedimentary records (Vočadlová et al. submited). First, the pioneering wood species began to spread (*Pinus, Betula pendula/pubescens, Betula nana*). Similar process has been documented on the sites in Krkonoše – Labský důl (Engel et al. 2010). Expansion of the wood occurred later than in Šumava due to the geographic position of Krkonoše. Interpretation of the pollen specter remains the problem of the mountain sites given by the large altitudinal gradient of the mentioned sites. Therefore, it is difficult to reconstruct expansion of the broadleaf trees (*Quecetum mixtum*) to the higher elevations. It is highly probable according to their representation in the pollen diagram which is larger than today.

The Holocene increase of temperatures is visible through rapid increase in amount of the *Pinus* and *Betula* pollens in the Czech basin. This process is well-documentable in Hrabanovská černava (Petr 2005) or former Komořany Lake (Jankovská 1988, 2000). However, no changes occur in the pollen record on the Chrást site (Petr et al. in press) because the site was covered with wood during the glacial period. Other taxons are exceeded by overproduction of the pine pollen therefore *Artemisia* or even *Helianthemum* have been recorded only marginally. It is difficult to record the vegetation mosaic palynologically (Fyfe 2007). Comparison with the malacozoological evidence from the lower stream of the Ohře River, which is environmentally related to the Labe River region than to the carst regions differing in the limestone bedrock and remarkable geomorphologic gradients, is observable (Ložek 1992). Various types of open habitats including the steppe ones (Ložek 1973, 1982) have been noticed for the Early Holocene of the lower stream of the Ohře River area which exclude existence of the dark dense wood. A gradual migration of the leafy woods (*Ulmus*, *Quercus*, *Tilia*, *Corylus* and *Fraxinus*) occurred around 8 200 BP according to the Hrabanovská černava profile (Petr 2005). No significant peak *Corylus* has been documented in the lowlands as it has been identified in the medium and higher elevated sites (Firbas 1949, Rybníčková and Rybníček 1996). A massive appearance of the hazel tree is typical for the Boreal. However, the reasons remain unclear (edaphic conditions, climate). The mixed oak woods prevail on the loess sites (e.g. charcoal record from the Neolithic site of Bylany, Peške et al. 1998). Their pollen record from the Middle Holocene is known only in the Labe River floodplain (Dreslerová et al. 2004). However, it probably is only a reflection of specific conditions of the multifarious floodplain. The changes in the floodplain vegetation are given mainly by the geomorphologic changes and formation of the floodplain levels. This phenomenon is manifested not only by succession in the former meanders but also in accessibility of the area for human activities. Therefore, the pollen record in the Labe River floodplain cannot easily be approximated for the entire lowland.

The regions of the West Carpathians and the Pannonia lowland are characterized by specific geological, geomorphological and climatic conditions and wide diversity of the vegetation where the Carpathian, Panonian and Central European phytogeographic regions meet (Meusel et al. 1992). This diversity was significantly influenced by the environmental changes on the turn of the glacial and Holocene period. The Holocene palaeoecological studies in the West Carpathians are unevenly distributed. The largest amount of data is available from Poland – a sequence from the Late Glacial till recent in the High Tatra Mts (Obidowicz 1996), Holocene sequences in the Polish part of Beskydy Mts (Obidowicz 2003, Margielewski and Zernitskaya 2003, Margielewski et al. 2003, Margielewski 2006) and in the Bieszcady Mts (Harmata 1987, 1995, Ralska-Jasiewiczowa 1972, 1989, Ralska-Jasiewiczowa et al. 2006). Later, radiocarbon-dated sequences dating back to the Late Glacial or Early Holocene were studied in the Outer-Carpathian Orava region (Rybníček and Rybníčková 2002), Inner Carpathian intermountain basins in the Liptov and Spiš regions (Rybníček and Rybníčková 1985, Jankovská 1988, 1998) and from lakes in the High Tatra Mts (Hüttemann and Bortenschlager 1987, Rybníčková and Rybníček 2006). Late Holocene springs were investigated by pollen, macrofossil and malacological analyses in the crossborder area between the Czech and Slovak Republics (Jankovská 1995, Rybníčková et al. 2005). Other Late Holocene sequences come from the NE parts of the Outer West Carpathians (Wacnik 1995, 2001) and from the Kremnické Mts, a small neovulcanite mountain range in the Inner West Carpathians (Rybníček and Rybníčková 2009). In the Romanian East Carpathians, an area which is environmentally comparable with our study area, some palaeoecological studies have been carried out (Björkman et al. 2002, 2003, Feurdean 2005, Feuerdan and Bennike 2004, Feurdean et al. 2007a, b, Wohlfarth et al. 2001, Rösch and Fischer 2000).

The Holocene lakes are found in Europe especially in the regions influenced by the last (Weichselian) continental glaciation or by the local mountain glaciation (Ehlers et al. 2011). Therefore, the lakes in the Central European which were not influenced by glaciation much are quite rare. The same phenomenon is observable also in the regions of the West Carpathian and Pannonia (Buczkó et. al 2009) where the lake sediments are very rare. Apart from the High Tatra (Rybníčková and Rybníček 2006), such sediments have almost never been researched in Slovakia (Buczkó et. al 2009). The well-know paleolimnologic sites are found in the Tisa River region (Magyary et al. 2010), in the vicinity of Balaton and then northward from Carpathian in Poland (Wacnik 1995, 2001). The Lateglacial has been identified on the site of Vracov in South Moravia (Rybníček and Rybníčková 1972, Svobodová 1997), it is a former lake. The early Holocene has been documented on the site of Čejč (Břízová 2009) and Dvůr Anšov (Svobodová 1997) and the early Holocene on the site of Svatobořice – Mistřín (Svobodová 1997). Evidences of several spring areas from the Holocene are known from the west edge of Carpathian (Rybníčková et al. 2005, Rybníček and Rybníčková 2008).

The evidences of the vegetation development in the Holocene in the West Pannonia lowlands (Slovakia) are considerably old. Kripell (1963, 1965, 1986) has processed 2 pollen profiles in the Záhorská lowland (Cerové – Lieskové, Zelienka) which cover the entire Holocene. The sites of Pusté Uljany (Krippel 1965) and Šúr (Kinzler 1936) are known from the Danube River lowland. The results show prevalence of the conifers in the glacial period and it has also shown majority of the leafy woods in the Early Holocene and the human impact in the Late Holocene. The turn of the glacial and the Holocene epochs is represented by a rapid decrease of the *Pinus* pollen. The woods of the *Quercetum mixtum* community expand (*Quercus*, *Corylus*, *Ulmus* and *Fraxinus*). The beginning of the Holocene is characterized by appearance of *Fagus*. Its expansion at the beginning of the Holocene was limited by the ridges of the Malé Karpaty mts. It expands to South Moravia (Vracov and Anšov sites, Svobodová 1997) at the beginning of the Middle Holocene when it starts spreading in Central Europe (Margi et al. 2008). Questions of openness of the European Holocene forests (Vera 2000, Mitchell 2005, Fyfe 2007) still remains unanswered. There is a relatively steady rate of the *Graminae* and mainly *Arthemisia* pollen. *Arthemisia* generally receded as the result of the forest expansion and temperature increase at the beginning of the Holocene (Lang 1994). Similar character of the vegetation was also in Hungary where the open forest with many steppe elements is presumed (Magyari et al. 2010). That means that the landscape was covered with an open forest which was of the steppe character on several places. The Santovka site in the Ipel Highlands (Petr et al. 2012) can be seen as the other evidence. It is a narrow valley in a travertine mound filled with organic sediments. The preliminary results show mixture of the forest and steppe molluscs. There is a considerable amount of the heliophilous woods, e.g. *Cottynus cotigria*, *Staphylea pinata* and *Cornus mas*. This fact supports the theory of the open forest even though that the AP/NAP ratio is about 95%.

The subsistence strategy of the Central European inhabitants, i. e. introduction of agriculture, use of pottery, occurred around 7 500 BP (Stäuble 1995, Whittle 1996). The first Central European farmers, who spread from the Balkan Peninsula and the Pannonian Basin, have unified archaeological character including the settlement structures with the longhouses and pottery (Thorpe 1996, Zvelebil 2004). They are members of the so called Linear Pottery Culture (LBK, Linearbandkeramik) according to the pottery decorated in a characteristic manner (Modderman 1988). The process of neolithization is related to an extensive shift in the Prehistoric society (Weisdorf 2005) and also representatives of a homogenous material culture in majority of the European regions. The Linear Pottery Culture spread in the fertile loess regions of Central Europe. The first emergence of the first cultural crops is related to the Neolithic inhabitants as well. The diet consisted of the *Triticum monococcum, Triticum dicoccum* and some other plants like *Pisum sativum*, *Lens lenticularis*, *Linum usitatissimum* and *Papaver somniferum* (Barker 2011, Kreuz and Schäfer 2011). The Neolithic wooden wells from Saxony (Tegel et al. 2012) yielded an unusual insight into the Neolithic world. There is evidence of existence of at least 300 years old oaks in the vicinity of the continual settlement which excludes theories about massive deforestation. The oak wood in well contains traces of the *Cerambyx cerdo* beetle which serves as the evidence of a favourable climate of that period.

The following period of the Holocene is characterized by increasing human impact. The most intensive impact is visible in the lowlands in Central Europe and on the medium elevated sites according to the pollen profile. However, it expands to the Czech mountains even in the Prehistory where it most probably influenced the extent of the alpine forest-free areas (Novák et al. 2010). After Middle Age colonization increase in the number of inhabitants; changes in agriculture and expansion of neophytes are visible in pollen spectra, too.

Aims of the thesis

1 – Pollen record evidence of the Pleistocene/Holocene boundary
2 – Diversity of the vegetation and environment during the Lateglacial in different regions and altitudes of Central Europe
2 – A Comparison of the Bohemian massif, the Carpathians and Pannonia
4 – Linking of the pollen record with other proxies like macrofossils, sedimentology and geochemistry

Šúr – a former Lateglacial and Holocene lake at the westernmost margin of the Carpathians

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Abstract

The former lake Šúr near Bratislava in western Slovakia holds a unique paleolimnological record of the Lateglacial and Holocene periods. The aim of this study was to reconstruct the development of the locality, including the gradual infilling of the lake. We reconstructed the development of the lake environment by combining results from a geochemical analysis with analyses of diatoms and plant macro-remains. We also carried out a pollen analysis to assess changes of surrounding terrestrial vegetation. Our results allow us to describe how the character of the lake changed over time. At the peak of the glacial period, it was a flow-through lake with sand deposition. Fluvial activity later ceased, and the locality became a vast oligotrophic lake. During the Holocene, gradual eutrophicaftion of the lake took place, to the point that the environment was almost halophilous. The pollen record contains evidence of the occurrence of woody species of a broad-leaved forest in the Lateglacial period in the Carpathians. The Holocene has left a record of the expansion of mixed oak forests; *Fagus* and *Carpinus* expanded around 4,500 BP. The development of the Šúr locality is more similar to localities in Hungary than to places situated north and west of the arch of the Western Carpathians.

Key words: Geochemistry, Geomorphology, Pannonia, Paleobotany, Paleolimnology,

Introduction

The regions of the Western Carpathians and Pannonia are characterized by specific geological, geomorphological and climatic conditions, and high vegetation diversity in the contact zone between the Carpathian, Pannonian and Central-European phytogeographic regions (Meusel et al. 1978). The western margin of this region at the same time plays an important role in the florogenesis of central Europe from the point of view of migrations and glacial refugia (Taberlet et al. 1998, Hewitt 1999). The key period for the development of the current vegetation of Western Carpathians is the Lateglacial period and the Early Holocene, when migrations of woodland elements from glacial refugia took place and, conversely, when species of open habitats barely survived (Lang 1994, Ložek 1973). The human influence on the distribution and species composition of vegetation gradually increased in the later period of the Holocene (Lang 1994). One way to reconstruct vegetation development in that period is a paleoecological analysis of natural archives. These archives are mostly represented by peat bogs and fens, and to a significantly lower degree also by lake sediments. The lake environment may exhibit high stability and continuous sedimentation (Cohen 2003). Lakes, moreover, allow us to utilize larger amounts of paleoecological proxy data and thus facilitate cross-verification of results (e.g. the multi-proxy approach). Lake sediments therefore provide a unique paleoecological record not only of the lake environment itself but also of its surroundings. Research of lake sediment fillings requires the use a combination of approaches ranging from paleobotany, sedimentology, geomorphology, geophysics to geochemistry (Bristow and Jol 2003; Hubbard and Glasser 2005). Only in this way it is possible to reconstruct changes in the lake environment in detail and correlate them with climate changes, vegetation and the human impact on the landscape.

Holocene lakes in Europe are distributed mainly in regions affected by the last glaciation, be it continental or local mountain glaciation (Ehlers et al. 2011). This is why lakes are relatively rare in the unglaciated part of central Europe. In the west Carpathians and the Pannonian lowland, lake sediments have been analysed in the Tisicum region (Magyari et al. 2008, Sümegi et al. 2011), around Lake Balaton (Medzihradszky 2005) and then north of the Carpathians in Poland (Obidowicz 1996). In Slovakia, lake sediments have practically not been studied (Buczkó et. al 2009), with the exception of the High Tatras (Rybníčková and Rybníček 2006). In south Moravia, we know the former lakes Vracov (Rybníčková and Rybníček 1972, Svobodová 1997) and Čejč (Břízová 2009).

Palynological localities in the western Carpathians are concentrated in their northern part, mainly in the Orava region and the Podtatranska kotlina basin (Buczkó et al. 2009). The current fragmentary palynological evidence presumes a continuous existence of a coniferous taiga in the area of the Spišská kotlina basin, which is documented from the Fullglacial (site

Sivárňa) (Jankovská and Pokorný 2008) to the Lateglacial period and the Holocene (Šafárka, Jankovská 1988). Comparable are the records from malacozoological localities in the same region (Farkašovo site, Ložek 2005), which show a combination of species typical of forest communities in a glacial environment. From the western edge of the Carpathians there are records from several spring areas of the Holocene age (Rybníček and Rybníčková 2008). Records of vegetation development in the Holocene from the western-Pannonian lowlands (Slovakia) are mostly of older age. Kripell (1963, 1986) analysed two pollen profiles from the Záhorská nížina lowland (Cerové – Lieskové, Zelienka), which contain a record of the entire Holocene. In the Danubian lowland is the locality Pusté Uljany (Krippel 1965, 1986) and the locality Šúr (Kinzler 1936), where the author analysed two profiles taken from its south-east edge. These studies lack radiocarbon dating. Their results show a predominance of conifers in the glacial period, a dominance of broad-leaved woody species in the Early Holocene and a human impact in the Late Holocene. Lastly, there are studies dealing with paleomeanders of the rivers Danube and Váh on the Žitný ostrov island (Pišút et al. 2010) dated to the Late Holocene. It is the locality Šúr which thanks to its area and environment appears to be a suitable locality with paleoenvironmental potential promising to close this gap in the paleoecological evidence.

The aim of the present study is a revision of the locality Šúr, where O. Kinzler (1936) had a profile designated “Pállfi major”. The specific objectives were to: (1) ascertain vegetation changes in the late Pleistocene and at the beginning of the Holocene, (2) to determine the development of the environment of the lake basin, (3) to compare the results with those from localities situated southward, in the Danube and Tisza river basins, and with those lying northward of the Carpathian arch, and (4) to revise older findings and date the most important environmental changes.

Study area and present day environment

The area under study is located in the Danubian lowland below the south-east slope of the Malé Karpaty Mts., approximately 6 km north-east of Bratislava (Fig. 1). From the north, the basin is delimited by the canalized watercourse of the Čierná voda River, from the south and the west by the Šúrský canal and from the east by an Upper-Pleistocene fluvial accumulation terrace (Geological Map of Slovakia 1:50,000, 44–22). The fen covering the basin is a north-west sloping plain between 128 and 130 m a.s.l. The dimensions of the basin are approximately 4.3 by 2.8 km in the north-to-south and east-to-west direction, respectively. The area is made up of Pleistocene and Holocene sediments (gravels and sands of accumulation terraces and organic humolites) overlying neogenous (Pannonian and Sarmatian) deposits (Maheľ 1986). From the north-west, the basin is permeated by alluvial fans of proluvial sediments extending from the valleys of the Malé Karpaty Mts. (Urbánek 1966, Lukniš 1977). The locality was drained in the 20th century (Puchmajerová 1948), which has caused an unbalanced water regime. The entire basin has a high groundwater table, which is evidenced by extensive pools that cover most of the basin during spring snow melting. The mean annual temperature is 10.3 °C, and the mean annual amount of precipitation is 657 mm (Dohnal 1965).

The vegetation of lake Šúr is highly diverse (Majzlan and Vidlička 2010), from aquatic communities to a xerothermic woodland, see D. Füry (2010). Dominant in the Šúr reserve is a boggy, tall-trunk alder forest (association *Carici elongateae* – *Alnetum glutinoseae*). Its appearance is influenced by stagnant water for part of the year, causing phenomena such as prop roots of *Alnus glutinosa*. Meadow and reed vegetation surrounds the boggy woodland itself. Waterlogged meadows are found at the north-west edge of the locality. Communities of the alliance Magnocaricion elatea are tied to the formation of organic sediments and create characteristic hummocks. Communities belonging to the alliance *Phragmition* have developed in regularly flooded places, replacing the original alder woodland. Current water vegetation is limited to an artificial water reservoir (Šúrský rybník) at the south-west edge of the locality and to isolated pools. The so-called Pannonian wood in the vicinity of the village of Černá voda is a sunny oak-hornbeam forest with a xerothermic to halophilous character. Intensive woodland grazing in the past has had a decisive impact on its character. Markedly halophilous vegetation with species such as *Tripolium pannonicum*, *Eryngium planum*, *Artemisia santonicum* subsp. *patens*, *Bupleurum tenuissimum* or *Plantago maritima* is present in part of the Pannonian wood.

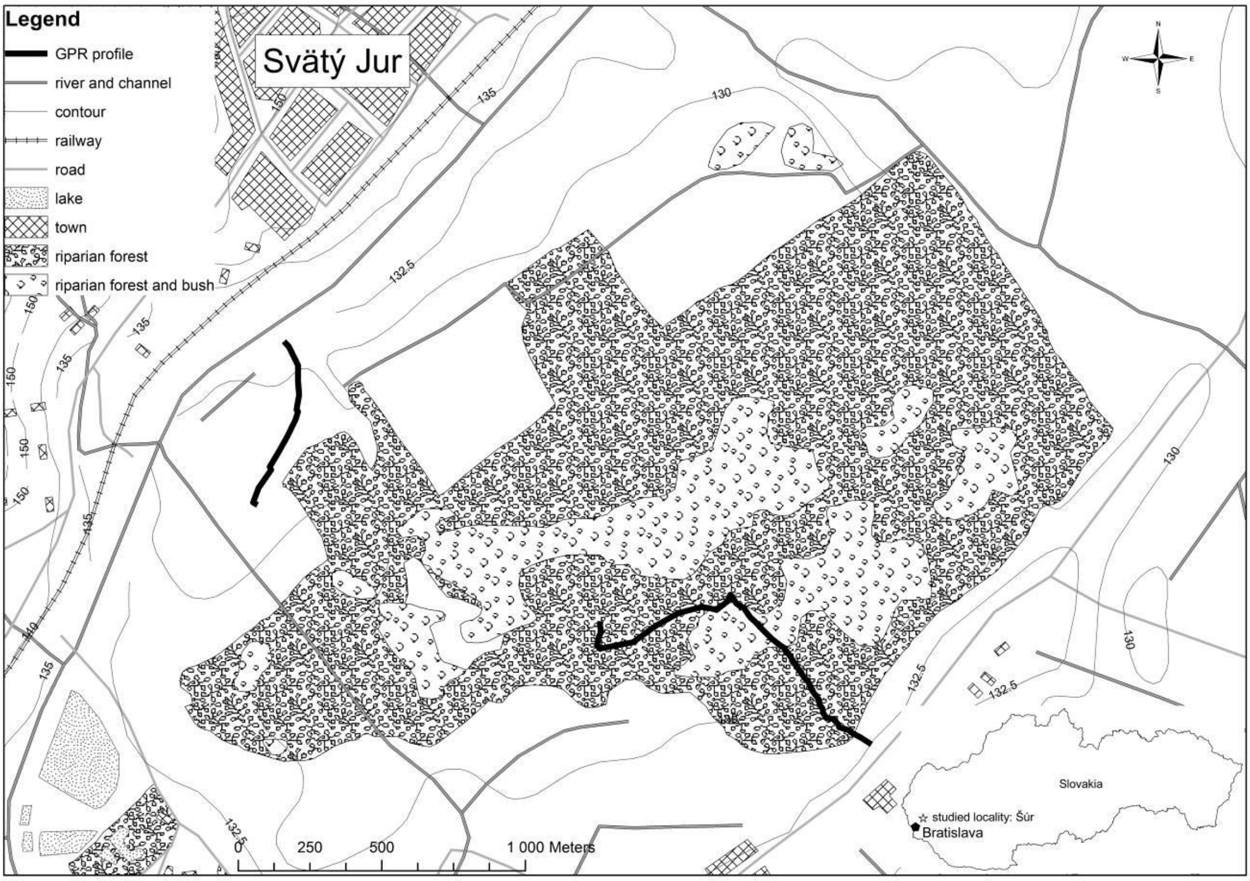

Fig. 1 – Map of Šúr site

Methods

Coring and sediment description

For the purpose of ascertaining the extent and spatial deposition of different types of sediments, GPR profiles (total length of 2,100 m) were created in the studied basin . We used a ground penetrating radar (GPR) - RAMAC - with a shielded Malå 250 MHz antenna. Profile lines were calibrated using regular hand-punched probes at intervals of approximately 120 m. The material from each probe was always described on the spot as to its spatial deposition, colour and granularity. The profile for the paleoecological analysis was taken (based on results of GPR profiling examining the thickness and spatial deposition of sediments and considering the accessibility of the locality) at the south-east edge of the basin (48˚13.893´ N, 17˚14.156´ E, 129 m.a.s.l.). The profile was sampled using an Eijkelkamp peat sampler (uncompressed cores of 5 cm diameter and 50 cm length) from two parallel boreholes to ensure the sampling of a sufficient amount of material for a macro-fossil analysis. In the profile under study, basic characteristics were ascertained describing the amount of the organic and mineral fraction and its chemical composition.

The **weight percent organic matter** in each core was determined by means of **loss-on-ignition (LOI)**. The LOI analysis (550 ˚C) was carried out according to Heiri et al. (2001) and Holliday (2004). The temperature used for drying was 105 °C for 24 hours, and the duration of the combustion was 3 hours. LOI of sediments indicates the rate of allochtonous production of organic material in the catchment and the organic productivity in the lake.

Magnetic susceptibility (MS) was determined using a Kappabridge KLY-2 device (Agico, Czech Republic). The results were normalized to get mass-specific magnetic susceptibility in m^3 kg^{-1} 10^{-9}. Magnetic susceptibility provides information about import of clastic sediments eroded in the catchment area or sediment input by overland flow during floods and mass movements from adjacent valley sides of the Malé Karpaty Mts. (Karlén et Matthews 1992; Shakesby et al. 2007).

Geochemical properties X-ray fluorescence analysis (EDXRF) was performed with a PANalytical MiniPal4.0 spectrometer with a Peltier-cooled silicon drift energy-dispersive detector. The ground samples were analysed after pouring into measuring cells with a Mylar foil bottom. The analyses were not calibrated and recalcutaled to element contents. Measured signals in counts per second (c.p.s.) were plotted, and only their relative changes were evaluated in terms of lithofacial or geochemical changes in the sediments (Grygar et al. 2010). Additionally, EDXRF unequivocally identified the growth of regional industrial contamination during the 20th century (Grygar et al. 2010).

AMS rariocarbon dating was provided by the Center for Applied Isotope Studies, University of Georgia. The quoted uncalibrated dates are given in radiocarbon years before 1950 (years BP). The error is quoted as one standard deviation and reflects both statistical and experimental errors. The date was corrected for isotope fractionation. The radiocarbon calibration program OxCal v4.1.7 (Bronk Ramsey 2009) and the calibration data set of IntCal09 (Reimer et al. 2009) were used for data calibration. Plant macro-fossils and charcoal fragments were used for the dating (Tab 1).

Paleoecological analysis

Samples for the **pollen analysis** were processed in a standard manor following the acetylation method employing KOH, HCl and HF (Moore et al. 1991). Pollen atlases (Moore 1991, Reille 1992, 1995, 1998 a Beug 2004) were used for pollen grain identification. Green algae of the genus *Pediastrum* were determined according to Jankovská and Komárek (2000) and Komárek and Jankovská (2001). A pollen diagram including the ascertainment of local pollen zones was composed using the programme POLPAL (Nalepka and Walanus 2003) including the analyses RAREFRACTION and PCA. The pollen sum in each sample was at least 500 grains. *Alnus* was not included in the sum of arboreal pollen.

Diatom preparation followed standard protocols for siliceous microfossils (Battarbee et al. 2001). Diatom concentration was traced using divinylbenzene microspheres as described in Grygar et al. (2007). We analysed 23 samples from the depths of 55 to 241 cm with resolution increasing with a depth from 10 to 2 cm. A minimum of 500 valves were identified and enumerated in samples within the interval 241–102 using optical microscope Olympus BX 40 at 1,000x magnification. Diatom taxa were identified following Krammer and Lange-Bertalot (1986–1991) and Schmidt et al. (2004) (Fig. 2).

Our analysis of **plant macroremains** was carried out using material obtained at the locality Šúr (Fig xx). The samples (50–120 ml in volume) were macerated in 10% KOH. Extraction of plant macroremains from the sediments followed the standard flotation and wet-sieving procedures (Warner 1988, Pearshall 1989, Jacomet and Kreuz 1999), using a sieve with mesh diameter of 0, 25 mm. Biological remains were picked out from the recovered fraction and scanned using stereo-microscope (x8-x56). Plant remains were identified using keys, atlases and other publications (Velichkevich et Zastawniak, 2006, Katz et al., 1965, Beijerinck, 1947, Cappers et al., 2006) and by comparisons with reference carological collections stored at the Department of Botany, Charles University in Prague. Quantitative and qualitative results are presented in diagrams plotted in POLPAL for Windows (Nalepka and Walanus 2003). The diagram for plant macroremains is divided into 4 local macrofossil assemblage zones (LMAZ; Su 1–4), numbered from the bottom to the top.

Results

Sedimentary settings

The entire part of the basin under study is covered with a fen in different stages of degradation (thickness of 50–150 cm). At the edges of the basin, however, the cover layer contains mineral soil. Below cover formations there are horizontally and subhorizontally laid layers with locally greater thickness. Layered diffractions on the radargrams form simple layers that are parallel or corrugated. These layers correspond to the stratified structure of gravel, sand, silt and loam laminated into thin to thick layers. Besides, composite diagonal diffractions corresponding with thinly to thickly stratified sand occur in the radargram at distances of 200–400 m from the eastern and western edge of the basin.

Based on an interpolation of the results from the sampled boreholes and the obtained radargram, it can be stated that the central part of the basin up to the depth of 5 m comprises a maximum of 3 to 4 periodically repeating layers with a higher content of sand to gravel, which are separated by interlayers 40 cm to a metre thick built of sandy-loam, silty-loam to loam layers. Approximately from the depth of 120–150 cm in the central and eastern part of the basin, the colour as well as granularity of the sediment changes from brown/black-brown to grey, these sediments being composed of alternating layers of intermediate to fine sands and sandy silts. These are followed from 230 to 250 cm of depth by pale grey loams. In the western part of the basin, there is an increase in the proportion of finer-grained fractions containing loams, the thickness of sandy layers is reduced, and their number becomes more variable. Moreover, the layers in this part of the basin are far more curved.

It stems from the above that sedimentation in the basin took place in periodic episodes characterized by a different sedimentation process, which corresponds with a lake environment as well as as with an environment with through-flowing water. There is also an apparent difference in development between the eastern and western part of the basin. In the western part, there is a markedly intensive influx of material from the area of the Malé Karpaty Mts.

Sediment description

The drill core sampled in the south-east part of the basin is composed of several layers (Fig. 2). At the base of the profile there is a fine, grey sand (241–250 cm) followed by a fine, grey organic sediment (198–241 cm) with a thin layer of a finer sand (217 cm). The next layer is a pale-brown organic sediment (92–198 cm) in which a layer is embedded of a greyish-brown organic sediment with a sublayer of coarser organic material (180–183 cm). A layered fen is found at the depth of 80–92 cm. The last layer is a brown decomposed fen peat with frequent wood remains (0–80 cm).

The bottom, sandy part of the profile (250 and 245 cm) contains nearly no combustible material. The proportional LOI gradually increases up to the depth of 237 cm, where it reaches 62%. In layers at depths between 237 and 102 cm, the proportion of LOI varies from 40 to 60%. This is followed by an increase in LOI, with a maximum of 83% at 93 cm followed by a moderate decrease to 65% in the surface layer.

Magnetic susceptibility ranges from 5 to $120 \cdot 10^{-6}$ SI. Elevated MS is at the base of the profile (250–231 cm). There is a distinctive peak at the depth of 87 ad 90 cm, otherwise MS is minimal. An increase occurs in surface layers (20–1 cm).

Three geochemical zones can be distinguished based on XRF proxy element analyses. GZ1, 250–92 cm: Mostly coarse siliciclastics were deposited under conditions of good drainage, i.e. in an open water body. Three episodes when deposited siliciclastics contained more alumosilicates, Ti, and Zr minerals, i.e., relatively less sand, are denoted by arrows in Al/Si log in Figure 2. The relative amount of siliclastics markedly decreased in zone GZ2 (92–45 cm) while substantially increased relative amount of Ca points to much poorer drainage, i.e., to the closing of the originally open water body. The element ratios indicate that silt and/or clay prevailed over sand in the sediment. The increased contents of S and P (not shown) point to eutrofication and an onset of anoxic conditions during and after sedimentation. The amount of siliciclastics is somewhat increased in the topmost layer (GZ3 - 45 cm to top), Ca content is still large, but S content is lower, which can be interpreted as a more oxic environment during sedimentation. The top 10 cm contained enhanced concentration of Zn, a convenient indicator of the most recent regional industrial contamination (Grygar et al., 2010).

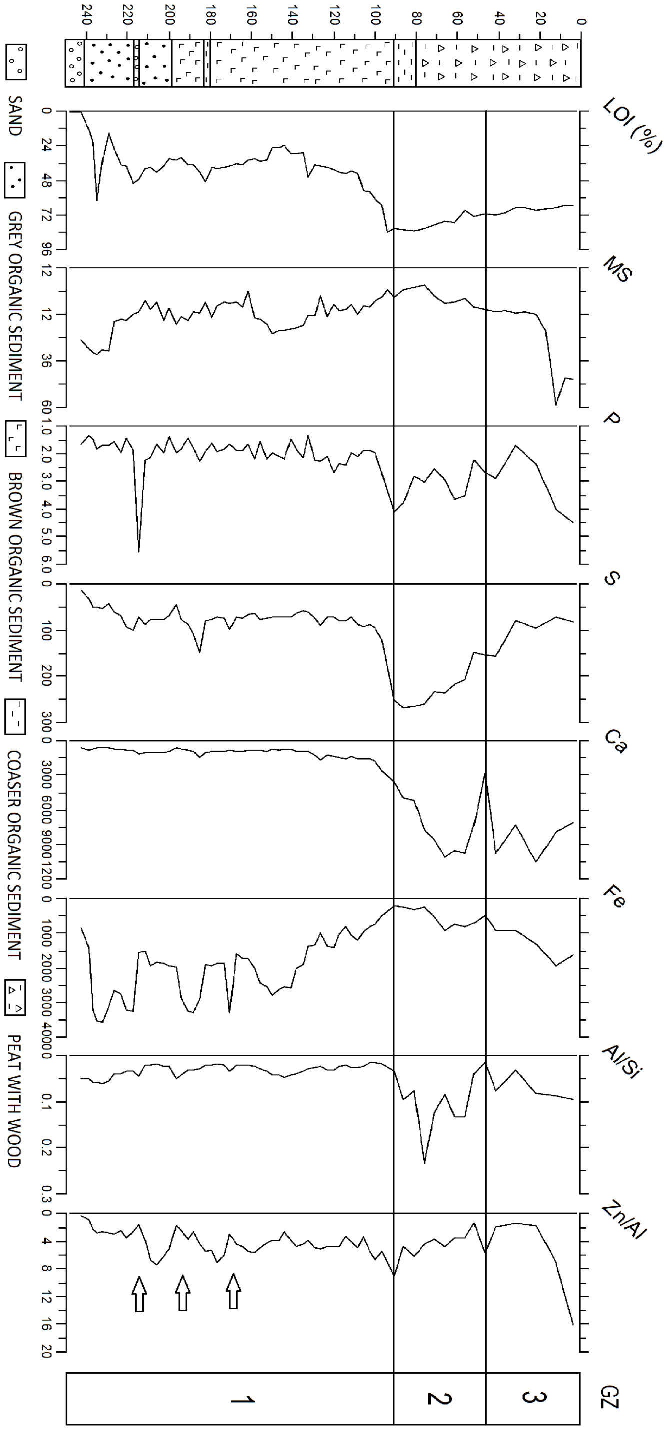

Fig. 2 – Graf of lithological and geochemical properties. Loss-on-ignition (%), Magnetic susceptibility ($\cdot 10^{-6}$ SI) and chemical elemements (mg/kg)

Radiocarbon data cover the time period from 1,480 BC to 28,750 BC (centres of calibration intervals 95% σ) (Tab. 1).

Tab. 1: Radiocarbon dating

Sample (depth)	Lab. code	Material	C14 age	$\delta^{13}C$ ‰	Calibration
87–90 cm	UG–5391	Seeds	3220 ± 25	- 27,9	1530–1430 BC
150–153 cm	UG–5589	Seeds	4600 ± 25	- 20,7	3499–3196 BC
204–207 cm	UG–5590	Plant fragments	4360 ± 30	- 13,3	3085–2904BC
210–213 cm	UG–7547	Seeds	6480 ± 25	- 25,16	5486–5374 BC
219–222 cm	UG–7548	Seeds	7250 ± 30	- 25,62	6215–6051 BC
225–228 cm	UG-5392	Charcoal	7130 ± 50	- 26,3	6079–5898 BC
241–245 cm	UG-5393	Charcoal	25 960 ± 60	- 26,3	29 062–28 521 BC

Pollen zones

LPZ S – 1 (231–241 cm): The AP to NAP ratio is around 90% (Fig. 3). *Pinus* prevails in the woody spectrum (90%). There is a strong presence of *Betula* and *Quercus* of around 10%. Other woody species are represented only marginally: this applies to *Picea*, *Ulmus*, *Tilia*, *Corylus*, *Fraxinus*, *Alnus* and *Salix*. Rarely detected were *Populus*, *Cornus*-type, *Frangula* and *Juniperus*. Grasses predominate in the herb spectrum (5%). *Artemisia*, *Thalictrum* and *Filipendula* exhibit a closed curve. Other taxa were rare: *Hordeum*-type, *Labiatea*, *Calluna vulgaris*, *Asteraceae* subfam. *Cichorioideae*, *Aster*-type, *Ranunculaceae*, *Chenopodiaceae*, *Rubiaceae*, *Urtica*, *Umbeliferae*, *Cannabis/Humulus*-type, *Pteridium aquilinum*, *Potentila*-type, *Rosaceae*, *Pulsatila*-type and *Rumex*-type. Local and wetland vegetation is dominated by sedges, *Potamogeton*, *Myriophyllum spicatum*, *M. verticilatum* and *Typha laifolia*. The spectrum of green algae is mainly represented by the genus *Pediastrum*. Predominating species are *P. boryanum* agg. and *P. duplex*, less so *P. kawraiskyi* and *P. angulosum*. Among other taxa, we detected *Tetraedron minimum* and the genera *Scenedesmus* and *Botryococcos*.

LPZ S-2 (147–229 cm): The AP to NAP ratio varies between 80 and 90%. The woody spectrum is dominated by *Quercus* (20–30%) and *Corylus* (10–25%). Other important woody species with a proportion of around 5% are *Ulmus*, *Betula*, *Picea*, *Fraxinus*, *Tilia* and the newly appearing *Fagus*. A closed curve of *Carpinus* is present above 180 cm. *Alnus* and *Salix* species represent local wetland vegetation. Rarely detected are *Acer*, *Cotinus coggygria*, *Cornus*-type, *Viburnum* and *Sambucus nigra* pollen. The composition of herbaceous vegetation is very similar to the previous zone S – 1. Also dominating are grasses, reaching a proportion of 5–10%. Newly detected are the following pollen types: *Heliantemum*, *Caryophylaceae*, *Carduus*, *Lythrum*, *Campanula*, *Scrophulariaceae*, *Plantago lanceolata*, *Anthemis*-type, *Polygonum*, *Lysimachia*, *Solanum dulcamara* and Cerealia. Local wetland and aquatic vegetation is also identical in composition to the previous zone S – 1. Only *Nuphar*, *Iris* and *Caltha* occur. At the beginning of the zone, there is an increase in the concentration of green algae. Conversely, their concentration markedly decreases at the depth of around 156 cm. This mainly concerns the taxa *Pediastrum boryanum* agg., *P. integrum*, *P. duplex*, genus *Scenedesmus* and *Tetraedrom minimum*. The genus *Botryococcus* does not alter its proportion. *Pediastrum kawraiskyi* completely vanishes in this period. *Pediastrum angulosum*, by contrast, increases its proportion at the end of the period.

LPZ S-3 (93–144 cm): The ratio of AP to NAP remains around 90%. In the woody spectrum, the proportion of beech increases from 5 to 30%. Similarly, hornbeam increases from 3 to 20%. *Corylus*, by contrast, retreats markedly from 25 to 5%. A similar trend is found in *Tilia* and *Ulmus*. The proportion of *Picea*, *Betula* and *Fraxinus* stays constant. Newly present is *Abies*, albeit sporadically. *Alnus* increases its proportion slightly. Rarely detected are *Salix*, *Frangula*, *Acer* and *Viburnum*. The spectrum of herbs is almost identical with the previous zone. Cerealia and *Plantago lanceolata* have an almost closed curve. Local vegetation is also identical with LPZ S – 2. The low concentration of green algae at the beginning of the season shifts at the depth of around 135 cm, where we see an increase in the proportion of *Pediastrum boryanum* agg., *P. integrum,* and partly also *Tetraedron minimum* and the genus *Scenedesmus*. A constant ratio is exhibited by *P. duplex* and the genus *Botriococcus*. The proportion of *P. angulosum* increases moderately. Samples from the depths between 93 and 0 cm are pollen-sterile.

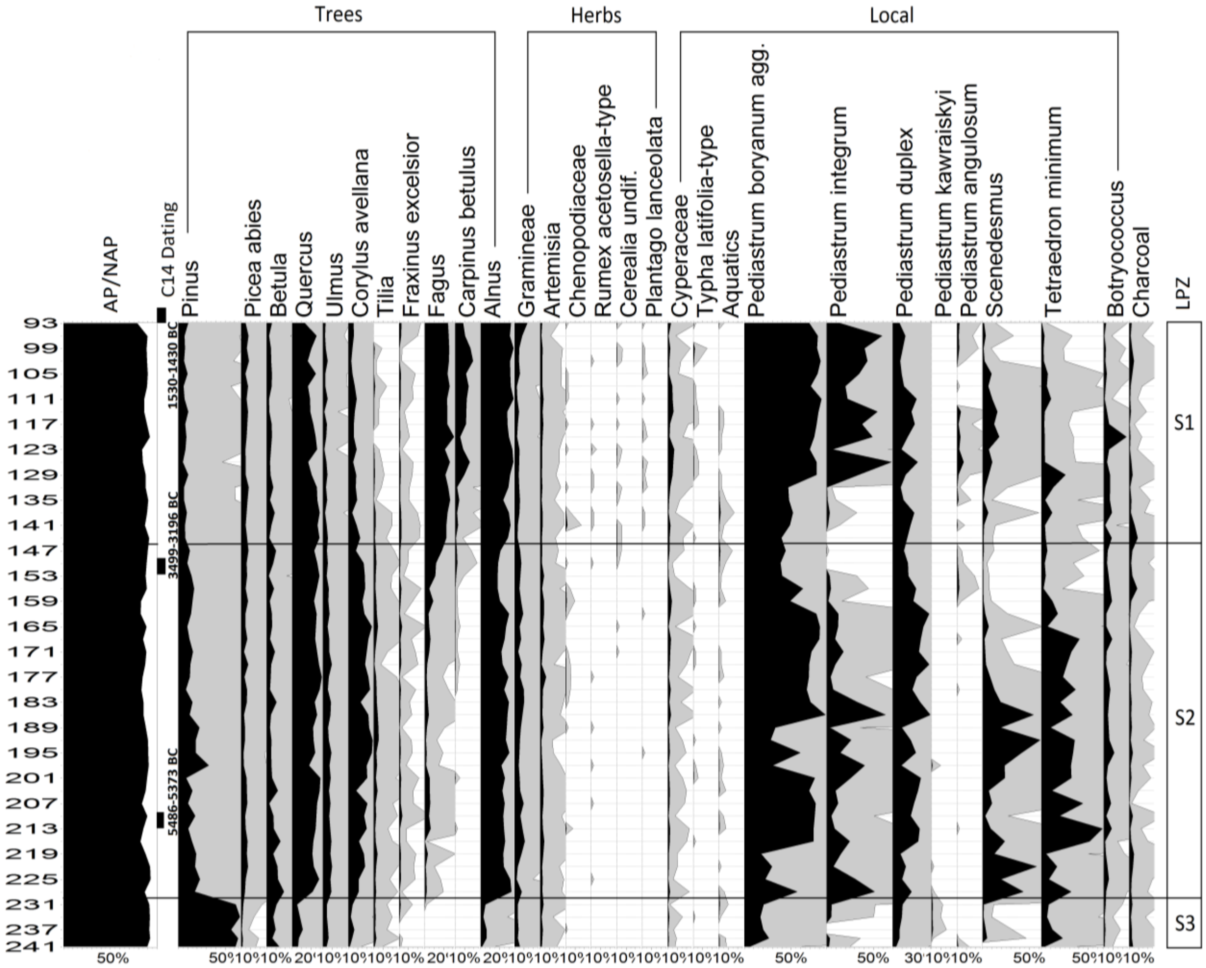

Fig. 3 – Pollen diagram

Macrofossils

LMAZ S-1 (228–250 cm): basal 3 samples: Pioneer phase. Bad taphonomic conditions and fluvial activity (Fig. 4). Earliest plants were aquatic and mire species: *Zannichellia palustris* subsp. *pedicellata*, *Potamogeton* cf. *coloratus*, *Carex* sp. (3 sided) and *Typha latifolila/angustifolia*. The aquatic environment is also indicated by the presence of *Chara* oogonia and *Cladocera* ephipphia at 241 cm, almost at the start of sedimentation. Teeth and bones, probably remains of fish are also present in this zone.

LMAZ S-2 (150–228 cm): 13 samples – good sedimentation and taphonomic conditions of lake sediment (*gyttja*) facilitated the preservation of a number of plant macro-fossils. Present are aquatic macrophytes, wetland and ruderal species, which indicate a higher trophic level of the environment; a number of them are facultative halophytes (marked *). The water environment is documented by species of aquatic macrophytes (*Batrachium* sp.*, *Najas marina**, Nymphaea alba*, Ceratophyllum submersum, Trapa natans, Potamogeton cf. coloratus*, P. filiformis, P. crispus, Zannichella palustris* subsp*. pedicellata**), the most abundant being *Myriphyllum spicatum**, which grows in shallow stagnant and flowing water at depths between 0.2 m and 5 m. The species tolerates low water temperatures and freezing of water, but it also grows in warm waters. It becomes overpopulated in eutrophic waters). Furthermore, there were littoral and bog species growing at water edges: *Alisma cf. plantago-aquatica*, Typha latifolia/angustifolia*, Poaceae, Schoenoplectus lacutstris, S. tabernaemontanii*, S.* sp., *Lythrum* sp., *Lycopus europaeus*, Solanum dulcamara*, Carex pseudocyperus*, Mentha aquatica*, Carex* sp. 3 sided, *Carex* sp. 2 sided, *Juncus sp., cf. Eleocharis.* The species *Cyperus fuscus*, which colonizes exposed sandy pond bottoms and also grows in dessiccating salinate soils, occurred with higher frequency. In addition, there were terrestrial stress-tolerant plant species signifying a high percentage of nutrients in the soil, which are able to colonize salinated substrates: *Urtica dioica, Rumex maritimus*, Polygonum persicaria/aviculare, Persicaria lapatihifolia, Eupatorium cannabinum*, Potentilla cf. reptans**. Unusual is the occurrence of achenes of birches growing on acidic, peaty soils: *Betula nana, Betula nana/humilis* (apparently dispersed by regional transport). Recorded is the occurrence of achenes of the species *Betula* sect*. Albae, Alnus glutinosa* and ovuliferous scales of *Pinus.* An aquatic environment is indicated by the genera *Chara* and *Nitella*, whose oospores occurred with higher frequency. This zone also contains ephippia of aquatic crustaceans of the order *Cladocera*. Also found were calcareous shells of a unicellular protozoan of the phylum *Foraminifera* (redeposition of tertiary marine sediments). The aquatic environment is documented by fragments of scales of the European perch (*Perca fluviatilis*); also found were small bones and pharyngeal teeth. This zone is also characterized by the presence of a larger amount of charcoal (0.5–5 mm).

LMAZ S-3 (114–150 cm): 6 samples, a change of environmental conditions, opening of the forest, high trophic level and salinity. Taphonomic conditions in this zone are favourable; gyttja and fen peat sediment facilitated good preservation of macro-fossils. This zone is dominated by diaspores of aquatic macrophytes: *Najas marina*, Myriophyllum spicatum*, Ceratophyllum submersum, Potamogeton* sp*.,* the most represented is the taxon *Zannichellia palustris* subsp. *pedicellata**, which could be identified down to the subspecies level. Species growing along the shore and on exposed pond bottoms also occur in this zone; many of these species are facultative halophytes*: *Alisma cf. plantago-aquatica*, Cyperus fuscus*, Typha latifolia/angustifolia*, Poaceae, Solanum dulcamara*, Menyanthes trifoliata, Carex sp.* (3 sided, 2 sided)*, cf. Eleocharis, Chenopodium album, Ch. Rubrum**. Achenes of *Alnus glutinosa* were found, too*.* A very important taxon in this zone is *Chara* sp*.,* which dominates in the macro-fossil record, accompanied by *Nitella* sp*.* Also present were ephippia of crustaceans of the order *Cladocera* and scales of *Perca fluviatis*. Pharyngeal teeth of cyprinid fish are preserved in this zone, too.

LMAZ S-4 (10–114 cm): 12 samples. The lake disappeared and turned into an indundated alder wetland with a high water table and periodically occurring pools. Aquatic species of vascular macrophytes in this zone were represented only by *Ceratophyllum submersum* and *Lemna minor/gibba*. Algae of the genus *Chara* and crustaceans of the order *Cladocera*, too, confirm the presence of open water. Dominant are *Typha latifolia/angustifolia* accompanied by other littoral species: *Lycopus europaeus, Solanum dulcamara, Urtica dioica, Carex pseudocyperus, Carex diandra, Carex sp. (3 sided), Carex vulpina* and *Juncus* sp*.* Exposed bottoms of periodic pools were colonized by *Cyperus fuscus.* Another species which occurred was *Urtica kioviensis*, a continental taxon growing at edges of pools*.* Achenes of the species *Alnus glutinosa* are rare but suggest the presence of an alder carr. The occurrence of the species *Bidens frondosa* at this depth indicates possible contamination. Terrestrial light-loving species were represented by *Fragaria vesca* and *F. viridis.* Also present were fish bones and charcoal (0.5–2 mm).

LMAZ S-5 (0–10 cm): 1 sample (surface sample) contains a record of current vegetation. There are macroremains of aquatic plants: *Lemna minor/gibba* (seeds) and ephippia of crustaceans of the order *Cladocera*. Alder carr species are represented by *Solanum dulcamara* (seed)*, Carex* sp*.* (3-sided nutlets)*, Urtica dioica* (nutlet) and *Alnus glutinosa* (fruit).

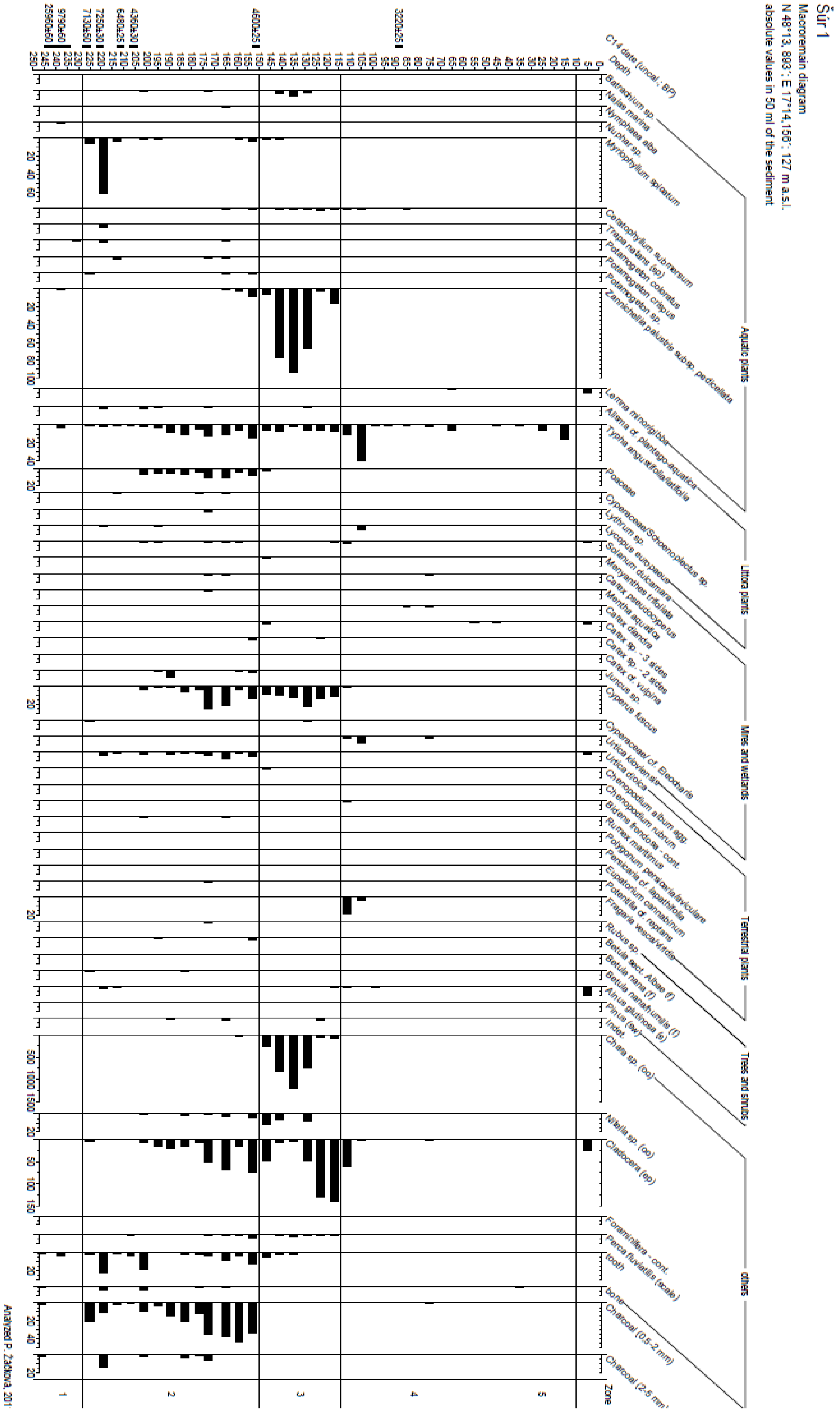

Fig. 4 – Macrofossile diagram

Diatoms

Diatom assemblages in the samples 102–241 cm (Fig. 5) are composed almost entirely (~90%) of small, colonial, alkaliphilous *Fragilaria* taxa sensu lato (e.g., *Staurosirella* or *Staurosira*), including *Staurosirella pinnata* , *Staurosira construens*, *S. pseudoconstruens*, *S. binodis* and *Fragilaria brevistriata*. At least three major changes in conditions within the lake are easily discernable thanks to a major decrease in diatom concentrations (Fig. 5) captured at 228–225, 153–144 and 102–93 cm. The latter concentration decrease was probably connected with lake burial, which could also explain the absence of diatoms in the following decimetres. We did find diatoms communities in younger sedimentary parts but in very low concentration ($2*10^6$ /g) and of different composition than in the lake period dominated by *Fragilaria* sp. s.l. The most abundant genera were *Gomphonema*, *Cocconeis*, and *Aulacoseira.*

Based on changes in diatom assemblages, we define the following diatom zones (LDZ):

LDZ S-1 (241–231 cm) nutrient-poor shallow water lake stage: total diatom concentration increased gradually to its highest value ($1\ 100\ *10^6$ /g). This zone is characterized by dominance of *S. pseudoconstruens*, and the highest concentration of *S. pinnata*.

LDZ S-2 (228–225 cm): diatom concentration decreased sharply to more than half of the value from the previous zone. *Fragilaria brevistriata* and *S. leptostauron* concentrations increased as *S. pseudoconstruens* and *S. pinnata* decreased. Among other species that appeared in both zones are *Aulacoseira* spp., *Cymatopleura solea* and *Navicula* spp., mainly *N. viridula*.

LDZ S-3 (219–162 cm): diatom concentration values gradually decreasing from 773 to $439\ *10^6$ /g. A slight concentration decrease of the dominant *S. pseudoconstruens* and *S. pinnata* and a slow relative increase of *F. brevistriata* is evident in this zone. This sequence can be related to higher nutrient income to the lake.

Sample at 153 cm: Unique in the diatom concentration minimum and a relatively high concentration of diatom species other than *Fragilaria* s.l. formed mainly by planktonic *Aulacoseira* spp. and the large *Cymbella ehrenbergii*. Diatom species composition points to strictly aquatic environment.

LDZ-4 (144–93 cm) eutrophic water body with low water level: After maximum of *S. binodis*, which appeared at the beginning of the zone, became dominant species *F. brevistriata*, which lives in eutrophic and alkalic waters,. The end of the zone was dominated by other species, most commonly *Amphora veneta*, and *Cocconeis placentula. A. veneta* as well as other present species in the end of this zone, e.g.*Neidium ampliatum*, *Gomphonema* and *Pinnularia spp.* survives in regurarly wet and moist conditions (VanDam et al. 1994).

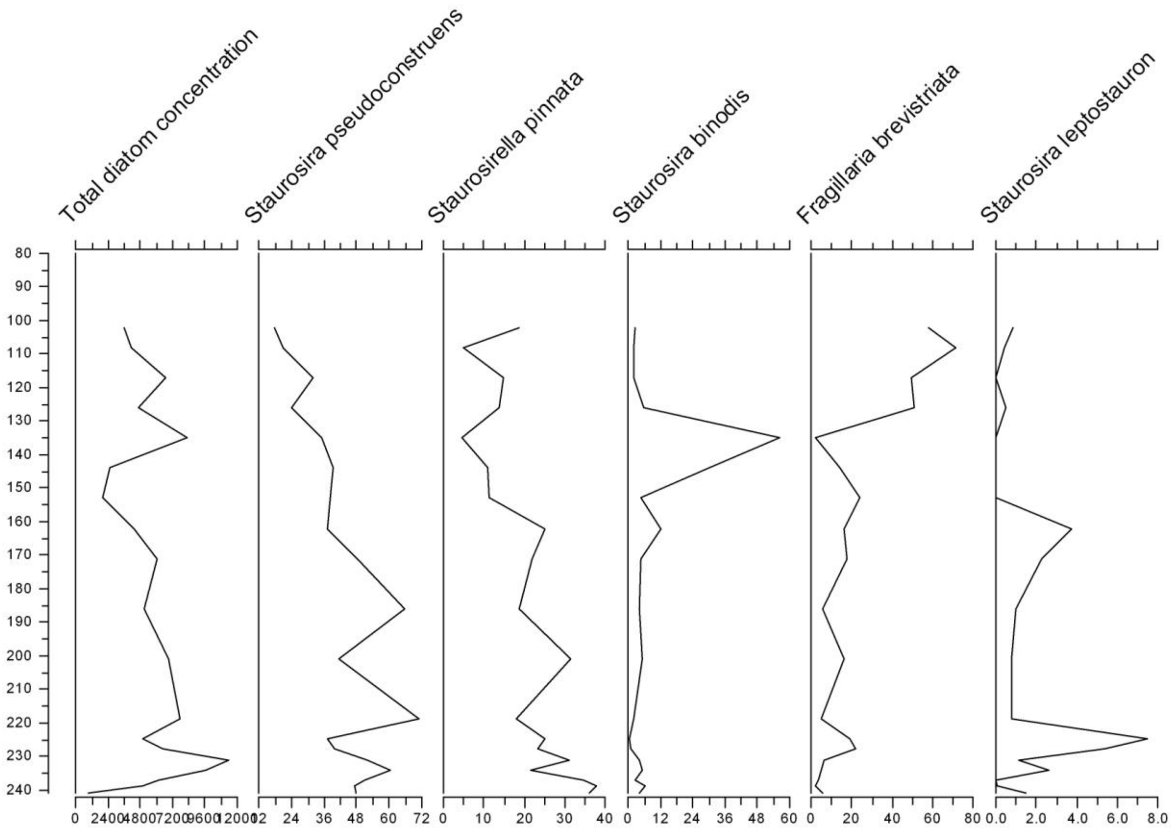

Fig. 5 – Diatom diagram

Discussion

Lateglacial period

The lake basin under study is part of a neotectonically active (Ruszkiczay-Rüdiger et al. 2005) subsidence depression margining the eastern foothills of the Malé Karpaty Mts. (Maglay 1999). The distinct character of sedimentation in the western part of the basin captured by the ground penetrating radar (Fig. 1) as well as punched probes suggests transport of material from the Malé Karpaty Mts., which is documented also by morphologically conspicuous alluvial fans (Urbánek 1966) extending into the basin. The detailed development of the Danube River basin around Bratislava is known only in the Late Holocene (Pišút 2002, Lehotský et al. 2010). It is therefore a question whether the layer of well sorted sand dated to 25,000 BP bears upon the fluvial activity of the Danube River (Gábris Gy. 1994, Gábris and Nádor 2007) or whether it is material carried down from the Malé Karpaty Mts.. But considering the short distance to the slopes of the Malé Karpaty Mts., the sand from the latter area would not be sorted so well. In any case, significant neotectonic activity took place in this region during the Pleistocene (Nádor et al. 2003, Gábris and Nádor

2007). It coincided with climate changes, which influenced not only the river regime (imbalanced water flow), behaviour (fluvial activity, branching) and the paths of watercourses but also their erosive activity (changing longitudinal profile, water content and vegetation) (sensu Vandenberge 2003). These changes are reflected by the variable sedimentary record from the locality Šúr. The underlying fluvial sand contains carbonified pieces of wood and pine bark dated to 29,062–28,521 BC. Further numerous charcoal found in fluvial sand correspond with an increased incidence of fires in cold periods of the last glacial period (Daniau et al. 2010) and more intense erosion (sensu Vandenberge 2003).

The pollen spectrum at the locality from the Lateglacial period is similar to localities situated in the Tisza basin from the Lateglacial period (Willis et al. 1995, Jakab et al 2009, Magyari et al. 2010). Besides the prevalent pine, mesophilous deciduous woody species are represented (*Corylus*, *Quercus*, *Ulmus* and *Tilia*). These broad-leaved woody species survived the LGM right in the Tizsa River basin (Willis et al 1995, Willis et al 2000, Willis and Andel 2004). Also significant is the paleoecological record of the Lateglacial period (47,000 ± 2,300 uncalBP to 25 050 ± 530 uncalBP) from the nearby paleolithic locality "Dzeravá skála" Cave (Kaminská 2005). This corresponds with charcoal assemblages dominated by *Pinus*, *Betula*, *Salix* and *Picea*; less frequent are *Larix*, *Corylus*, *Fagus* and *Ulmus* (Hajnalová and Hajnalová 2005). The profile also contains skeletal material of small woodland mammals (Horáček 2005). Layers from the LGM and Lateglacial period, however, also contain archaeobotanical material from the aeneolithic period (Hajnalová and Hajnalová 2005), so they can hardly be interpreted as proof of surviving woodland communities in the Lateglacial period in the Malé Karpaty Mts.. Direct evidence proving the survival of mesotrophic woody species is missing in the Lateglacial period in the sub-Tatran basins (Jankovská 1988, Jankovská and Pokorný 2008). The sporadic presence of their pollen is probably a result of their long-distance transport (Jankovská 1988). At the analysed locality Šúr, by contrast, the proportion of pollen of deciduous woody species is high, which indicates their local presence in the Lateglacial period. The discovery of *Betula nana* at the Šúr locality (depth of 228 cm), which is today extinct in Slovakia (Hendrych 1998), suggests the distribution of boreal and alpine species in the glacial period. Basal fen peat layers of Lake Balaton (Czerny and Nagy-Bodor 2000, Cserny and Nagy-Bohor 2005), for example, document tundra elements such as *Dryas octopetala*, *Betula humilis* and *B. nana*. This together with pollen evidence of *Helianthemum* and *Pulsatilla* from the Šúr profile reveals a combination of xerophilous and boreal species in the glacial period.

The lake had an oligotrophic character at the end of the glacial period. The lower proportion of green algae in the palynomorph spectrum at the depth of 231–241 cm is related rather with an oligotrophic environment and a colder climate than with a lower waterline in the lake. Also detected is the cold-loving species *Pediastrum kawraisky*, which today is distributed in north-east Europe (Komárek and Jankovská 2001). *Pediastrum kawraisky* is known from the Lateglacial period also from similar localities such as the Komořanské jezero Lake (Jankovská 2000) or from the Czech Cretaceous Basin in central Bohemia (Losert 1940, Petr 2005).Recent occurrence of small fragilaroid species of diatoms is bound to Arctic lakes (e.g. Antoniades et al. 2007, Guilizzoni et al. 2006, Ilyashuk et a. 2009) and mountainous regions (Schmidt et al. 2004). These lakes are usually small (up to 1 km) and oligotrophic. They have an extended ice cover and are fed by meltwater from glaciers. Considering the local conditions within each site, these lakes could have formed in different periods. We, however, suggest that the post-glacial period made central Europe a region with the ideal conditions for these newly formed lakes. Cosmopolitan fragilariod species might therefore be used as a biostratigraphical marker within small areas of central Europe. We compared the results of our analysis with those from two other sites: former lake "Velanská cesta" in south Bohemia (Bešta 2009) and buried lake in the floodplain of the Morava River near the village of Rohatec in south Moravia (A. Píšková, unpublished results). Both these lake sediments contain a phase dominated by small *Fragilaria* taxa, namely *S. pinnata*, *S. construens* and *S. pseudoconstruens* – associated mainly with the Allerød period. The concentration of plant macro-fossils is low and corresponds with an aquatic environment. A limnic environment is documented by the macrophyte species *Nuphar* sp., *Zannichellia palustris* subsp*. pedicellata,* which implies waters with higher salinity, and *Potamogeton coloratus*, which occurs in clean, more likely stagnant and shallow basic waters (Hollingsworth 2010). Also present is *Typha*, which colonizes the littoral zone of lakes. Also found were ephippia of aquatic crustaceans of the order *Cladocera*, pharyngeal teeth of fish and small pieces of charcoal. From these findings, we can reconstruct a shallow oligo- to mesotrophic lake in an environment of increased erosive activity.

Holocene

The break of the last glacial/Holocene periods manifests in the profile as a rapid drop in the amount of *Pinus* pollen. At the same time, there is an expansion of woody species of the *Quercetum mixtum* community such as *Quercus*, *Corylus*, *Ulmus* and *Fraxinus*. The canopy of the surrounding woodland is not entirely closed. There is a distinct proportion of *Artemisia* pollen, which indicates disturbed habitats and is typical of the glacial period. The surrounding subsoil probably has an influence as well – terrace gravelous sands. *Fagus* appears at the beginning of the Holocene. Its spread at the beginning of the Holocene was, however, limited by the ridge of the Malé Karpaty Mts.; at south-Moravian localities (Vracov, Anšov, Svobodová 1997), it starts to occur only at the beginning of the mid-Holocene, when it spreads through central Europe (Margi 2008). The expansion of *Alnus* at the beginning of the Holocene is, conversely, associated with gradual overgrowing of a shallow lake, so-called autosuccession. Questions surround the character of the woodland vegetation in the surroundings of the locality and the interpretation of the pollen spectrum – the question of openness of European Holocene forests (Vera 2000, Mitchell 2005, Fyfe 2007). In the Šúr profile, there is a relatively constant proportion of *Gramineae* pollen and especially pollen of *Artemisia*, which generally declines by the beginning of the Holocene (Lang 1994), as a consequence of forest expansion and a rise in temperature. Considering the size of the former lake, pollen immissions concern a larger area. The theory of an open forest in Pannonia is supported by interesting evidence from the nearby Mesolithic locality Sereď (Bárta 1957). Charcoal indicates *Quercus*, *Pinus* and *Rosaceae*. The local large mammal fauna comprises, among others, *Equus asus*, *Bos taurus* and *Sus scrofa*. A malacozoological analysis indicates xerothermic to steppe but also woodland species. With the exception of *Helix pomatia*, molluscs are not purposely consumed by humans. Even though it was a Mesolithic settlement, a dominating human influence on the landscape (by forest burning, for example) cannot be assumed. This means that the landscape was covered with an open-canopy forest, locally even of a steppe character, see the high proportion of *Artemisia* pollen in the Šúr profile. In the lake record from the Šúr locality, there is practically no evidence of microcharcoal, even from the time of prehistoric agriculture in the mid-Holocene. Sporadic charcoal found in macro-fossils mainly come from grasses and indicate local events. Small charcoal float well on water. The vegetation in Hungary, where an open-canopy woodland with numerous steppe elements is reconstructed (Magyari et al. 2010), had a similar character. In the region of central Hungary, where saline (Hortobágy region) or sandy soils (Kiskunnság) predominated, there are multiple pieces of evidence of steppe dominance from the early to mid-Holocene (Jakab et al. 2004, Sümegi et al 2005, Magyari 2011), which are caused by edaphic conditions.

A change of vegetation took place around 4,600 BP. There was a marked expansion of *Fagus*, while *Corylus*, *Ulmus* and *Tilia* retreated. *Carpinus* expands significantly, which is usually explained by a human impact on the landscape (Ralska –Jasiewiczowa 1964). In the same period, this also occurs at localities in the Bílé Karpaty Mts. north of the Šúr site (Rybníčková et al. 2005, Rybníček and Rybníčková 2008) as well as in the Tizsa Basin at the locality Sárlo-Hát (Magyari et al 2010), for example, where an expansion of *Fagus* and *Carpinus* took place between 5,000 and 4,000 BP. This period falls into the transition between the aeneolithic period and the Bronze Age (Furmánek et al 1991), when south Slovakia was intensively occupied by prehistoric settlements. This cultural change can manifest in a higher frequency of pollen of cereal grasses and *Plantago lanceolata* in the pollen record, which is regarded as an indicator of pastures (Behre 1986). These so-called secondary anthropogenic indicators have been deduced from localities in north-west Europe (Behre 1981, 1986). It is therefore necessary to consider the distinct natural conditions of the

Pannonian lowland, especially in the case of the genus *Artemisia*. Although the current appearance of the Hungarian Puszta is a result of human activity (Magyari 2011), halophilous vegetation is above all conditioned by the climate (evaporation) and the subsoil. In the case of the locality Šúr, halophilous vegetation is present to this day (Majzlan and Vidlička 2010).

At the beginning of the Holocene, the cold-loving species *Pediastrum kawraiskyi* briefly predominates in the lake environment. Its occurrence at the beginning of the Holocene is also documented in the Komořanské jezero Lake in north-west Bohemia (Jankovská 2000), which can be explained by the influence of the nearby Ore Mountains, redeposition or, more likely, by gradual competitive exclusion of glacial elements by their Holocene vicariants. In the macro-fossil spectrum, the eurythermous species *Myriophyllum spicatum* is on the rise, indicating shallow standing as well as gently flowing waters. According to Koop 2004, it prefers a basic environment with heightened presence of fish, which is matched by the frequency of fish scales (*Perca fluviatilis*) and pharyngeal teeth in the profile. Also recorded is *Trapa natans*, which is evidence of a warmer environment; in Bohemia, it is massively recorded at former Švarcenberk Lake (Chvojka et al. 2010) and Komořanské jezero Lake (Řeháková 1986). According to Hannon et Gaillard (1997) *Trapa natans* colonizes waters up to 3 m deep with an optimum between 1 and 2 m. Our diatom analysis proves a lake stage within the coring site at least from 241 to 93 cm. In younger sediments, the diatom absence points to dry conditions. Ecological requirements of worldwide, chainforming, low biovolume Fragilaroid species that are present in our core are similar. A shift from *Staurosira pinnata* to other mainly larger species indicates the Holocene warming and shallow water (Perrin et al. 2006). *Fragilaria pseudoconstruens* is an intermediate species on a gradient between glacial (*S. pinnata*) and interglacial conditions. Diatom succession from *S. pseudoconstruens*, *S. pinnata* through *S. binodis* to *F. brevistriata* indicates an increased influx of nutrients (Tinner et al. 2008). *Fragilaria brevistriata* is typical of shallow habitats that become warmer in the summer, also being typical for coastal (high conductivity) lakes (Schmidt et al. 2004). Above 162 cm, large subdominant species with higher nutrient needs occur, e.g. eutrophic *Anomoeoneis sphaerophora* (Lysáková et al. 2007). Lake stage dominated by small cosmopolitan fragilariod species (241–162 cm) can be characterized according to recent alpine analogues (Schmidt et al. 2004) by prolonged ice cover, short growing season, low or moderate water temperatures, low nutrients, clear-water phases with high light penetration. The lake was alkaline and oligo- to ultra-oligotrophic. From the taken at 162 cm onwards, the lake became richer in nutrients and the dominance of *F. brevistriata* points to a drop in the lake waterline.

In the mid-Holocene, the trophic level of the environment markedly increased, and the lake took on a subhalophilous character. Similar is the development in the Holocene at

Balaton Lake (Cserny and Nagy-Bodor 2000). Recorded are macro-fossils of macrophytes of mesotrophic to eutrophic waters: *Batrachium* sp., *Najas marina*, *Nymphaea alba*, *Nuphar* sp. or the rare *Ceratopyllum submersum*, limited to the warmest regions. The fossil records from central and eastern Europe document that this species is tied to interglacial optima (Velichkevich et Zastawniak 2008). *Zannichellia palustris* subsp. *pedicellata* prefers both stagnant and flowing, shallow, eutrophic, waters and may also tolerate higher salinity, as does *Cyperus fuscus*, which colonizes exposed pond bottoms and is abundant at the locality.

At the depth of 162–132 cm in the lake environment, the proportion of green algae decreases in the palynomorph spectrum – genus *Pediastrum* and *Tetraedron minimum*. Strongly present is *P. angulosum*, an indicator of riparian vegetation (Komárek and Jankovská 2001). Furthermore, there is a decrease in the concentration of diatoms, an increase in silicon content in the geochemical analysis. Analogously, the increased carbon content in the macro-fossil analysis may, too, be related to a drop of the waterline and likely also the area of the water surface as a consequence of gradual filling of the lake. Another piece of evidence is the drop in the presence of fish scales and teeth. The oscillation of the waterline has not been clearly explained. These were definitely local changes of the lake's water regime. The mid-Holocene period is climatically stable, and there is no known analogy in the broader region (e. g., Starkel 2011, Davis et al. 2003) with which it could be compared.

At the depth of 93 cm there is the last layer of lake sediments dated to 1530–1430 BC. A fenn peat sediment, which is separated by a sharp lithological boundary, contains neither a pollen nor a diatom record. Plant macro-fossils do not show vegetation succession either, not even the disappearance of open water. The locality was probably overgrown by an alder carr, which covers the locality today. Alder disturbs the sediment mechanically because of windthrow (uprooting) and by chemically altering the subsoil with the aid of its symbiotic bacteria. The result is a loss of a stratified paleoecological record in the upper 90 cm. It is a consequence of vegetation succession that little depends on the surrounding environment or possible human influence. Our geochemical analysis also indicates an anaerobic environment (high sulphur content). Plant macro-fossils also occur very sporadically, showing a permanently inundated environment. Communities were formed by tall sedges, *Typha latifolia,* alder and a transient mosaic of shallow pools inhabited by small aquatic crustaceans of the order *Cladocera*. Diatom concentration and composition of the last analysed sample (56 cm) prove wet or regularly wet and more acid conditions than in the lower lake zones. *Staurosira pinnata* needs very low N and P and moderate Si concentrations (Michel et al. 2006).

The geochemical record of the upper 40 cm shows intensive industrial pollution. Indicators of industrial pollution are heavy metals such as Cd or Bi. The locality is out of the reach of floods on the Danube but is close to the industrial town of Bratislava.

Conclusion

The unique ecosystem of Šúr Lake is the result of a gradual disappearance of a large glacial lake. Its sediments hold a record of the Lateglacial period and a significant part of the Holocene. By combining the results of our sediment analysis with paleobotanical evidence, we succeeded in reconstructing changes that took place in the aquatic environment and in surrounding vegetation. In the Lateglacial period, the lake had a cold, oligotrophic character. The surrounding landscape was covered by a pine forest with frequently admixed broad-leaved trees (such as *Quercus*, *Ulmus*, *Tilia* and *Corylus*). The local landscape thereby differed from areas in the northern part of the western Carpathians and from areas west of the Carpathian arch. In the case of Moravia and Bohemia, the occurrence of mesophilous woody species in the Lateglacial period is not documented. The Holocene warming is manifested in the pollen record as an expansion of mesophilous species to the detriment of pine. *Fagus* appears at the same time. It later spread north and west of the Carpathians. The aquatic environment does not record such a radical changeover, and exhibits a certain inertia. The increase in eutrophy takes place gradually and steadily. The productivity of the aquatic environment reaches its maximum in the mid-Holocene period, which is demonstrated by the geochemical record, the concentration of diatoms and the presence of subhalophilous aquatic species. Littoral vegetation includes alder, which gradually takes over the whole locality. Around 4,500 BP, *Fagus* expands, *Carpinus* appears, and the antropogenic influence is indicated by abundant pollen of cereal grasses. There is no certain direct connection between these changes. Open water disappeared in the period after 3,200 BP. In the sedimentation record, this is manifested by a sharp border between lake sediments and organic layers which originated in the anoxic environment of an alder forest at the depth of 93 cm. At the sample site, there is no record of gradual vegetation succession from a lake environment to an alder woodland, which is a result of disturbances influenced by alder. Although the areal extent of lake sediments at the Šúr locality is still not precisely known, it was probably the largest Holocene lake in Slovakia.

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High vegetation and environmental diversity during the Late Glacial on the example of lowlands in the Czech Republic

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Abstract

The diversity of vegetation and the environment in the Late Glacial period in the Elbe region is illustrated by a comparison of three palynological localities. The localities differ in their history, profile lithology and position relative to the Elbe. The Hrabanovská černava profile holds a record of the development of a shallow lake, which was surrounded by a cold continental steppe in the Early Dryas. Evidence of a pine forest in the Late Glacial period is captured in the surroundings of the profile Chrást. The Mělnický úval – Přívory locality is an interdune infill, where marl sediments redeposited in shallow water. The surrounding vegetation was diffuse and influenced by erosion. In the Early Holocene, the landscape was covered by an open birch-pine forest. Broad-leaved woody species appeared later. Localities in the Elbe region share a high proportion of pine throughout the Holocene as a result of the spread of drift and terrace sands. The human impact in the mid Holocene manifests as evidence of intensive charring of localities.

Keywords: Late Glacial, Early Holocene, Palynology, vegetation diversity, Czech Republic, lowlands, floodplain,

Introduction

Central-European Late-Glacial climatic conditions are generally reconstructed as unstable. The younger Dryas was the most recent cold oscillation of the Pleistocene, which affected the entire Northern hemisphere (e.g., Alley 2000, Broecker et al. 2010, Taylor et al. 1993, Severinghaus and Brook 1999). This period is characterized by intensive erosive-accumulation processes. Lakes and marshes formed under the influence of these processes. The Holocene is altogether climatically stable and without large fluctuations but is accompanied by changes in vegetation and the fauna (Ložek 1973, Lang 1994).

Late-Glacial palynological evidence is recorded mainly at higher elevations of the Czech Republic (Rybníčková and Rybníček 1996, Pokorný 2004b). Some localities were created after the retreat of montane glaciers such as in the Labský důl valley (Engel et al. 2010), the Plešné jezero Lake (Janovská 2006) or the Stará jímka locality in the Šumava Mts (Mentlík et al. 2010). The Late-Glacial vegetation at this locality is reconstructed as a montane tundra. An upward shift of the treeline took place as late as in the Early Holocene. Many montane peatbogs originated in the Late Glacial period (Svobodová et al. 2002).

A number of localities have also been found at colline elevations, for example, Kameničky (Rybníčková and Rybníček 1988), Velanská cesta (Bešta et al. 2009). There is a detailed Late-Glacial log from the locality Švarcenberk (Pokorný 2002) and from other places of the Třeboň basin (Jankovská 1988). Vegetation at medium elevations has been reconstructed as comprising birch, pine and willow stands.

Paleobotanical evidence of the Late Glacial in the lowlands of the Czech Republic is only sporadic. In Moravia, there are records from the localities Vracov (Rybníčková and Rybníček 1972, Svobodová 1991), Dvůr Anšov (Svobodová 1997) and Černovír (Jankovská 2003). Only the turns of the Late Glacial and the Holocene (Jankovská 2000) and younger periods are logged at the Komořanské jezero lake.

A different character of the vegetation in the Late Glacial period has been recorded in the Western Carpathians, where evidence of the continual presence of a forest is present in the sub-Tatran basins not only in the Late Glacial (Jankovská 1988, Rybníček and Rybníčková 2002) but also in the LGM and MIS 3 periods (Jankovská and Pokorný 2008). The Late-Glacial vegetation has been interpreted as predominantly coniferous forests with the occurrence of *Larix* and *Pinus cembra*. In the Pannonian lowland, there is a relatively high proportion of broadleaved woody species besides conifers in the Late Glacial. This is documented in the Tisza region (Magyary et al. 2010) but also in west Slovakia and the locality Šúr on the outskirts of Bratislava (Petr et al. submited).

The Late Glacial and Early Holocene periods along the middle section of the river Elbe was studied by Ložek and Šibrava (1982), who focused mainly on fluvial sediments, fossil soils and malacozoology. Research of the Elbe basin is summarized in the works of Růžičková and Zeman (1994), Dreslerová et al. 2004, and Kalicky 2004. S. Butler (1993) carried out tentative analyses of material from several localities, including meanders of the river Elbe in an area called Kozly and the catchment of the Pšovka stream. With the exception of the locality Chrást from the Late Glacial (Petr et al. in press), meanders of the Elbe studied palynologically are of Holocene age (Břízová 1998, Dreslerová et al. 2004). Profiles indicate a floodplain vegetation dependent on the development of the river. Late-Holocene localities were strongly influenced by human activity.

Another important locality is the Hrabanovská černava fen, where H. Losert (1940a) processed altogether four profiles and also attempted to identify certain herbs in addition to pollen grains of woody species. He ascertained the age of the lake sediment under study to be of Late-Glacial vintage. Ložek (1955) carried out an analysis of fossil molluscs of the Hrabanovská černava. Absolon (1969) examined limnic sediments at the Hrabanovská černava and its immediate surroundings. Further palynological research of the locality was carried out by Pacltová and Hubená (1994), who processed a Holocene profile in the part situated south of the former lake. H. Losert (1940b) also carried out a palynological study of the Mělnický úval valley. Research of freshwater chalk sediments near the village of Malý Újezd (near the town of Mělník) carried out by Ložek (1952) was focused on potential mining of the deposit. The author performed a malacozoological analysis of several profiles of Holocene age. Absolon (1972) carried out a detailed study of the area of the Mělnický úval with a focus on the stratigraphy of limnic sediments including an analysis of fossil ostracods.

The objective of this study is to compare three pollen profiles in the Elbe region formed in the Late-Glacial interstadial. The localities underwent different development and their sedimentary infill is entirely different. Differences in their origin and complexity of their development nicely illustrate the diversity of conditions and environmental changes in the lowland at the end of the Pleistocene.

Site description

All sites of interest are situated in the central part of the Bohemian basin along of river Elbe (Fig. 1). The underlying geology is built of marine chalk sediments and is for the most part overlaid by Quaternary surface deposits – loess and river terraces (Balatka and Sládek 1965). Present-day climate conditions are characterized by a mean annual temperature of 8.7 °C and a mean annual sum of precipitation of 527 mm. (meteorological station in Mělník; Culek 1996).

The **Hrabanovská černava** fen is located at the NW fringe of the town Lysá nad Labem. The altitude of the locality is 185 m.a.s.l. The former lake at the place of today's fenny meadows was formed in the Late Glacial development of a sand dune and damming of flow from springs at the southern foot of the slope (Absolon 1969). Fens developed at the opposite side of the dune are of Holocene age (Pacltová and Hubená 2004). The locality comprises a complex of fenny meadows, waterlogged willow stands, small water bodies and sandy pinewoods, today surrounded by fields and pine forests. Today's vegetation diversity is a result of past geomorphological development and prolonged intensive human activity (Husáková et al. 1988). Present-day small water bodies in the central and southern part of the locality are a remnant of peat mining at the end of the 19th century. Parts of the fenny meadows at the locality have been drained by a system of ditches. The profile under study was sampled in the northern part of the reservation, where there are sediments of a glacial lake (location 50° 13‘ 10‘‘ N 14° 50‘ 11‘‘). For the purpose of dating the origin of the sand dune, a profile which would intercept drift sand material for pollen analysis and dating was sampled. A profile through the dune was taken from a pit on the side adjacent to the former lake. The location of the pit is 50° 13‘ 10‘‘ N; 14° 49‘ 58‘‘.

The **Mělnický úval – Přívory** locality is located 5 km south-east of the town of Mělník in the depressed area of the Mělnický úval. The altitude is 175 m.a.s.l. The Mělnický úval is an 18 km long shallow valley separated from the Labská floodplain by the Cecemínský and the Turbovický hřbet ridges with a relative altitudinal difference of around 50 metres. The infill of the Mělnický úval valley is composed of drift sands, fens and redeposited marl (Absolón 1972). The locality has been completely drained and turned into a field. The profile under study was sampled between the villages of Přívory and Vavřinec at a place called “Wet meadows”, where H. Losert (1940a) supposedly took his original profile. The location of the profile is: N 50° 18‘ 39.3‘‘, S 14° 33‘ 43.8‘‘.

The **Chrást** site is a former meander of the river Elbe situated between the Cecemínský hřbet ridge and the Holocene floodplain of the Elbe. Meanders south of the locality between the villages of Chrást and Ovčáry are of Holocene age (Dreslerová et al. 2004). The bedrock is a gravel-sand terrace from the last glacial period (Kalicki 2006). The surrounding Pleistocene gravel terraces were described mainly by Balatka and Sládek (1962) and Žebera (1956). Růžičková and Zeman (1994) and Kalicki (2006) described the Holocene alluvial deposits in the study area. A Holocene environmental reconstruction based on pollen data from the nearby sites Chrást, Kozly and Tišice is presented by Břízová (1998), Dreslerová et al. 2004) and Dreslerová and Pokorný (2004). The locality is situated 1.5 km south of Všetaty village (50° 15´N; 14° 35´E) about 2 km from the present-day river course and 5 m above its water level (Fig.1). Cornfields prevail in the surrounding landscape whereas semi-natural habitats such as dry pine forest or alluvial wetland vegetation are present locally.

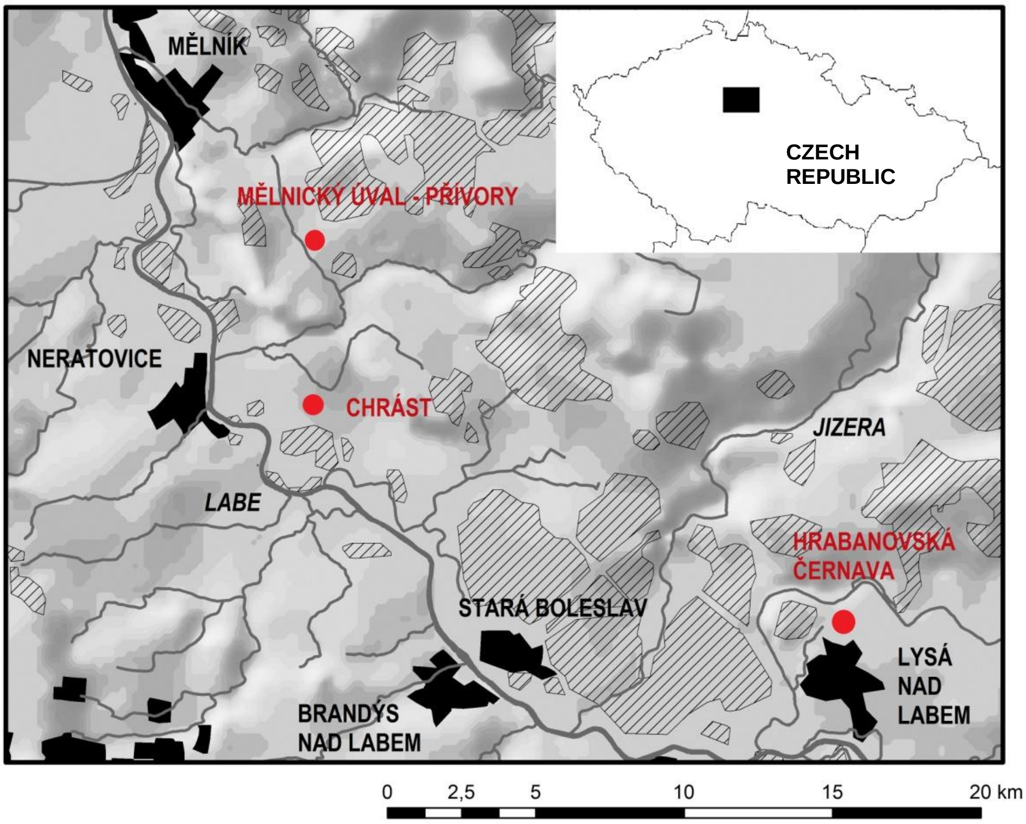

Fig. 1. – The location of the study sites

Methods

Profile sampling

At the **Hrabanovská černava,** sediment was sampled using a piston corer (diameter 5 cm). Samples for pollen analysis were taken from the profile at 3 cm intervals, omitting a sandy layer at the depth of around 200 cm. The bore core was then divided into 10 cm sections to obtain mollusc shells and plant macrofossils (by flotation on sieves of 0.25 mm mesh aperture) for the purpose of dating. The **Hrabanovská černava – dune** profile was dug, but taking samples of the fen underlying the drift sands was limited by ground water. The profile was therefore taken from an open pit using an open tube sampler 5 cm in diameter. From the bore core, five samples were taken for pollen analysis. Plant material for radiocarbon dating was obtained by flotation. The upper sandy fen (0–40 cm) was not analysed. The **Mělnický úval – Přívory** profile was taken at the locality from a pit using three sheet metal boxes 50×20×20 cm in size hammered into the walls of the pit. The topsoil and a layer of sediment strongly influenced by recent agricultural activity were not sampled. Samples for pollen analysis were taken from the profile at 2 cm intervals down to the depth of 40 cm and at 3 cm intervals from the depth of 40 cm downwards. The sediment was then divided into 10 cm thick layers and subjected to flotation. Shells of molluscs and plant macroremains for radiocarbon dating were obtained from the sediment. A trench was dug at the **Chrást** locality to expose a stratigraphic section. The profile was excavated the section of the pit studied, which was 2×2 m in area and 2.85 m deep. After field documentation, samples were taken into steel boxes (10×10×50 cm). Every 3 cm of the lithological record (or more if sandy layers were present) were sampled for the pollen analysis, and a sample macrofossil and charcoal analyses was taken every 10 cm of the section.

Pollen analyses were carried out following the standard acetolysis method using HCl and HF acids (Moore et al. 1991). Pollen grains were determined using pollen keys (Beug 2004, Reille 1995, 1998). No less than 500 pollen grains per sample were counted. Only the case of the Hrabanovská černava – dune profile, fewer grains were counted because of low concentrations of pollen. Pollen diagrams were plotted using POLPAL for Windows (Nalepka and Walanus 2003) including numerical analyses (Rarefraction, Conslink, PCA) for the visualization and the interpretation of the pollen data and determination of local pollen zones.

Radiocarbon dating was performed using the C^{14} AMS method at the Radiocarbon Laboratory in Poznań. The pine trunk was dated using the conventional C^{14} method at the Radiocarbon Laboratory of Nuclear Physics Institute of the Academy of Sciences of the Czech Republic in Prague. All radiocarbon dates were calibrated using the program OxCal 4.1. (Bronk Ramsey 2009). The results of radiocarbon dating are presented in Table 1.

Statistical analyses - In total, 116 samples were subjected to a macroremains analysis, and 65 (44 without Holocene samples) pollen taxa were distinguished among the sites under study.

CANOCO v. 4.5 (ter Braak and Šmilauer, 2002) was used to compare all samples as to the species composition of plant pollen. A detrended correspondence analysis (DCA) was carried out to check the length of the gradient.

The maximum length of the gradient was 1.93, so a principal components analysis (PCA) was performed. A logarithmic transformation of the percentage data centred by samples and species was used.

Results

Lithological description

Hrabanovská černava profile

Organic litter

3 - 20 cm dark brown organic humus

20 - 45 cm gray brown organic peat

45 - 52 cm dark gray peat with mollusk

52 - 62 cm dark ochre organic peat with gray calcium rich layers

62 - 86 cm gray black calcareous peat

86 - 110 cm gray brown calcareous clay

110 - 130 cm light brown lake marl

130 - 132 cm layer of mollusk shells

132 - 195 cm brown peat

195 - 204 cm well sorted sand

204 - 218 cm dark brown peat with sand

218 - 230 cm light gray sand with clay

Hrabanovská černava - dune profile

0 - 40 cm peat with sand

40 - 150 cm aeolian sand, well sorted

150 - 155 cm clay sand

155 - 165 cm Aeolian sand

165 - 168 cm organic layer

168 – 170 cm Aeolian sand

170 – 172 cm clay sand

172 – 173 cm coarse sand

173 – 175 cm Aeolian sand

175 – 178 cm organic layer

178 – 182 cm Aeolian sand

182 cm slightly organic layer

Alternation of peat and sand

192 cm organic layer

192 – 198 cm Aeolian sand

198 – 200 cm organic layer

200 – 205 cm Aeolian sand with coarse sand

205 cm coarse sand

Samples for palynology: 166, 176, 183, 191 a 199 cm

Mělnický úval – Přívory profile

Recent soil and degraded peat not sampled

50 cm upper present day surface

0 – 15 cm light gray soil with mollusks

15 – 16 cm mollusks layer

16 – 30 cm black degraded peat

30 – 38 cm red brown degraded peat with sand and rusty patches

41 – 55 cm rusty clay sand

55 – 80 cm gray lake marl with sand

80 – 92 cm coarse sand with lake marl

92 – 108 cm gray lake marl with sand

108 cm coarse sand

Chrást profile

O - 35 cm antropogenic material

37 – 67 cm degraded calcareous silty grayish brown peat of terrestrial origin.

67 – 142 cm mixture zone of calcareous clays and silty clays layers of different colors with predominant limnic origin.

142 – 179 cm Slightly calcareous sandy layer including thin layers (app.1cm) of clay and clay loam of fluvial-limnic origin.

179 – 223 cm Strongly calcareous laminated layer of pale brown clay interrupted by dark layers of decomposed peat. This layer is of limnic and terrestrial origin and is characterized by redeposition and bioturbation processes. Upper 4 cm of this zone are composed form calcareous, strongly degraded clayey peat impregnated by FeOH rich solutions of grey color coming from decomposed organic matter of terrestrial origin.

223 – 259 cm non calcareous decomposed organic peat layer of terrestrial origin.

259 – 285 cm slightly calcareous loamy sand material of fluvial - limnic and also aeolian origin. Upper 4 cm are slightly organic and calcareous rich sandy clays of mostly limnic origin.

Pollen analysis

Hrabanovská černava - LPZ H1 (206–217 cm) (Fig. 2). Pollen in this sample is present in low concentration and has been poorly conserved. AP predominate in the spectrum (up to 80%) over NAP. The pollen spectrum is dominated by *Pinus sylvestris*; other woody species are sporadically represented by *Betula*, *Betula nana*, *Picea abies*, *Alnus*, *Salix* and *Tilia*. Cyperaceae predominate in the herb spectrum; less represented are *Gramineae*, *Artemisia*, *Chenopodiaceae*, *Asteraceae* subfam. *Cichorioideae* and *Campanula*. Also recorded are algae of the genus *Bothryococcus*. A layer of drift sand at the depth of 197–206 cm does not contain a pollen record.

LPZ H2 (197–138 cm). The AP to NAP ratio in this zone varies between 25% and 50%. *Pinus sylvestris* predominates in the AP spectrum. Represented is *Betula*, *Alnus*, *Salix*, to a lesser degree *Juniperus*, *Picea abies*, *Betula nana* and *Salix herbacea*-type pollen. Only sporadically recorded are *Tilia*, *Abies, Carpinus*, *Corylus*, *Carya* and *Pterocarya*. The herb spectrum is dominated by Cyperaceae. Gramineae *Artemisia* and *Helianthemum*, which have a closed curve. Recorded are *Thalictrum*, Chenopodiaceae, Ranunculaceae, *Gypsophila repens*-type, *Anemone*-type, *Asteraceae* subfam. Cichorioideae, *Linum*, *Plantago lanceolata*, *P. alpina*, *P. media*, *Rumex acetosella*, *Filipendula* and some others. Local aquatic pollen types are strongly present; dominant taxa are *Myriophyllum spicatum*, *M. verticilatum*, *Potamogeton*, *Ranunculus* subgen. *Batrachium*, *Nymphaea*, *Nuphar* and *Typha latifolia*. Algae have a strong presence, too, *Pediastrum boryanum* agg being dominant. Other members of the genus, *P. integrum*, *P. duplex* and *P. kawraiskyi* are represented to a lesser degree and disappear by the end of the LPZ.

LPZ H3 (135–78 cm) In this zone, AP predominate over NAP, the ratio being between 90 and 85%. Pine is the main dominant with a proportion ranging from 60% at the beginning of the zone to 90% at its end. The increase in the proportion of pine is compensated by a drop in the curve of birch from 35% to less than 10%. Other woody species are initially present but only sporadically; the only detected taxa are *Alnus*, *Picea abies*, *Populus*, *Tilia* and *Fagus*. The second half of the LPZ (102–78 cm) is characterized by an increase in the number of woody species. *Quercus*, *Corylus*, *Abies alba*, *Tilia* and *Fagus* start to appear. Shrubs are represented only by willow and sporadically juniper. Herbs are represented mainly by the genus *Artemisia* and the families Gramineae and Cyperaceae. Their curve is around 5% and is closed. Only the genus *Artemisia* retreats near the end of the period. Other herbs are present only sporadically: *Thalictrum*, *Helianthemum*, *Anthemis*-type, Ranunculaceae, Asteraceae subfam. Cichorioideae, *Rumex acetosella*- typ, *Aster*-type, *Filipendula*, Chenopodiaceae, Umbelliferae, Rubiaceae, *Polygonum aviculare*. Aquatic species are mainly represented by algae of the *Pediastrum boryanum* aggregate. Aquatic macrophytes are rarely represented by the taxa *Potamogeton*, *Myriophyllum verticillatum*, *M.*

spicatum and *Nymphaea*, which disappear together at the depth of around 102 cm. The occurrence of algae of the *Pediastrum boryanum* aggregate ends in the layer at 111 cm.

LPZ H4 (75–18 cm) exhibits rapid development. An oscillation in AP occurs around 85–90 %. In the woody spectrum, *Pinus* recedes to 45%, but other woody plants increase. Newly present are *Ulmus* and *Carpinus*. *Quercus* reaches 20% and *Betula* 10%. Similarly, *Picea* reaches over 10%. *Fraxinus*, *Fagus*, *Populus*, *Tilia*, *Corylus* and *Salix* are rare. Sporadically present are *Viscum*, *Calluna* and *Frangula*. Herbs are represented mainly by the Cyperaceae, to a lesser degree Gramineae, *Artemisia* and *Thalictrum*. At the beginning of the period, there is a high proportion of the pollen type Asteraceae subfam. Cichorioideae, which later disappears, however. Scarcely present are *Filipendula*, *Thalictrum*, Chenopodiaceae, *Aster*-type, *Anthemis*-type, *Plantago lanceolata* and *Rumex acetosella*-type. The aquatic element is represented by *Typha latifolia* and *Utricularia*.

LPZ H5 (15–3 cm) The proportion of AP drops to 85%. The proportion of conifers grows in the woody spectrum (*Pinus* and *Picea*) above that of deciduous trees. The curve of *Pinus* rises above 50%; *Picea* reaches 5%. *Quercus* and *Betula* both have 5%. Scarcely recorded are *Ulmus* and *Fraxinus*. Willows are represented below 5%. *Juniperus* starts to appear, heather is less common, and *Viscum* occurs sporadically. Herbs exhibit certain changes. Also significant is the increase of *Avena*-type, *Centaurea cyanus*, Chenopodiaceae, *Rumex acetosella*-type, *Plantago lanceolata* and Asteraceae subfam. *Cichorioideae* pollen. Sparsely represented are *Plantago media*, *P. media*, *Thalictrum*, *Filipendula*, *Fagopyrum*, *Centaurea scabiosa*, *C. jacea*, Umbelliferae etc.

Hrabanovská černava – dune (Fig. 3) The AP/NAP ratio decreases from 50% in the bottom layer (199 cm) to 10% in the top sample (166 cm). The woody spectrum is composed mainly of *Pinus sylvestris*. Less common are *Betula*, *Aldus* and *Picea*. Other woody species (*Abies*, *Corylus* and *Tilia*) may indicate contamination. The only shrubs detected are *Salix*, *Salix herbacea*-type, *Ephedra distachia*-type, *Juniperus* and *Betula nana*. Sedges, which reach a proportion of over 50%, predominate in the herb pollen spectrum. Less abundant are *Gramineae*, *Helianthemum*, *Chenopodiaceae*, *Artemisia* and others. In the uppermost layer, there is a significant amount of pollen of the *Gypsophila repens* type. Aquatic algae are represented only by the genus *Pediastrum*.

Mělnický úval – Přívory - LPZ P1 (Fig. 4) (106–76 cm) AP/NAP fluctuates between 40% and 90%. The woody spectrum is composed mainly of pine with a proportion between 20% and 80%. The proportion of *Betula* varies between 10% and 20%. Remaining woody species are represented sporadically, only *Alnus* and *Picea* being more common. Willow has a closed curve. *Salix herbacea*-type occurs only sporadically. *Betula nana* and *Juniperus* are present only at the very base of the profile. In the herb spectrum, a closed curve is exhibited by *Artemisia* and *Gramineae*. Also markedly present are *Thalictrum*, *Chenopodiaceae*, *Hordeum*-type, *Gypsophyla repens*-type and *Sanguisorba minor*. Less numerous are *Helianthemum*, *Filipendula*, *Plantago lanceolata*, *Hordeum*-type, *Anthemis*-type, Ranunculaceae and *Asteraceae* subfam. *Cichoroideae*. Cyperaceae (5–40%) can be considered as local marsh pollen types types. Aquatic macrophytes are sporadically represented by *Myriophylum spicatum* and the genus *Nymphaea*. Aquatic algae are represented mainly by the abundant *Pediastrum boryanum* agg., *P. duplex* and *P. integrum* occur sporadically.

LPZ P2 (73–38 cm) AP/NAP varies between 90% and 80%. *Pinus* predominates with a proportion of around 70%. *Betula* fluctuates between 10% and 20%. Sporadically present are *Alnus*, *Picea*, *Ulmus* and *Populus*. Shrubs are represented only by an incomplete curve of *Salix*. *Juniperus* is also recorded at the beginning of the zone. Herbs do not differ too much in their composition from the previous zone. *Gramineae* and *Artemisia* dominate. Less represented are *Thalictrum* and *Chenopodiaceae*. Sparsely recorded are *Heliantemum*, *Hordeum*-type, *Anthemis*-type, *Ranunculaceae* and *Asteraceae* subfam. *Cichorioideae*. Local hygrophilous types comprise *Cyperaceae* with a proportion of around 10% and *Filipendula*. The only aquatic macrophytes are sporadic *Nymphaea* and *Myriophyllum spicatum*. Aquatic algae are represented practically only by *Pediastrum boryanum* agg., which disappear at the end of the LPZ.

LPZ P3 (36–24 cm) The AP/NAP ratio drops from 95% to 70%. The pollen spectrum of woody species is still dominated by *Pinus*, even though it decreases from 90% to 60%. *Betula* takes up 10%. Newly occurring genera are *Quercus*, *Tilia*, *Corylus* and *Fagus*. Herbs are represented less than in in the preceding LPZ. *Gramineae* clearly dominate; much less common or even sporadic are *Artemisia*, *Thalictum*, *Chenopodiaceae*, *Ranunculaceae* and *Asteraceae* subfam. *Cichoroideae*. *Cyperaceae* significantly increase their presence from 5%

to over 20% in this period. Neither aquatic macrophytes nor aquatic algae are present in this zone.

Chrást LPZ CH1 (261 – 279 cm) (Fig. 5) AP/NAP ratio is about 80%. Curve of *Pinus* increases from 40 to 90%. While *Betula* decline from 30 to 10%. *Salix* and *Juniperus* form closed curves. Pollen of *Alnus*, *Picea*, *Ulmus* and *Tilia* was very rare. NAP is dominated by grasses and sedges. *Helianthemum*, *Chenopodiaceae* and *Thalictrum* occur occasionally. Water species were represented e.g. by *Myriophyllum*, *Batrachium* and algae *Pediastrum*.

LPAZ CH2 (121 – 258 cm) AP/NAP ratio varies between 50 – 85%. *Pinus* (50 – 80%) and *Betula* (5 – 20 %) dominated, whereas *Picea*, *Juniperus*, *Alnus* and *Salix* were rare. In NAP, sedges (30%) prevailed over grasses (5%). Variable occurrence had pollen taxa: *Artemisia*, *Ranunculaceae* and *Umbeliferae*. Occurrence of water taxa (*Myriophyllum*, *Potamogeton* and *Pediastrum* was sporadic.

LPAZ CH3 (86 – 120 cm) AP/NAP ratio is about 70 %. *Pinus* dominated, but curve falls from 80 to 50%. Only in zone broad-leaved woody species of mesophilous habitats expanded (*Corylus, Fraxinus, Quercus, Tilia*). Curve of *Betula, Picea, Tilia, Quercus, Corylus* and *Alnus* rapidly increases. *Ulmus*, *Fagus* and *Abies* appeared. Grasses and sedges still create an important component of NAP spectra. Other herbs taxa (*Artemisia*, *Chenopodiaceae*, *Thalictrum*, *Ranunculaceae* and *Umbeliferae*) were less common. *Cerealia* pollen appeared. Wetland taxa absented, the only with exception was pollen of *Typha latifolia*. Microcharcoal (including grasses type) had massive occurrence and increasing tendency since depth of 100 cm. Quality of preservation in this zone was bad (mechanical and chemical damaged pollen grains).

Pollen grains from the depth of 0 – 86 cm are largely degraded and not identifiable; therefore the pollen record cannot be used for the further interpretation.

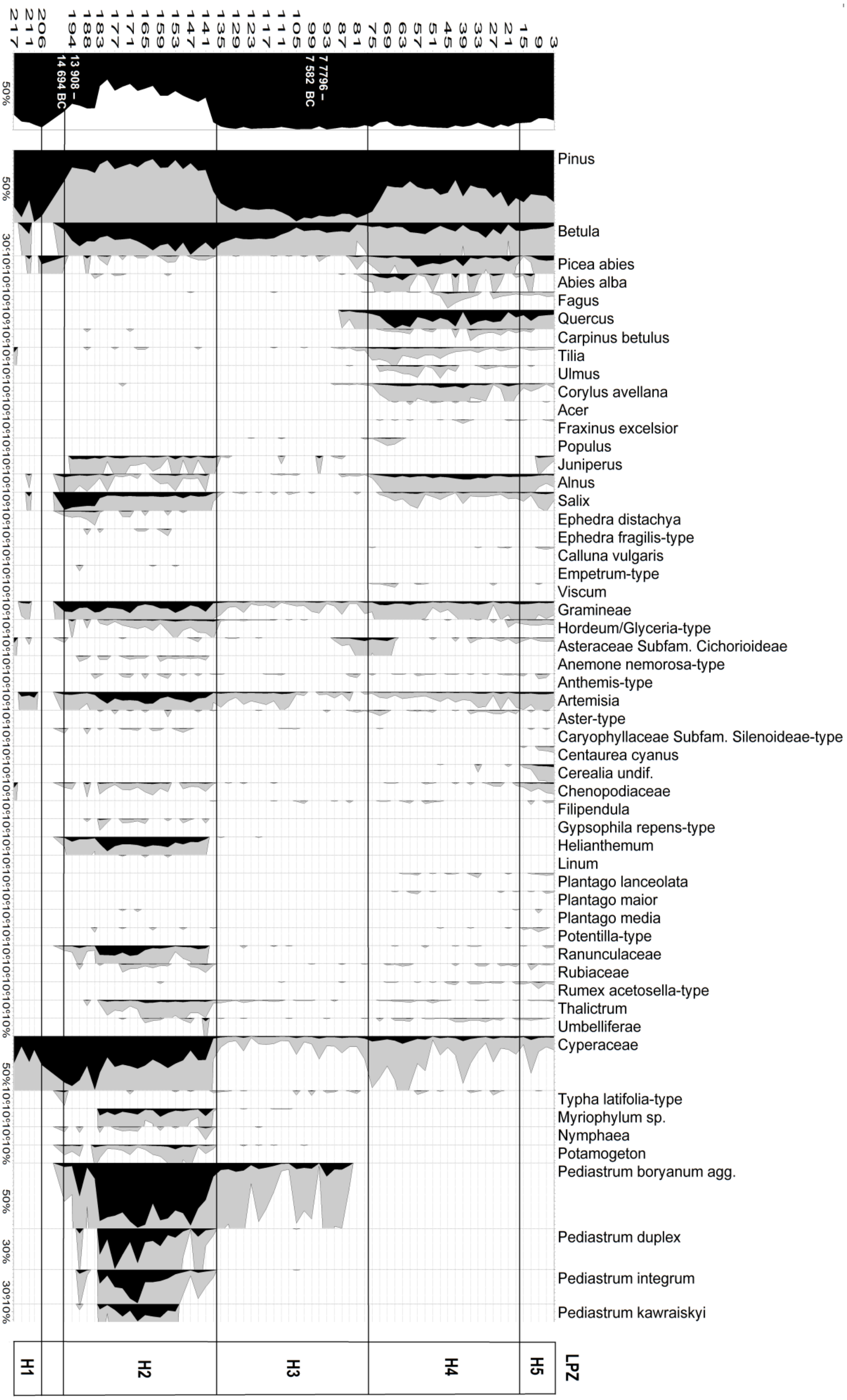

Fig. 2 –Hrabanovská černava: pollen diagram

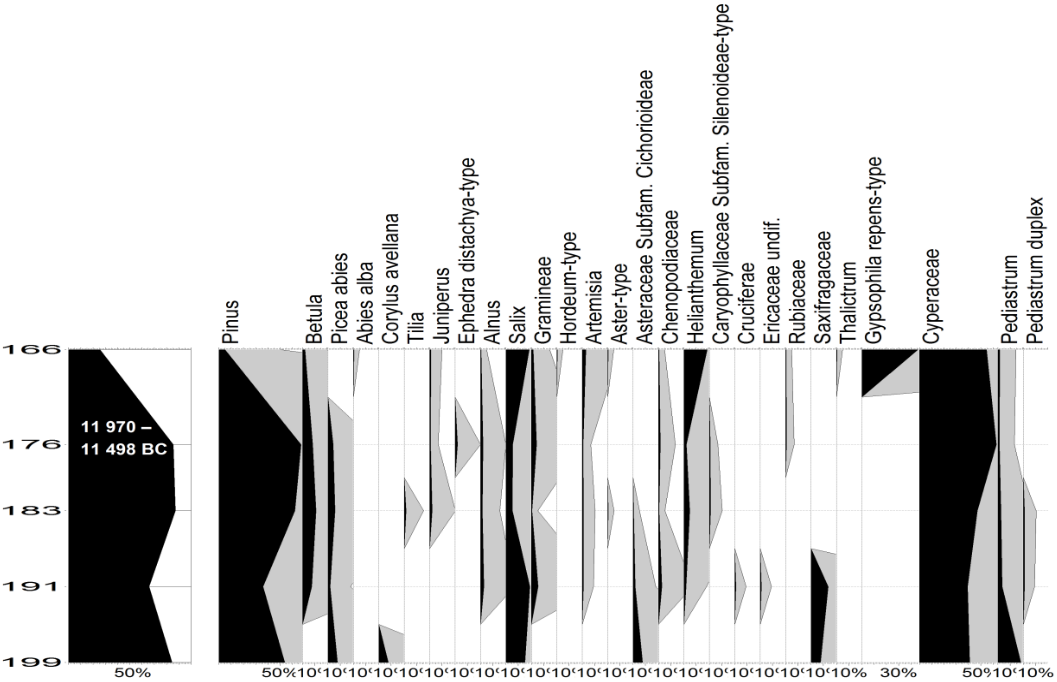

Fig. 3 – Hrabanovská černava – dune: pollen diagram

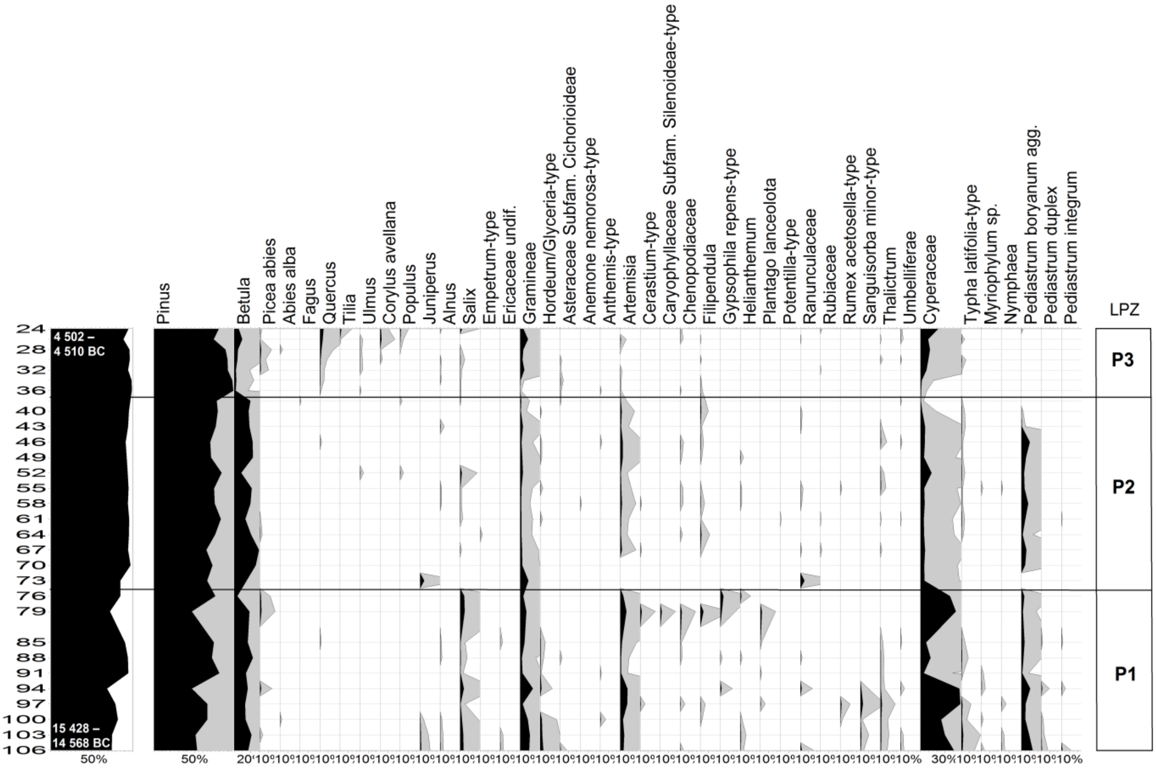

Fig. 4 – Mělnický úval – Přívory: pollen diagram

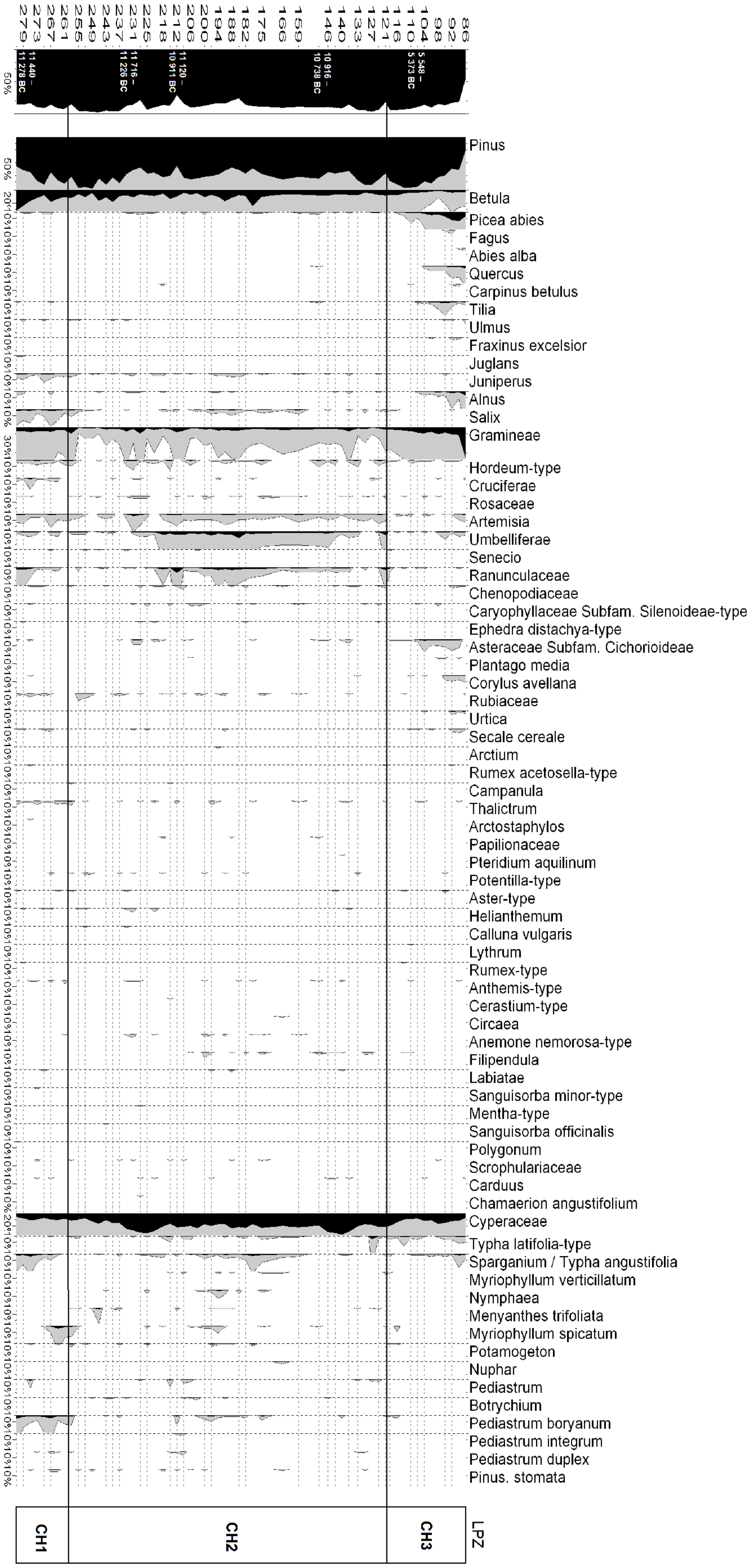

Fig. 5 – Chrást: pollen diagram

Radiocarbon dating (Table 1)

Sample (Depth)	Lab. No.	Material	^{14}C age (BP)	Calibration (BC)
Hrabanovská černava 80 – 90 cm	Poz-9083 AMS	Mollusc shells	8 660 ± 50	7 7796 – 7 582
Hrabanovská černava 100 -110 cm	Poz-10535 AMS	Mollusc shells	11 310 ± 60	11 343 – 11 140
Hrabanovská černava 110 – 120 cm	Poz-9328 AMS	Mollusc shells	12 500 ± 60	12 280 – 12 280
Hrabanovská černava 190 – 200 cm	Poz-9329 AMS	Mollusc shells	13 630 ± 60	13 908 – 14 694
Hrabanovská černava – duna 165- 178 cm	Poz-9083 AMS	Plant seeds	11 850 ± 100	11 970 – 11 498
Mělnický úval – Přívory 20 – 30 cm	Poz-10526 AMS	Mollusc shells	5 600 ± 40	4 502 – 4 510
Mělnický úval – Přívory 100 – 110 cm	Poz-10527 AMS	Mollusc shells	14 200 ± 70	15 428 – 14 568
Chrást 105 – 110 cm	Poz-21028 AMS	Ash charcoal	6 510 ± 40	5 548 – 5 373
Chrást 145 – 150 cm	Poz-20980 AMS	Pine wood	10 750 ± 60	10 916 – 10 738
Chrást 210 – 215cm	Poz-22832 AMS	Menyanthes seed	11 010 ± 60	11 120 – 10 911
Chrást 230 – 235 cm	Crl-6199B Con.	Pine trunk	11 523 ± 120	11 716 – 11 226
Chrást 275 – 280 cm	Poz-22833 AMS	Menyanthes seed	11 450 ± 60	11 440 – 11 278

Table 1. Radiocarbon dates (AMS)
BC = before Christ, BP = before present (1950)

Results of statistical analysis

The DCA shows a first-axis gradient length of 1.93 standard deviations, indicating that linear ordination techniques are appropriate. The first two axes of the PCA result explain 60.2% of the total variance; axis 1 explains 43.2% (Fig. 6).

Figure 6 - Principal components analysis (PCA) ordination biplots of sample and pollen-type. Different period are displayed separately: (a) Hrabanov, (b) Chrást, (c) Mělnický úval-Přívory (square - Hrabanovská černava, circle - Chrást, star - Mělnický úval -Přívory; black- Early Holocene, grey - Younger Dryas, white - interstadial).

Along Axis 1, records with a predominance of steppe species have a positive score, while records with a dominance of a pine forest have a negative score. This axis may represent a gradient from cold and dry steppe vegetation to a pine forest with a relatively closed canopy. Alternatively, axis 1 could be interpreted as a successional trend in the development of vegetation from Younger Dryas to the Early Holocene.

Axis 2 indicates a trend between samples of mixed vegetation of floodplain positions with a significant presence of marshes and samples with abundantly represented vegetation confined to dry habitats (steppe vegetation, pine stands).

The results of the ordination for the Hrabanov locality show a change of vegetation along the first axis. Vegetation dominated by steppe species in the Younger Dryas period turned into a pine forest in the Early Holocene. The second axis differentiates a gradient from a marsh-lake vegetation in the interstadial period to a relatively dry vegetation of pine woodlands and steppes. The Chrást log, by contrast, is characterized by lower definition of records in individual periods. A pine forest but also a mixture of marsh and steppe vegetation is recorded here as a variable mosaic in all periods under examination (interstadial, Younger Dryas and Early Holocene). The Přívory site holds evidence of a vegetation gradient composed of a mixture of steppe and marsh species in the period of the interstadial and from the Younger Dryas to the Early Holocene vegetation with a dominance of Pine along the axis.

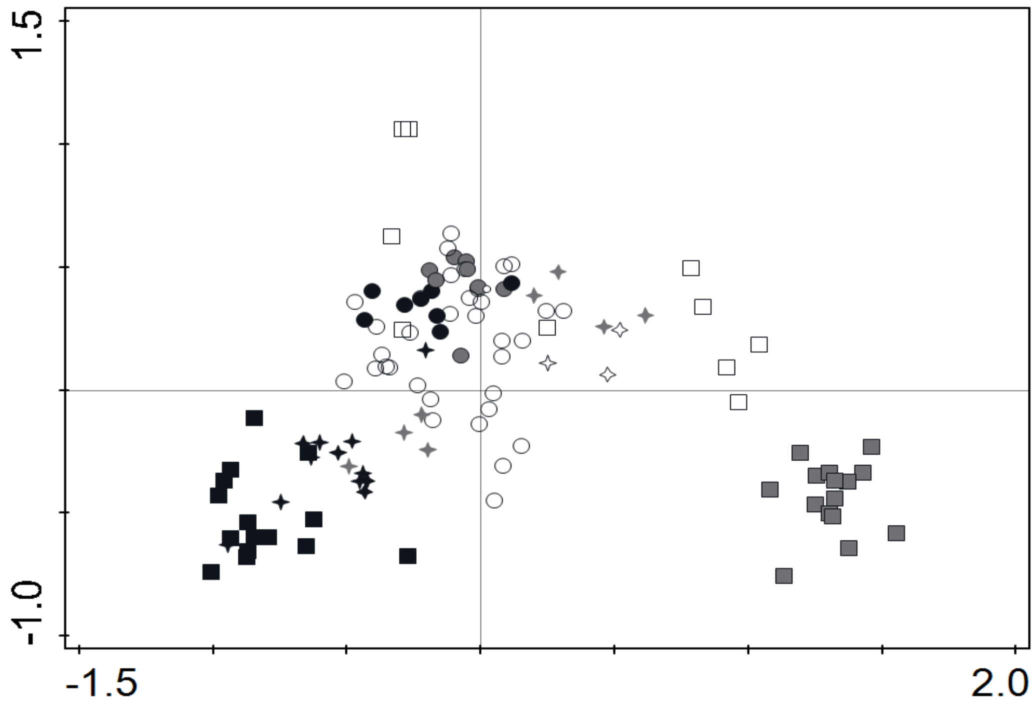

Fig. 6 - Comparison of localities; square - Hrabanovská černava, circle - Chrást, star - Mělnický úval –Přívory, white – Lateglacial interstadial, grey - Younger Dryas, black – Early Holocene

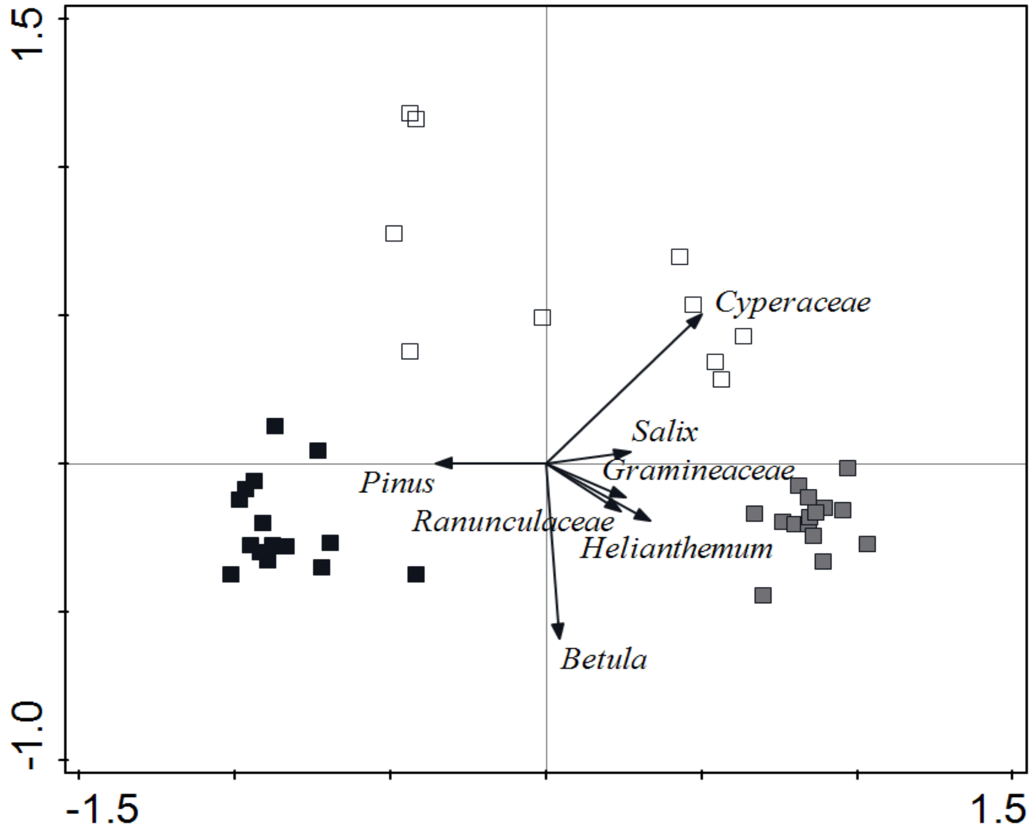

Fig. 6a - Hrabanovská černava; white – Lateglacial interstadial, grey - Younger Dryas, black- Early Holocene

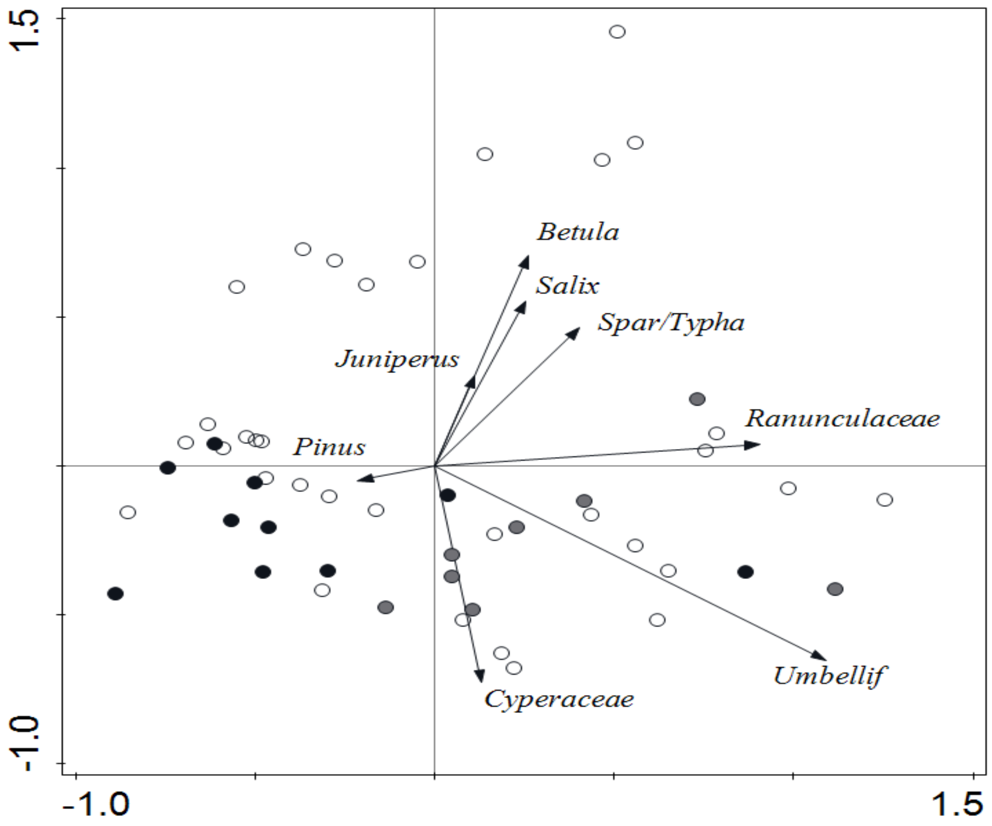

Fig – 6b - Chrást; white – Lateglacial interstadial, grey - Younger Dryas, black- Early Holocene

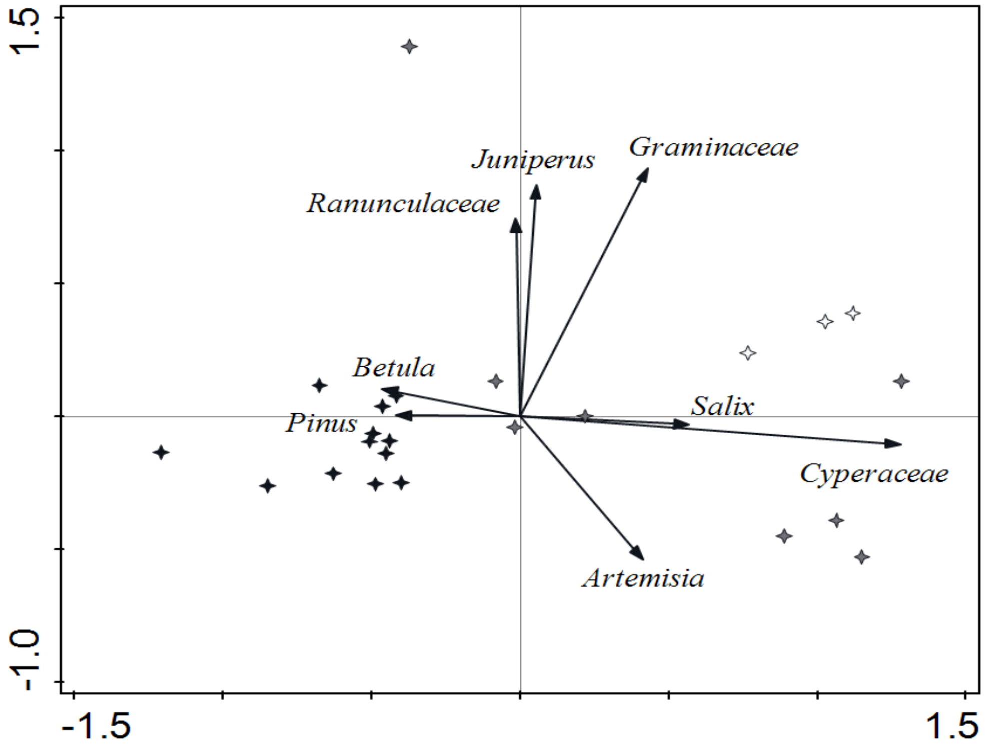

Fig – 6c - Mělnický úval – Přívory; white – Lateglacial interstadial, grey - Younger Dryas, black- Early Holocene

Discussion

Late Glacial interstadial

The base of the sediments of the localities under study has been dated to the Late Glacial interstadial. The formation of lakes and peatbogs in this period was relatively frequent in central Europe (Berglund et al. 1996). The climate of the Late Glacial period was characterized by forceful fluctuations associated not only with a change of the biota but also of the relief. In the Late Glacial interstadial, warming and amelioration of the precipitation regime took place. Lakes, in which limnic and organic sediments accumulated, formed thanks to the improvement in climatic conditions. This also applies to the relatively flat central Elbe region, where the main factor affecting diversity is the floodplain of the Elbe and its surroundings.

The Hrabanovská černava lake was created at the end of the Late Glacial interstadial deposition of a drift sand dune, which dammed up the flow from a spring basin (Absolón 1969). This process is documented in the profile by a layer of sand at the depth of 198–192 cm. This was not a one-off process, as shown by the complex lithology of the profile Hrabanovská černava – dune, which has been dated to around 11,970–11,498 BC. Increased eolean activity at the end of the Allerød was caused by a drop in temperature and a retreat of vegetation (Broecker et al. 2010). Similar evidence has been found at the locality Slepičí vršek in the Třeboň Basin, where a layer of charcoals from the end of the Allerød is buried under a layer of drift sand (Pokorný and Růžičková 2000). In the pollen log, this is indicated by a decrease of the proportion of woody plants at the depth of 185 cm.

The origin of limnic sediments in the Mělnický úval valley is more complicated because of its size (Absolón 1972). In the area of the villages Přívory and Všetaty is a zone of drift sands, which has dammed the wide valley from the south-east to the north-west. This created numerous ponds with communities of ostracods deemed to be of Late Glacial age. The profile Mělnický úval – Přívory has been dated to 15,428–14,568 BC. The profile has a complex lithology, which indicates an influx of material from the surroundings and intermittently flowing water. Pollen of *Sanguisorba minor* is a possible indicator of erosion of nearby marl slopes. Unfortunately, this dynamic environment had a negative effect on sedimentation. In the pollen log, this shows as strong unsteadiness of curves. Losert (1940b) reported the occurrence of macroremains of *Betula nana*, *B. alba*, *Potentilla anserina*, *Heleocharis palustris*, *Hippuris vulgaris*, *Ranunculus sceleratus, Arctostaphylos uva-ursi* and *Potamogeton alpinus*. This suggests a mosaic of water bodies and surrounding terrestrial vegetation.

The locality Chrást was created by cutoff of an Elbe meander around 11,500 BP. At the base of the profile, there is a layer of fluvial sand formed by fading fluvial activity.

Vegetation is composed of pioneer communities of willows and birch (LPZ CH-1) as well as species of exposed fishpond bottoms and disturbed habitats. Later, a shallow water body formed, but this process was aborted by the formation of a woody fen (LPZ CH-2). Conditions in the vicinity of the floodplain facilitated the occurrence of forest formations. Forest vegetation dominated by *Pinus* (LPZ CH-2) therefore developed after the cessation of fluvial activity, which is documented, for example, by fossil trunks (Petr et al 2013) or macroremains of *Fragaria vesca*.

Younger Dryas – Last cooling

The Younger Dryas was the most recent cold oscillation at the end of the Glacial period, when strong cooling of the entire Northern Hemisphere took place (Alley 2000, Broecker et al. 2010). The Younger Dryas was an altogether short period (ca 1,100 years). In Europe, however, it is well documented in the sedimentary and paleological record (Amman 2000) as a marked cold oscillation associated with a regression of vegetation.

The Hrabanovská černava fen was a relatively large but shallow lake; aquatic macrophytes were massively abundant in the lake environment. The lake differed from mountain localities in having a high proportion of pollen of aquatic macrophytes. Mountain lakes such as the Labský důl lake (Engel et al. 2010) or the Plešné jezero lake (Jankovská 2006) were exposed to a colder climate, and their pollen records contain no pollen of aquatic macrophytes, only spores of *Isoëtes*. The spectrum of green a Late Glacialae includes *Pediastrum kawraysky*, which today is distributed in northern Europe (Komárek and Jankovská 2001). In the early Holocene, it is known from the Komořanské jezero lake (Jankovská 2000), from where it was subsequently displaced by Holocene vicariants. There are also relatively large pollen grains of grasses (*Hordeum*-type), which correspond, for example, with the genus *Glyceria* (Beug 2004); their occurrence correlates with indicators of an aquatic environment. The occurrence of *Hordeum*-type or even *Secale*-type pollen in the Glacial period and Early Holocene before the Neolithic is relatively frequent, as documented by localities in Europe (Tinner et al. 2007). It illustrates the diversity of pollen of wild grasses. The pollen spectrum at the Hrabanovská černava locality indicates an open, steppe landscape. Conspicuous dominants are *Artemisia*, *Chenopodiaceae* and mainly *Helianthemum* pollen. Unusual is pollen of *Linum*. This, together with a low proportion of pollen of woody plants (*Pinus* and *Betula*) rules out local presence of trees. A possible exceptions are members of the genus *Salix*, which are confined to the littoral zone of lakes. The rarefracted analysis reaches its maximum in LPZ H-2; the AP/NAP ratio reaches its minimum, by contrast. Open, steppe vegetation hosted a larger number of herbs than can be intercepted by a pollen analysis in forest vegetation. Similar results are also shown by pollen analogies (Kuneš et al. 2008) from the Altai Mts where, however, the proportion of

Helianthemum is not as high and comparative samples do not come from lake sediments. One analogy with the Altai Mts might reside in the continental climate, which amplifies the influence of local microclimatic conditions, promoting vegetation diversity (Chytrý et al. 2008, Pelánková et al. 2008). H. Losert (1940b) reports the occurrence of pollen of *Hippophaë ramnoides*, which was not confirmed during the revision of the locality. The author probably reasoned based on analogies to the Alpine environment, where *Hippophaë* is common even in the Glacial period and is limited to the vicinity of watercourses (Lang 1994). Pollen grains of *Hippophaë* are similar in size and partly also morphology to those of *Helianthemum* (Beug 2004). The author could have confused these two taxa in his time.

At the locality Mělnický úval – Přívory, the environment and vegetation was very similar to the previous period. The locality had a character of shallow ponds with sporadic aquatic vegetation. The sedimentary record, unfortunately, is not stratified very well so as to contain a detailed chronology of the Late Glacial. It provides evidence of erosion processes at the turn of the Pleistocene, however.

At the locality Chrást, the pollen record remained unchanged. The drop in temperature at the beginning of the Younger Dryas is nevertheless well documented in the sedimentary record. There was a shift from a limnic environment with the formation of lake chalk to sedimentation of coarse sands. This was caused by fluvial activity of the river Elbe, which had an imbalanced water regime in the Younger Dryas (Vandenberge 2003). The macroremains record contains, among others, mainly charcoals and only sporadically plants. Frequent charcoals indicate an influence of fire during cold periods of the Glacial period (Daniau et al. 2010). *Larix* and *Pinus cembra* are not recorded, although V. Jankovská (1992) reports a possible occurrence of *P. cembra* in the Doksy region at the turn of the Glacial period and the Holocene. These trees are typical of Glacial forests in the Carpathians and possibly the Moravian Gate (Jankovská and Pokorný 2008). The Chrást profile contains besides *Pinus* also charcoals of *Picea* (Petr et al 2013). The locality lies on the western border of the presumed area of distribution of spruce in the Late Glacial (cit.). The presence of pollen of broadleaved woody plants (*Tilia* and *Corylus*) is a result of long-distance transport. There is no evidence of their occurrence in the Late Glacial period in central Europe (Bittman Lachersee). Broadleaved woody plants in the Late Glacial are known from central Europe only from Hungary (Magyary et al. 2010, Willis et al. 2010) and western Slovakia (Petr et al. submited). The Carpathian Arch was apparently a prominent biogeographical boundary at the time. Redeposited pollen of exotic woody plants (e.g., *Carya*, *Pterocarya*, *Ilex*) as evidence of eolean erosion in the Glacial period and redeposition of older sediments are another case. Eolean activity in the Glacial period was generally higher than today, and this does not apply only to the LGM, when loess sedimented (Fuhrer et al. 1999).

Holocene

Rapid warming and development of the vegetation occured at the beginning of the Holocene. At Hrabanovská černava, this manifests on the one hand as an increase of pine and birch, and as a retreat of herbs on the other. Diversity markedly decreased under the influence of high pollen production of pine and birch. The locality still retained its character of a shallow lake with rich aquatic vegetation. In the sedimentary record, an organic gyttja was replaced by the forming of lake chalk. The disappearance of the open water body has been dated to around 8,200 BP, when aquatic elements disappeared. The formation of freshwater limestones is typical of the Early Holocene. In the Elbe region, there is an analogous situation near Malý Újezd (Ložek 1952). The formation of freshwater limestones indicates warming and an increase in precipitations. The activity of springs is very important in local conditions, see the sedimentation of meadow chalk at the end of the Allerød period in the Chrást profile. These changes in the pollen record did not happen at the Chrást locality; the locality was covered by a sparse woodland already in the Glacial period. The Glacial period/Holocene transition is evident here only in the sedimentary record, when sedimentation of sands ceased and sedimentation of fine floodwater clays commenced. This was determined by the change in the water regime of the Elbe, its cutting into the landscape and the formation of the Holocene floodplain (Vandenberge 2003, Kalicky 2006), during which floodwater clays, not gravel-sand, sedimented outside of the riverbed. The locality had a character of a shallow pond being gradually filled in by runoffs.

Ponds disappeared and a fen began to sediment at the locality. The prevalence of pine and birch is typical of the beginning of the Holocene in the Czech Republic, except only for the highest mountain elevations (Šumava and Krkonoše Mts), where the treeline gradually moved upwards and a forest replaced the mountain tundra. Overproduction of pine pollen overshadowed other taxa, which is why *Artemisia* or *Heliantemum* are recorded only sporadically in the Hrabanovská černava profile. Their presence rules out the existence of a forest with an entirely closed canopy. Palynologically, it is difficult to intercept the spatial mosaic of vegetation (Fyfe 2007). According to Vera (2000), one important factor were large herbivores, which were common in the Early and Mid Holocene.

It is also interesting to compare these findings with the malacological evidence from the Early Holocene, in which species of open habitats were common next to forest elements. This was to a considerable extent influenced by the character of ecological conditions of pine forests, which can host heliophilous species (Novák and Sádlo 2005, Novák et al. 2012). Truly forest species spread only in the Mid Holocene (Ložek 1973). Evidence of this comes from karst regions, which cannot be directly compared with the Elbe region because they differ in having a limestone bedrock and extreme geomorphological gradients. Much closer is the analogy with floodplains of minor streams from the lower course of the river Ohře, where diffuse woodland vegetation with snail species of open habitats is assumed at the beginning of the Holocene (Ložek 1982). The ecological conditions at the time facilitated the persistence of chernozems, which did not get degraded in the early Holocene (Eckmeier et al. 2007) under an open-canopy woodland.

Around 8,200 BP, gradual migration of broadleaved shrubs and trees took place (i.e., *Ulmus*, *Quercus*, *Tilia*, *Corylus* and *Fraxinus)*, as documented by the Hrabanovká černava profile. Unfortunately, the sedimentary record from this locality is only sketchy, so we cannot interpret the chronology of the spread of these species in the Elbe region in more detail. At the localities under study, there is no noticeable peak of *Corylus* like there is at medium and higher altitudes (Rybníčková and Rybníček 1996, Pokorný 2004b). Massive spread of hazel is typical of the Boreal period (Talantire 2002). The biostratigraphical classification of the Holocene in Central Europe is based on this (Firbas 1949). This classification was derived mainly from profiles sampled at medium elevations, not from lowlands. The reasons for this difference are unclear. It could be caused by edaphic conditions, a persistent deficit of precipitations, but there is no evidence for this. Mixed oak woodlands dominated by *Quercus* were the predominant type of vegetation in places covered by loess. Evidence for this comes from the anthracological record from the Neolithic period (e.g., Bylany, Peške et al. 1998). In the Elbe region, a pollen record corresponding to mixed oak woodlands in the Mid Holocene is recorded only in the Elbe floodplain (Břízová 1998). This is rather a reflection of specific conditions of the diverse floodplain environment. Vegetation changes within the floodplain were determined mainly by geomorphological changes, that is, meandering of the watercourse, the water table or the creation of floodplain terraces and the related extent of flooding. These factors affected not only vegetation succession in cut-off meanders, but also the accessibility of the area for human activities. The pollen record in the Elbe floodplain therefore cannot be straightforwardly approximated for the entire lowland.

The Mid and Younger Holocene in the Czech Lowland already saw a fully developed primeval settlement. Humans had colonized practically all suitable places. The pollen record was dominated by *Pinus*, *Fagus*, *Abies.* Other mesophilous woody plants are recorded only minimally. Considering the population density, we cannot assume the existence of extensive forest complexes, where these shrubs and trees could grow. The pollen log of the Hrabanovská černava in the Mid Holocene also holds evidence of local charring. Anthropogenic indicators started to appear along with relatively few cereals. Prehistoric farmers preferred more suitable soils than the drift sands in the vicinity of the locality. The increase of human activity and deforestation of the surroundings of the locality is reflected in the pollen log (LPZ H-4) by an increase in species diversity, which approaches the level reached in the Younger Dryas (LPZ H-2). The AP/NAP ration remains constant, however, which is to a certain extent caused by high pollen production of *Pinus*. An analogical situation is recorded at the Chrást profile, where changes are not as pronounced, by contrast. The uppermost layers of the profile Hrabanovská černava contain evidence of the Medieval period, which in the Elbe region (Kozáková and Kaplan 2006) exhibits as a rise of anthropogenic indicators, typically *Centaurea cyanus* and *Agrostemma githago*. Sediments of Mid Holocene age (dated to around 6,200 BP) are completely degraded at the locality Chrást. This was caused by charring and postdepositional processes (formation of Dopleryte) accompanied by activity of springs and evaporation (Petr et al. in press), leading to a loss of a stratified paleoecological record. In the pollen log, the human impact is manifested in the openness of the landscape and an increase of ruderal taxa around the horizon of 6,000 BP. The Mid and Younger Holocene is not recorded at the locality Mělnický úval – Přívory at all. In the modern time, the fen was drained and ploughed (Absolon 1972), causing degradation of the fen sediment.

Conclusion

Changes of the environment and its diversity on the background of climatic changes at the end of the most recent Glacial period and beginning of the Holocene in the Elbe region have been demonstrated by a comparison of three pollen profiles, which differ in their origin and history. The Hrabanovská černava Fen was a shallow lake that got terrestrialized in the Early Holocene, creating a calcareous low moor. The Late Glacial meander Chrást has a complex history that is recorded in its sediments. It nevertheless has a uniform pollen diagram in the Late Glacial and Early Holocene. There is a clear boundary between the Pleistocene and Holocene periods in the pollen spectrum. The locality Mělnický úval - Přívory is a former small, shallow interdune lake filled by redeposited marl in an environment influenced by running water. The limiting factor for the vegetation of the Elbe region was a deficit of precipitations. Trees and forest species were confined to the floodplain. There is evidence of the occurrence of *Pinus*, *Betula* and *Picea*. Outside of the floodplain, there was a cold steppe with a strong presence of *Artemisia* and *Heliantemum*. In the Late Glacial period, the diversity of the environment facilitated contact among species that are today typical of alpine communities (e.g., *Betula nana*) and species of steppes (e.g.. *Heliantemum*). This could have influenced the phylogenies of certain taxa that are phytogeographical separated today. The apparent uniformity of pollen spectra of the Early Holocene is determined by the taphonomy of these pollen spectra, a predominance of pine and birch pollen and a suppression of herbs. Forests of this period were open and hosted a surviving steppe malacofauna. Vegetation in the Elbe floodplain had a different character, which was determined by the environment and the geomorphology of the Holocene floodplain. A human impact is evident in the Mid Holocene. It later became the principal factor governing the character of the vegetation in the environment of the Czech Lowland.

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Late-glacial and Holocene environmental history of an oxbow wetland in the Polabí lowland (Elbe River, Czech Republic); a context dependent interpretation of a multi-proxy analysis.

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Abstract

This study presents a paleo-environmental reconstruction of an oxbow wetland covering the past 11,500 years. The origin of the oxbow lake and development of the floodplain wetland and changes of the surrounding vegetation are reconstructed by means of palaeobotanical analyses, radiocarbon dating, detailed sediment stratigraphy and micromorphology of samples taken from a former paleo-meander of the Elbe River in the Czech Republic. The sedimentary record of the section *Chrast* was chosen due to its exceptional position within the area of former oxbow lakes. Using a multi-proxy approach we investigated how this environment reflected climatic changes during the Holocene Results show that *Chrast* section covers the period from the Late-glacial to the Middle Holocene, which is climatically very unstable and characterized by extended vegetation and sedimentological changes. The macrofossil record gives a detailed evidence of Allerød vegetation. The sedimentological record reflects changes in fluvial activity (meandering-braided transition in channel pattern) during the Late-glacial/Holocene and postsedimentological changes (occurrence of a *doplerite* layer) in the middle Holocene. We follow three independent lines of interpretation: (a) a local autogenic environmental-succession process, (b) a regional process driven by climate change, (c) a role of stochastic and indeterministic process.

Keywords: Oxbow wetland, floodplain deposits, macrofossils, pollen analysis, micromorphology, succession, random events

Introduction

Mire ecosystems can store a wealth of information about past ecological conditions and offer potential clues on how understand the character, strength and periodicity of climatic changes in the past (e.g. Frenzel 1983; Enstorm et Wright 1984). The reason for this is that mire vegetation often accumulates organic material year after year. For the proper understanding and subsequent correct interpretation of the palaeobotanical record, three assumptions should be made; (1) Production and accumulation rate of organic matter must be greater than its decay (2) The accumulation of organic matter should happen without interruption. (3) Diagnostically essential features of plants must be preserved well.

It is well-documented that these requirements are satisfied in the case of peat or lake sediments, where disintegration or redeposition is minimal, which can lead to the appearance of regularly laminated sediments in case of lakes (e.g., Saarnisto 1986; Hajdas et al. 1993; Tinner et Lotter 2001; Litt et at. 2001). On the other hand, the palaeoecological record in floodplain fluvial sediments is significantly different to lake or peat sediments due to many disturbances and the influence of stochastic, allochtonous processes.

It is generally accepted that rivers represent geomorphic entities that are highly sensitive to environmental change, but it is ever more recognized that the fluvial response is extremely complex, with considerable spatiotemporal variability (Knox 1983, Törnqvist 2007). The development of any floodplain is based on dynamic interaction between water, land and biota under the pressure of climatic changes (Mol et al. 2000; Makaske 2001; Vandenberghe 2003; Herget et al. 2007). The floodplain consists of contrasting types of abiotic habitats and vegetation communities which form a complicated pattern, changing spatially over time. Impacts of various climatic, hydrological and biotic conditions, such as dynamics of water stream, sedimentary processes, successional stages of vegetation, disturbance events, animal and human activities, alternate on a scale of years to hundreds of years. Unfortunately, a little palaeobotanical work has been carried out, due to exceptional heterogeneity of the alluvial environment of floodplains, although it generally presents an attractive source for the preservation of the palaeobotanical and sedimentological record. Traditional concept of basin filling suggest following phases that can be found in the form of layers within the studied section: (a) the bedrock material as a bottom of a flowing river; (b) the early phase of the sedimentation in water column with water and/or waterfront plant with only a short life, after the emergence of an oxbow lake; (c) the middle phase of sedimentation when there is an optimum for the littoral species of the lake environment, especially the perennial clonal graminoids; (d) the terminal phase of terrestralization with land species including evergreen tree species (Ritchie 1995; Břízová 1998). Törnqvist

(2007), for example, reports that changes of climate are reflected by rivers through a) the discharge regime, b) changes in channel pattern (fluvial style); and c) changes in the longitudinal profile by means of aggradation or degradation (incision).

In this paper we focus on interpretation of the palaeoenvironmental record of the *Chrast* section (the Elbe river floodplain, Czech Republic). This section is records a complex sedimentation sequences including abrupt changes in lithology, disturbance events and post-sedimentation processes. In our research we decided to apply a multi-proxy approach that combines several methods in order to provide complexity and build up also a detail reconstruction of past environment and processes. Our study includes not only commonly used pollen analysis, but also macrofossils analysis (Birks et Birks 2000), charcoal analysis, geomorphological, sedimenthological (Bridge 2003), microstratigraphical (Budek 2010; MacCarthy et al. 1998; Stoops 2003) and geochemical approaches. This approach enables us to reconstruct an oxbow wetland with local vegetation, trace long-term succession, consider regional landscape patterns and describe sedimentological events in the past 11,500 years. We have suggest three independent lines of interpretation, separately focusing on (a) local autogenic environmental-succession processes, (b) a regional process driven by climate change, (c) and the role of stochastic and indeterministic processes.

Study region

The study area is situated in lowland at the upper flow of the Elbe River, one of major rivers in Central Europe. The Elbe River, after first ten kilometers of its course in the Giant Mountains piedmont, falls into the lowland formed by Mesozoic marine deposits (Czech Cretaceous Basin), which have alkaline character, mostly covered by acidic Tertiary/Quaternary riverine gravels (Fig. 1). Though the siliceous gravel deposits are nutrient-poor, the floodplain is richer because of the solution percolating from the bedrock. The stratigraphy of the surrounding Pleistocene gravel terraces were studied mainly by Balatka and Sládek (1962) and Žebera (1956). Their interpretation is difficult due to the loess cover and relatively plain relief. Růžičková and Zeman (1994) and Kalicki (2006) described the Holocene alluvial deposits in the study area. The Holocene environmental reconstruction based on the pollen data from nearby sites Chrást, Kozly and Tišice was described by Břízová (1998), Dreslerová et al. (2004) and Pokorný (2005).

For now, the studied site near *Chrást* village is the only palaeomeander found in Czech part of the Elbe stream with the sedimentological record covering the end of the Last Glacial and Holocene period. The locality is situated 1.5 km northerly from Všetaty village (50° 15´N; 14° 35´E) in a low river terrace, distant about 2 km from recent river course and 5 m above its present-day water level (Fig. 1). Cornfields prevail in the surrounding landscape whereas semi-natural habitats such as dry pine-oak forest or alluvial wetland vegetation near present day floodplain of Labe river are locally present. Former Late glacial Chrast oxbow narrow strip is covered by drained ruderal vegetation now under influence of fertilization of surrounding intensive agriculture management. The recent annual average temperature of the region is 8.7 °C and the annual precipitation is 527 mm (Culek 1996).

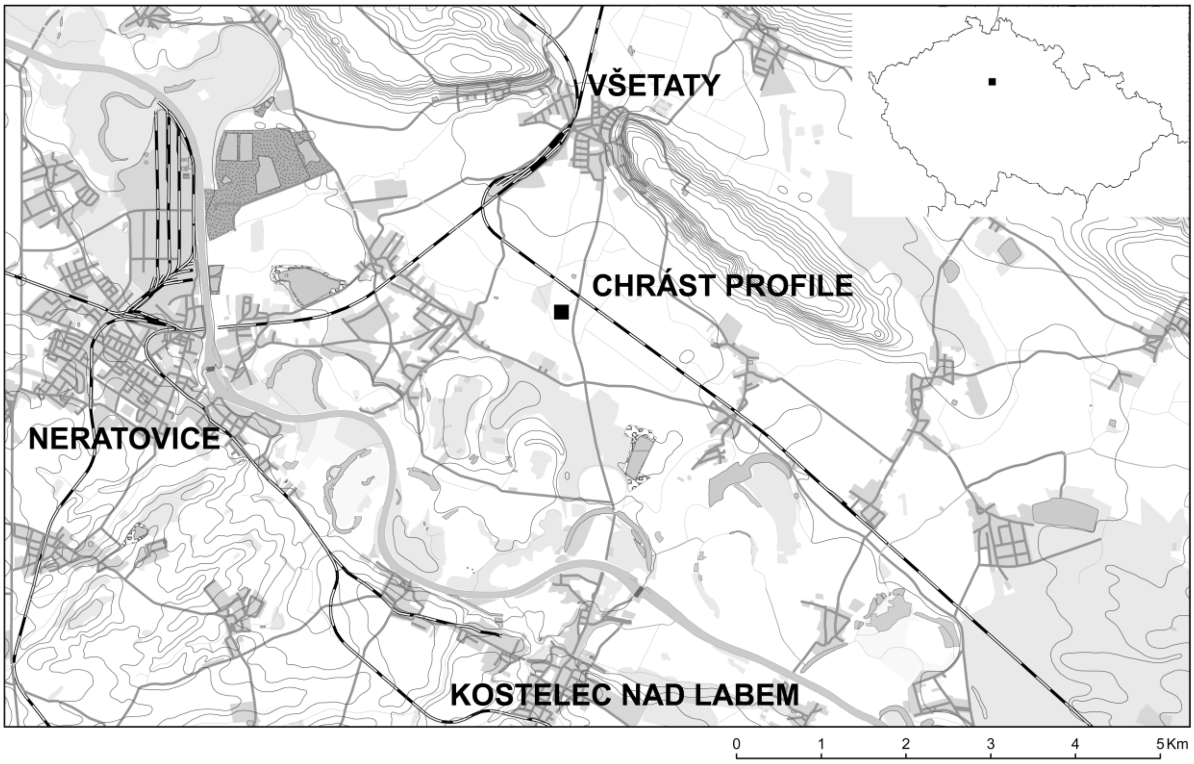

Fig. 1 – The location of the section *Chrast*.

Methods

Trench *Chrast* was cut to expose a stratigraphic section. The location for this trench was chosen after large field survey and detailed screening of the locality using digital maps. In the beginning of the visible former oxbowlake, detectable due to different vegetation cover, was excavated the studied section in pit in size of 2 x 2 meters and 2.85 meters deep. The field documentation was followed by continual sampling into steel boxes (10 x 10 x 50 cm). Every 3 cm of the lithological record (or more if the sandy layers were present) were sampled for the pollen and geochemical analysis and each 10 cm of the section was sampled for the purpose of the macrofossil and charcoal analyses. The lithologically different parts of the section (Fig. 2) were sampled into small Kubiena boxes for the purposes of micromorphological study. Dividing of the profile into zones was made on the base of the lithological description (zones marked CH0–CH6 for all of the section). In the pollen analysis, the alternative zoning (zones marked 1–3) was made by cluster analysis (Conslink) implemented within the program POLPAL (Nalepka and Walanus, 2003).

Radiocarbon dating was performed using the method of C^{14} AMS in the radiocarbon laboratory in Poznań. The pine trunk was dated by C^{14} conventional method in the radiocarbon laboratory of the Nuclear Physics Institute AS CR v. v. i. in Prague. The total acquired five radiocarbon dates have been calibrated using the program OxCal 4.1. (Bronk Ramsey 2009). The results of radiocarbon dating are presented in Table 1.

Micromorphological approach was applied for solving the question of the Last Glacial and Holocene transition. Small blocks 3 x 4 cm were sampled in lithological record in range of 68–173 cm below the surface. Samples were in situ dried, impregnated by resin and thin sectioned in the laboratory of the Institute of Geology ASCR, v. v. i. in Prague and followed by the standard description (Stoops 2003; Bullock et al. 1985).

Chemical analyses cover mainly ICP EOS (inductively coupled plasma/emission optical spectroscopy) analyses of main macroelements. The acid leachable fraction of macroelements was measured for each of the lithologically different horizon. The precisely weighted sample (0.5 - 1 g) was with 20 ml of the 20 % aqueous hydrochloric acid (ultrapure, Merck) in a beaker covered by a watch glass. After the reaction ceased, the content was left to stand overnight. The solid material remained was filtered over a filter paper (blue strip) and extensively washed with water. Finally, the volume was made up to 100 ml in a volumetric flask. The chemical analyses were performed by ICP EOS technique on an Intrepid DUO spectrometer (ThermoFisher) in the Institute of Geology ASCR v. v. i. in Prague. The amounts of macroelements (Ca, Fe, K, Mg, Mn, Na, P, S) were measured using the standard experimental conditions recommended by the manufacturer. Dual plasma view, 2.5 ml/min sample intake were used. For the calibration, mixed standard solutions were prepared combining the commercial 1000 ppm solutions of single element in 2 % nitric acid solution. The calcium concentration is independent of the red-ox conditions and does not reflect the amount of oxygen/reducing activity in the mother solution.

The organic matter was measured using LOI analysis (550 ˚C) according to Heiri et al. (2001) and Holliday (2004). Temperature used for drying was 105 °C and the length of combustion was 3 hours.

The magnetic susceptibility was measured using the kappabridge KLY-4 in the Laboratory of paleomagnetism of Institute of Geology ASCR, v. v. i. in Průhonice.

Pollen analyses were proceeded by using the standard acetolysis method, including using HCl and HF acids (Moore et al. 1991). Pollen grains were distinguished using the pollen keys (Beug 2004; Reille 1995, 1998). The pollen sum in each sample was at least 500 grains. The pollen diagram was plotted in POLPAL program for Windows (Nalepka and Walanus 2003) including the numerical analyses (Rarefraction, Conslink, PCA) for the visualization and the interpretation of the pollen data. Pollen taxa were divided into regional group of terrestrial ones (Fig. 3) and local group (Fig. 4) of wetland ones.

Samples for macrofossils analyses (varying between 350–360 ml) were soaked in water and if necessary, boiled with 5 % KOH. The extraction of plant macrofossils from the sediments followed the standard flotation and wet-sieving procedures (Wasylikowa 1986; Pearshall 1989; Jacomet and Kreuz 1999), by using the sieve of 0.25 mm in diameter. The botanical macrofossils were picked out from the recovered fraction and scanned by using stereo-microscope (the magnification x8-x56). The identification was carried out with seeds and fruits atlases (Katz et al. 1965; Beijerinck 1947; Schermann 1967; Berggren 1969; Cappers et al. 2006; Velichkevich and Zastawniak 2006) and by the comparison with the recent reference material stored at the Department of Botany, Charles University in Prague.
Antracological and xylotomy analyses of charcoal and wood remains were performed only on fragments from the largest fraction (>2 mm). The identification of charcoal fragments, carried out using an episcopic microscope, was done with an interactive identification key (Heiss 2000) in addition to the standard references (Schweingruber 1990). The quantitative and qualitative data coming from the plant macrofossils and charcoal identification are presented in the macrofossils diagram (Fig. 5) plotted using the POLPAL program for Windows (Nalepka and Walanus 2003).

Lithological zones CH0 and CH6 were not analyzed due to insufficient preservation of palaeo-botanical record.

Results

Radiocarbon dating (Table 1). Chronostratigraphic division of the Late Glacial and Holocene used in the article follow Walker et al. (1999), chronological boundaries consider also Bjorck at al 1998. Dates from the base of the section (11 450 ± 60 BP; 11 523 ± 120 BP) corresponds with the Allerød/Bølling interstadial, the date 11 010 ± 60 BP corresponds with transition from Allerød to the Younger Dryas, the date 10.750 ± 60 BP corresponds with the beginning of the Younger Dryas. The fragment of a charcoal of *Fraxinus excelsior* recovered in depth of 105–110 cm was dated to the Middle Holocene (6 510 ± 40 BP; Middle Atlantic).

Table 1.

Radiocarbon dates (AMS) from the *Chrast* section

AD =Anno Domini (after Christ), BC = before Christ, BP = before present (1950)

Depth (cm)	Lab. no.	Method	Material	^{14}C age (BP)	Cal. (BC)
105 – 110	Poz-21028	AMS	Ash charcoal	6 510 ± 40	5 548 – 5 373
145 – 150	Poz-20980	AMS	Pine wood	10 750 ± 60	10 916 – 10 738
210 – 215	Poz-22832	AMS	Menyanthes seed	11 010 ± 60	11 120 – 10 911
230 – 235	Crl-6199B	Con.	Pine trunk	11 523 ± 120	11 716 – 11 226
275 – 280	Poz-22833	AMS	Menyanthes seed	11 450 ± 60	11 440 – 11 278

Lithology (Table 2; Fig. 2). Six main lithological zones (CH1 – CH6) of the Chrast section were described on the basis of sedimentological and microstratigraphical observations.

Micromorphology (see Table 3; Fig. 2). The micromorphological observations were applied on a part of section from the depth of 173 cm to 68 cm (9 samples in total).

Chemical analyses, loss on ignition (LOI) and magnetic susceptibility (MS) (see Table 3). Calcium concentration was remarkably high in zones CH1, CH3, CH5 and CH6. Within all of the section (Fig. 2), the calcium concentration in the leachates was well correlated with clay ratio in the sediment (Table 2) and with the appearance of mollusc shell fragments (Table 3) and algae oospores of *Characeae* (Table 3, 4; Fig. 5). Figure 2 shows that the relation of leachable Fe with the sulfur/SO4 content in the depths of 120-140 cm and 230-250 cm (zone CH 2, CH 5). The micromorphological observation confirmed that the layer 120-140 cm is extremely rich in bacterial spherical products (FeS_2 - pyrites). As can be seen, increased values of phosphorus in the zone CH 5 in depths of 70-90 cm and 130-140 cm and in zone CH 2 in 240-250 cm correlate with the increased values of organic matter measured by LOI and due to micromorphological observation also correspond with the appearance of organic matter rich layers i.e. material precipitated from organic rich solutions (Table 3). The total magnetic susceptibility varied between 450 to 1.5 $*10^{-6}$ SI. Generally, the highest values reflected the presence of clay fraction while the lowest ones reflected the presence of sandy diamagnetic fraction and organic material (zone CH 4).

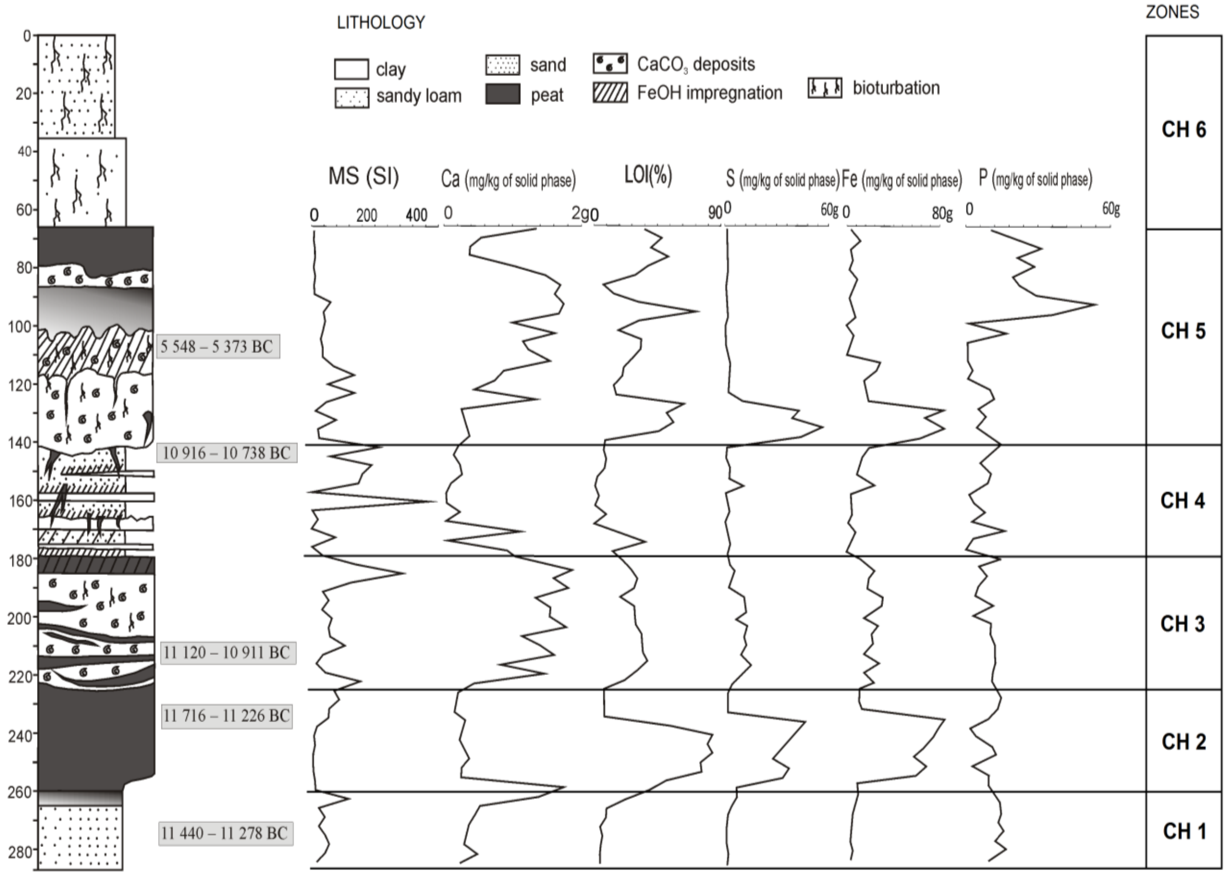

Fig. 2 – The section *Chrast* and its geochemical properties and processes; I. – accumulation of organic matter is reflected in increased amount of Fe, S, LOI, P and Mg, while MS and carbonates are low; II. – Carbonate precipitation is reflected in increased amount of Ca and Mg; III. – FeOH precipitation is reflected mainly by the increased amounts of Fe and slightly increased amounts of MS; IV. – Magnetic susceptibility reflects predominantly the supply of exogenic very fine grained material, it means clay minerals deposited from suspension; V. – Increased amounts of LOI, S and Fe in the facie macroscopically free of FeOH or organic matter reflects the presence of bacterial producing pyrite nodules; VI. – Most of the traced geochemical and magnetic elements except S and Fe show increased values in the depth of 70 and 90 cm below the surface. This reflects the process of slow oxidation (burning) when P coming from organic matter is fixed into carbonates and CaPO4 originates.

Table 2.

The litological description of the *Chrast* section.

Stratigraphy and lithological description of the *Chrast* section.

Depth (cm)	Colour	Lithology	Depositional environment
Zone CH0			
Below 285	Not analyzed	Sandy gravel layer strongly saturated by water.	Fluvial
Zone CH1			
285–265	10YR 7/1	Slightly calcareous loamy sand, light gray with a very gradual change toward to the overlaying layer. This layer is sitting with an abrupt change on the former one.	Fluvial/Aeolian/Limnic
265–259	10YR 6/1	Calcareous sandy clay, gray, with an abrupt change and increasing amount of organic matter toward to the overlaying layer.	Limnic
Zone CH2			
259–223	7.5YR ¾	Non calcareous decomposed and compacted peat, dark brown, with an abrupt change toward to the overlaying layer.	Terrestrial
Zone CH3			
223–185	10YR 2/2 10YR 8/2	Strongly calcareous laminated layer of clay interrupted by 1-4 cm thin layers of decomposed peat, with an abrupt change toward to the overlaying layers. The colour is varying due to the presence of more calcareous or more peaty material from very dark brown to very pale brown. Root bioturbation is slightly recognizable and the change toward to the overlaying layer is abrupt.	Limnic-terrestrial (redeposition, bioturbation)
185–179	10YR 3/1 10YR 5/2	Calcareous, strongly degraded clayey peat impregnated by FeOH rich solutions coming from decomposed organic matter. Colour is varying from very dark gray to grayish brown due to the state of the decomposition of peat. The change toward to the overlaying layer is abrupt.	Terrestrial-limnic

Zone CH4			
179–142	10YR 6/4 10YR 7/1 10YR 2/2	Slightly calcareous sandy layer including thin layers (app.1cm) of clay and clay loam, with eroded surface in the depth of 159 cm, 169 cm, 166 cm, 175 cm. The colour is varying due to the oxidation and reduction processes and due to the grain size changes between light yellowish brown and light gray, with an abrupt change toward to the overlaying layer. Obvious presence of coarse grains of mica. Voids are filled by decomposed organic material with Mn oxides, very dark brown.	Fluvial-limnic (root bioturbation)
Zone CH5			
142–118	10YR 6/1	Calcareous clay, gray with an abrupt change toward to the overlaying layer.	Limnic (bioturbation, ox-reduciton)
118–102	5YR 5/8	Calcareous silty clay, yellowish red, with a very gradual change toward to the overlaying layer.	Limnic (root bioturbation, oxidation)
102– 86	10YR 4/2	Calcareous clay layer, dark grayish brown, with an abrupt change toward to the overlaying layer.	Limnic (root bioturbation, oxidation)
86– 80	10YR 8/3	Calcareous silty clay, very pale brown, with a gradual change toward to the overlaying layer.	Limnic (root bioturbation, oxidation)
80– 67	10YR 2/1	Calcareous clay impregnated by organic matter rich solutions, macroscopically described as decomposed black peat with an abrupt change toward to the overlaying layer.	Terrestrial-limnic (root bioturbation,oxidation)
Zone CH6			
67– 35	10YR 5/2	Degraded calcareous silty peat grayish brown, with an abrupt change toward to the overlaying layer.	Terrestrial (root bioturbation)
37– 0	10YR 3/2	Very dark grayish brown antropogenic material.	Antropogenic (degradation)

Table 3.

Comparison table of main micromorphological features of the *Chrast* section. Micromorphological description of the *Chrast* section (Fig. 2)

Depth (cm) zone	subzone	Micromorphological characteristic	Interpretation
Sample X1			
173 Zone CH4	A (bottom)	Single grain microstructure of sandy material with monic grain distribution	High lithological variability as a result of differing provenience and origin. Phases of unstability and redeposittion are altering with phases of stagnant water with the organic matter accumulation and carbonate precipitation. Postdeposittional presence of redox FeS bacteria.
	B	Intergrain channel microstructure of sandy loam, grey to orange crystalic matrix, carbonate void coating, partly decomposed organic matter.	
	C	Intergrain channel microstructure of sandy loam, horizontal pores and crystalic matrix with grey-orange colour, void coating and the presence of partly decomposed organic matter. FeS bacteria products.	
	D (top)	Single grain microstructure of sandy material with monic grain distribution.	
Sample X2			
150 Zone CH4	A (bottom)	Intergrain channel microstructure of well sorted sandy loam. Channels infilled by decomposed and partly decomposed organic matter, FeS bacteria products, crystalic B fabric of light brown matrix.	Phases of unstability presented by washouts with continuous organic matter production. Postdeposittional presence of redox FeS bacteria.
	B (top)	Simple packing to intergrain microagregate microstructure of sandy material, dark brown matrix with decomposed and partly decomposed organic matter, locally very poorly sorted material, lenses of redeposited braunhlem plasma, carbonate concentrations and products of FeS bacteria.	
Sample X3			
135 Zone CH5	A (bottom)	Microaggregate to channel microstructure of silty loam, FeOH counting, decomposed and partly decomposed organic matter, products of FeS bacteria, depleation pedofeatures.	Phases of stagnant water and dessication. Postdeposittional impregnation by Fe rich solutions, presence of redox FeS bacteria.
	B	Intergrain microaggregate microstructure of sandy layer, light and dark brown matrix, partly decomposed organic matter, products of FeS bacteria, relicts of horizontal bedding, strong bioturbation.	
	C (top)	Single grain microstructure of silty loam, gefuric related distribution. Crystalic B fabric, hematite microaggregates, FeS products of bacteria rare, decomposed organic matter, bioturbation.	

Sample X4		
120 Zone CH5	Intergrain microaggregate and channel microstructure of silty loam, light brown crystalline matrix, carbonate precipitation, mollusca shells, decomopsed and partly decomposed organic matter, FeOH impregnation, bioturbation.	Stable alkaline, stagnant environment carbonate precipitation, continous organic matter production postdepositional impregnation by Fe rich solutions.
Sample X5		
105 Zone CH5	Intergrain microaggregate and channel microstructure of silty loam composed of quartz grains and carbonate crystals, channels and chambers, gray brown and crystalic matrix, mollusca shells and *Chara* oogonias very common, FeOH impregnation presented as a *doplerite*, decomposed and partly decomposed organic matter, bioturbation	Long-term stable alkaline conditions, with rich carbonate precipitation, organic matter production postdeposittional impregnation by Fe rich solutions, origin of doplerite appearance
Sample X6+X7		
90 + 80 Zone CH5	Channel microstructure of silty loam composed of quartz grains and carbonate crystals and aggregates, channels and chambers, grey brown and crystallic matrix, carbonate and mollusca and *Chara* oogonias concentrations postdeposittionaly corroded and impregnated by ferrum hydroxides. Root bioturbation, presence of decomposed and partly decomposed organic matter.	Long-term stable alkaline conditions, with rich carbonate precipitation, organic matter production postdeposittional impregnation by Fe rich solutions, corrosion of carbonate features, doplerite appearance
Sample X8+X9		
75 + 68 Zone CH5	Subangullar blocky microstructure of organic matter rich matrix, channel and chamber microstructure of carbonate rich matrix. Channels and vughs, cracks, matrix composed mainly by carbonate crystals (fragments of shells occure) or organic rich solutions. Colour of matrix depends on the lithology and varies from light grey to reddish brown.	Long-term alkaline conditions with carbonate precipitation, high organic production, postdeposittional impregnation by Fe rich solutions, corrosion of carbonate, origin of doplerite layers.

Analyses of plant macrofossils and pollen

Results of macrofossils analysis, presented in the diagram (Fig. 5), show significant changes. Six local macrofossilsassemblage zones (LMAZ) were distinguished by cluster analysis (Conslink) implemented within the program POLPAL (Nalepka and Walanus, 2003); in addition, after comparison with sedimentology is visible that macrofossils zones correspond with lithological zones. Species diversity and abundance of plant macrofossils were the most extensive at the zones CH1, CH2 and CH3; moreover, preservation of the macrofossils (e.g. surface sculpture) was markedly fine in these zones. By contrast, the sandy zone CH4 was poor in quantity of subfossil seeds and fruits, only charcoal and wood fragments prevailed. The zone CH5 contained also a small amount of vascular plant macrofossils and surface sculpture of plant macrofossils was considerably degraded; only oospores of green algae *Characeae* in zone CH5 were frequent, all that can be seen in figure 5.

Table 4

The macrofossil assemblage description and interpretation
Macrofossils assemblages of the *Chrast* section (Fig. 3).

Depth (cm) Zone context	Macrofossil assemblages description
Zone CH1 **285–260** Samples 1-5	Zone CH1 covers early stage of organic sedimentation. This corresponds with the beginning of the vegetation succession. High number of recorded species shows easy way of botanical ecesis and low interspecies competition. High species richness in this zone is remarkable. Different groups of plant comunities distinguised here covers species with different requirements for moisture and nutritiens; this indicates heterogeneity in habitats under the disturbation pressure during dynamic changes of the river channel. Oospores of alage *Chara* are incrustatted by calcium. This indicates shallow carbonate-rich water body with fluctuating water-level and clay or loam bottom. Diaspores of water macrophytes, sedges and reeds indicate an oligo-mesotrophic lake with littoral vegetation on the shore line.

Zone CH2 **260–225** Samples 6-12	Macrophytes and mire species in the zone CH2 indicate a presence of an unstable shallow lake and transitional mire vegetation. High level of organic production caused terrestralization of the water body. Spatial heterogeneity of habitats and pressure of disturbances are lower.
Zone CH3 **225–175** Samples 13-20	In the zone CH3 is remarkable restoration of still water habitat with well developed littoral vegetation, similar to the zone CH1. It shows retrogression of the succession and higher level of disturbances.
Zone CH4 **175–140** Samples 21-29	Zone CH4 is extremely poor, mainly charcoal and wood fragments can be found. Other plant macrofossils are missing. This can be interpreted as a bottom of the river without vegetation, or floodplain under the influence of the big flood episodes or postdeposition lose of the macroremains due to the influence of bioturbation and oxidation processes.
Zone CH5 **140–86** Samples 30-43	For the Zone CH5 is significant low content of plant macrofossils. Vegetation cover is poor in species, probably due to the influence of food or bioturbation and high level of mineralization. Presence of oogonias of *Chara* and nutles of *Schoenoplectus tabernaemontani* indicate the mesotrophic water body rich in carbonate. *Fraxinus* charcoal was redeposited. Ruderal species shows influence of floods.

Results of the pollen analysis, presented in pollen diagrams (Fig. 3, 4), show indistinct changes and the observed pollen spectra was rather uniform, therefore only three local pollen assemblage zones (LPAZ), identified using cluster analysis, were distinguished. Apart from zone CH5b, it is difficult to determine any development or changes in the diagram. This was also confirmed by PCA and by the Rarefraction analysis (Fig. 3).

Description of pollen assemblages:

LPAZ 1: 261 – 279 cm (Zone CH1)

AP/NAP ratio is about 80%. Curve of *Pinus* increases from 40 to 90%. While *Betula* decline from 30 to 10%. *Salix* and *Juniperus* form closed curves. Pollen of *Alnus*, *Picea*, *Ulmus* and *Tilia* was very rare. NAP is dominated by grasses and sedges. *Helianthemum*, *Chenopodiaceae* and *Thalictrum* occur occasionally. Water species were represented e.g. by *Myriophyllum*, *Batrachium* and algae *Pediastrum*.

LPAZ 2: 120 – 260 cm (Zone CH2, CH3, CH4, CH5a)

AP/NAP ratio varies between 50 – 85%. *Pinus* (50 – 80%) and *Betula* (5 – 20 %) dominated, whereas *Picea*, *Juniperus*, *Alnus* and *Salix* were rare. In NAP, sedges (30%) prevailed over grasses (5%). Variable occurrence had pollen taxa: *Artemisia*, *Ranunculaceae* and *Umbeliferae*. Occurrence of water taxa (*Myriophyllum*, *Potamogeton* and *Pediastrum* was sporadic.

LPAZ 3: 86 – 120 cm (Zone CH5b)

AP/NAP ratio is about 70 %. *Pinus* dominated, but curve falls from 80 to 50%. Only in zone broad-leaved woody species of mesophilous habitats expanded (*Corylus, Fraxinus, Quercus, Tilia*). Curve of *Betula, Picea, Tilia, Quercus, Corylus* and *Alnus* rapidly increases. *Ulmus*, *Fagus* and *Abies* appeared. Grasses and sedges still create an important component of NAP spectra. Other herbs taxa (*Artemisia*, *Chenopodiaceae*, *Thalictrum*, *Ranunculaceae* and *Umbeliferae*) were less common. *Cerealia* pollen appeared. Wetland taxa absented, the only with exception was pollen of *Typha latifolia*. Microcharcoal (including grasses type) had massive occurrence and increasing tendency since depth of 100 cm. Quality of preservation in this zone was bad (mechanical and chemical damaged pollen grains).

Pollen grains from the depth of 0 – 86 cm are largely degraded and not identifiable; therefore the pollen record cannot be used for the further interpretation.

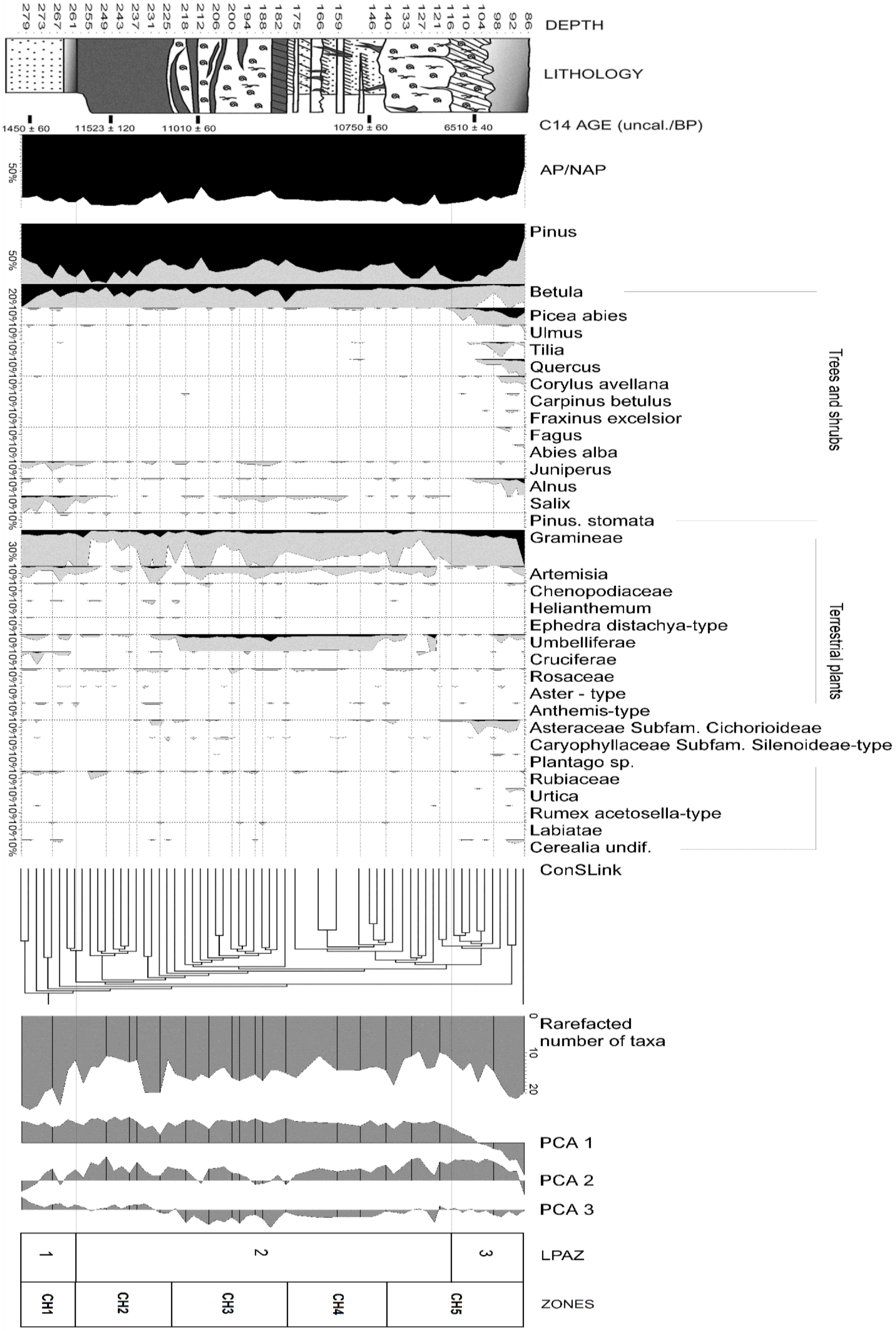

Fig. 3 – The Pollen diagram of terrestrial species

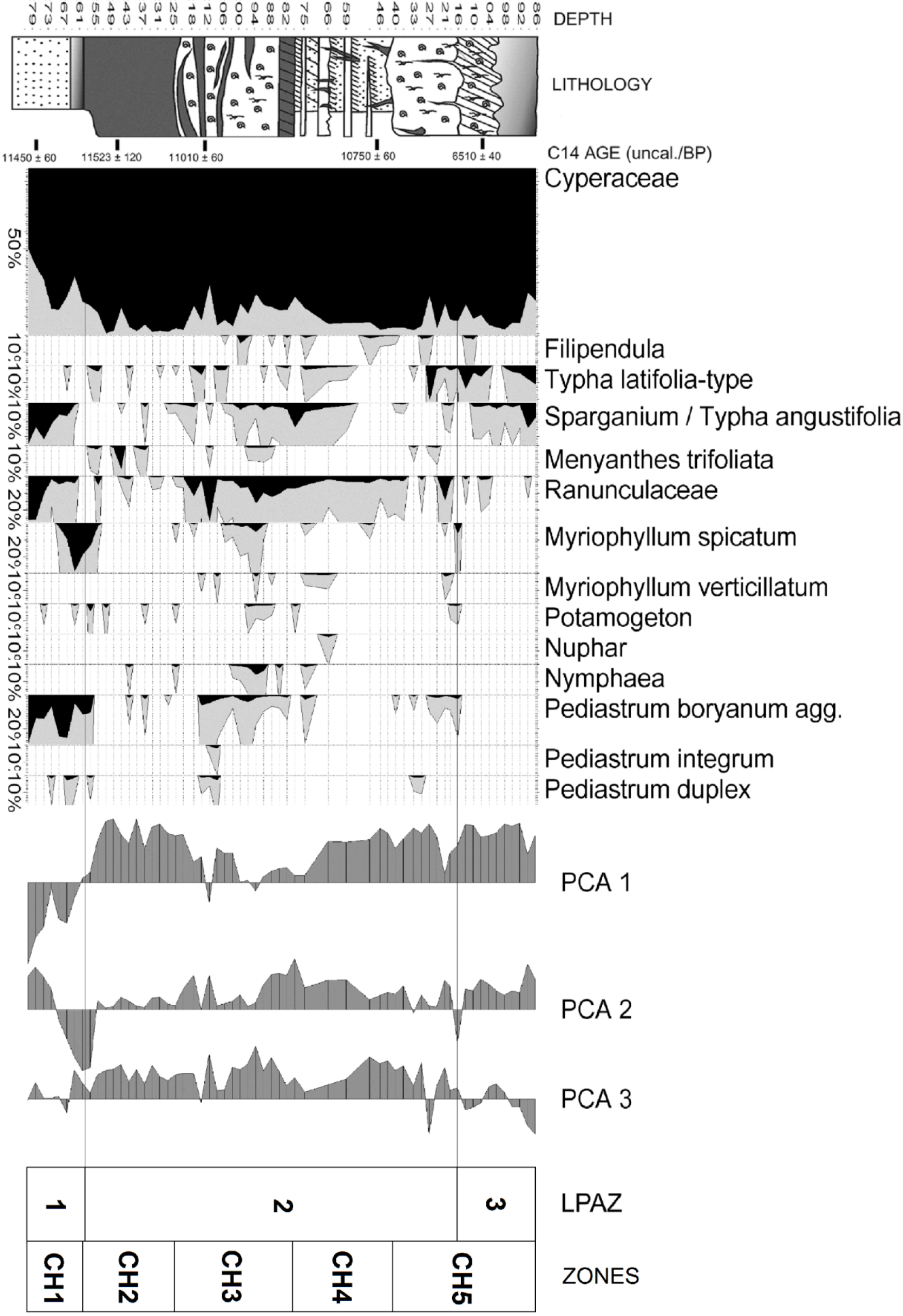

Fig. 4 – The Pollen diagram of local species

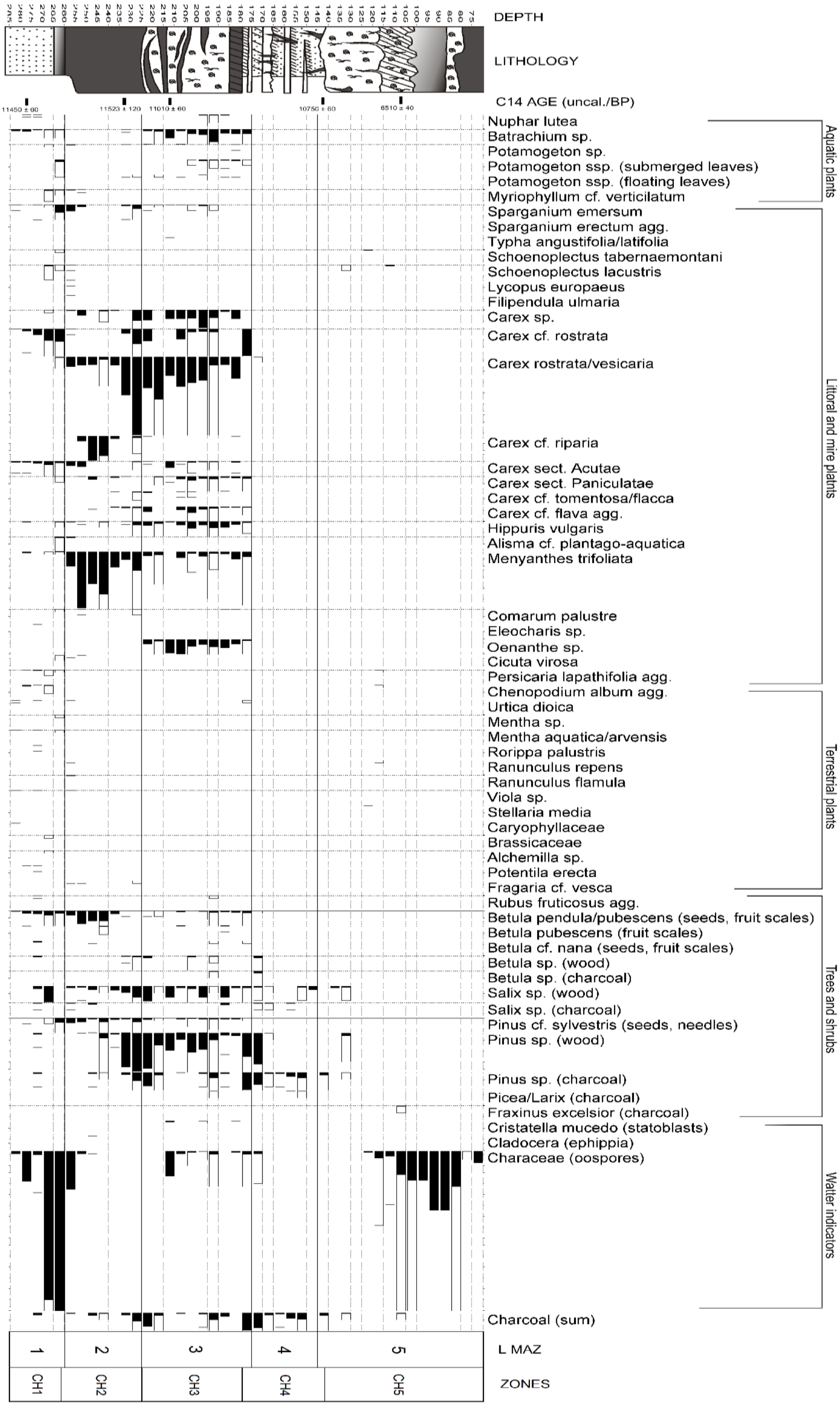

Fig. 5 – The macrofossil diagram. *Potamogeton* submerged leaves – CH1 zone: *P. pusilus*., *P. obtusifolius*.; CH3 zone: *P. filiformis*.

Discussion

Interpretation of context 1. Local environmental processes

The first approach to the interpretation of the section is based on local changes of the environment and vegetation. Our results documented that erosion-accumulation processes and vegetation succession occur during infilling of the inactive river channel.

Sedimentation processes:

Our results provide compelling evidence that the development of the palaeo-river channel *Chrast* is more or less derived from the general scheme described in the introduction.

Gravels and sands described in the bottom of the section *Chrast* (CH0) represent former channel bed-load of an active river. In the following period (CH1–CH3), the inactive river channel was filled up by overbank deposit (silt and clay), represented by suspended-load sediments that accumulate on floodplains in the environment of slowly-flowing up to stagnant water. Two types of sediments alternated; (a) the loamy or clayey sediments were formed in still water rich in percolated carbonates, whereas (b) the nutrient-poor organic sediments were created under the terrestrial conditions. These changes are illustrated by the geochemical record in zones CH1–CH3 (Fig. 2); the increase of Ca and Mg positively correlates with the carbonate precipitation while their decrease in the zone CH2 (220–260 cm) on behalf of increase of S and Fe characterizes the sedimentation phase of organic material and bacterial activity.

Dramatic change occurs in depth of 179 cm, at the beginning of the zone CH4, due to occur of sandy layers. Sandy layers give an evidence for the accumulation phase during flood events and represent overbank deposits as reviewed by Aslan (2007); this is connected with floodplain aggradation as states Makaske (2001). Detailed micromorphological investigation revealed presence of clay layers in this zone CH4 (Fig. 2). The alternation of sand and clays was a result of fluvial activity impacts of braided river into limnic environment. Number of studies has documented braided river system as a typical morphological phenomenon of splitting river channels (e.g. Makaske 2001, Vandenberkhe 2003, Törnqvist 2007) and our results provide evidence for such a split channel of the Elbe River.

The record in the CH5 zone is somewhat striking, despite the chemical changes, several remarkable horizons of different colors were found (Fig. 2). The chemical sedimentation of a calcium-rich matter was characteristic for this zone. This material is interpreted as the lake marl, originated in shallow limnic environment during a long period of activity of underground water sources rich in carbonates. At the base of the studied zone CH5 (depth range 120–140 cm), the intensive bacterial activity was identified chemically and even micromorphologically (Table 3). In the bottom of zone CH5, the increase in carbonate accumulation and also the increase in organic matter occur (the LOI curve up to 70%); Fe and S values are strikingly high, too. The geochemical structure was largely influenced by post-depositional changes caused by the activity of root systems and bacterial activity linked to it. Higher parts of the zone CH5 (67 – 120 cm) are remarkable for the significant increase of Ca and Mg and also for the minimal values of MS (probably due to the reaction to diamagnetic carbonate). Also the values of Fe and S are very low. This geochemically homogenous part of zone CH5 is macroscopically light reddish and microscopically black which reminds of horizons rich in organics or iron. These layers were indentified as a *doplerite*. This native hydrocarbon material emerged before total decomposition of topsoil within the largely degraded and antropogenously influenced fen. The sapric porous horizon (Dinc et al. 1976; Fox, 1985) with the decomposed organic matter (Manoch 1970; Fox, 1985) started to be transported downward the section in form of solutions and so the emergence of *doplerite* occurred (Koopman 1988). We found that this substance further precipitated and created a solid, opaque crust. Additionally, *doplerite* layer does not contain many plant macrofossils, although it resembles as a layer rich in organics and also values of LOI and P indicated presence of organic acids. We suggest that this appears as a consequence of a penetration of these acidic solutions, the subsoil layers rich in carbonates were corroded partially. The sedimentology of this zone is thus based on the competition of several disparate processes. The sedimentation of clay matrix, the carbonate precipitation and the accumulation of organic substance, the bioturbation and postsedimentation processes caused the intensification of a bacterial activity followed by the decomposition of most of organic matter including the macrofossils, the corrosion of carbonate layers, the establishment of *doplerite* solution, and its motion through the site.

The youngest zone CH6 is characterized by the sedimentation within a fen which was consequently degraded and largely anthropogenically influenced. The record of local fires can be observed in the form of black colored sediment within the studied section and proven thank to the presence of micromorphologically visible charcoal. The microscopic charcoal particles documenting the human influence were also identified in the pollen slides. The section is covered by an anthropogenic backfill from the second half of the 20th Century.

Vegetation succession – history of local vegetation and changes in hydroseres Zone CH1 represents the initial phase of the vegetation succession and is characterized by the contemporary occurrence of three groups of species which differ in requirements on their habitat. The first group consists of species which are able to promptly colonize habitats with well utilizable nutrients. These competitively weak species indicate the influence of constant disturbances. This group includes vegetation of stoneworts (*Chara*) and still water macrophyte plants (*Nuphar lutea*, *Potamogeton filiformis, Batrachium* sp.), which occurs in shallow water bodies (alluvial pools, oxbows) with stagnant or slowly moving water with mineral sediment. Second group consists of littoral species which are able to withstand changes of water level and colonize sandbanks (*Alisma, Sparganium, Eleocharis, Hippuris, Schoenoplectus*). And third group presents annual nutrient-demanding herbs of alluvial sediment accumulation on the banks (*Persicaria lapathifolia, Rorippa palustris, Chenopodium, Ranunculus repens, Mentha, Urtica*). Substrata is usually gravel and sand with a good nutrition supply as reviewed Šumberová et Lososová (2011). This “ruderal” group of annual nithropilous wetland herbs has its optimum in the zone CH1 and remarkably recedes due to transitional terrestralization and the competition of perennials and appears in the zone CH3 where carbonate and clay sedimentation is renewed.

The group of perennial clonal species, responsible for extinction of the oxbow lake and origin of the fen in undisturbed environment, has optimum in the zone CH2 and persists in the zone CH3. Clonal, perennial plants prevailing here: (a) graminoids (*Carex rostrata/vesicaria, C.* sct*. Acutae, C.* sct*. Paniculatae, C. tomentosa/flacca, C. flava*) and (b) dicotyledonous plants (*Menyanthes, Comarum, Cicuta*). The vegetation is classified as a calcium-rich fen due to the occurrence of species preferring calcium-rich environment, e.g. *Carex flacca/tomentosa* and *Carex flava*The chemical structure of the sediment correspond with it content of Ca is lower and suppress by higher organic production (Fig. 2). The presence of woody species in these phases of the succession can be interpreted as rather influence of heterogeneity of the environment (see below).

The succession series in the zone CH3 is largely influenced by increase of hydrological activity, which was connected with precipitation of carbonates. Founded plant macrofossilsgive evidence about presence of slow moving or stagnant water with still water macrophytes (*Nuphar*, *Batrachium*, *Potamogeton*) also with macroalge (*Chara*). Fluctuating of water in the shoreline is indicated by the species which are adapted on these conditions (*Hippuris*, *Sparganium*, *Batrachium, Oenanthe*). Littoral sedges occurred as well (*Carex rostrata*, *C.* sect. *Paniculatae*, *C*. *flava* agg.). In the zone CH3, the frequent occurrence of *Oenanthe* sp. mericarps is remarkable. *Oenanthe* stands commonly occurs in lowland alluvial floodplains, on sites with an exposed bottoms or on sites flooded by shallow water, but it can also grow in greater depths of up to 1 m.

In the following zones (CH4–CH6), the succession can be estimated on the basis of the palaeobotanical data with the difficulties only. However, afore-mentioned interpretation of the sedimentation processes indicates the vegetation which produces a large amount of fast decomposing and mineralizing biomass. The oospores of *Characeae*, with calcium carbonate incrustation, proven in large amount, indicate a shallow water, periodical floods and light. The wood fragments and the charcoal (*Betula, Salix, Pinus, Fraxinus*), by contrast, indicate the presence of shrub and a forest vegetation in the vicinity of the studied site. The presented evidence suggests an occurrence of eutrophic wetland with the prevalence of tall graminoids (e.g. *Phragmites*). This hypothesis is supported by finds of several achens of *Schoenoplectus tabernaemontani/lacustris*, which indicates reed bed habitats. This eutrophic wetland was, in some episodes, overgrown by scarce canopy of woody plants. Similar vegetation types and signs of changes of the succession stages are frequent in the area of interest even today. Some human impact to the vegetation is likely, too.

Interpretation of context 2. Large-scale environmental processes.

The explanation of local patterns of the studied deposits using large-scale environmental processes is a common approach in palaeoecology. This approach shows how meander infilling reflects the global changes on the landscape level. It was nicely visible that results of analyzed section *Chrast* corresponded with general characteristics of environmental development in the Late Glacial and Holocene.

Meander infilling as a result of landscape development and climatic changes:

The climatic and the environmental Quaternary changes are of a principle influence on dynamics of fluvial systems in Central Europe which was not affected directly by the continental ice cover (Vandenberge 2003; Maddy 2001; Tyráček 2001; Tyráček and Havlíček 2009). We detected different mechanisms of fluvial regime response to environmental-climate forcing acting via (1) changes in the discharge regime (hydrological condition), (2) changes in channel pattern (fluvial style) and (3) changes in the longitudinal profile by means of aggradation or degradation (river incision). These changes may result in river terraces development and river architecture pattern at a shorter time scale and at the Holocene scale in the sedimentation of alluvial soils (Törnqvist 2007). These global changes were traced in sedimentary and palaeoecological record on the site of *Chrast*.

Allerød and Bølling:

During the interstadial complex Allerød/Bølling when the water regime of the rivers in Central Europe was of a meandering character (Vandenberge 2003; Pastre et al. 2003; Andres et al. 2001; Houben 2003). The water flow within the branch in the first part of Allerød is visible in sandy sedimentation in the zone CH1 and in macrofossils of short-age plants which indicate the constant disturbances caused by the activity of the river. The second half of Allerød is characterized by the fen development without sedimentation of a sandy material. That indicates a decrease of fluvial activity. The increased organic production serves as an evidence for the improvement of a climate which allowed succession of vegetation in hydroseries.

Younger Dryas:

The Allerød/Younger Dryas transition is visible as the lithologic interface of the zones CH2 and CH3. macrofossils diagram reflects transition in water regime by the presence of water macrophytes and *Characeae.* During the cold stage Younger Dryas, the river water regime changed frequently from meanders to braided on our studied site, the evidence is only indirect – the sedimentation of a coarse sand with presence of charcoal and wood fragments of *Pinus* and *Salix* (zone CH4).

Holocene:

The beginning of Holocene is represented by the aggradation of fine carbonaceous clays, so called *alm* (or lake chalk; CH5) without the coarse sand fraction. Episodes of sedimentation of *alm* aggradation in the glacial and in the beginning of Holocene can be explained by the influence of several factors which could act apart or together – the change of hydrological conditions (decrease of flood events), the change of climate (rapid and short time instability climatic conditions followed by the years of drought (Bohncke and Hoek 2007) and the change of the evaporation rate. Ložek and Šibrava (1982) assumed increased evaporation rate in the Elbe River area for the periods of instability during the Late Glacial period. Moreover, the Early Holocene deposition is probably connected with the increased spring activity during the Holocene climatic improvement (Ložek 1973; Roberts 1998). The presence of *alm* is well known from the same time period also from other localities within the Elbe lowland (Hrabanovská černava - Petr 2005; Malý Újezd - Ložek 1952).

In the zone CH6, sedimentation was influenced by anthropogenic activities in the surrounding landscape. Pollen analysis shows ruderal species and cereal pollen. macrofossils (charcoal), micromorphology and geochemistry indicated traces of local fires (micro-charcoal of grasses and bent-grass) in the degraded peat.

Development of the vegetation in the regional level:

Transported pollen grains and macrofossils from the surrounding landscape can partly explain the vegetation diversity on the region level. While the origin of shallow water bodies, banks and fens with characteristic vegetation can be seen in local conditions, the presence of other groups of macrofossils can be evaluated as a result of the influence of other vegetation types in the close surrounding out of the site. Pine, birch and mesophilous herbs and shrubs (*Fragaria, Alchemilla, Viola, Potentilla erecta, Rubus*) could grow in older succession stages on alluvium elevations or in surrounding out of the present alluvium, but also directly on young and frequently disturbed sediment load where long-term plant survival is very difficult whereas the establishment is easy.

At the bottom of studied section (zone CH1) the number of species as well as the differentiation of their requirement on the environment is the largest. This may suggest a great diversity of plant communities during early development of the inactive river branch in the glacial. In chngeableconditions water bodies can persist longer or are periodically renewed (Bos 2001).

Pollen analyses detected in the Late Glacial period (zones CH1–CH3) that in the surrounding landscape the herbaceous vegetation rich in species of open habitats with birch *(Betula pendula/pubescens, B. nana)*, willow (*Salix* sp.) and pine (*Pinus sylvestris*) prevails. The local occurrence of pine was detected by the presence of pine wood and needles. Several spruce charcoal particles were recovered from the zone CH3. Similarly, the spruce is represented in the pollen diagram as well. Its occurrence in the Czech Cretaseus basin on its western boundary is presumed already in the Last Glacial Maximum (Latalowa and Knaap 2006). On the contrary, the sporadic occurrence of pollen of mesophilous woody plants is most likely the result of long-distance transport due to absence of macrofossil evidence. These woody plants have not been detected for the Last Glacial in this part of Central Europe yet (Bittmann 2007).

Late Glacial forests in this time period are typical for Western Carpathians (Jankovská 1988, Jankovská and Pokorný 2009), while for the western parts of the Czech Republic open habitats are predominantly reconstructed (Pokorný 2002). The Late Glacial pollen record from Central Bohemian lowland is known only from Hrabanovská Černava site (Petr 2005). The former small shallow lake was detected at the area situated 18 km E from *Chrást* site and 4 km N from the Elbe River. The pollen record of this site is considerably different; open steppe taxa (*Helianthemum*) prevailed and trees were represented only marginally. We can therefore conclude that forest vegetation was restricted to the favorable habitats along the river. Wet and nutrient-rich soils under mild microclimate condition were responsible for the riverine gallery forests development which are recently present both in tundra and steppe environment (Tockner et al. 2009). Similar results are shown in Chytrý et al. (2008) on example of the recent vegetation of southern Siberia; the continental climate amplifies dependence of the vegetation on local geomorphologic conditions.

Interpretation context 3: Out of general stories and rules. Meander infilling as a unique concomitance resulting from random processes.

If the interpretation of the lithological record is based on the evidence local development or on global context, the usual interpretation show the studied section as a result of the homogenous development and try to explain as much data as possible in terms of generally valid processes. We decided to apply another interpretation in order to show randomness and unpredictability in our data considering chanciness in external influences and circumstances.

The complexity of information value.

The studied section is a result of superposition of several episodes of unknown span which represent fragments of past processes. These episodes are mainly driven by various allogenic and autogenic processes (e.g. climate change, vegetation succesion), which has impact to litholigical record. Missing sedimentary records, so called *hiatuses*, are very common phenomenon, caused by erosion - processes that interrupt continuous sedimentation. Compared to the development of lakes or peats, there is higher frequency of erosion events in the river systems (e.g. floods, bottom currents), which interrupt the local development. The studied record of the *Chrast* section reflects only a part of local geodiversity (types of sediments) and biodiversity (species, types of vegetation) and their representation in time (stratigraphic sequences, succession lines). Therefore record of studied section is unique and there are no identical parallel records on the Elbe River. There can be analogous lithology on other rivers, but not the structure of species. What is more, it is highly probable that our section is not representative even for the each site of the oxbow lake. The filling of the oxbow lake could be influenced by different processes on spatiotemporal variability and palaeoecological record can be a result of a large diversity in a small area, at least in this case of largely diversified conditions of a Late Glacial river environment.

Global versus local processes:

Palaeo-record of the *Chrast* section was formed by random events, which are the result of distant global processes, but in the case of our section appear as an unexpected chance event. For example the reintroduction of a gravel-sandy sedimentation which buried fen vegetation during Younger Dryas has been interpreted as consequence of a general process operating at least in the whole Central Europe. Then the deterioration and the instability of a climate were expressed in increased tendency to the formation of braided pattern of the river instead of genesis of meanders. However, we should admit that this sedimentation regime most probably did not start its activity at once in the whole vast Elbe River alluvium but that it occurred significantly sooner or later or maybe under specific conditions it did not occurred at all. What is more, the described change of sedimentation did not have to be necessarily in relation to beginning of the formation of braided pattern of the river but only in relation to replacement of the meandering stream. Only further excavations and analyses of dated sediments would allow us to decide between these two possibilities.

Conclusion

The sedimentary section of the Elbe River palaeochannel near *Chrast* was discovered after the observation of aerial photographs and maps in the Polabí region Czech Republic.. Our results show that after the abandonment of the channel, the shallowepisodically flown-through oxbow lake occurred. This event -dated to the period of the Late Glacial. The sediment, recovered from the middle part of the palaeochannel, contained the palaeoenvironmental record of changes within the Elbe River alluvium in the period of the Late Glacial and Holocene;. Palaeobotanical results suggest that the Elbe River alluvium operated as micro-climatically favorable refuge of Late Glacial landscape which may be proven by presence of macrofossilsof conifers including charcoals of spruce.

The end of Pleistocene and the beginning of Holocene global changes are evidenced in the form of proxy-data which provide the information about changes of the Elbe River fluvial regime.. The sedimentary record of the Holocene period provides the evidence for complicated development of the site, which is the best described by the micromorphological analysis. The local development during the Middle and Younger Holocene is, on the basis of macrofossils analysis, reconstructed with difficulties only and the pollen analysis provide the information of a surrounding landscape scale

The multi-proxy approach to the interpretation of the *Chrast* sedimentary infill enables us to reconstruct the local development of the abandonment of river channel and observe the vegetation succession and the local sedimentation processes to linking on the landscape level in relation to global changes of climate. The processes which do not fit the general interpretational frame of global or local changes are emphasized. These processes could occur by chance as a result of the heterogeneity of the alluvium environment.

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A continuous record of deglaciation and postglacial environmental change in the Bohemian Forest, Czech Republic: the history of a central-European upland in the last 17,500 years

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Abstract

This study presents results of research into a complete sedimentary record covering a time span of 17.5 kyr in the Bohemian Forest, central Europe. With altitudes above the Lateglacial equilibrium line and location in between the former ice cap of the Alps and the Scandinavian Pleistocene ice sheet, the Bohemian Forest is a key region for the understanding of the Lateglacial climate and glacial development in central Europe. A multidisciplinary approach to the analysis of sediments allowed to estimate the rates of both local and regional changes in relation to major ecosystem changes linked to environmental and catchment developments and climatic thresholds. In the Bohemian Forest, the Lateglacial/Holocene transition was characterized by climatic oscillations, which took place between 17.5 kyr and 11.5 kyr BP. Cold oscillations (from 17.57 ± 1.97 kyr to 16.15 ± 1.36 kyr and ~15.5 kyr cal BP) are indicated by low primary production of organic matter, changes in erosion intensity, intense eolian activity and were probably associated with regional glacier readvances. Eolian activity is indicated by higher silt content, higher content of rubidium in the sediment and the absence of a closed vegetation cover. The largest environmental dynamics were recorded between the Bølling/Allerød interstadial and the Boreal period (~15.3–9.6 kyr cal BP) when the oscillations were in accord with oscillations recorded in other parts of Europe. At the Preboreal/Boreal transition (10.8 kyr cal BP), increased density of the forest canopy led to a change in species composition. The Boreal period was associated with amelioration of the climate, soil stabilization, expansion of vegetation and increased organic sedimentation.

Key words: paleoenvironmental reconstruction; glaciation; vegetation development; Bohemian Forest

1. Introduction

During cold periods of the Pleistocene, the Bohemian Forest, a central-European Hercynian mountain range located in the northern foreland of the Alps, belonged to an area lying between the extensive Alpine and Scandinavian ice sheets. Only local mountain glaciation, mostly limited to cirques, developed in the mountain range. These small glaciers could more sensitively react to environmental changes and were therefore, despite their limited area, able to reflect regional climate changes occurring in the Pleistocene.

This study presents results of research into a complete sedimentary record covering a time span of 17.5 kyr. Our reconstruction is based on analyses of a drill core sampled from a peatbog located in lateral moraines of the cirque of the Černé jezero Lake in the Bohemian Forest, south-west part of the Czech Republic. This cirque is the second most overdeepened by glacial erosion and the third largest in the Bohemian Forest (Křížek et al., 2012). The sampled drill core is one of the longest complete sedimentary records of landscape development under conditions of mountain glaciation during and after deglaciation in the Czech Republic. This profile is the most thoroughly dated section in this mountain range. It comprises 12 dated samples (two optically stimulated luminescence samples and ten radiocarbon-dated samples). A paleoenvironmental reconstruction has been carried out based on an analysis of multiproxy data acquired using geological and biological investigations and dating methods in light of results from other localities of mountain glaciation in the Bohemian Forest (Ergenzinger, 1967; Votýpka, 1979; Hauner, 1980; Pfaffl, 1998; Raab and Völkel, 2003; Jankovská, 2006; Pražáková et al., 2006; Vočadlová et al., 2006; Reuther, 2007; Mentlík et al., 2013) This analysis facilitates a broader extrapolation of our findings to the area of the entire mountain range.

Climate changes have been recorded in bore cores sampled all over Europe (Woillard, 1978; De Beaulieu et Reille, 1992; Seret et al., 1992; Guiot et al., 1993; Hajdas et al., 1995; Pazdur et al., 1995; Brauer et al., 1999; Goslar et al., 1999; Ammann et al., 2000; Leroy et al., 2000; Litt et al., 2000; Bohncke et Hoek, 2007; Magny et al., 2007), but more detailed records concerning the reaction of the environment (erosion intensity and sedimentation in relation to vegetation development) to climate changes in areas of limited mountain glaciation in European medium-altitude mountain ranges are incomplete. Moreover, studies on postglacial and Holocene variation and the conditionality of processes taking place between abiotic and biotic factors of the landscape at the local level are missing.

The objective of this study is to determine the impact of global (European) climate changes on the development of the environment and the dynamics of natural processes (*e.g.*, erosion, migration of woody species or succession) in central-European medium-altitude mountain ranges on the example of the Bohemian Forest in the period starting with the deglaciation of the last glaciation, including an assessment of the rate at which these local processes reacted to global changes. Can climatic oscillations of the Lateglacial traced in the sedimentary record be correlated with glacier advances described from other glaciated areas of the Bohemian Forest?

2. Background and study site

The Bohemian Forest mountain range (called the Bavarian Forest on the German side and the Bohemian Forest or Šumava on the Czech side of the state border) lies on the eastern fringe of the Hercynian system in central Europe (Fig. 1) and the southern part of the Bohemian Massif. During the Last Glacial Maximum (MIS 2, ~20 kyr BP), the mountains lay only ~150 km north of piedmont glaciers in the northern foreland of the Alps. During this time, the range was more humid than the Giant Mountains; the other Hercynian mountain range located ~250 km north-west of the Bohemian Forest. Glaciation in the Giant Mountains was more extensive than in the Bohemian Forest and was characterized during the LGM by wall-side and alpine valley glaciers (Nývlt et al., 2011). Deglaciation of the Giant Mountains began around 14 kyr BP, and the range was already ice-free at the beginning of the Holocene (Engel et al., 2011; Chmal and Traczyk, 1999). During the LGM, the uppermost parts of the Bohemian Forest range were affected by mountain glaciation, the ELA was 1050–1150 m a.s.l. and glaciers had a character of cirque glaciers with shorter tongues (Ergenzinger, 1967; Hauner, 1980; Vočadlová et Křížek, 2009; Mentlík et al., 2013). There is no consensus on the number and extent of glaciers in the range. More glacial landforms have been described on the western, windward (German) side than on the Czech side of the range (Ergenzinger, 1967; Hauner, 1980; Raab et Völkel, 2003). However, only 13 localities (five on the Czech side and eight on the German side) are considered to hold unequivocal evidence of cirque development. Factors which predominantly influenced the distribution of glaciers were: summit plateaus, cold aspect and leeward position of the preglacial valley-heads (Vočadlová et Křížek, 2009; Mentlík et al., 2010). Eight glacial lakes remain in this mountain range to this day. The rest of the lakes were terrestrialized and turned into peatbogs. Current knowledge on the age and stratigraphy of glaciation in the Bohemian Forest is incomplete. Almost all dated relics of glaciation are of Late Pleistocene age (MIS 2) (Raab et Völkel, 2003; Pražáková et al., 2006; Mentlík et al., 2013). Only in the Kleiner Arbersee area is the maximum age of the last glaciation determined by infrared stimulated luminescence to be 32.4 ± 9.4 kyr (Raab and Völkel, 2003). The average exposure age of dated moraines was found to be ~25–19 kyr in the Kleiner Arbersee area (dated by Reuther, 2007 and age recalculated by Mentlík et al., 2013) and ~19.5–14.0 kyr in the Prášilské and Laka valleys

(Mentlík et al., 2013). This temporal asynchrony is probably caused by improving accuracy of exposure dating methods. Deglaciation of the range began ~14 kyr cal BP (Raab et Völkel, 2003; Pražáková et al., 2006; Reuther, 2007), but individual localities differ in the timing of deglaciation. Mentlík et al. (2013), based on exposure dating, determined that the last glacier advance in Prášilské and Laka valleys occurred around 14 kyr BP.

Our study site, the cirque of the Černé jezero Lake (49°10′46″N, 13°10′53″E, 86.3 ha, altitude range 353 m, deepest point 967.5 m a.s.l.) lies on a mica-schist and paragneiss bedrock with quartz and quartzite intercalations on the north-eastern slope of the Bohemian Forest. In general, five generations of moraines recording two phases of Würmian glaciation are preserved (Vočadlová et al., 2006). The locality was deglaciated at the end of the Late Pleistocene but it is not dated. The drill core was taken from a small basin north of the lake (0.5 ha, 1,030 m a.s.l.). The core section under study contains about 3.5 m of organic material (peat and gyttja) and 1.7 m of minerogenous sediments. It is neither possible nor meaningful to obtain a sample from the bottom of the nearby Černé jezero Lake because of technical limitations and disruption of the succession of bottom sediments by anthropogenic interventions (*e.g.,* military training), landslides and avalanches falling from the cirque headwall. Moreover, the lake is currently a protected locality with restrictions on interventions into the natural ecosystem.

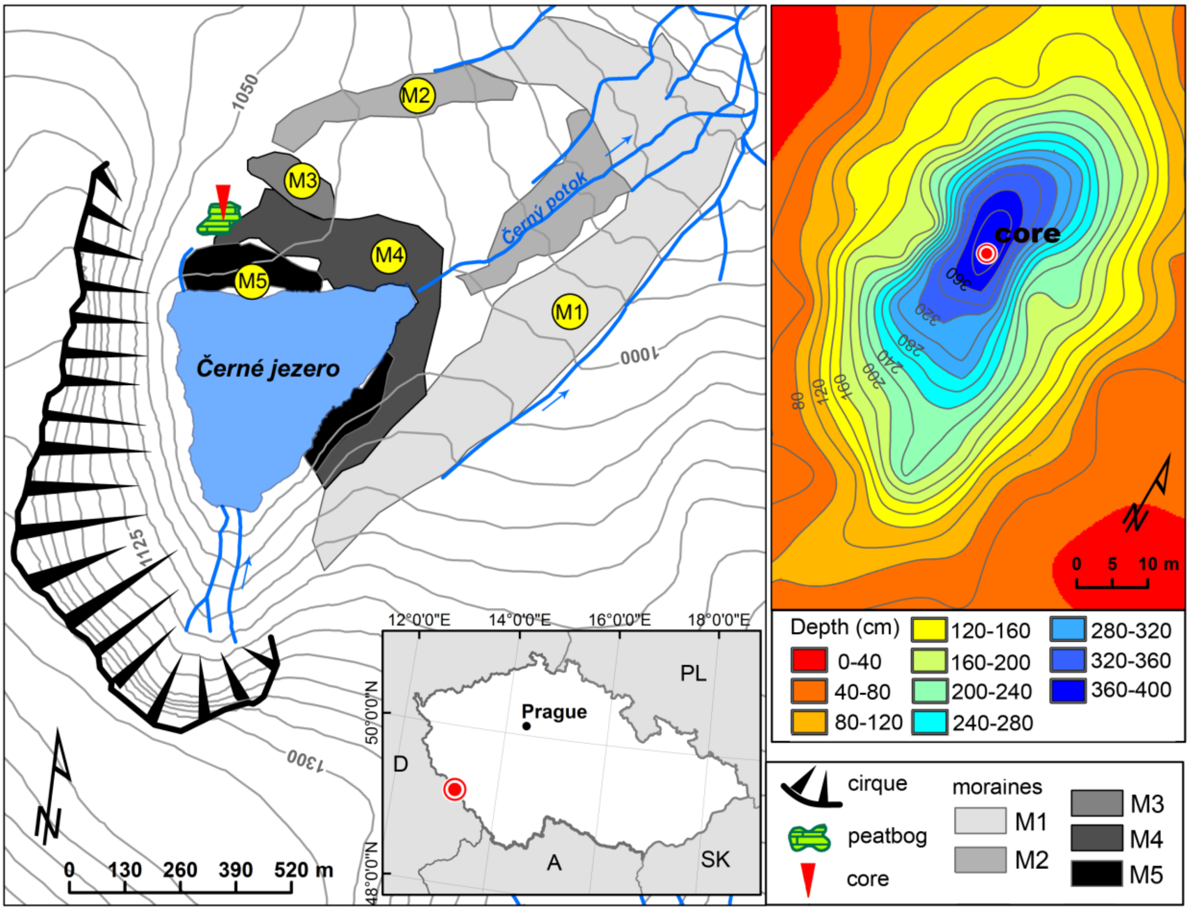

Fig. 1. Location of the study site. The contour map (on the right) presents depths of peat on the core site.

3. Methods

3.1 Coring and sampling

A core sample was taken at the centre of a forested peatbog in the vicinity of the Černé jezero Lake (49°10′57″N, 13°10′48″E, 1,028 m a.s.l.). The peatbog is situated in a shallow depression bounded by moraine ridges on three sides and by a cirque headwall on the fourth. The surface of the peatbog is drained and covered by a planted spruce grove. The point of drilling was chosen based on a map of the peatbog's thickness to be at its deepest spot. This map was created using geophysical data verified by probes. Six geophysical profiles along transects through the peatbog were obtained using a ground penetrating radar (RAMAC CU II, 250 MHz and 50 MHz antennas). A 520 cm long core was retrieved using an Eijkelkamp peat sampler (uncompressed cores 5 cm in diameter and 50 cm in length) for the first 400 cm and a percussion gouge sampler (core 6 cm in diameter and 200 cm in length) for the lower 120 cm. The core was subsampled for different geological, geochemical and botanical analyses.

3.2 Substrate characterization and chemistry

The colour (according to Munsell soil colour charts), general texture characteristics and lithostratigraphy of the substrate were systematically described in the field. Samples for different analyses were taken from the core at specialized laboratories.

Particle size analysis was performed in the lowermost part of core base (357–515 cm) at 3 cm intervals. Only this part of the core was suitable for this analysis because it contained no plant macrofossils and only low amounts of organic deposits. Samples were prepared according to Gale and Hoare (1991). Grain-size distribution for material smaller than 2 mm was determined using a laser-diffraction particle size analyser Sympatec Helos/KF-MAGIC with a Quixel dispersion unit. Two objectives were used: 0.4–200 µm and 1–3,500 µm.

Magnetic susceptibility (MS) was determined in samples taken at 3 cm intervals from depths of 230–520 cm using Kappabridge KLY-2 device (Agico, Czech Republic). The data were normalized to mass-specific magnetic susceptibility in 10^{-9} m^3 kg^{-1} of material. Measurements were not done in the uppermost part of the core because of the presence of organogenous material (peat), which generally exhibits monotonous and very low MS with no interpretive value.

The **weight percent organic matter** in the core was determined by means of **loss-on-ignition** (LOI). LOI was measured at 3 cm intervals at depths of 230–520 cm and at 5 cm intervals at depths of 0–225 cm. All samples were dried at 105 °C for 24 h and ignited at 550 °C for 3 h (Heiri et al., 2001).

Exoscopic analysis (Whalley, 1996, pp. 357–375; Le Ribault, 2003) was carried out on one sample (from the depth of 514 cm). Quartz grains from the sample were divided by washing to yield a size fraction of 250 to 500 µm. The sample was boiled in 35% HCl, washed with distilled water and dried. Fifty grains from the sample were selected under a binocular microscope, mounted on carbon tape, gold-plated and their image was captured under an electron scanning microscope (Cameca SX 100). The occurrence of microtextures on the surface of quartz grains was recorded, especially textures conditioned by the glacial environment (Fitzpatrick et Summerson, 1971; Cremer et Legigan, 1989; Mahaney, 2002; Le Ribault, 2003).

Geochemical element analyses were performed by energy dispersive X-ray fluorescence spectrometry (XRF) using a MiniPal 4.0 device (PANalytical, the Netherlands) with an Rh lamp and a Peltier cooled Si PIN detector. Powdered samples were poured into plastic cells with Mylar foil bottoms 25 mm in diameter. Al and Si signals were acquired at 4 kV/200 µA with a Kapton filter under He flush (99.996% purity), K and Ti at 12 kV/100 µA with an Al filter in air, Zr and Rb at 30 kV/200 µA with an Ag filter in air. The detector signals (in counts per second) were not calibrated; however, for a given matrix, the signals were proportional to concentrations of elements.

3.3 Biological methods

Subsamples for **pollen analysis** were taken at 3 cm intervals at depths of 230–400 cm and at 5 cm intervals at depths of 5–230 cm. Pollen samples were processed following the standard acetolysis method including hydrofluoric acid treatment (Moore et al., 1991). No less than 500 pollen grains per sample were counted. Pollen identifications follow Moore et al. (1991), Beug (2004), Reille et al. (1995, 1998). A pollen diagram including a numerical analysis and a determination of local pollenanalytical zones (LPZ) was created using the programme POLPAL (Nalepka et Walanus, 2003). The pollen diagram was divided into four local pollen zones using the CONSLINK analysis. Samples from the depth range of 400–520 cm were not included in the analysis because they contained low amounts of preserved pollen.

Each sample for **plant macrofossil analysis** comprised 150–300 ml of sediment. Samples were soaked in water and if necessary boiled with 5% KOH. Extraction of plant macrofossils from the sediments followed standard flotation and wet-sieving procedures (Warner, 1988; Pearshall, 1989; Jacomet et Kreuz, 1999) using a 250 μm mesh sieve. Botanical macrofossil samples were removed from the recovered fraction and scanned using a stereoscopic microscope (8–56x magnification). Quantitative and qualitative results of identifications are presented in the macrofossil diagram plotted using the application POLPAL (Nalepka et Walanusz, 2003). Local macrofossil assemblage zones (LMAZ) were distinguished using the statistical analysis Conslink (POLPAL programme) and divided into four zones CJ 1–4.

3.4 Dating and chronology

Two dating methods were used to determine the core's chronology: ^{14}C radiocarbon AMS analysis and optically stimulated luminescence (OSL). Ten samples were radiocarbon dated at the Center for Applied Isotope Studies, University of Georgia. Uncalibrated dates are given in radiocarbon years before 1950 (years BP). The error is quoted as one standard deviation and reflects both statistical and experimental errors. The dates are corrected for isotope fractionation. Calibration of radiocarbon data was carried out using the freely available programme OxCal v4.1.7 (Bronk Ramsey, 1995) and the IntCal09 calibration dataset (Reimer et al., 2009). A “classic” age-depth model based on linear interpolation between dated levels was applied to determine accumulation rates. The model was constructed using *clam* software (Blaauw, 2010). The weighted average of all estimated calendar years was used as the best central-point estimate (Telford et al., 2004). The margin of error of the model was 2 standard deviations. The mass accumulation rate was derived for individual sections of the model.

Two samples in the lowermost minerogenic part of the core were dated using the OSL method. The dating was provided by the Research Laboratory for Archaeology and the History of Art in Oxford, UK.

4. Results

4.1. Lithostratigraphy

The bottom part of the core (depth of 355–520 cm) predominantly consists of a minerogenic sediment; the upper part (0–355 cm) is built of highly organic material: gyttja and peat (Fig. 2). The core can be divided into five main units (I–V) reflecting changes in colour, grain size distribution and LOI – in other words, sedimentation environment changes described by different analyses.

Furthermore, five geochemical lithologic zones (GLZ) can be distinguished in the sediments poor in organic matter 300–520 cm (Fig. 2). Their boundaries are usually sharp in MS, Al/Si, Zr/Ti and Rb/K logs, indicating alternating sedimentary environments. Differences of element ratios in GLZ1 to 3 are to a certain degree related to changes in grain size; i.e., the upward coarsening of the sediment in GLZ2 is concurrent with an increase in the Al/Si ratio. In the sampled profile at depths between 300 and 520 cm, we can distinguish three sections exhibiting marked changes to the trends in measured characteristics (grain size, magnetic susceptibility, LOI and the content of the following elements: Rb, Al/Si, Zr/Ti and Rb/K) around the depths of 410 cm, 380 cm and 325–340 cm (Fig. 2).

The lowermost part of the core (**Unit I**, 394–520 cm) consists of layers of grey (Gley 1 4/N and 2.5Y 4/1), poorly sorted silty sand and a sandy silt sediment, both void of organic matter. The median of grain size varies from 4.4 to 171.6 μm (at the depth of 381 cm and 421 cm, respectively) and reflects changes in sand and silt content. Three sections exhibiting lower median grain size can be discerned at the depths of 460–490, 430–445 and ~410 cm. The content of clay is stable at the depth of 415–520 cm and then rises. The coarsest sediment is found at the depths of 421, 402.5, 451 and 501 cm. Magnetic susceptibility shows alternating decreases and increases in MS values but increases from 430–490 cm onwards. A rapid decrease from 148 to $105.10^{-9}.m^3.kg^{-1}$ begins at 412 cm, and then the value rises again. LOI is constant (~2–3%), an increase is visible towards the boundary of the unit. On the surface of quartz grains taken from the base of the core (514 cm), microtextures indicating glacial transport have been found (*e.g.*, angular outlines, rounded outlines, medium reliefs, low reliefs, conchoidal fractures, straight steps, striations and curved grooves). The presence of a fine laminated sediment (silt and fine sand) and absence of gravel indicate the development of a limnic environment at the coring site. Variability in the Al/Si and Zr/Ti ratio (grain size proxy sensu Grygar et al., 2010) at the depths of 410–520 cm (GLZ1 and GLZ2) refers to lamination of the sediment, too.

Unit II (355–394 cm) consists primarily of differently coloured, poorly sorted medium silty layers (382.5–394 cm, 376–381 cm and 361–370 cm) and silty sand sediments (at depths of 370–376 cm and 355–361 cm) with one distinct layer of fine silt at the depth of 381–382.5 cm. The content of organic compounds increases overall. The median of grain size is generally low with coarsening at the depths of 360 and 375 cm. Magnetic susceptibility exhibits distinct changes in this unit. An increase of MS at 382–400 cm is followed by a huge sudden decrease from 147.3 to 25.7 10^{-9} m^3 kg^{-1} at 380 cm which is followed by a peak at 371 cm. A continuous decrease in MS (from 146.7 to -4.8 10^{-9} m^3 kg^{-1}) follows up to 230 cm. Loss-on-ignition varies between 3 and 14% except for the depth of 375–387 cm where a distinct peak occurs at 381 cm (LOI is 30%). This peak lies in a distinct layer of fine, dark brown silt (381–382.5 cm) with few undecomposed macrofossils. The peak is visible not only in the LOI curve but also in the magnetic susceptibility data (very low) and the results of the geochemical analysis (Fig. 2). Unfortunately, the sedimentary record at the depth of 380–400 cm is strongly compressed.

Unit III (197–355 cm) is sharply separated from the foregoing zone and is composed of a monotonous black (10YR 2/1) gyttja layer. The steep transition between Unit II and III is recorded in changes of LOI, MS, P, S and Al/Si curves between the depths of 355 and 360 cm (Fig. 2). The LOI curve steadily rises from the depth of 355 cm upwards with values from 13 to 91%; magnetic susceptibility has slightly negative values. A remarkable, nearly sudden decrease in Rb and Zr content occurs between the depths of 340 and 320 cm; this decrease is centred in GLZ4. There are no granulometry data for siliciclastics at this depth range (the content of organic matter was too high for the grain size analysis), but the Al/Si ratio, a granulometric proxy (Grygar et al., 2010; Bábek et al., 2011), is very similar at the end of GLZ3 and in GLZ4, both MS and LOI show neither a distinct environmental change nor facies shift in GLZ4.

Unit IV (62–197 cm) differs from the previous in colour and a lower degree of organic material decomposition. This unit is composed of strong, brown (7.5YR 4/6) fibrous peat.

Unit V (0–62 cm) takes up the uppermost part of the core and comprises four parts layered as follows: (1) 50–62 cm – very dark brown (7.5YR 2.5/3) peat; (2) 26–50 cm – very dusky red (2.5YR 2.5/2), fibrous peat; (3) 9–26 cm – very dark brown (10YR 2/1) peat; and (4) 0–9 cm – a litter layer of plant residues in relatively undecomposed form.

Loss-on-ignition in the whole core exhibits a very strong negative correlation with magnetic susceptibility. The correlation coefficient of loss-on-ignition and magnetic susceptibility is –0.9517 (level of significance $p = 0.05$). Rubidium content shows a strong negative correlation with LOI (*r* = -0.94; confidence level *p* = 0.05) and is strongly positively correlated with magnetic susceptibility (*r* = 0.94; *p* = 0.05).

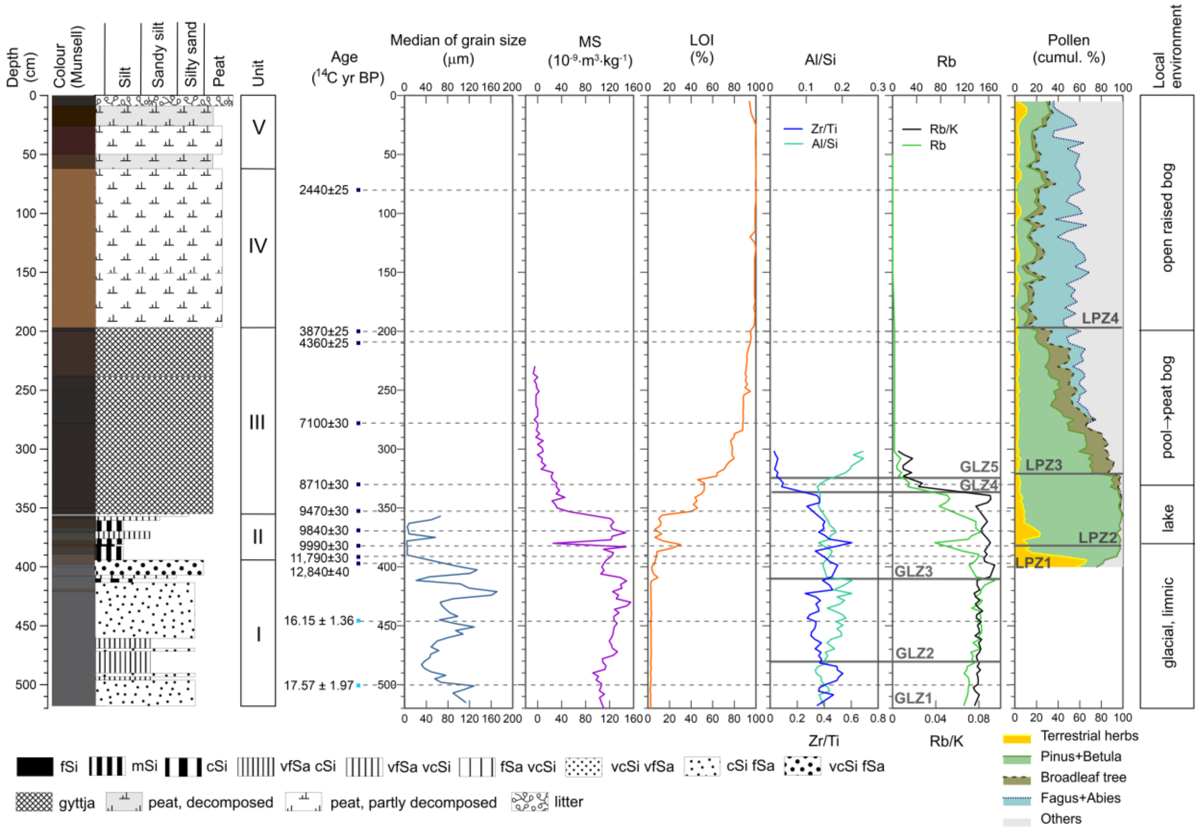

Fig.2. Presentation of lithologic, chronologic, and selected geochemic and botanic data from the analysis of the profile. Notes: MS – magnetic susceptibility; LOI – loss-on-ignition; GLZ – geochemical lithologic zones; LPZ – local pollen zones; Si – silt; Sa – sand; f - fine; m – medium; c – coarse; v – very.

4.2 Chronology

The two oldest datings measured by optically stimulated luminescence at the depth of 445.5 cm (16.15 ± 1.36 kyr) and 500.5 cm (17.57 ± 1.97 kyr BP) in Unit I indicate the maximum age to be at the end of the LGM (Fig. 2). The oldest radiocarbon date (uncal. 12,840 ± 40) lies at the transition between Unit I and Unit II at the depth of 397 cm and indicates a maximum age of 15,669 –14,958 yr cal BP (Table 1).

Radiocarbon dates of ten ^{14}C samples from the peatbog near the Černé jezero Lake.

Unit	Depth (cm)	Laboratory code	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	Calibrated age (cal yr BP, 2σ range)	Calibrated intercept age (cal yr BP)	Median age (cal yr BP)
IV	80	UGAMS-3933	-29.9	2440±25	2699–2356	2505	2473
III	200	UGAMS-3934	-24.8	3870±25	4413–4184	4311	4312
III	210	UGAMS-3935	-28.7	4360±25	5030–4856	4921	4920
III	278	UGAMS-3936	-27.2	7100±30	7996–7854	7926	7938
III	330	UGAMS-3937	-28.3	8710±30	9764–9551	9650	9646
III	352.5	UGAMS-3938	-29.0	9470±30	11,060–10,587	10,722	10,710
II	369	UGAMS-3939	-27.0	9840±30	11,303–11,201	11,240	11,238
II	382	UGAMS-3940	-29.9	9990±30	11,613–11,283	11,454	11,447
II	391.5	UGAMS-3941	-22.8	11,790±30	13,775–13,464	13,634	13,646
I	397	UGAMS-3942	-22.5	12,840±40	15,669–14,958	15,320	15,294

Table 1. Radiocarbon dates of ten ^{14}C samples from the peatbog near the Černé jezero Lake.

A changing accumulation rate is apparent from the age-depth model (Fig. 3). The shape of the curve shows that the lowest rate of sedimentation occurs at the depth of 382–397 cm. The rate of sedimentation, by contrast, gradually increased from layers at the depth of 382 cm towards younger layers at the depth of 80 cm.

The accumulation rate ranges is from 0.03 to 0.66 mm yr^{-1} (Fig. 3). The section with the highest rate of sedimentation (0.66 mm yr^{-1}) is found at the depth of 80–200 cm and belongs to Unit IV, which is composed of coarsely fibrous peat with a low degree of decomposition and compaction (Fig. 2). Other parts with a higher rate of sedimentation, conversely, represent sections with very low content of organic material at depths of 369–382 cm and 397–500.5 cm. The absolutely lowest rates of sedimentation are recorded at the depth of 382–397 cm (Fig. 3), which is characterized by rapid alternation of layers as well as a pronounced shift in a range of observed characteristics such as LOI, magnetic susceptibility, grain size and the content of pollen grains of woody plants (Fig. 2).

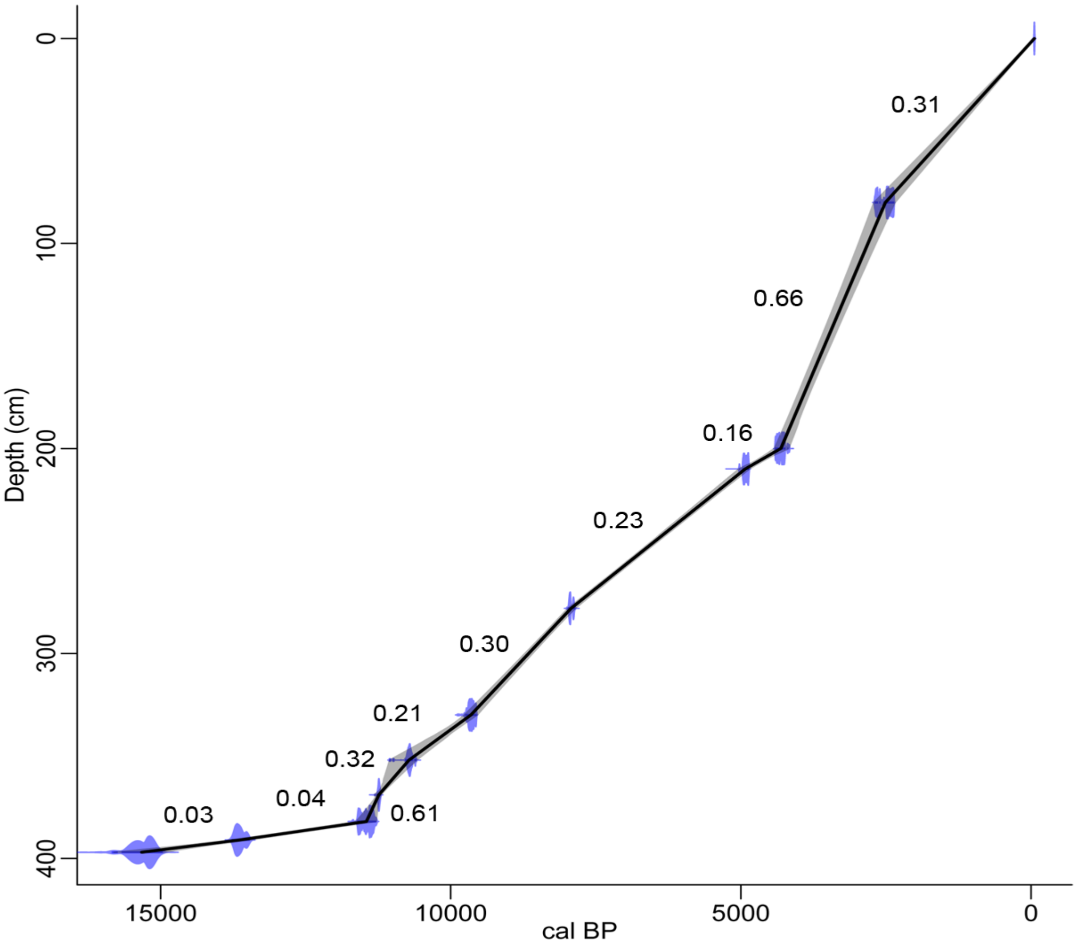

Fig. 3. Age-depth model based on radiocarbon data, numbers in graph represent the accumulation rate in mm yr^{-1}.

4.3 Biological evidence

4.3.1 Palynological analysis

The core was divided into four local pollen zones (LPZ 1–4) numbered from the bottom to the top based on results of the pollen analysis (Fig. 2 and Fig. 4).

LPZ-1 (391–400 cm): The AP/NAP ratio is ~25%. *Pinus* and *Betula* dominate in the arboreal pollen spectrum (10% each). *Salix* has a 5% proportion. *Picea* and *Alnus* pollen is rare. Grasses dominate in the non-arboreal pollen spectrum (close to 50%). *Artemisia, Cyperaceae, Heliantemum, Caryophyllacerae, Anthemis*-type*, Rubiacea, Chenopodiaceae* and *Thalictrum* all have a considerable proportion. *Ephedra distachia*-type and *Sanguisorba minor*, for example, are infrequent.

LPZ-2 (320–388 cm): The AP/NAP ratio is 70–90%. *Pinus* (40–80%) and *Betula* (15–50%) dominate in the arboreal pollen spectrum. A considerable part of *Picea, Ulnus* and *Corylus* is in the uppermost part of this zone, where there is a lower proportion of *Quercus*, *Tilia* and *Alnu*s; *Salix* is retreating. NAP decreases from 30% to 5%. Grasses, *Cyperacea* and *Artemisia* still dominate. Other taxa are present only sporadically: *e.g.*, *Asteraceae* subfam. *Cichorioideae*, *Senecio*-type, *Rubiaceae*, *Hordeum/Glyceria*-type, *Filipendula* and *Pteridium aquilinum*. *Sphagnum* spores and *Pinus* stomata are rare.

LPZ-3 (195–317 cm): The AP/NAP ratio is constant at about 95%. *Pinus* pollen decreases from 60% to 5%; similarly in *Betula* (from 30 to 5%). *Picea*, by contast, increases from 5 to 50%. *Fagus* pollen shows up at the depth of ~280 cm, *Abies* at the depth of 239 cm. *Fagus* and *Abies* both reached a proportion of 20%. *Carpinus* is present sporadically. *Corylus* (~10%), *Quercus* (5%), *Tilia* (less than 5%) and *Fraxinus* have a constant presence. The *Alnus* proportion increases moderately. The herbal spectrum is present only slightly; grasses and *Cyperacea* dominate. *Pteridium aquilinum, Vaccinium, Filipendula, Potentilla*-type and *Ranunculaceae* are rarely detected. *Sphagnum* spores exhibit exhibit an increasing presence among non-pollen objects; *Picea* stomata were also found.

LPZ-4 (5–190 cm): The AP/NAP ratio fluctuates between 80 and 95%. At first, *Picea* (20–60%), *Fagus* (~20%) and *Abies* (5–35%) dominate in tree pollen spectrum. *Betula* and *Alnus* (~10%), but also *Corylus* and *Quercus* have compact curves. *Carpinus, Tilia, Fraxinus*, and *Ulnus* are recorded sporadically. Grasses dominate the herb spectrum. *Cyperaceae*. *Cerealia, Plantago lanceolata* and *Artemisia* show up on a larger scale. Species such as *Urtica, Umbeliferae, Ranunculacea, Vaccinium* and *Pteridium aquilinum* are recorded only sporadically.

The rarefracted number of taxa in the whole core is constant. PCA results show distinct changes at the depth of ~390 cm followed by gradual evolution reaching and invariable state at 200 cm.

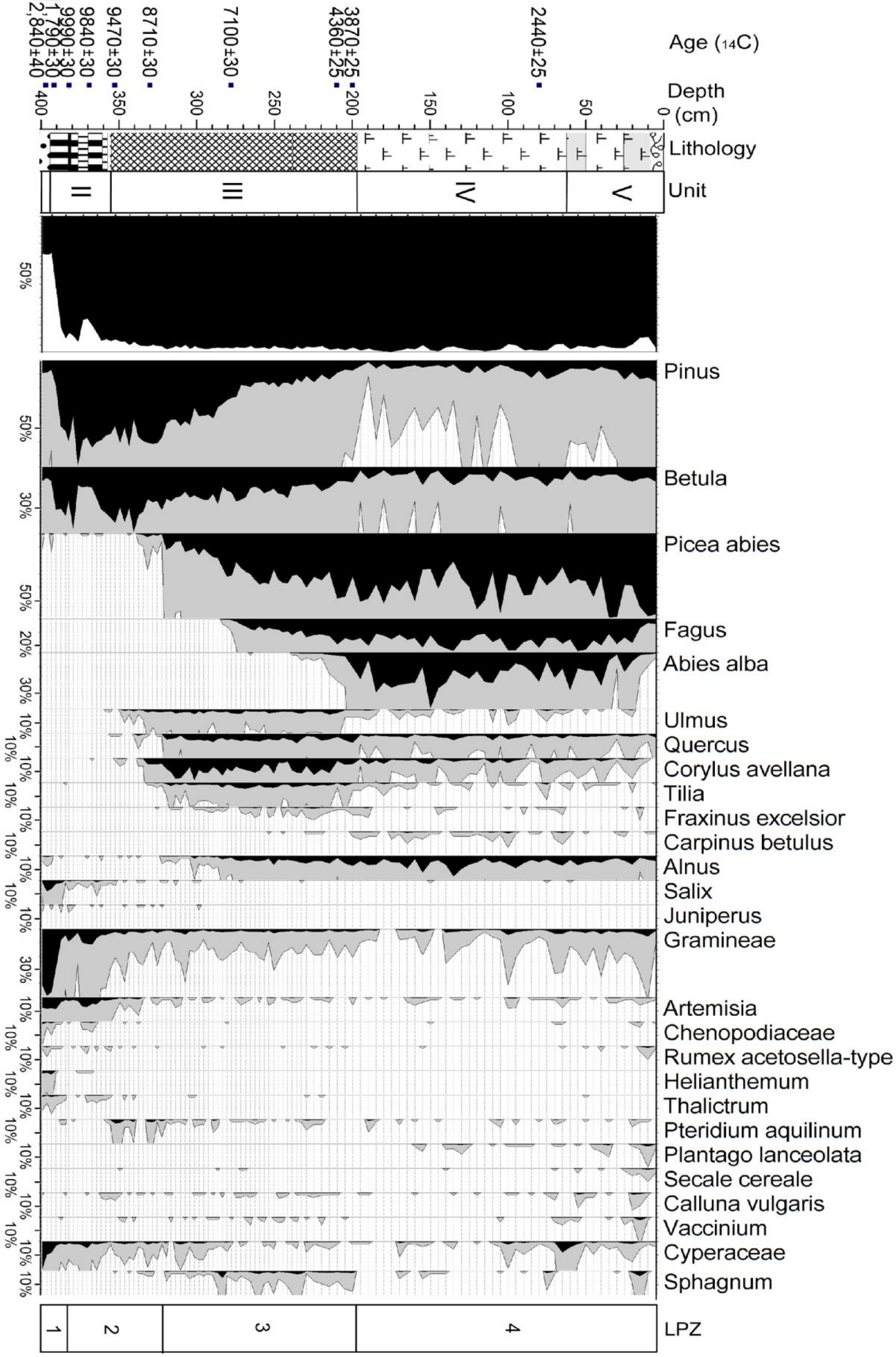

Fig.4. Pollen diagram of the profile (depth from 0 to 400 cm).

4.3.2 Macroremains analysis

The diagram of plant macrofossils (Fig. 5) was divided into four local macrofossil assemblage zones (LMAZ 1–4), numbered from the bottom to the top. The zones were distinguished using the statistical procedure Conslink (POLPAL programme, Nalepka et Walanusz, 2003).

LMAZ-1 (380–400 cm): Plant macrofossils indicating stress-tolerant vegetation (sedges, mosses) covered by dwarf birch shrubs (*Betula nana*) and fungi sclerotia (*Cenococcum* geophilum) suggesting erosion were present in this zone (Table 2).

LMAZ-2 (330–380 cm): This zone includes macrofossils of water plants (*Isoëtes echinospora*) and littoral vegetation (*Juncus bulbosus, Carex rostrata, Scirpus sylvaticus, Bolboschoenus yagara*). Tree macrofossils were represented by birch fruits (*Betula nana, Betula pendula/pubescens*), pine (*Pinus sylvestris*) and spruce (*Picea* abies) seeds; birch dominated, however. Some zoological remains of aquatic crustaceans (*Cladocera*) were found. Indicators of erosion (*Cenococcum geophilum*) and vegetation of cliffs and boulder screes (*Selaginella selaginoides* and *Calluna vulgaris*) were present.

LMAZ-3 (200–330 cm): Aquatic and littoral vegetation was still present in this zone. Peat-bog vegetation (*Carex limosa, Rhynchospora alba, Vaccinium/oxycoccus*) emerged. *Betula*, *Picea* and *Abies* dominated among tree macrofossils.

LMAZ-4 (0–200 cm): Raised bog vegetation (*Andromeda polyfolia, Eriophorum vaginatum, Trichophorum* sp., *Oxycoccus* cf. *palustris*) and spruce (*Picea abies*) and fir (*Abies alba*) macrofossils prevailed in this local zone.

Zone (depth/cm)	Species	Palaeovegetation	Environment
LMAZ-1 (400 – 380)	*Betula nana* (fruit, scale) *Betula pendula/pubescens* (fruit) *Carex* sp. - 2 and 3 sided (achene) *Bryophyta* (thallus) *Cenococcum geophilum* (sclerotium)	Stress-tolerant vegetation with dwarf birch shrubs, sedges and mosses	Glacial landscape, blocked succession. Low temperature. Disturbances are indicated by sklerocia of Coenococcum geophilum.
	Isoëtes echinospora (megaspore)	Isoetes vegetation: *Isoëtea*	
LMAZ-2 (380 - 330)	*Sparganium angustifolium* (achene) *Juncus bulbosus* (seed)		Lake ecosystem: oligothrophic mountain shallow lake whit fluctuating water level.
	Carex rostrata(achene) *C*. cf. *nigra*(achene) *Scirpus sylvaticus*(achene) *Bolboschoenus yagara* (achene) *Poaceae* (caryops)	Vegetation of reeds and tall-sedges beds: *Phragmitio-Caricetea*	Littoral zone of the lake with reed and tall-sedge vegetation. High level of grand water.
	Selaginella selaginoides(megaspore) *Calluna vulgaris* (seed)	Acidophlilous vegetation of alpine cliffs, cirques and boulder screes	
	Betula nana (fruit) *Betula pendula/pubescens* (fruit) *Pinus sylvestris* (seeds) *Picea abies* (seeds) *Vaccinium* (charcoal) *Rubus idaeus* (endocarp)	Birch - pine mire forest in the lake surroundings	
	Cladocera (ephippia)	Zoological remanis of water Crustacea	
	Cenococcum geophilum (sclerotium)	Fungi remains – erosion of the surface	
	Isoëtes echinospora (megaspore)	Isoetes vegetation: Isoëtion	
LMAZ-3 (330-200)	*Juncus bulbosus* (seed)		Extinction of the lake ecosystem and forming of the peat bog ecosysteme.
	Sparganium angustifolium (achene) *Scirpus sylvaticusi* (achene) *Juncus bulbosus* (seed)	Littoral and wet meadow vegetation	
	Carex rostrata (achene) *Carex canescens* (achene) *C. echinata* (achene)	Peat-bog vegetation: *Oxycocco-Sphagnetea*	

	Rhynchospora alba (achene) *Eriophorum vaginatum* (achene) *Vaccinium/Oxycoccus* sp. (achene)		
	Scheuchzeria palustris (seed) *Carex limosa* (achene)	Peat-bog hollows vegetation	
	Picea abies (seed, seed-wing, needle) *Pinus sylvestris* (seeds) *Betula pendula/pubescens* (fruit, fruit scale) *Betula pubescens s.l.* (fruit, fruit scale)	Pine-birch mire forest	
	Cladocera (ephippia)	Zoological remanis of water Crustacea	
	Cenococcum geophilum (sclerotium)	Fungi remains - erosion of the surface	
	Charcoal - highest concentration		
LMAZ-4 (200 - 0)	*Andromeda polyfolia* (seeds, fruit capsule) *Eriophorum vaginatum* (achene) *Trichophorum sp.* (nutlet)	Raised bog vegetation	Open raised bog ecosysteme surrounded by bog spruce forest.
	Picea abies (seed, needle) *Abies alba* (seed, needle)	Bog spruce forest, which occurs along the edge of mountain bogs	

Table 2. Local macrofossil assemblage zones (Fig. 5).

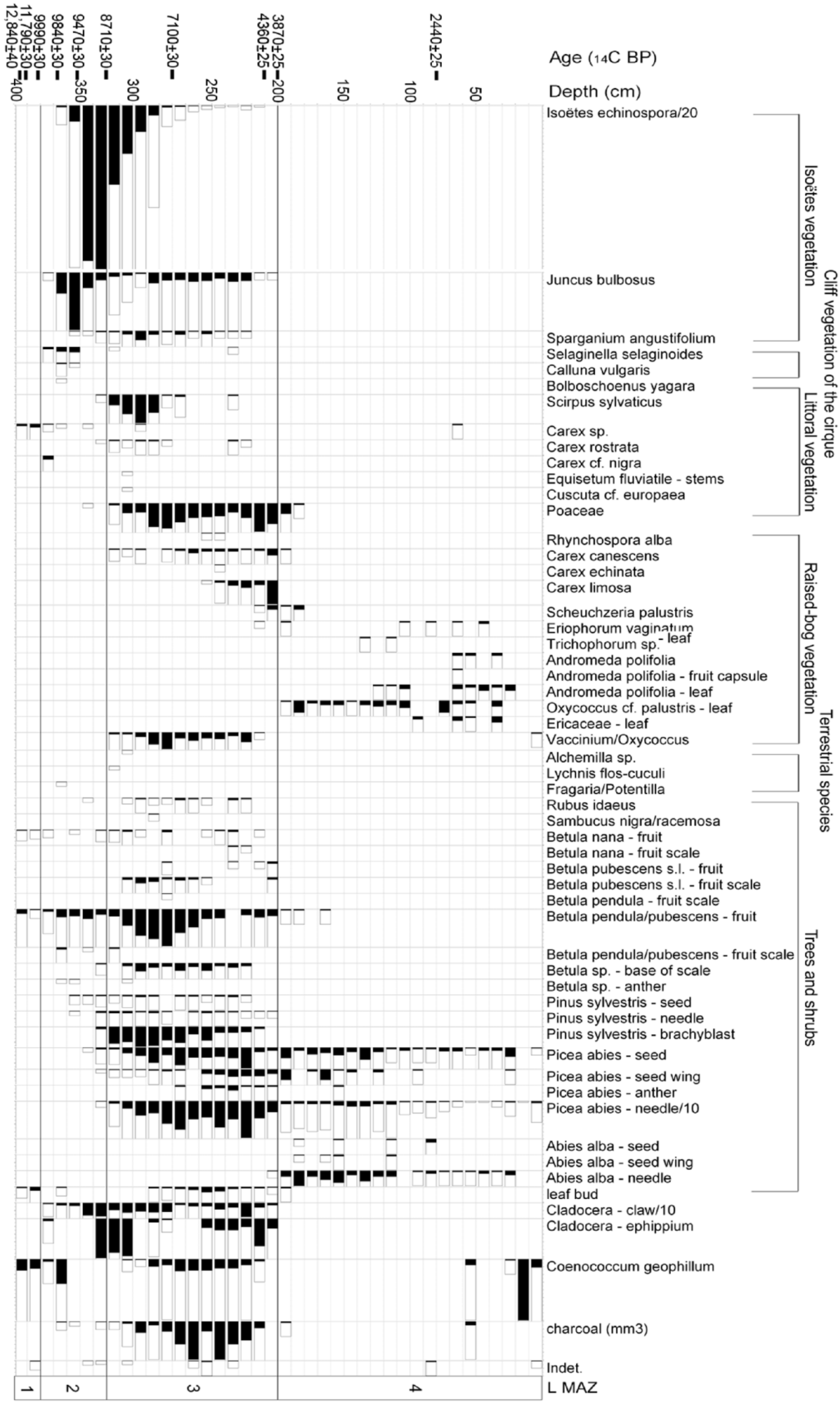

Fig. 5. Macrofossil diagram.

5. Interpretation and discussion – A palaeoenvironmental reconstruction

5. 1 Lateglacial environment and cold oscillations

During the LGM, summit areas of Hercynian mountains were covered with a treeless polar desert formed by glacial and periglacial processes (De Beaulieu et Reille, 1992; Seret et al., 1992; Huijzer et Vandenberghe, 1998; Chmal et Traczyk, 1999; Raab et Völkel, 2003; Pražáková et al., 2006; Huguet, 2007; Reuther, 2007; Engel et al., 2010). The climate remained cold regardless of the climate amelioration of the Late Pleistocene. This is documented by very low primary production of organic matter corroborated by a low content of phosphorus and sulfur, low LOI and absence of macroremains and pollen (Fig. 2). The entire period of the Late Pleistocene was characterized by a higher rate of sedimentation; a 110 cm thick layer of limnic sediment got deposited over a period of 2,000 years. Under continental, cold and predominantly dry conditions of the Late Pleistocene, increased eolian activity took place in the region. This is signified by an elevated amount of silt fraction material in the sampled core present throughout the Late Pleistocene. It has been found that increased rubidium content is associated with this fraction. The presence of rubidium has also been traced in lake sediments of the Plešné jezero Lake (Pražáková et al., 2006) in the southern part of the mountain range. Variation in Rb content in sediment sequences is usually interpreted in terms of relative content of siliciclastics with respect to carbonates (Koinig et al., 2003; Schmidt et al., 2006; Bábek et al., 2011 and reference herein) or in terms of the relative proportion of chemical and physical weathering (Pražáková et al., 2006 Bábek et al., 2011 and references therein). In the first case, Rb content or the Rb/Sr ratio increases with decreasing carbonate content; in the second, Rb content drops after the onset of chemical weathering. The change in the Černé jezero Lake cannot be attributed to variations in the relative proportion of carbonates because these are practically missing or occur in negligible amounts throughout the profile. The decrease in Rb content cannot be attributed to the weathering mechanism either because the Rb/K ratio actually changes with the same magnitude as the Rb/Al ratio or the Rb content itself. Furthermore, K is expected to be affected by weathering in the same manner as Rb. Bábek et al. (2011) reports changes in the Rb/K ratio in paleosol-loess sequences, where a "clean" effect of pedogenesis of parent loess causes an effect of about 20%. Additionally, the change in the Zr/Ti ratio is simultaneous with that in the Rb/K ratio, which points rather to a shift to a different source of sediment material because neither Ti nor Zr can be affected by chemical weathering under cold to temperate climates in the area studied. Changes in the Zr/Ti and Rb/K ratios are also slightly affected by granulometric changes in the sediment, i.e. they somehow reflect differences in sorting due to sediment transport and deposition in the aquatic environment. This is clear from a slight change in Zr/Ti and Rb/K logs between 415 and 408 cm. That the Rb is of eolian origin is therefore very likely.

Eolian material got trapped in summit parts of the mountain range and in leeward areas. This material got washed away by intensive precipitations, reaching sedimentation areas and ultimately the sedimentary record. A similar process of sedimentation of eolian material has been described from high-altitude environment in the Zugspitzplatt region of the Alps, where loess probably of Egesen age has been discovered (Küfmann, 2003). During cold periods of the Lateglacial, eolian transport was very pronounced in the entire region of central and eastern Europe. Moreover, the distribution of loess and dune activity to the south of the Scandinavian ice sheet is evidence of dry, Arctic climate conditions with strong eolian activity in central and north-west Europe during the Late Würm (Meyer et Kottmeier, 1989; Huijzer et Vandenberghe, 1998; Florineth et Schlüchter, 2000; Bogaart et al., 2003). This means that the transport of rubidium was related to atmospheric circulation of a supra-regional scale.

A cold oscillation indicated by a drop in erosion and decreased transport of clastic material occurred 17.57 ± 1.97 kyr ago (depth of 500 cm, OSL dating). This is reflected in the sedimentary record by predominant sedimentation of finer material (lower median grain size). During colder oscillations, a lack of liquid water caused a decrease of the power of flowing water, which precludes the transport of coarser material, solids being mostly transported in the form of a suspension.

This period was followed by a mild moistening and warming of the climate, which led to intensified erosion. At times of more intensive erosion and washout, increased transport of clastic material (sensu Karlén et Matthews, 1992; Koinig et al., 2003; Bakke et al., 2005; Schmidt et al., 2006) took place, which is manifested by coarsening of the sediment around the depth of 455 cm. The increasing proportion of sand reflects an intensification of surface runoff and increased erosion, which occurred at the beginning of warmer and moister periods during snow melting. Mountain slopes were highly unstable during these periods, which together with relatively low temperatures essentially blocked vegetation succession. Bogaart et al. (2003) describe an increase of hillslope erosion, sediment supply and fluvial transport capacity at the transition between stadial and interstadial climatic condition during the Last Glacial-Interglacial transition.

The last pronounced Lateglacial cold oscillation was preceded by a period of intensified erosion recorded at the depth of ~420 cm (15.7 kyr cal BP according to the age-depth model). The most recent cold fluctuation of the Late Glacial period is recorded at the depth of ~410 cm (16.4–14.8 kyr cal BP, age-depth model age), which corresponds to the Oldest Dryas period.

Because of missing dating of moraines in the study area, we cannot for the time being entirely precisely determine whether the identified cold periods correlate with post-LGM glacier readvances around the Černé jezero Lake. It is, however, possible to look for relationships with dated glacial advances at other localities in the Bohemian Forest (Raab et Völkel, 2003; Reuther, 2007; Mentlík et al., 2013). Based on a similar number and morphology of moraines, similar morphometric characteristics of the area (*i.e.* aspect, elevation and cirque morphology) and short distance, it has generally been presumed that the retreat of glaciation in the area of the Černé jezero Lake was synchronous with that of the glacier in the area of the Kleiner Arbersee lake 7 km away (for more information on glaciation, see Raab, 1999; Raab et Völkel, 2003; Reuther, 2007). This would mean that moraine ridges originated between 20.7 ± 2 and 15.5 ± 1.7 ^{10}Be kyr sensu Reuther (2007), resp 25–19 kyr (recalculated by Mentlík et al.; 2013). This scenario is extremely unlikely, however, because cold oscillations identified in the sediments by the Černé jezero Lake are a lot younger. The origin of moraine ridges in the vicinity of the Černé jezero Lake correlate more with glacier advances in the surroundings of the Prášilské jezero and Laka lakes (from ~19.5 to ~14 kyr sensu Mentlík et al., 2013), which are situated, as is the cirque of the Černé jezero Lake, on the leeward side of the Bohemian Forest *ca* 13 and 20 km away. This hypothesis is supported by the facts that sedimentation at the coring site began 17.57 ± 1.97 kyr ago (OSL age) and that it has not since been interrupted by the advance of the glacier. The glacier of the Černé jezero Lake therefore retreated to the cirque prior to this period, so the last lake moraine (M5) was formed later. This last glacier advance is indicated by a distinct change in grain size and MS recorded 16.4–14.8 kyr cal BP, which corresponds to the Oldest Dryas. By the retreat of the glacier to the cirque face, the sedimentation area of the lake at the site of the boring got definitively separated from the source of meltwaters and material from the glacier, altering the character of sediments. A colder climate with pronounced eolian activity recorded at the depth of 410 cm is therefore supported not only by a marked fining of the sediment but also by increased Rb content, which reaches its maximum here. In this period, the glacier in the more southward-lying area of the Prášilské jezero Lake (15.7 ± 0.6 kyr, Pras2 moraine) and lake Laka (16.2 ± 1.9 kyr, Laka1 moraine; see Mentlík et al., 2013) advanced, too. This more pronounced drop in temperature is immediately followed by warming during the Bølling/Allerød interstadial complex, when the lake floor of the Kleiner Arbersee was ice-free before 14–15 kyr cal BP (14.5 ± 1.8 ^{10}Be kyr BP; Raab and Völkel, 2003; Reuther, 2007). The most recent dated lake moraines in the Bohemian Forest so far are of Older Dryas age and have been described from the Prášilské jezero and Laka lakes (Mentlík et al., 2013).

5.2 Lateglacial-Holocene transition

From the perspective of environmental changes, the most dynamic period recorded in the Bohemian Forest is the end of the Pleistocene from the Bølling/Allerød interstadial complex until the Boreal period. In this period, sedimentation in the lake at the sampling site declined, which is indicated by compression of the sedimentary record at depths between 380 and 400 cm. This was caused by low influx of material resulting from low precipitations and low water inflow. Warming was indicated by an increase in organic material content at the beginning of the Bølling/Allerød period in the sampled sediment (at the depth of around 397 cm; 12.840 ± 40 ^{14}C yr BP, 15.7–15.0 kyr cal BP). This climatic warming initiated a retreat of the snow and firn cover, causing stripping of the surface covered with a predominantly nutrient-poor rock mantle, cryogenic screes, glacial accumulations and deluvia. In this period, the highest-altitude areas of the Bohemian Forest were still above the treeline. In the paleobotanical record from the the Lateglacial period, in line with results from other glaciated localities of the Bohemian Forest (Raab, 1999; Jankovská, 2006), grassy communities (*Poaceae, Cyperaceae, Artemisia*) with a low proportion of pioneer woody species (*Betula, Pinus*) initially dominate. Woody species, however, appear in the macrofossil record only after the conclusion of the PBO, so they probably dispersed to higher altitudes of the mountains from larger distances during the Bølling/Allerød and the Younger Dryas. Initial soils got disturbed by slope processes, as documented by the occurrence of species indicating habitats disturbed by erosion (*Sanguisorba minor*, sclerotia of *Coenoccocum geophilum*) in the pollen and macrofossil spectrum. Stress-tolerant vegetation (grasses, sedges, mosses) was able to colonize rock surfaces, and the occurrence of littoral vegetation (*Carex rostrata*, *Scirpus sylvaticus*, *Bolboschoenus yagra*) is documented at the site of the boring.

Warming at the beginning of the Preboreal period (11.6–11.3 kyr cal BP) has been documented by an increase in primary production by the vegetation indicated by an elevated proportion of AP and a rapid rise of the LOI curve (Fig. 2). In the sedimentary record, this warming is manifested as a 1.5 cm thick layer of improperly decomposed organic material. A similar episode has also been recorded in the Kleiner Arbersee Lake at the depth of 670–674 cm (Raab, 1999). Its age has been determined to be ~11.5 kyr cal BP using an age-depth model created using the program clam based on four radiocarbon data reported by Raab (1999). Similarly, discoveries of cladocerans in lake sediments from another glaciated locality, the Plešné jezero Lake in the southern part of the mountain range, document warming at the Younger Dryas/Preboreal transition around 11.6 kyr cal BP (Pražáková et al., 2006). This was at the same time an episode of low water levels in lakes associated with decreased precipitation sums over the European continent in this period (Magny et al, 2007).

At the sampling site, the shallow water body even dried out. In western parts of central Europe, low water levels often corresponded with sedimentation of peat and organic detritus in close-to-shore areas whereas episodes of high water levels in lakes were characterized by accumulation of more minerogenic sediments (Magny et al., 2007). Strong warming 11.6 kyr cal BP indicating the beginning of the Preboreal period has also been recorded in other parts of Europe (Goslar et al., 1999; Amman et al., 2000; Renssen et Isarin, 2001; Kobashi et al., 2008). The beginning of the tempering of the climate was nevertheless followed by further fluctuations in temperature and moisture, for example, the cold PBO ~11,3 kyr cal BP (Bohncke et Hoek, 2007; Magny et al., 2007), which manifested in north-west Europe first as a dry and continental period followed by a sudden switch to a more humid climate (Bos et al., 2007, Magny et al., 2007). These colder early-Holocene climatic fluctuations slowed down the development of fully closed vegetation, which is clearly marked by a decline in the proportion of woody plants and an increase in the proportion of pollen of grass communities in the pollen diagram. Sparse vegetation on the bare surface was not enough to reinforce slopes and sufficiently prevent erosion and washout from slopes. Disturbance events and slope instability are supported by findings of macrofossils of acidophilous vegetation of rocky habitats (*Selaginella selaginoides, Calluna vulgaris* and *Coenococcum geophilum*) in the profile. It was the material released by these disturbance events which overlaid the described organic layer sedimented in the preceding warmer fluctuation and prevented its decomposition in an anoxic environment (increased P and S content in the profile at depths around 382 cm).

In the Preboreal and Boreal period, pioneer woody species (*Pinus, Betula pendula/pubescens* and *Betula nana*) began to massively spread to higher altitudes of the Bohemian Forest; their more extensive expansion occurred with the rising of the treeline as late as in the warmer part of the Preboreal period. The area around the Černé jezero Lake was covered by a boggy birch-pine forest. Still diffuse, open vegetation (*Calluna vulgaris, Sellaginela selaginoides, Rumex acetosella*) remained higher up on the slopes, so the surrounding steep slopes were still prone to erosion (alternating layers of sandy and sandy-clayey sediment at the depth of 350–400 cm). The first woody species to colonize the surroundings of the Černé jezero Lake was birch (11.5 kyr cal BP) followed by pine (around 11 kyr cal BP), and spruce first appeared around 10 kyr cal BP. The pollen record of the expansion of spruce is delayed behind the macrofossil record, indicating that spruce appeared thanks to suitable microclimatic conditions (humidity), at first locally and later in the wider area (Fig.). In the macroremain record from the period 11.3 kyr cal BP, there is first evidence of the existence of an oligotrophic mountain lake (< 2 m deep) colonized by Arctic species (*Isoëtes echinospora, Cladocera*) and a developed littoral vegetation (*Carex rostrata, C. cf. nigra, Scirpus sylvaticus, Juncus bulbosus*). Also found were macroremains of certain plant species now extinct in the Czech Republic or species extinct in their primary habitats, for example, *Bolboschenus yagara* (secondary occurrence in the littoral zone of south-Bohemian fish ponds and on nutrient-poor acid grounds, Hroudová et al., 2007) or *Sparganium angustifolium* (Plešné jezero Lake and Černé jezero Lake, now extinct, the closest present-day locality being the the Roháčské pleso Lake in Slovakia, Kubát et al., 2002). Communities of cold-loving aquatic pteridophytes of the genus *Isoëtes* are recorded in the Boreal period also in the Plešné jezero Lake (Jankovská, et al. 2006) and at the Stará jímka locality (Mentlík et al., 2010).

At the turn of the Preboreal and Boreal period, in connection with continental warming and stabilization of the climate, the density and species composition of the forest changed. Pine and birch got gradually displaced while erosion and influx of clastic material ceased, and mixed oak woodlands began to appear (*Quercetum mixtum – Quercus, Tilia, Ulmus*; Fig. 3). These, however, were found mainly in the foothills and never reached the Černé jezero Lake (absence of macroremains). The vast altitude gradient in the surroundings of the locality also had an impact on the composition of vegetation and the speed of spread of individual species.

5.3 Holocene environmental development

Roughly 10.5 kyr cal BP was the time when the last significant change in the development of the natural environment of the Bohemian Forest took effect. The climate got stabilized, which resulted in vegetation development and thus inhibition of erosion. As a consequence of continuous enrichment of the aquatic environment with mineral compounds and a concurrent temperature increase, conditions suitable for development of aquatic vegetation caused sedimentation of organogenous material to prevail over that of minerogenous material, and a layer of subhydric, highly organic material (gyttja) began to form on the bottom of the lake. In the sampled profile, this phenomenon manifested as a shift in MS, a 50% decrease in the content of Rb and an almost four-fold increase in LOI (depth of 355 cm). This climatic oscillation had a regional impact because it also affected the Plešné jezero Lake through an increase of primary production signalled by the maximum value of cladoceran sedimentation (Pražáková et al., 2006). This is a record from the beginning of the Boreal period, which brought increased precipitations and thus decreased continentality to the European climate (Davis et al., 2003; Magny in Elias Ed., 2007). In the sedimentary record from the northern part of the Bohemian Massif (Labský důl Valley in the Giant Mountains; in Engel et al., 2010), this oscillation had no effect because there was still a glacier in this mountain range 10.8 kyr cal BP. The more massive glaciation in the Giant Mountains retreated at a slower rate than in the Bohemian Forest thanks to higher continentality of the climate and higher altitude of the mountain range. The presence of glaciers thereby influenced the local climate and local vegetation development. The development in the Bohemian Forest therefore corresponded more with the development recorded at lower altitudes in mountain ranges (Svobodová et al., 2002) or in areas of western and southern parts of central Europe (Bos et al, 2007; Magny et al., 2007).

During the course of the Boreal period, the forest exceeded the altitude of the lake and even took over the summit plateaus, which inhibited erosion and decreased the influx of inorganic material. This happened ~9.6 kyr cal BP, and these processes are documented in the sedimentary record by, for example, an increase in LOI, vegetation composition in the pollen record but also by a stark decrease in Rb content (around the depth of 330 cm), which is associated with the dust fraction. In contrast to what appears to be the case between 355 and 520 cm, the magnitude of the change in the Zr/Ti and Rb/K logs between 320 and 340 cm is too pronounced to be attributed to granulometric changes. Unfortunately, large admixture of organic matter made grain size measurements impossible at around 330 cm. The higher Rb content in the sediment was maintained at the beginning of the Holocene thanks to input of material eroded from summit plateaus. When, however, summit parts of the range got forested in the Boreal period, which inhibited erosion and slope processes, this source of eolian material expired. According to the AP/NAP ratio, the forest canopy at the locality closed around 8.5 kyr cal BP, which coincides precisely with the end of the occurrence of fine-grained material rich in Rb (Fig. 2). This phenomenon has a wider impact area. The "local" reason for the observed change in Rb content is indirectly supported by a very similar, dramatic decrease in Rb content in the Plešné jezero Lake after the onset of interglacial conditions reported by Veselý in Pražáková et al., 2006 about 70 km away from the area under study. In contrast to these two other Bohemian Forest lakes, the Rb and K content in the sediments of the high-alpine lake Sägistalsee changed in almost the same manner over the last 9 kyr, according to Koinig et al. (2003), as in the Černé jezero Lake. It is obvious that the Rb/K decrease cannot convey a "pure climatic" signal, as assumed by Pražáková et al. (2006). Unfortunately, Pražáková et al. (2006) did not publish logs for other elements in their report to evaluate the hypothesis concerning the different provenance of the sediment in the lake although it is obvious that this phenomenon was definitely also primarily driven by environmental (climate) changes.

During the Atlantic period, deciduous forest communities developed (indicated by the curve of *Quecetum mixtum*, Fig. 2). Beech appeared at the beginning of the Atlantic period (*ca* 8 kyr cal BP), which is also reported by Svobodová et al. (2002). This is relatively early compared to the northern part of the Bohemian Massif and is related with the geographic proximity of the Danube river basin from where beech spread (Magri et al., 2006). Fir expanded to lower parts of the range around 4.5 or 4.3 kyr cal BP based on the pollen and the macroremain record from the core under study, respectively. Hornbeam (*Carpinus*) started to occur in the same period, but it barely reached the proximity of the locality under study (low pollen proportion). The period of the climatic optimum brought gradual filling of the lake at the site of the boring (predominance of littoral species) and its consequent disappearance (aquatic indicators *Isoëtes* and later *Cladocera* disappear from the macroremain record). Approximately 4.5 kyr cal BP, the water body disappeared completely, and the locality turned into a montane ombrotrophic peatbog, on the surface of which there were initially small pools or hollows (indicated by *Scheuchzeria palustris* and *Carex limosa*). The expansion of beech at the end of the Atlantic period marked the beginning of the formation of today's podzols.

In the Late Holocene (Subboreal) period, the Bohemian Forest was covered with spruce-fir forests with an admixture of beech at lower altitudes (Svobodová et al., 2002). Fir and spruce invaded the direct vicinity of the Černé jezero Lake. The locality had a character of an upland moor surrounded by a waterlogged spruce forest, as evidenced by macrofossils. Formation of a closed canopy caused shading and a decrease in species diversity of the forest and as well as the peatbog.

Ancient and modern anthropic colonization of the Bohemian Forest is documented in the uppermost part of the profile by anthropogenic indicators (*Cerealia, Plantago lanceolata*, in some cases also *Urtica*). Surfaces layers of the profile got degraded in the 20th century by draining of the peatbog and planting of a spruce monoculture.

6. Conclusions

The discussed sedimentary record from a kettle lake and subsequent peatbog in an intermoraine depression in the vicinity of the glacial cirque of the Černé jezero Lake holds a continuous record of climate and environmental changes from the Lateglacial times through the entire Holocene. Such a complete sedimentary profile has not been compiled anywhere else in the Bohemian Forest so far (both on the Bohemian and Bavarian side). The profile presented here, which extends to the end of the LGM, therefore provides the most detailed record of the development of vegetation in this region and an idea of the character of sedimentation and natural processes over the last more than 17 thousand years. As it turned out, abrupt changes (increases and decreases) traced in the records of geochemical, granulometric and paleobotanical characteristics in the profile were induced by events of two-fold spatial extent: (1) local (disturbances within the catchment) and (2) regional or supra-regional (climate changes).

The transition from Lateglacial to Holocene interglacial conditions in the Bohemian Forest is characterized by climatic oscillations. These took place between ~17.5 kyr BP and

11.5 kyr BP and were marked by changes in the sedimentary record. Cold oscillations manifested as changes in the intensity of erosion and low primary production of organic material. It is clear that intensive eolian activity took place during cold phases (from 17.57 ± 1.97 kyr to 16.15 ± 1.36 kyr and before ~15.5 kyr cal BP), which is also documented by an increased content of the dust fraction indicated by elevated rubidium content in the sedimentary record. That this was a regional process is documented by similar discoveries at another locality in the Bohemian Forest in the southern part of the mountain range (Plešné jezero Lake). The beginning of the sedimentation in the study area might be correlated with the retreat of glaciers from the cirque's foreland after the LGM and the pronounced Lateglacial cold oscillations with the last glacial readvances during cold phases of the Lateglacial. The last pronounced cold oscillation took place ~15.5 kyr cal BP, which corresponds with glacier readvances recorded in the southward lying glaciers of the Prášilské jezero and Laka lakes. Then the Bølling/Allerød climate amelioration and deglaciation came. The degree to which the development of glaciation in the area of the Černé jezero Lake after the LGM is synchronous with that in other glaciated areas of the region cannot be determined with pinpoint accuracy because of missing dating.

The period between the Bølling/Allerød transition and the beginning of the Boreal is a period of dynamic environmental changes, distinct climatic oscillations (changes in global temperature and continentality of the climate), vegetation succession and changes in the rate of erosion. Climatic warming at the onset of the Bølling/Allerød interstadial was recorded ~15.3 kyr cal BP and is evident from a rising curve of LOI, a drop in the Rb curve and from the pollen record. This corresponds with records from other central-European sites. The bare surface originally fixed by an ice and snow cover was disturbed by erosion and slope movements and got gradually covered with diffuse vegetation. Cooling during the Younger Dryas was not in any way strongly apparent in the sampled profile because of compaction of the sedimentary record.

Warming at the beginning of the Preboreal period (11.6–11.3 kyr cal BP) brought a distinct change of sedimentation in the study area manifested as a jump in the proportion of organic material. This was not a local phenomenon because analogous changes in sedimentation and evidence of warming also appeared at other localities in the Bohemian Forest and in central Europe. This short warm oscillation was followed by the colder PBO period. During the Late Preboreal and Boreal periods, characterized by a rise in precipitations, pioneer plant species (*Pinus* and *Betula*) started to massively colonize higher-altitude parts of the range. From a local perspective, the period 11.3 kyr BP was significant in that evidence of the existence of a cold oligotrophic lake in an intermoraine depression first appeared in the paleobotanical record.

At the turn of the Preboreal and Boreal, the density of the forest canopy and its species composition changed. The Boreal period is associated with amelioration of the climate, soil stabilization and ensuing changes in intensity of erosion, expansion of vegetation and increased organic sedimentation. Holocene warming (10.8 kyr cal BP) brought increased productivity of local ecosystems and marks the beginning of the process of terrestrialization of the lake at the site where sediments were sampled. The most recent pronounced twist in the character of the natural environment occurred 9.8–9.6 ago, when closed-canopy vegetation developed as a result of continuous warming and increasing humidity, thereby inhibiting erosion. These processes were very distinctly reflected in the sediments by a rise in the LOI curve, changes in the pollen and macroremains record but also by an almost complete disappearance of rubidium from the sediments. The reason for the minimization of Rb content in the sediment was inhibited erosion of the source material (fine eolian material accumulated on summit plateaus) and its subsequent sedimentation and further redeposition. Forestation of summit plateaus and the closing of the forest canopy in the northern part of the range took place round 8.5 thousand calendar years BP. According to the pollen record in successive periods, vegetation succession progressed in accordance with the development recorded at other central-European localities; i.e., from an open tundra, through a birch-pine forest to a community of broad-leaved woody plants and finally a beech-fir forest. From a local perspective, stabilization of the climate and an increase in primary production of vegetation in the Boreal and Atlantic periods manifested around the Černé jezero Lake as a gradual transformation of a shallow lake into an ombrotrophic peatbog (4.5 kyr cal BP) gradually overgrown by a waterlogged spruce forest. At the end of the Atlantic period, beech started to invade the area, marking the beginning of the formation of today's podzols.

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Holocene dynamics of the alpine timberline in the High Sudetes

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Abstract

The study focuses on the High Sudetes that represent the most distinctive islands of alpine forest-free area among hercynian mid-mountains of Central Europe. Based on data from newly taken cores and previously published pollen profiles, comparison of the development of the alpine timberline position is carried out. The first of the analysed pollen profiles – the Labsky důl core in the Krkonoše Mts spans the whole period of the Holocene, the Keprnik and Mezikotli profiles in the Hruby Jesenik Mts bring information from the Subboreal/older Subatlanticum turn to the present. An exceptional position of the Krkonoše Mts in terms of permanent presence of the alpine belt throughout the Holocene was confirmed. Three oscillations of the alpine timberline during the Lower Holocene were detected in the profile from the Labsky důl site. In the Hruby Jesenik Mts a temperature dependent forest-free area existed at least since Subboreal to the present.

Key words: alpine timberline; High Sudetes; Krkonoše Mts; Hruby Jesenik Mts; Holocene

Introduction

The term alpine timberline (defined according to Körner 1999) stands for the ecotone between forest and alpine belt or subalpine shrub formations. A fundamental factor determining a gradual decline of forest with increasing altitude is the temperature decrease (Körner 1999). Recently, many forest advances to higher elevations are recorded as a reaction to temperature increase (Holtmeier & Broll 2005; Kullman 2007). Nevertheless, the general upward shift of the alpine timberline is determined rather by long-term climatic trends than by actual temperature conditions (Paulsen et al. 2000).Moreover, reactions to climatic changes are often opposing (ascent of the timberline due to higher temperature and its descent due to higher precipitation or drought, Wilmking et al. 2004).

A certain variation of the alpine timberline position due to partial climatic oscillations during the Holocene can be traced down. In the Central Alps the fluctuation range of the timberline is supposed to reach up to 200 m (Tinner & Theurillat 2003). For the High Sudetes (Krkonoše and Hruby Jesenik Mts) and Western Carpathians, oscillations up to 400 m are quoted (Firbas 1952; Ložek 2001) though this question remains open. Recently, some new cores have been taken in the Krkonoše Mts and Hruby Jesenik Mts and thus new information about formation of the alpine timberline ecotone throughout the Holocene can be presented. The aim of this study is to describe the newly constructed pollen diagrams from the High Sudetes with respect to the alpine timberline position and to discuss the development of the alpine forest-free area extent during the Holocene.

Methods

Study area

The High Sudetes with its primary forest-free areas are supposed to be the best developed alpine areas among central European hercynian mid-mountains (Jenik 1961). They include the Krkonoše Mts. (∼ Giant Mountains/Karkonosze/Riesengebirge), the Kralicky Sněžnik and the Hruby Jesenik Mts (Fig. 1). The study area is characteristic by relative high precipitation (around 1 500 mm per year). The average annual temperatures range from 0.1 ◦C in the highest parts of the Krkonoše Mts (Sněžka 1 602 m a.s.l.) to 1.1◦C in the Hruby Jesenik Mts (Praděd, 1 493 m a.s.l.). The alpine timberline is formed by Norway spruce (*Picea abies* [L.] Karst.). The timberline ecotone grades either into dwarf pine (*Pinus mugo* Turra) growths in the Krkonoše Mts or into alpine grasslands (Krkonoše and Hruby Jesenik Mts). The actual alpine timberline position is situated on average at 1 230 m a.s.l. in the Krkonoše Mts and at 1 310 m a.s.l. in the Hruby Jesenik Mts (Treml & Banaš 2000). The extent of the forest free area has been strongly influenced by man who increased it in the past by deforestation (Jenik & Lokvenc 1962; Jenik & Hampel 1991).

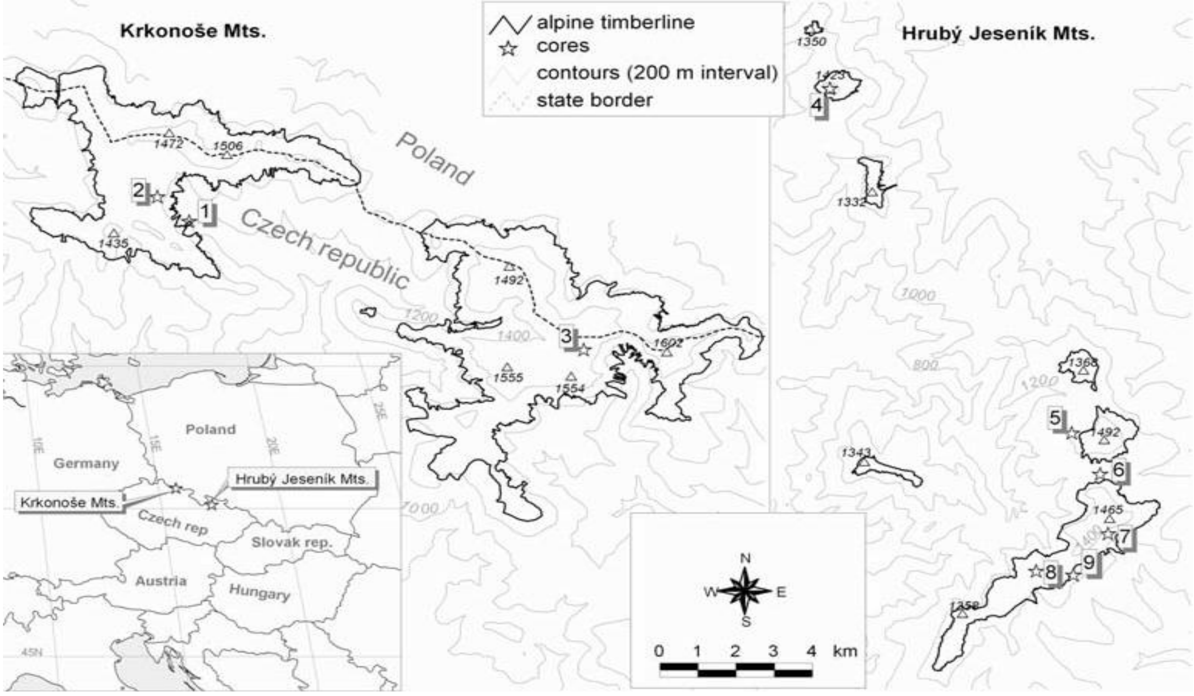


Fig. 1. Study sites in the High Sudetes. 1 – Labsky důl, 2 – Pančava peat bog (Huettemann & Bortenschlager 1987; Speranza et al. 2000a; Jankovska 2001) 3 – Upa peat bog (Svobodova 2002), 4 – Keprnik, 5 – Velky Děd, 6 – Barborka, 7 – Velka kotlina, 8 – Velky Maj (5–8, Rybniček & Rybničkova 2004), 9 – Mezikotli.

Pollen analysis and sedimentology

This study presents three new profiles that bring information about the history of the alpine belt in the Krkonoše and Hruby Jesenik Mts. Pollen records come from the Labsky důl valley (Krkonoše Mts), Mount Keprnik and Mezikotli (Hruby Jesenik Mts). The locality Labsky důl (cirque bottom, 990 m a.s.l., 50◦45_46__N, 15◦33_08__E) is situated in a fossil lake of glacial origin filled with deposits (Engel et al. 2005). This profile provided the longest pollen record ever analysed in Krkonoše – from late glacial period to the present. The locality lies close to the timberline which is lowered here by avalanches. Except the upper layer of peat character the 1 283 cm deep profile contained mainly inorganic matter. A part of the profile between 810 and 830 cm was contaminated by peat sediment from the upper parts (ca 500–650 cm) during the sampling. It is proved by markedly different composition of the pollen spectra (Jankovska 2004). According to pollen composition, sediment properties and radiocarbon data, the other parts of the profile were not contaminated.

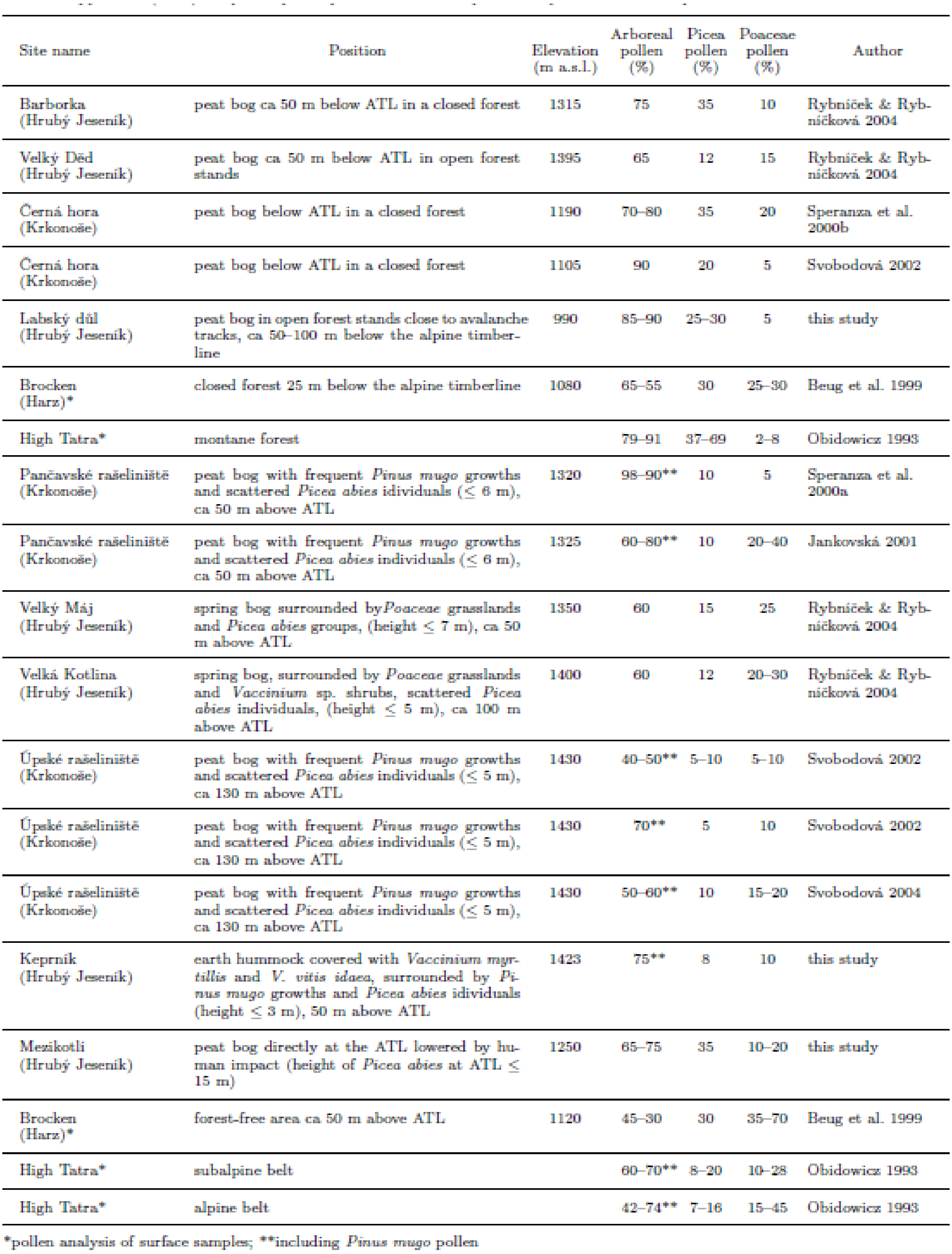
The profile from the Mount Keprnik (1 429 m a.s.l., 50◦10_15__N, 17◦06_57__E) was taken from a pit dug in an earth hummock. The organic sediment had a peat character with sedge remains. The locality is situated on the summit plateau in the northern part of the mountain range at a distance of 200 m (60 m of altitude) above the timberline. The third pollen profile comes from Mezikotli (1 250 m a.s.l., 50◦02_46__N, 17◦58_46__E), which is the bottom of a nivation hollow. A small peat bog with lagoons is situated directly at the alpine timberline lowered here due to athropogenic impacts and avalanches. The analysed 125 cm deep profile has a peaty character with frequent fine clasts (sediments of slope wash) on the base.

The cores were sampled every 5 cm (Keprnik, Mezikotli) or every 10 cm in the case of Labsky důl. The samples for pollen analysis were processed following the standard acetolysis method. The pollen diagrams including stratigraphic zones were created using TILIA software (Grimm 1992). The sediment from Labsky důl was analysed also in terms of proportion of the organic matter (determined by loss-onignition) and particle size distribution (determined by wet sieving). Based on those two indicators the segments of the profile with similar characteristics (particle size distribution, organic matter proportion, colour) – so called lithostratigraphic units – were determined. Radiocarbon dating was carried out by laboratories in Erlangen, Poznan (accelerator mass spectrometry 14C) and at the Faculty of Science of the Charles University in Prague (conventional 14C). All the absolute data are expressed as uncalibrated radiocarbon years BP. Chronostratigraphic zones are used according to Lang (1994).

Interpretation of the alpine timberline altitudinal shifts

When interpreting the pollen diagrams in relation to the timberline position, emphasis was placed namely on the proportion of arboreal and non-arboreal pollen (AP/NAP). This proportion enables to determine, although not precisely, whether forest or forest-free area dominated in the vicinity of the profile (Obidowicz 1993). Nevertheless, a comparison of the recent pollen record and vegetation composition had to be made to avoid misinterpretations resulting from specific local conditions. Concerning the AP/NAP rate, the critical arboreal pollen percentage fluctuates generally within the range of 70–80% in the area of the timberline or just below (Table 1). In the case of the variations of AP/NAP, it was always taken into account whether the change of the value was not caused by a change of the dominant species with different (higher or lower) pollen production. Also the changes of the *Poaceae* pollen percentage were regarded as an indicator of the forest advance or retreat. Pollen percentage of *Poaceae* usually varies more notably between forest and forest-free area than AP/NAP or the *Picea* pollen percentage (Obidowicz 1993; Beug et al. 1999, Table 1).

Macroscopic remains of woody species which provide better information about the timberline position (Tinner & Theurillat 2003) were analysed in the Mezikotli profile, stomata were counted in the Labsky důl and Mezikotli cores. In the case of the Keprnik site, neither macroscopic remains of woody species nor stomata were present in the processed samples.



Site name	Position	Elevation (m a.s.l.)	Arboreal pollen (%)	Picea pollen (%)	Poaceae pollen (%)	Author
Barborka (Hrubý Jeseník)	peat bog ca 50 m below ATL in a closed forest	1315	75	35	10	Rybníček & Rybníčková 2004
Velký Děd (Hrubý Jeseník)	peat bog ca 50 m below ATL in open forest stands	1395	65	12	15	Rybníček & Rybníčková 2004
Černá hora (Krkonoše)	peat bog below ATL in a closed forest	1190	70–80	35	20	Speranza et al. 2000b
Černá hora (Krkonoše)	peat bog below ATL in a closed forest	1105	90	20	5	Svobodová 2002
Labský důl (Hrubý Jeseník)	peat bog in open forest stands close to avalanche tracks, ca 50–100 m below the alpine timberline	990	85–90	25–30	5	this study
Brocken (Harz)*	closed forest 25 m below the alpine timberline	1080	65–55	30	25–30	Beug et al. 1999
High Tatra*	montane forest		79–91	37–69	2–8	Obidowicz 1993
Pančavské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* idividuals ($\leq$ 6 m), ca 50 m above ATL	1320	98–90**	10	5	Speranza et al. 2000a
Pančavské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals ($\leq$ 6 m), ca 50 m above ATL	1325	60–80**	10	20–40	Jankovská 2001
Velký Máj (Hrubý Jeseník)	spring bog surrounded by*Poaceae* grasslands and *Picea abies* groups, (height $\leq$ 7 m), ca 50 m above ATL	1350	60	15	25	Rybníček & Rybníčková 2004
Velká Kotlina (Hrubý Jeseník)	spring bog, surrounded by *Poaceae* grasslands and *Vaccinium* sp. shrubs, scattered *Picea abies* individuals, (height $\leq$ 5 m), ca 100 m above ATL	1400	60	12	20–30	Rybníček & Rybníčková 2004
Úpské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals ($\leq$ 5 m), ca 130 m above ATL	1430	40–50**	5–10	5–10	Svobodová 2002
Úpské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals ($\leq$ 5 m), ca 130 m above ATL	1430	70**	5	10	Svobodová 2002
Úpské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals ($\leq$ 5 m), ca 130 m above ATL	1430	50–60**	10	15–20	Svobodová 2004
Keprník (Hrubý Jeseník)	earth hummock covered with *Vaccinium myrtillis* and *V. vitis idaea*, surrounded by *Pinus mugo* growths and *Picea abies* idividuals (height $\leq$ 3 m), 50 m above ATL	1423	75**	8	10	this study
Mezikotlí (Hrubý Jeseník)	peat bog directly at the ATL lowered by human impact (height of *Picea abies* at ATL $\leq$ 15 m)	1250	65–75	35	10–20	this study
Brocken (Harz)*	forest-free area ca 50 m above ATL	1120	45–30	30	35–70	Beug et al. 1999
High Tatra*	subalpine belt		60–70**	8–20	10–28	Obidowicz 1993
High Tatra*	alpine belt		42–74**	7–16	15–45	Obidowicz 1993

*pollen analysis of surface samples; **including *Pinus mugo* pollen

Table 1. Recent pollen percentages below and above the alpine timberline (ATL) in the High Sudetes, High Tatras and Harz, taken from the uppermost (0 cm) samples of pollen profiles or from the pollen analysis of surface samples.

Results

Labsky důl profile

The profile that is crucial for the reconstruction of the timberline position in the Krkonoše Mts at the beginning of Holocene comes from the locality Labsky důl. The simplified pollen diagram (Fig. 2) shows data from Late Glacial period to Boreal which correspond to the profile depth 1 283 cm to 790 cm. Pollen curves of *Salix* sp., *Juniperus* sp., *Betula nana* type, *Ephedra distachya* and *E. fragilis* type and also the presence of the pollen of *Pinus* haploxylon type (i.e. *Pinus cembra*) delimit clearly the forest-free stage in the profile. The higher pollen curve of *Pinus sylvestris* type is produced by pollen from the local *Pinus mugo* stands or by influx of *P. sylvestris* from lower altitudes. Combination of both factors is probable. The organic matter content is very low (8% on average). Together with the particle size distribution (silty sand) and the presence of algae (*Pediastrum boryanum* var. *longicorne* and *Pediastrum integrum*), it shows the lake phase of the profile. At the base of the U2 lithostratigraphic unit (LD1) and around 9 500 BP (LD2) a markedly lower AP percentage was recorded. Both above mentioned AP curve depressions are combined with the increase of the Poaceae pollen. In this period the alpine timberline was still situated below the Labsky důl site, hence both recorded pollen composition changes (LD1, LD2) should probably be interpreted rather as a general forest retreat than as a local disturbance of forest.

In early Boreal the AP curve approaches and then passes constantly 80%. After ca 8 200 BP the proportion of organic matter in the lake sediment rises (from 7–9% to 20–25%). Thus the timberline passed the level of Labsky důl profile as late as at the beginning of Boreal. At that time it was composed of pioneer woody species (*Pinus* sp., *Betula* sp.). It follows that the timberline reached the upper locations with a certain time lag which corresponds to relatively late deglaciation (Engel et al. 2005). A notable decrease of the arboreal pollen rate could be detected in the Labsky důl profile around 8 200 BP (LD3). It is set off by contamination of the matter below this part of the profile. Even other parameters (an increase of the pollen of *Juniperus* and *Betula nana* type, a lower proportion of organic matter in the sediment) probably indicate that forest-free area had expanded in the Labsky důl. Nevertheless, it is not clear, whether this expansion was caused by large-scale disturbance or by climatic oscillation.

After this event, the AP percentage has oscillated only weakly in the range of 80–90%. It is suggested that a similar state of forested and unforested areas as today was established and it has been preserved due to frequent disturbances (avalanches, debris flows). The Norway spruce as a recent timberline forming species has occurred at the locality since at least 7 000 BP according to the stomata record.

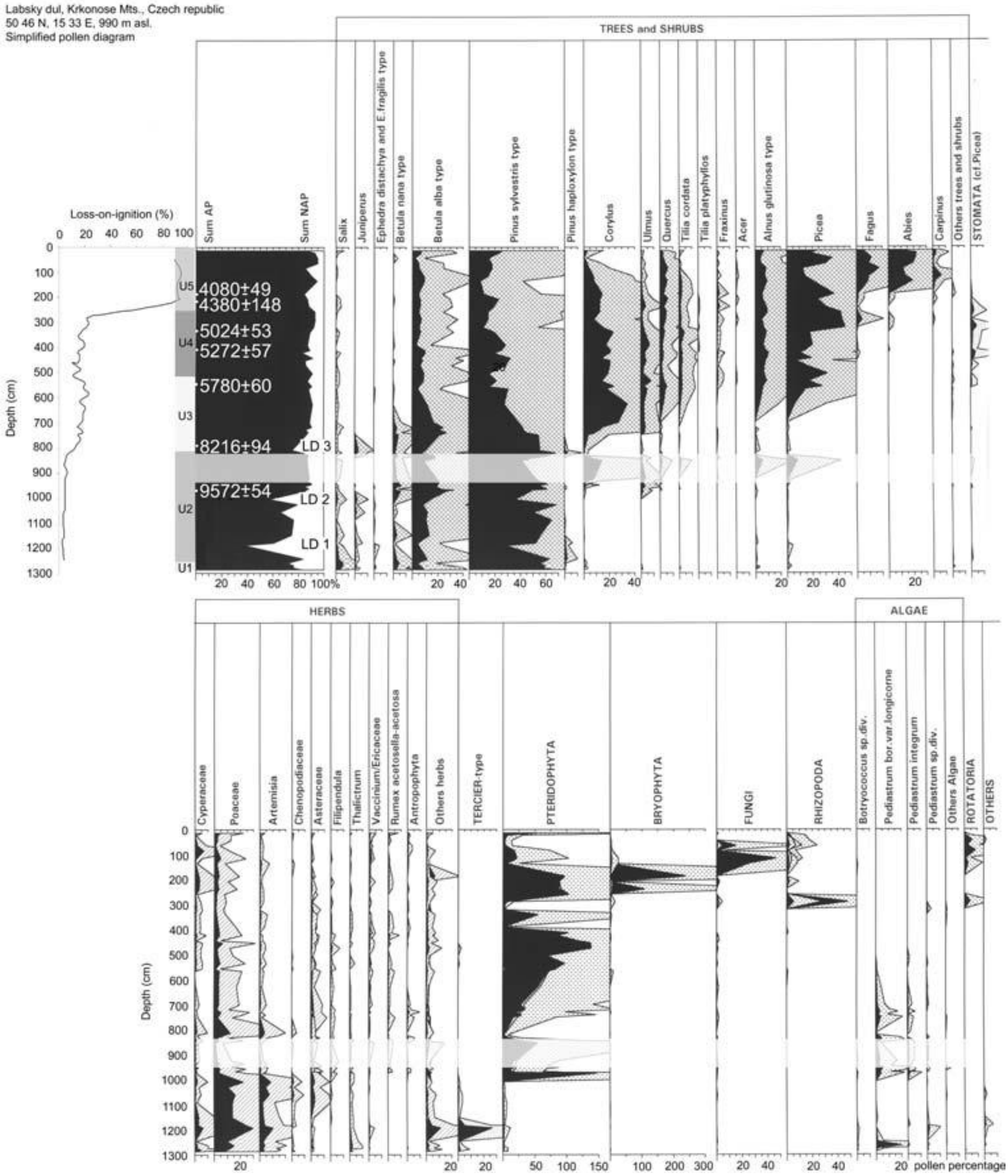


Fig. 2. Simplified pollen diagram, radiocarbon data, loss-on-ignition and litostratigraphic units (U1–U5) in the "Labský důl" core. Light rectangle across pollen diagram indicates the contaminated part of the profile (810–830 cm depth).

Keprník profile

At the summit of the Mount Keprnik the AP proportion in Subatlanticum zone was held between 70 and 80% (zone K1, K2, Fig. 3). At the same time no woody species stomata were found in the investigated profile. The profile shows the regression of woody species typical for mixed oak forests and the progression of beech and fir in the K2 zone. Direct indicators of human activities are present in the uppermost layers (K3). The time scope of the profile is Subboreal and Subatlanticum. With respect to the absence of spruce stomata remnants and the AP percentage lower than 80%, very low *Picea* pollen sum (in exposed windy position with high pollen influx from lower areas), it could be concluded that the alpine timberline has not reached the summit area of Keprnik Mt. since Subboreal/Atlanticum turn. It is proved also by occurrence of the earth hummocks since at least ca 2 090 BP. Those landforms are usually quickly destroyed as they are colonised by trees (Treml & Křižek 2006).

Mezikotlí profile

According to radiocarbon data (1 520 ± 39 BP, Erl-Jesenik 10/06-1), the pollen profile from the Mezikotli site spans the period from Late Subatlanticum till present (Fig. 3). The Pollen composition between base and the depth of 85 cm probably reflects fir-beech forests which extended to higher elevations than today (the nearest specimens of *Fagus sylvatica* recently occur 100 m below the analysed site). Stomata of Picea were abundant in all samples of this part of the profile and therefore the occurrence of the Norway spruce directly at or above the site is evident.

During the following period (profile depth 75–50 cm – till ca 530 BP) dynamic changes of vegetation composition are recorded. Fir, beech and hornbeam gradually declined, while the proportion of *Picea* and *Pinus* pollen increased. *Picea* pollen reached as much as 45 % of pollen spectra, at the same time the amount of the arboreal pollen scillated between 80–90%. In this period the upper limit of closed forest was certainly situated above the level of the Mezikotli site.

Pinus pollen rate significantly increased after 530 BP (profile depth 40–20 cm), which could be a consequence of the decrease of local woody species pollen numbers. During this period *Pinus sylvestris* could constitute early succession stages of forest on forest clearances in lower elevations. At the same time the *Picea* pollen curve sharply decreased and also stomata of *Picea* were not detected in the 40–35 cm part of the profile. The AP/NAP rate decreased even below 50 % and the pollen curve of *Poaceae* increased up to 15–20%. A distinct decline of the alpine timberline due to anthropogenic impacts is suggested to be the reason of the recorded changes in the pollen composition. From 50–40 cm depth of the profile the pollen curve of direct human indicators (Cerealia, weeds) as well as indirect human indicators [*Chenopodiaceae*, *Artemisia* sp., *Rumex acetosella* and *Plantago lanceolata*-type (which is undistinguishable from *Plantago alpinum* naturally occurring in the Hruby Jesenik Mts)] started to increase.

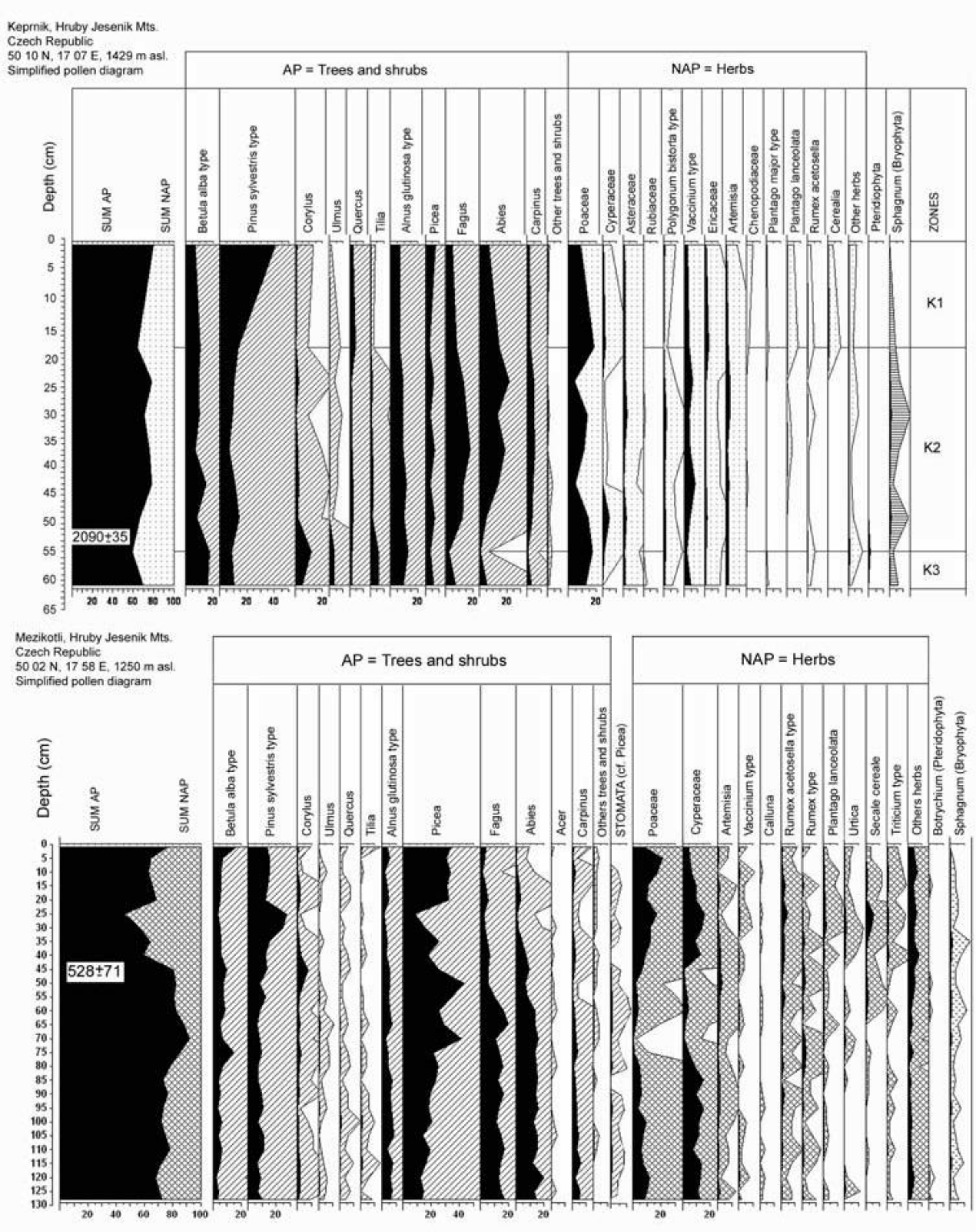


Fig. 3. Simplified pollen diagrams and radiocarbon data (marked with the white rectangles within the AP curve), summit of the Mt. Keprník (1 429 m a.s.l.) and the Mezikotlí site (1 250 m a.s.l.).

Discussion

Timberline fluctuations in the Krkonoše Mts In the Labsky důl profile, three distinct oscillations of arboreal pollen curve were detected (LD1, LD2, LD3). While LD1 and LD2 were most probably caused by a general downward shift of the alpine timberline, the third oscillation (LD3) could be induced by a large-scale disturbance as well. The alpine timberline was situated at or above the Labsky důl site before this oscillation, hence the disturbance event could be displayed in pollen spectra in similar way as a general forest retreat.

After the mentioned oscillations, the timberline definitively passed the Labsky důl site. A cold oscillation (7 600 ± 130 BP), which was probably expressed in the timberline dynamic, is documented by Huettemann & Bortenschlager (1987) from neighbouring Pančava peat bog (cca 900 m W from Labský důl site, 1 320 m a.s.l.), based on high proportion of pollen belonging to herbs or dwarf shrubs species (25–30% – *Poaceae*, 10% – *Calluna* sp.). This means that at given time (~7 600 BP) either the timberline had not yet reached the Pančava peat bog or it had been already lowered below its level. In the following period during the Atlanticum and Subboreal the alpine timberline reached at least the level of Pančava peat bog and apparently it varied only a little – the percentage of AP at Pančava peat bog fluctuates around 90% (Huettemann & Bortenschlager 1987; Speranza et al. 2000a; Jankovska 2001). Nevertheless according to Speranza et al. (2000a) there was another colder period between 2 640 ± 60 and 2 480 ± 35 BP. However, there is no evidence which would substantiate the decrease of the ATL position due to this cold oscillation.

Also in the period of Older Subatlanticum no marked trend in forestation or deforestation of the region was detected in the highest parts of the Krkonoše Mts. At less elevated Pančava peat bog the woody species percentage reaches 90% of the pollen spectrum (Jankovska 2001), at Upa peat bog (1 430 m a.s.l., east Krkonoše Mts) it reaches approximately 80% (Svobodova 2004). A considerable proportion (20–30%) of the pollen spectrum belongs to pine pollen which comes mainly from local *Pinus mugo* stands.

Based on existing data it is not possible to determine the exact level that the closed forest reached in the climatic optimum. Most likely a closed tall-trunk stand cannot be expected in locations with occurrence of well developed sorted patterned ground with distinctly raised centres (approximately above the level of 1 430–1 450 m a.s.l., Křižek 2007). Those landforms usually change their morphology into the flat-topped patterned ground after the colonisation of trees or shrubs (Sekyra et al. 2002). The highest current positions of the timberline are situated at altitudes 1 350–1 390 m a.s.l. (Treml & Banaš 2000). The maximum difference in the timberline position compared to the present was therefore less than 100 m. The above mentioned lower rate of the timberline oscillation corresponds to the temperature reconstructions (Hieri et al. 2003) that estimate the extent of long-term summer temperature oscillations in the Middle and Upper Holocene to 1◦C.

Development of the alpine timberline in the Hruby Jesenik Mts during the Upper Holocene

The profiles from the Hruby Jesenik Mts that have ever been analysed in terms of pollen composition contain the record of the period between the Atlanticum/Subboreal turn and the present. High representation of *Corylus avellana* pollen (Rybniček & Rybničkova 2004) indicates the hazel stands in the summit locations (about 1 300 m a.s.l.) at the beginning of Subboreal, nevertheless there is no direct evidence in form of macroscopic remains to support this hypothesis.

At localities that are forest-free at present, relatively low proportions of arboreal pollen (approximately 60%) and high percentage of Poaceae (10–15%) were recorded in the Older Subatlanticum, notably at Velký Máj (Rybníček & Rybníčková 2004, summit plateau, 1 350 m a.s.l.) and also at Velká kotlina (cirque headwall, 1 400 m a.s.l.), where the oscillations were more pronounced (10–30% of the Poaceae pollen). That indicates the permanent forest-free area at given localities in this period, although it could oscillate at avalanche tracks in the area of the Velká kotlina cirque. A slightly higher AP proportion in the Older Subatlanticum zone was recorded at the summit of the Keprnik Mt. (70–80%), however a forest-free area is documented here by occurrence of earth hummocks in this period (Treml et al. 2006). According to Mezikotlí profile, the alpine timberline was situated above 1 250 m a.s.l. during this period.

At localities that are currently forested (Barborka, Velký Děd – Rybníček & Rybníčková 2004), the AP proportion came up to 90% since the Atlanticum/Subboreal turn and the pollen percentage of *Poaceae* fluctuated around 5–8%. A noticeable decrease of representation of arboreal pollen, mainly beech and fir, was recorded in most profiles at around 500 BP (zone K3 in the case of Keprnik, before 528 BP in the case of Mezikotli profile). This can be ascribed above all to the influence of human activities (Jeník & Hampel 1991).

Thus, it is suggested that a very limited treeless space occurred at the Atlanticum/Subboreal turn in the Hruby Jesenik Mts. However, this area must have been consecutively extended during Subboreal because there is evidence of treeless area from Keprník, Velký Máj and Velká kotlina sites during the Older Subatlanticum.

With respect to the present vertical extent of the alpine belt in the High Sudetes it can be assumed that in the Hrubý Jeseník Mts the alpine forest-free area was more “endangered” during the Holocene than in the Krkonoše Mts As far as positive long-term temperature oscillations 0.5–1◦C for Central Europe are considered (Haas et al. 1998; Hieri et al. 2003), the temperature dependent forest-free areas had to disappear almost entirely in the Hrubý Jeseník Mts. By contrast, in the Krkonoše Mts large forest-free areas were present throughout the Holocene. Nevertheless, the occurrence of many plant species and diversified communities dependent strictly on forest-free areas (Jeník 1961) indicates that the forest-free enclaves in the High Sudetes had to exist in the long term. However the presence of forest-free patches in the Hrubý Jeseník Mts depended rather on soil conditions, water regime or slope inclination than on temperature.

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Human impact on Holocene floodplain development at catchment of the Těšetička-Únanovka river, South Moravia - Czech Republic

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Abstract

In the microregion of the river Unanovka, which has an archeologically reconstructed settlement development, 2 boreholes were drilled. Palaeoecological data was obtained from pollen analysis and macroremains; phosphates; magnetic susceptibility; granulometry and radiocarbon dates were measured. The base of the flood sediment is dated back to the start of the neolithic, where on a gravel base, a layer of organic sediment settled made up of the neighbouring vegetation, deciduous forests. In agricultural prehistory until the beginning of the early middle ages flood sediments start to be deposited, the vegetation has a ruderal character with Alder dominating. The process of accumulation and erosion in the neighbouring region accelerated from the height of the middle ages.

Keywords: holocene, floodplain, paleoecology, human activities, settlement pattern.

1. Introduction

Human settlements have always been closely connected to rivers and streams, which were important in terms of subsistence strategies. Rivers and their floodplains are therefore an important factor in the settlement of the cultural landscape. This relationship is more pronounced after the transition to agriculture, where water is essential for the livestock.Human impact on rivers in central Europe can be traced back to the beginnings of agriculture (Lang - Nolte 1999). This led to deforestation of the landscape, the establishment of fields and an increase in the level of erosion. The process leading to the filling of the floodplain is significantly influenced by changes in vegetation, where the most significant factor is the geology and geomorphology. The character of the vegetation cover in the Holocene became increasingly influenced by human activities, mainly in the area of pre-historical ecumenical. The significant relationship of Great Moravian aglomerations (from the 9th century AD) and floodplain environment has been discussed for a long time in the Czech Republic (e.g. Opravil 1983, Poláček 2001, Macháček et al. 2007). Direct interventions into watercourses are characteristic of the Middle Ages (the construction of mills, ponds, bridges, etc.). The maximum human impact on rivers is of course from today.

Alluvial plains are an indirect indicator of the state of the climate, vegetation cover and anthropogenic impact. These reflect the developments that can define the flow of a specific watercourse. Spatial and chronological differences in their formation can explain the development of the whole micro-region, however these are outweighed by general trends for the Central European region (Kalis et al. 2003). Their genesis is locally influenced by short-term climatic fluctuations and catastrophic events (Zolitschka et al. 2003). Sediments of small streams have already provided some important profiles depicting the history of the Holocene floodplains. According to them, it is assumed that anthropic intervention should affect most of our floodplains from the Middle Ages (Ložek 1998). In regions with intensive prehistoric settlements erosion and accumulation as a result of human activity can be expected and then relatively accurately dated. The disadvantage of paleoecological record in the floodplain are frequent hiatus, activities inherent to the dynamics of water flow and difficulties in distinguishing climate change from anthropogenic impact (Zolitschka et al. 2003). In the case of small streams a crucial contribution also comes from the material from the immediate vicinity (flushes). The result is a complex construction of river floodplains, which must also impact upon the research and interpretations of its development.

Research of the river floodplain in relation to archeology in the Czech Republic is still rather marginal. Aspects of the work are focused on the landscape of Podkrušnohoří, where large surface mines created a unique opportunity to study the construction of floodplains and associated archaeological records in the scale of many kilometers, for example the Lužicky stream basin (Neustupný 1985). Another example was middle Polabí, where around the site of Tišice, there was an attempt to link archaeological and palynological results (Dreslerová - Pokorný 2004). In Moravia was investigated the floodplain of the Morava river near Mikulčice (Opravil 1962; 1978; 1983; Poláček 1997; Svobodová 1990) and Pohansko near Břeclav (Doláková et al. 2010).

We have focused on the paleoecological record potential of the sediments from the relatively small drainage basins. The Těšetička/Únanovka stream in South Moravia is an example of small lowland stream in close proximity to important archeological sites, especially Těšetice-Kyjovice "Sutny" with evidence of longterm prehistoric human occupation (Fig. 1). The main aim of this investigation is direct comparison of the palaecological record from the Těšetička/Únanovka alluvium and archeological evidence of previous occupation of the catchment.

2. Site description

The Únanovka stream is located in South Moravia (near Znojmo). The site is located on the border of the Bohemian-Moravian Highlands, the Jevišovická hills and Dyje-Svratka valley that belongs to Inner-carpathian lowlands. The Únanovka stream springs up in the area Únanov at an altitude of about 280 meters and ends at about 185 meters with the confluence with the Jevišovka. The extent of the basin is approximately 12 km² (Vlček et al. 1984, 281).

Geologically the microregion lies on the boundary of the Dyje Massif and Carpathian foredeep. Part of the area is covered with scattered river terrace sediments and loess. The area of the Sutny archeological site is made up of loesses upon which developed brown soil. Towards the west, a granite bedrock appears and the thickness of the soil cover in the forest declines.

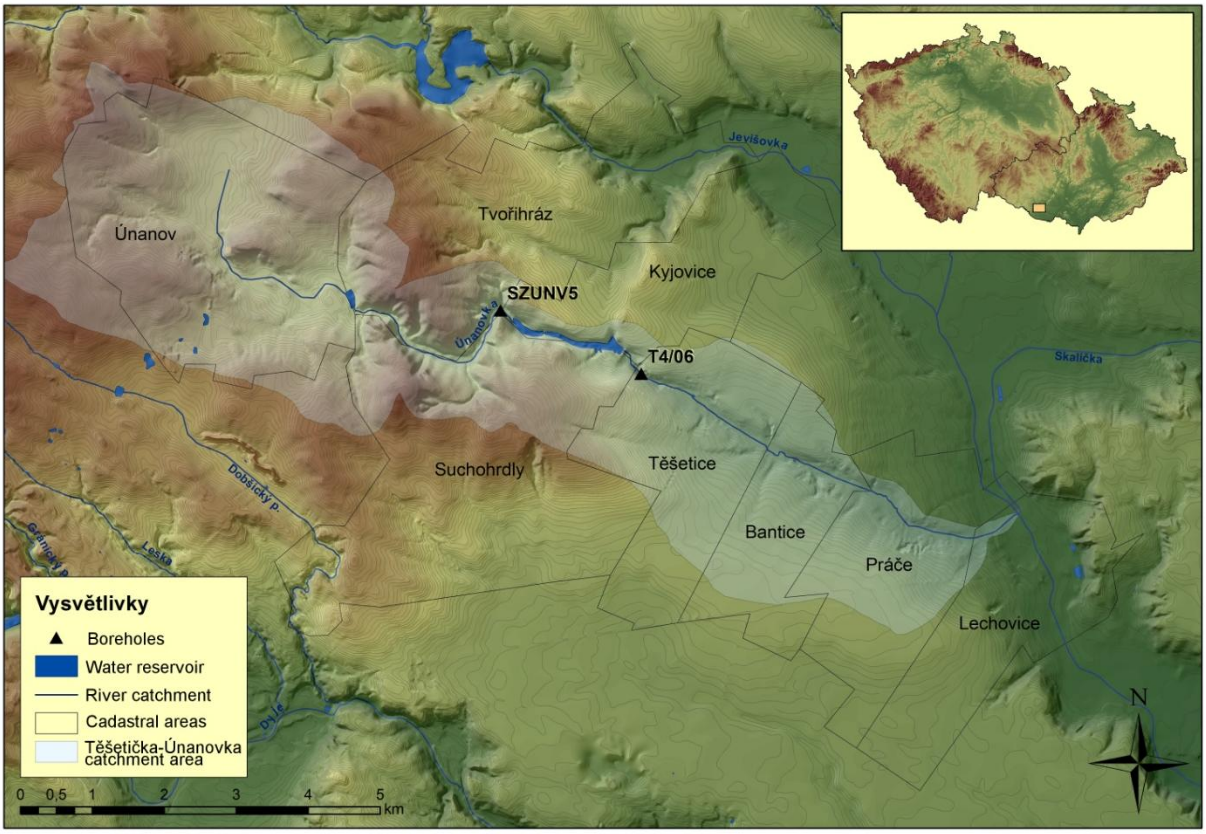

Fig. 1) Localization of the Boreholes (Created by M. Hlavica)

3. Archaeological evidence

The Tesetice microregion has interested amateur archeologists from the turn of the 19th / 20th century (J. Palliardy and F. Vildomec, Podborský et al. 2005, 13-18). From the end of the 40s, there has been an archeological expedition from Masaryk University active in the Znojmo area (Podborský - Vildomec 1972). The systematic excavation of the poly-cultural site at Těšetice-Kyjovice "Sutny" started in 1967 (Podborský et al. 2005). The research of this site is added to from 2005 by systematic research of the microregion, focusing both on the re-identification and search for new sites (Šabatová 2011).

Znojmo is an old settlement and in the landscape can be found traces of virtually all prehistoric and historical periods (Fig. 2). Agricultural settlements from the Neolithic period are focussed on the gentle slopes of the alluvial floodplain with loess loam subsoil above the river Únanovka, and occasionally around a now-extinct smaller watercourse. All of Neolithic cultures occupied the same type of residential location. The situation is the same as the nearby river Jevišovce (Stuchlík 2006, 17-19).

In the early Eneolithic settlement, the strategy is changing, population shifts into micro elevated positions, now covered by forest (Šabatová 2010, 338-339; 2011). Sites settled by the Boleraz phase are significant in elevated positions, outside a few objects of the Baden culture have been documented (Podborský et al. 2005, 161-169). The settlement of the Funnel Beaker culture was pre-dated to a younger period. There are very numerous examples in the microregion of the activities of the Bell Beaker Culture (late Eneolithic), whose settlement strategies are closer to those of the Early Bronze Age (cf. Šabatová in print).

Significant increases in settlement in the Bronze Age and in the Hallstatt period, not only in the fertile loess, but also in elevated positions, is then noted (Bíško 2011; Podborský et al. 2005, 13-42; Šabatová 2010; in print). From the Těšetice area alone there are seven dated sites from the Bronze Age and the Hallstatt.

Least of all so far, are the records of activity from the protohistoric periond in the microregion (Podborský - Vildomec 1972, 219, 223). But in the wider region there is evidence of settlement and funeral activities (Kovárník 2008; Meduna 1980, 154-155, 274-275; Podborský -Vildomec 1972, 224). Also other populations models assume significantly lower populations in the protohistorical period (Dreslerová 2012, 212).

There are disputes about the rate of settlement of the microregion from the early middle ages; however there is documented evidence of activity (Bíško 2011; Podborský - Vildomec 1972; Vokáč – Moník 2001, 250).

The development of Slavic settlement structures in the region, have not been systematically captured, with the exception of the centres (Znojmo "Fort" and Znojmo Castle, see Procházka – Doležel 2001, 28). At the end of early hill fort period in the old settlements they were able to stabilize the population structure, which, with the exception of extinct villages, persists for the rest of the Middle Ages and into the modern era.

From an archaeological point of view it is very difficult to say to what extent residential areas are contiguous and to what extent therefore the deforestation of the area during a period of the most intensive prehistoric activity in the area of the Tvořihrázsky forest. But it is possible to consider, based on the significant population decline since early history, starting again today with the reforestation forest area. In the Tvořihráz area there are two extinct village (Měřínský 1969, 11; Nekuda 1961, 39; Peřinka 1904, 17). On the maps of the first military mapping (For the area of South Moravia for the years 1763-1764 , Semotanová 2001, Fig. 87) there are 4 fishponds visible in the floodplains of the Unanovka before Těšetice. The maps of the second military survey show all ponds in the floodplain Únanovky emptied, but the construction of the Únanovský mill is visible and the Hájkův mill at Těšetice (cf. Peřinka 1904, 22). The Bohunice pond, where the borehole SZUNV5 was drilled was clearly renew at the start of the 20th century and the Unanovsky pond has also been renewed. The current flow of the river Únanovky in some parts has been artificially modified, as in connection with the construction of ponds, so apparently in an effort to maximize the economic exploitation of alluvial meadows. The Těšetice dam on the Únanovka river was built from 1981 to 1983.

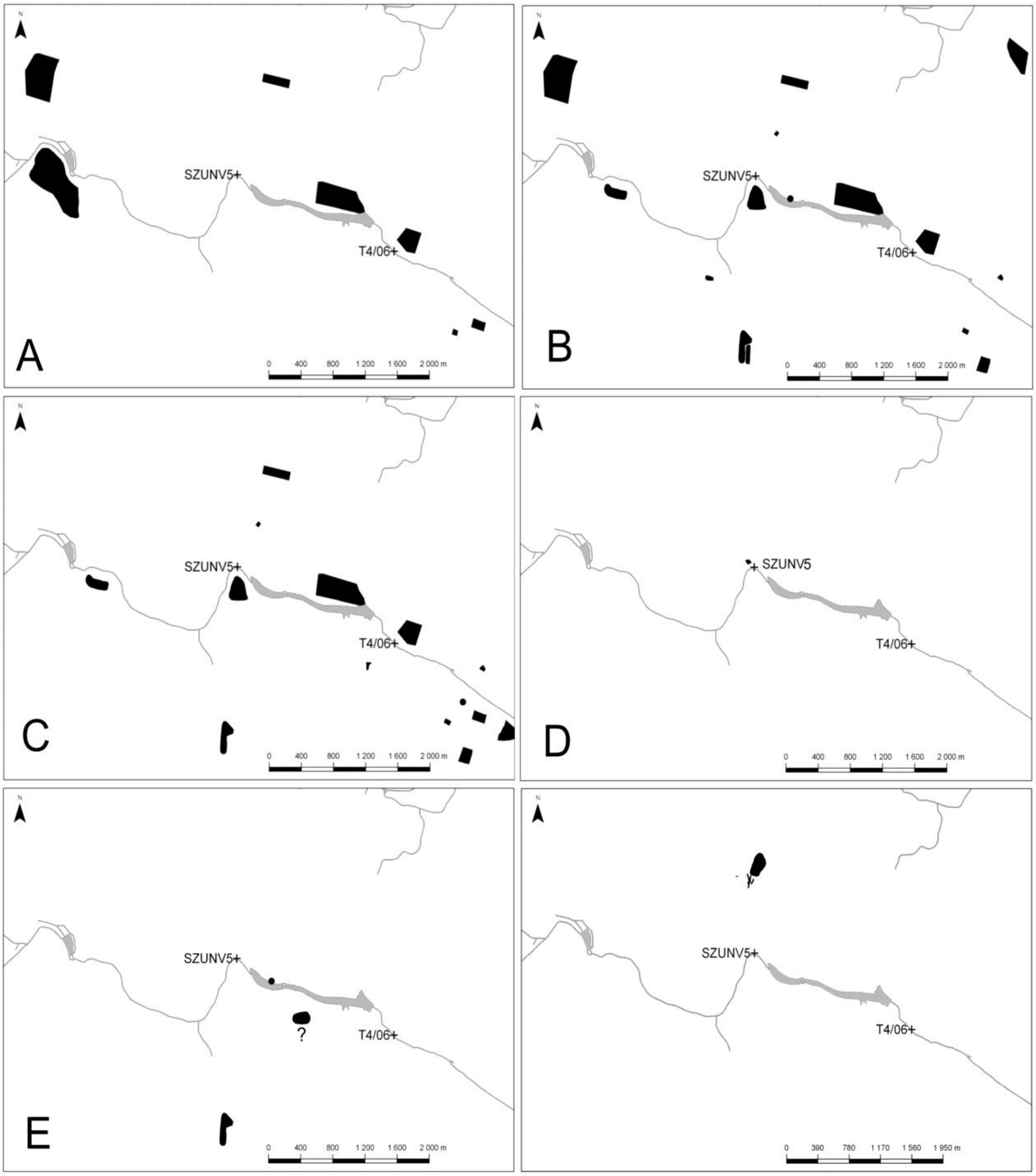

Fig. 2) Overview of all populated positions with the exception of pure modern activities. A = The Neolithic (5600 - 4500 BC), B = The Eneolithic (4500 - 2100 BC), C = The Bronze Age and Hallstadt period (2100 - 480 BC), D = La Tène (480 – 30 BC), E = The Early Middle Age (550 – 1200 AD), F = High Middle Age (1200 – 1410 AD). Basic Resources: Podborský - Vildomec 1972; Podborský et al. 2005; Šabatová in print.

4. Methods

In 2006, there were several geological bore-holes into quaternary sediments (Valová 2007), of which bore-hole T4/06 was located in the floodplain of the river Únanovka below the current dam (Fig. 1), the place that is closest to the stream of the long studied poly-culture area of Těšetice-Kyjovice "Sutny". The second analysed bore-hole SZUNV5 was located in the space above the floodplain dam under the hillfort "Starý zámek" (Šabatová 2008; 2010). This borehole was taken after the complex field survey of sediments by handle drill equipment in the are above water reservoir. The bore-hole T4/06 was carried out by employees of the Czech Geological with the drilling rig Lumes SIG-Mounty 2000/93H to a depth of 360 cm (Valová 2007, 27). The SZUNV5 (located above the dam – Fig. 1) bore-hole was drilled with a vibration drill kit from Elijkelkamp to a depth of 390 cm. Drill core was divided up into ten centimeters section samples.

For borehole T4/06 the following methods were used: pollen analysis, radiocarbon dating, laser granulometry. Samples from borehole SZUNV5 were analyzed by these methods: laser granulometry, pH, magnetic susceptibility measurements, macroremain analysis, pollen analysis, radiocarbon dating and malacofauna analysis. Grain size distribution was determined by the Retsch AS200 (fractions over 0.063 mm) and by the CILAS 1064 (fractions below 0.063 mm).

Active soil reaction (pH in distilled water) was measured by Precision Digital pH meter OP-208 according to the methodology set A. Majer (Kuna et al. 2004, 116). Phosphates (calculated to P_2O_5) were extracted with hydrochloric acid (Cawanagha et al. 1988) from a soil sample prepared by A. Majer (1984) and determined colorimetrically according to the methodology of J. Murphy and J. P. Riley (1962). Loss on ignition (LOI) was measured at 550 ° C (mainly measured as the proportion of organic matter) and 950 ° C (representing mainly carbonates) standard methodology (eg. Heiri et al. 2001).

Measurement of magnetic susceptibility (MS) of dried samples weighing 23 g was carried out on a Kappabridge KLY-2 (Agico, Ltd.) at the Institute of Geology ASCR, v.v.i.To plot the data a non-standard MS mass was expressed in $m^3.kg^{-1} \times 10^{-9}$ with an error of measurement for each sample ± 2%.

The macroremain analysis used a fraction of the sediment fraction of size 0.25 to 0.063 mm. A stereoscopic microscope was used with magnification of 10x and 30x. Fruits, seeds, mosses and twigs with buds were collected from the sediment. Fruits and seeds were determined using the special keys (Anderberg 1994; Berggen 1969; Berggen 1981; Bojnanský – Fargašová 2007; Cappers - Bekker - Jans 2006). Mosses were identifiedby the Bryological laboratory at the Institute of Botany and Zoology, Masaryk University. Twigs and buds were determined, if possible, using Keys (Bažant – Ešnerová 2010; Červenka - Cigánová 1989) and compared with recent buds of woody plants. The results were processed in the program PolPal (Walanus - Nálepka 2004).

Samples for pollen analysis were prepared by standard acetylation method, including the use of hydrochloric acid and hydrofluoric acid (Moore et al. 1994). Part of the samples from borehole T4/06 was used to increase the number of pollen grains subject to concentration using a heavy liquid $ZnCl_2$. The pollen diagram was compiled using the program POLPAL (Walanus and Nalepka 2004).

Two samples from borehole T4/06 were radiocarbon dated in Poznań (http://www.radiocarbon.pl/). Radiocarbon dating of samples from borehole SZUNV5 was carried out in the laboratory using AMS in a laboratory in Georgia (http://cais.uga.edu/programs_applications/radiocarbon_apps/radiocarbon_dating.htm). For the dating plant macroremains were used.

Borehole	**Layer**	**Lab. code**	**Material**	**Age, years BP**	**δ13C,‰ 14C**	**Calibration (2δ), years BC/AD**	**Period**
T4/06	210-205 cm	POZ-33593	mud	1725±35	-	240-401 AD	subatlantic, turn of the Roman period and Migration period
T4/06	300-305 cm	POZ-33594	mud	2970±40	-	1371-1052 BC	subboreal, Middle and Late Bronze Age
SZUNV5	110-120 cm	UGAMS 5372	seed	760 ± 40	-27.4	1187-1295 AD	turn of the Early and High Middle Ages
SZUNV5	200-210 cm	UGAMS 5373	seed	910 ± 30	-25.6	1034-1207 AD	the last phase of Early Middle Ages
SZUNV5	290-300 cm	UGAMS 5374	seed	2180±30	-25.0	366-166 BC	subatlantic, Late Iron Age (middle La Tène)
SZUNV5	370-380 cm	UGAMS 5375	seed	6150±30	-24.2	5211-5008 BC	Early Neolithic (Linearbandkeramik Culture)

Tab. 2. Radiocarbon data; OxCal v4.1.5 Bronk Ramsey (2009), r: 5 Online: https://c14.arch.ox.ac.uk/oxcal/OxCal.html.

5. Results

5.1 Sedimentological, geochemical and petrophysical characteristics (borehole SZUNV5)

Due to variation in the records of loss on ignition at 550°C and 950°C to (LOI_550 and LOI_950), magnetic susceptibility (MS), active soil reaction (pH) and phosphates (P_2O_5) and especially granularity, color and studied section was divided into six lithological segments (Fig. 3).

The base consists of the entire profile of gravel-sand sediment (390 cm) consisting of angular fragments of granite and quartz, which passes into the organic-rich sandy dust (390-350 cm). According to radiocarbon dating the lithological transition corresponds to the Neolithic period. This corresponds to the acidic soil reaction with the lowest values of magnetic susceptibility. Phosphate values are low with increasing trend and a sharp peak at 355 cm, which correlates with a high proportion of organic matter.

The second and third segment (350-275 cm) is defined arbitrarily and time falls within the Eneolithic to the Iron Age (C14 -260 ± 60). It is characterized by low values of magnetic susceptibility, a relative enrichment in dust fractions compared to older or younger sediments and oscillating values and organic phosphates with the highest values on the basis of the actual sequence which is also characterized by a sharp increase in pH. At 325 cm fragments were identified of ceramics or daubing and bone fragments of large mammals (detrminated by M. Nývltová-Fišáková), which occur both at 305 and 295 cm (Fig. 3).

In the middle part of the profile (275-235 cm, the fourth segment, which corresponds to the period of Roman and Migration) magnetic susceptibility values and phosphate values are significantly lower if compared to the sediments of the Middle Ages. It might reflect increased grain size of particles (sand size). Sedimentation rate is lower than in the Middle Ages, but higher than in the older periods.

The fifth segment (235 to 75 cm) corresponds to the Middle Ages, however, sedimentation rate is higher, as well as the proportion of the dust fraction and carbonate precipitates. Magnetic susceptibility is higher than in previous periods, but does not reach the values of modern times. In the period between the dates 14C 1105 AD and the early Middle Ages, there is a significant increase in the magnetic susceptibility and the proportion fine clastic material. Phosphate values are the highest in entire profile, whereas scarce organic material does not reach the highest values. At 185 cm fragments of ceramics and daub were identified.

The uppermost part of the profile (0-75 cm depth) corresponds to the modern era. it is characterized by up to five times higher magnetic susceptibility values than in other parts of the profile (diameter 313 m3.kg-1 × 10-9). These increased values are most probably connected with anthropogenic pollution and atmospheric fallout of magnetic particles produced by industry - fossil fuel burning, metallurgical processes etc. (Evans & Heller, 2003; Petrovsky et al. 2000; Schmidt et al. 2005). At the same time, there is decreased sedimentation rate and proportion of carbonate precipitates.

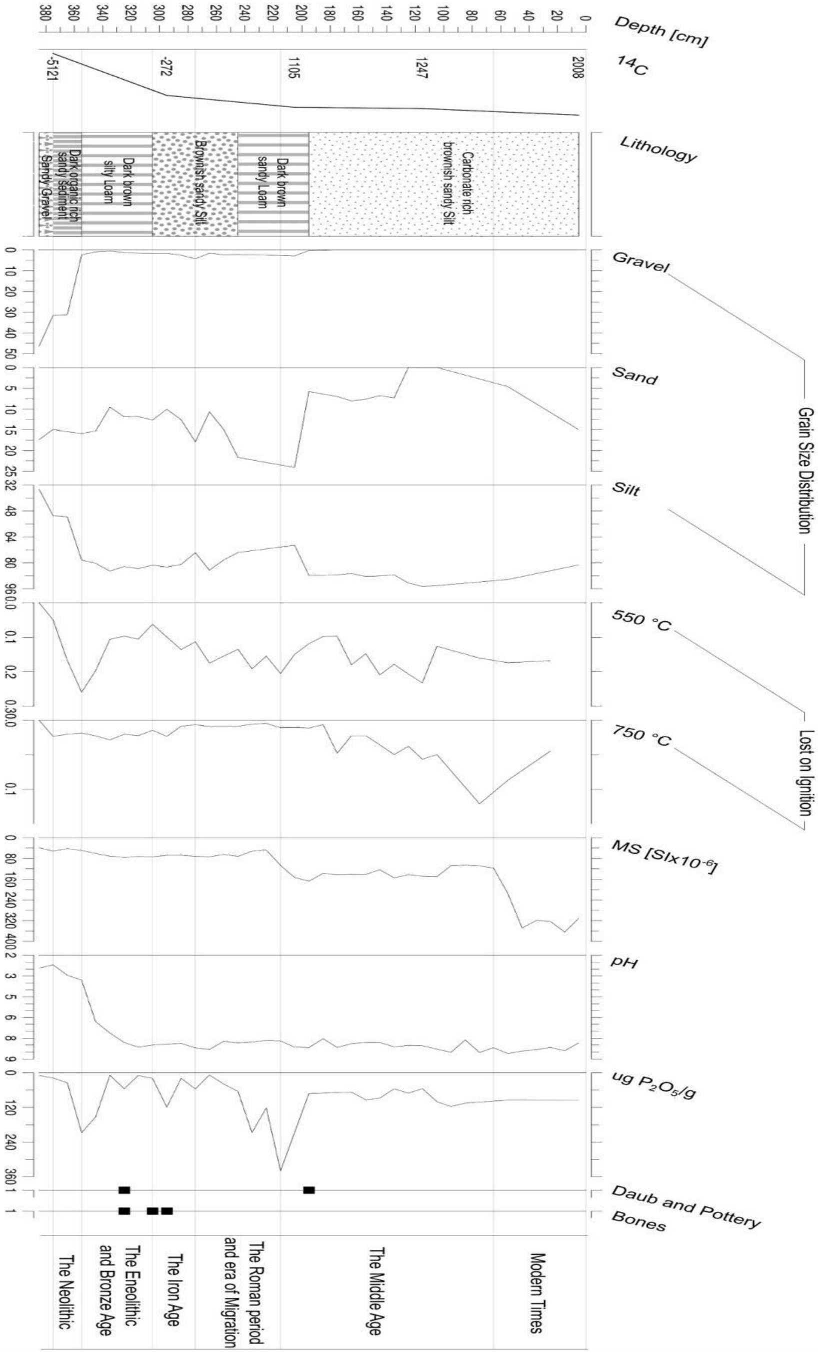

Fig. 3) Distribution of absolute data, lithology, representation grain fractions on results of loss on ignition, magnetic susceptibility, pH, phosphates, findings of artifacts and bones in the boreále SZUNV5

5.2 Macroremain analysis (borehole SZUNV5)

The results are shown in Figure 4. In total, 29 samples were analysed. Of these, 2 samples contained no macroremains (from the depth of 250 and 260 cm) and 3 samples included only fragments of seeds of *Sambucus* sp. (from the depth of 300, 310 and 320 cm). Mainly in samples from 300 to 380 cm, there is a higher volume of charcoal.

At a depth of 380 cm, *Drepanocladus aduncus* was found. This moss grows in wetlands, on damp soils, rocks and even wood. At a depth of 370 cm, a fragment of the moss *Eurynchium* sp. was identified. In Czech Republic, there are only two species of *Eurynchium angustirete* and *E. striatum*. Both mosses have similar ecology and habitat: they grow on humic soils in semi-shaded or shaded places (Kučera 2004-2009).

At lower layers up to 260 cm, species of trees (for example *Tilia* or *Carpinus*) and shrubs (*Corylus* , *Cornus* sp.) occur. At a depth of 380-390 cm, a bud of Salix sp. was found and at a depth of 360-370 cm, a bud of cf. *Alnus glutinosa* was retrieved. Species of herbs include predominantly species of forests and forest edges (*Moehringia trinervia, Stellaria holostea*), of wetlands and river banks (*Lycopus europaeus, Urtica dioica*) and probably aquatic plants (*Ranunculus* sp. Sect. *Batrachium*).

From a depth of 240 cm, the amount of macroremains of *Carex* sp. increases. In lower layers they occurred rarely. Except wetland species (*Carex* sp., *Caltha palustris*), there is also a growing number of ruderal species (*Chenopodiaceae*). Trees and shrubs are disappearing. From a depth of 150 cm, a few fragments of acorn of *Quercus* sp. and undetermined buds appear.

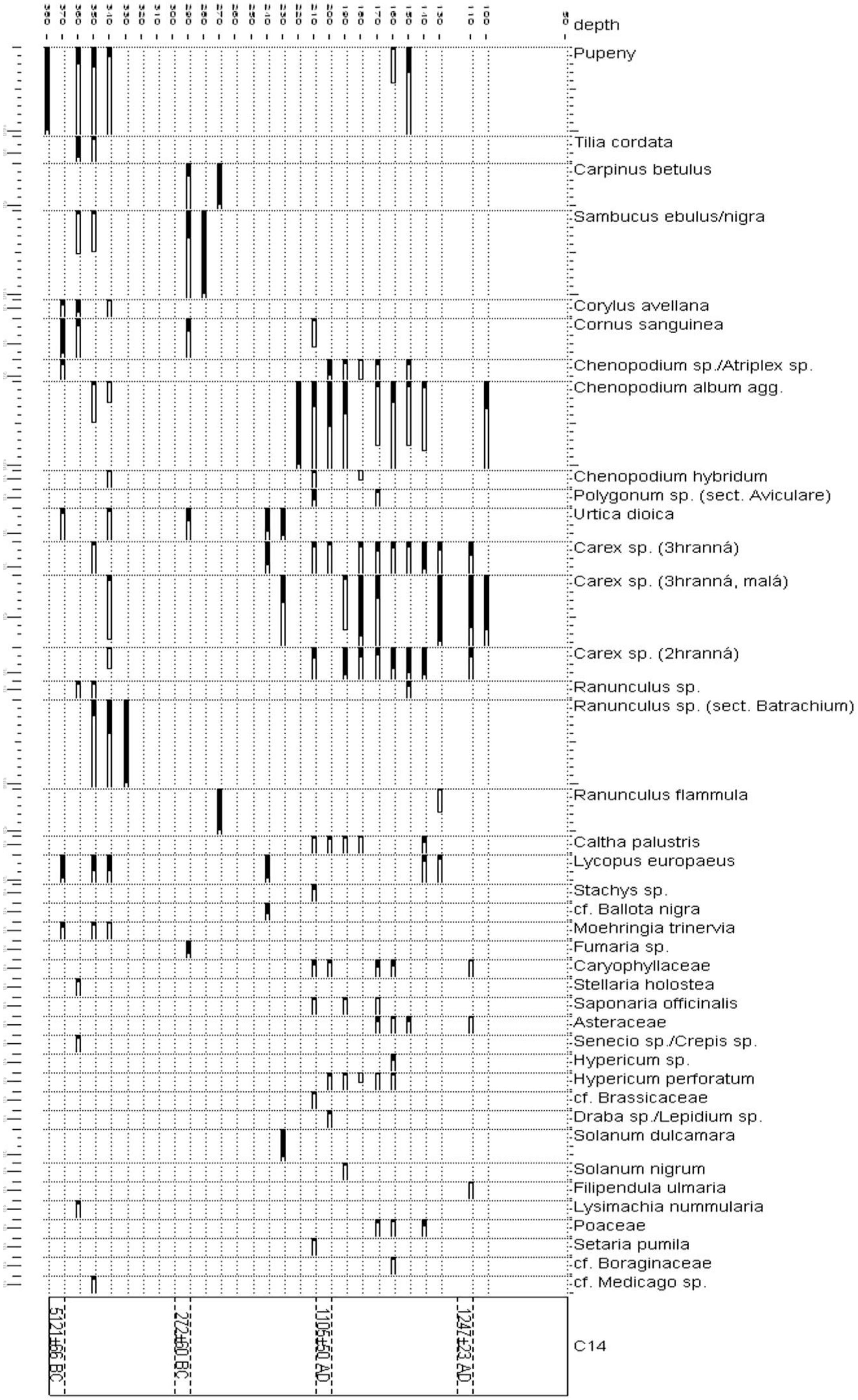

Fig. 4) Distribution plant macroremains in borehole SZUNV5

5.3 Malacofauna (borehole SZUNV5)

Relatively, most items were found at depths of 50, 240, 270 and 280 cm. The material consists partly of undeterminable fragments. The identified species of gastropods were mostly residents of warm moist habitats, bivalves (depths 280 and 240 cm) lived directly in a water environment, which is consistent with the location of the borehole. With respect to the quantity of material, the malacological record did not lead to a significant change in the palaeoecological interpretations.

0cm: 1 pc *Vallonia pulchella*
50 cm: 2 pcs *Vallonia pulchellla* , 9 pcs gastropods *Succinea oblonga*
210 cm: 1 pc indeterminable fragment mollusc, 1 pc *Vallonia cf. pulchella*
240 cm: 2 pcs *Succinea oblonga*, 1 pc *Carychium tridentatum*, 1 pc *Pisidium* sp, 6 indeterminate fragments of different molluscs
250 cm: 1 pc *Vertigo angustior*
260 cm: 1 pc indeterminable fragment mollusc
270 cm: 1 pc *Carychium tridentatum*, 1 pc *Discus* cf. *Perspectivus*, 4 pcs indeterminable fragments of gastropod shells
280 cm: 2 pcs *Pisidium* cf. *casertanum* , 3 pcs indeterminate fragments of molluscs
290 cm: 1 pc indeterminate fragment (family Clausiliidae?)
300 cm: 1 pc indeterminable fragment mollusc

5.4 Pollen analysis (Borehole SZUNV5)

The ratio of tree pollen (AP) and herbs (NAP) in the pollen spectrum is in layers 360 and 350 cm about 85% (Fig. 5). In other samples (340, 330 and 320 cm) the ratio decrease to 55%. In the spectrum of wood (360 and 350 cm) *Corylus* dominates (30%), which later subsides. Similarly, the frequency of *Tilia* and *Betula* decreases*. Pinus* and *Picea* have a constant share of around 10%, less well represented are *Quercus*, *Ulmus*, *Fraxinus*, *Alnus*, *Fagus* and *Abies*. The pollen spectrum is dominated by grasses and sedge. There are smaller amounts of Caryophyllaceae and Chenopodiaceae, cereal pollen occurred from 350 cm. The share of micro-carbon particles caught in the pollen spectrum rose.

Concentration of pollen grains in the preparations was very low, maintaining quality was still good. In layers from 310 cm and above only rare pollen grains (mainly pine) were recorded, which made it impossible to obtain a representative amount of pollen grains.

5.5 Borehole T4/07

Throughout pollen diagram superiority of herbaceous vegetation over trees was observed. *Pinus* had a strong share of the woods around 10% and a maximum in the upper layer 115 - 126 cm (Fig. 5). *Corylus* has the opposite tendency, with its share falling from 15% to less than 5% in the upper layers. There is a similar trend with *Carpinus* and *Tilia*. Floodplain forest tree species have a share of around 10%. Further loss of tree species was recorded from a depth of 210 cm. Some of these trees from the pollen spectra almost disappeared - especially *Quercus, Tilia, Fraxinu, Picea*, *Ulmus*. The representation *Corylus* of declined. A higher proportion than in the subsoil were found only species of floodplain forests, mainly *Alnus* and *Salix*. Sporadic occurrence of pollen of *Picea*, *Abies* and *Fagus* is limited to the lower half of the profile. Conversely, pollen of *Sambucus nigra* is present in the upper part. The herbal part of the spectrum is dominated by grass pollen and Chenopodiaceae. Less represented other pollen taxa, ie cereals, or *Polygonum aviculare* , *Rumex acetosella*-type, *Plantago lanceolata* and *Humulus* / *Cannabis*, and more. There were also vegetation of water bodies and wetlands: Cyperaceae, *Myriophyllum spicatum*, *Typha*, *Filipendula*.

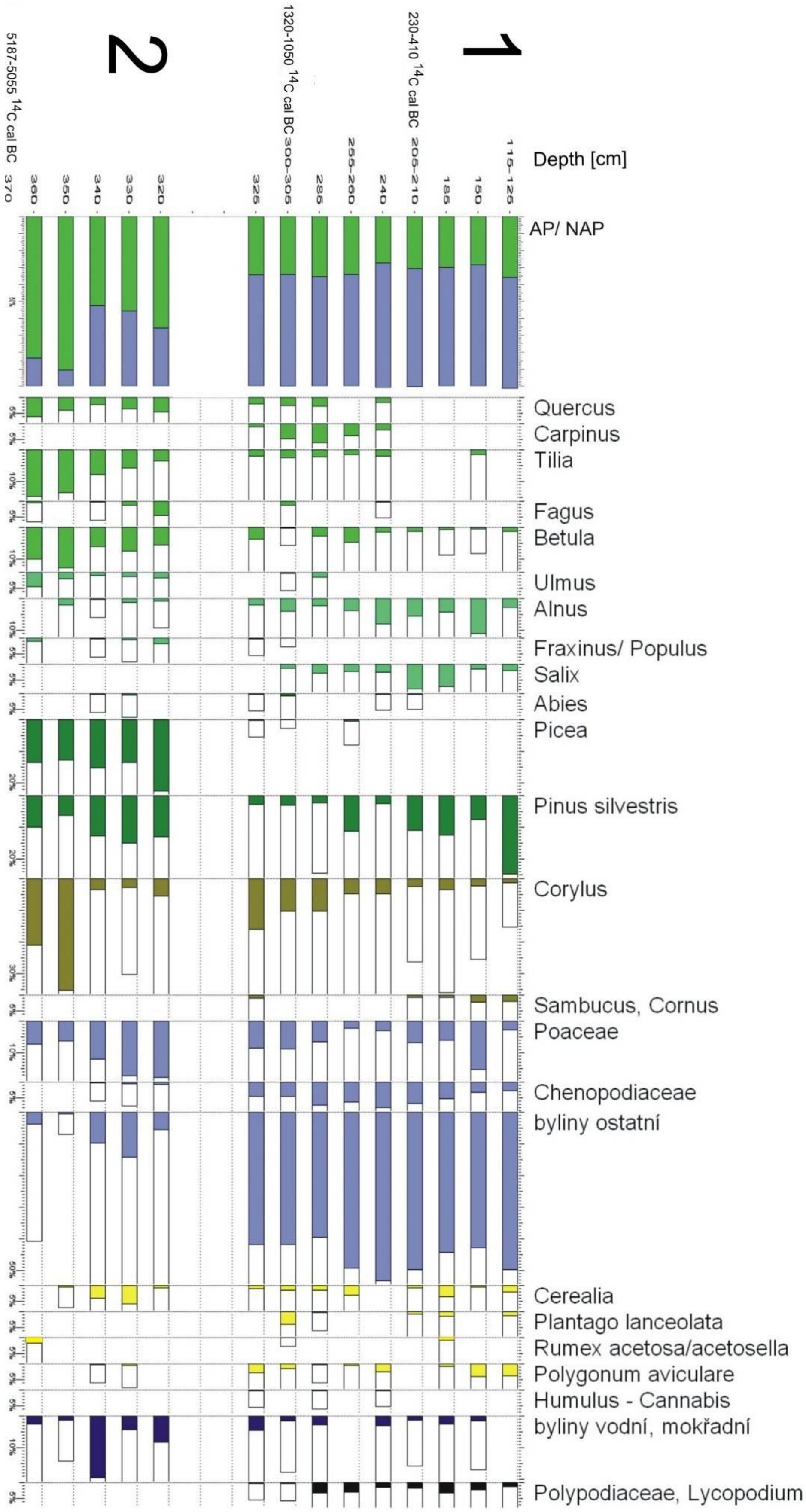

Fig. 5) Distribution of pollen grains in boreholes SZUNV5 and T4/2006

6. Discussion

The oldest sediments captured from the SZUNV5 borehole in the floodplain of the earlier to mid-Holocene (the period prior to the beginning of agricultural prehistory) has a stony character without the accumulation flood loams and flushes. Development could be analogous to the floodplain of the Morava river in its lower reaches (Kadlec et al. 2009; Grygar et al. 2010), where the Morava floodplain was covered with gravel, possibly causing sedimentation and peat formation. The start of the alluvial clays is in the floodplain of the Morava near Strážnice by around 8000 BP, which is comparable with the base floodplain sediments in the SZUNV5 borehole. A *Corylus* husk dated from the organic horizon (lithological segment 1) following the rocky base provided a radiocarbon date corresponding to the early Neolithic (Tab. 2). These sediments are relatively acidic when compared with the subsequent period (lithological segment 2), which is likely be caused by a greater contribution of alkaline material. The macroremains record does not show a developed alluvial vegetation in the first segment, but rather reflects forest communities (Fig. 4). The surrounding vegetation was composed of mixed oak forests (Quercetum mixtum), and rock outcrops probably covered pine (Fig. 5). The significantly deep valley has a great impact on the diversity of vegetation, where on a relatively small area, we can assume the existence of many societies. These are called valley phenomenon. The influence of human and agricultural activity is not evident in the pollen record, which may seem surprising given the proximity of Neolithic settlements within 1 km downstream and upstream of the river, but it is a phenomenon (Dreslerová 2012, 206). The increase in dust fractions and the amount of organic material in the first segment is interesting. Possible explanations include a change in the facial area of the riverbed, natural sedimentation, regime change from the old to the middle Holocene, when there is a full development of forest vegetation and forest soil pedogenesis. For example, trees fall into and across rivers in forested floodplains; there is also a high input of organic material of all sizes from trunks to the microscopic. Even in small floodplains (with small trees), organic debris forms small dams (Brown 2001, 112). On the other hand, this organic-rich layer was detected across most of the floodplain in the bore-hole transect (Recent geophysical and drilling results are not included in this paper). It could be analogical to organic rich silt-clay loam layers detected across alluvial sediments from the Wetterau by A. Lang and S. Nolte (1999, 209).

Sedimentation is relatively slow during the period before the onset of the Iron Age (Fig. 3, lithological segment 1 and 2). During this period, the vegetation changes. There is the pollen record: declining hazel, and wood vegetation is made up of oak, spruce or pine. Ruderal species appear (*Artemisia* and *Chenopodium*). The increase in human activity in the Eneolithic and Bronze Age (lithological segment 2) is indicated by the pollen grain and micro-carbon particules; the increase in human activities affecting the vegetation is noticeable. Between the Eneolothic and the Bronze Age there were no significant differences: cultural changes in paleoecological record of this are not visible, which corresponds to the dynamics in archaeological record.

The only prior archeobotanical research relating to prehistory in the microregion was conducted at the Sutny site by E. Opravil (1961). When this research primarily studied anthracologically rich material (total of 966 fractions). The largest part of the material comes from Halstatt objects, only a few of the objects are from the Bronze Age and Neolithic. The species composition of charcoal from the Tesetice Hallstatt according to Opravil (1961) characterized by numerous representations heliophilous species, mainly shrubs, growing commonly in open areas, forest edges or forming undergrowth in light forests. The author divided the species into three ecological groups:

a) species significantly thermophilic with pannon elements
b) heliophile xerophilous trees from forest edges and bushy hillsides
c) trees shade-loving and hydrophilic, occurring largely only in continuous closed forest complexes.

The found trees decided that here was the most widespread communities Quercion pubescentis Association, which is the main form of forest vegetation in the present. An interesting finding is ash from *Acer tataricum*, which now appears in Central Slovakia. Macroremains from this period were not recorded in the boreholes. Palynologically this period is characterised by the expansion of the genus *Abies* even to lower altitudes, which until that time had been dominated by mixed stands of oak (Rybníček - Rybníčková 2001). Fir-beech and beech-fir forests with a substantial share of spruce began to form (Rybníček - Rybníčková 2001). In the lowland areas, beech and fir did not reach such an extension as in the higher elevations (Jeník 1970; Jankovská 1997), which was not such an intensive influence on mankind and agriculture. Nevertheless, these kinds are sporadically detected in basin (eg. Location Vracov, Svobodová 1990; Macháček et al. 2007) and also in the charcoal spectra from archaeological situations (findings by P. Kočár). At the same time we can observe a decreasing curve of *Ulmus, Quercus, Tilia, Fraxinus* and *Corylus*. It could indeed affect the occurrence of other species. The decline in elm pollen curves or hornbeam is sometimes regarded as a phenomenon caused by anthropic feeding of the leafy branches of this tree to cattle (Jeník 1970; Jankovská 1997). At the same time it must be noted that, based on archaeological evidence the Bronze Age and Hallstatt period are most represented in the microregion. Given that archaeologically exposed is only small part of the total land area of the basin, so it is not possible to mechanically interpolate the development of the systematic excavated settlement of Těšetice-Kyjovice "Sutny" on the whole microregion.

The Subatlantic period (from 800 / 500 years BC to the 6th to 13th century AD) we have paleoecological record only from the borehole T4/07 (there is no palynological and macroresidual record in SZUNV5 sediments from this period). The sample from a depth of 2.05 to 2.10 m was dated 230-410 AD (end of the Roman period and the beginning of the Migration period).

Jankovska (1997) assumes that the wet climate during this period supports the massive development of the growing band of *Fagus-Abies*, which penetrated deep into the lower positions. In our pollen diagram by increased humidity could demonstrate extension of floodplain forests. The influence of humans may be related to the retreat of forest trees such as *Abies, Carpinus, Fagus, Picea, Quercus, Ulmus.* Into deforested areas and light woodlands again the light-loving plants spread, such as *Pinus*, *Betula* and various shrubs, such as *Sambucus*-type. Increased percentage of families Chenopodiaceae, Asteraceae and the *Sambucus* indicates increased nitrification of the substrate as a result of human activity. In borehole SZUNV5, the paleoecological evidence from this period are missing and the extent of sedimentary record (if any proceeded) is restricted probably just the older part of the lithological segmet 3 (but not documented by radiocarbon-dating).

Middle ages changes are reflected in the SZUNV5 borehole (part of segment 3 and whole of the fourth segment) not only qualitatively but also quantitatively. At the turn of the Early to High Middle Ages (radiocarbon date of 1187-1295 AD) indicators suggest a high degree of anthropogenic impact. First of all, the deposition rate is manyfold higher than in the previous period. The height of the deposition rate in this period is a clear indication of rapid landuse change. Temporal analogous deposition rate growth was recorded for example in central Belgium (e.g. Rommens et al. 2006). Macroremains analysis demonstrated the presence of humid plains by moving to Ruderals (for example, a high proportion of *Chenopodium album*). The increase in the magnetic susceptibility may be related to the high proportion of fine fractions as beneficial material corresponding to the Upper soil levels. The main medieval change is supported by radiocarbon dating (Fig. 3) and sedimentological: there is a growth in the number carbonates, which is probably related to the loess soil erosion during the High Middle Ages and modern times. Organic matter content is lower than what corresponds with the observation of Rommens et al. (2006) for this period. Magnetic susceptibility values are higher, which is in accordance with the observation of many authors dealing with anthropogenic pollution for this period (Hanesch - Scholger 2002; Heller - Evans 2003; Qin - Wang 2005). Other values, other than the growth of rough grain fractions did not show any greater deviations. This may indicate the contribution of exogenous material (eg originating from erosion on fields). Another option is weathering eluvia of forest soils during soil erosion caused by the clearing of the forest. From written sources, it turns out that the forest was economically used as a source of wood in the Middle Ages.

Alluvial environments in the High Middle Ages reflected the development of eutrophic demanding vegetation (eg *Urtica*) recorded in macroremains from the profile of SZUNV5. The return of macroremains of Oak at a depth of 150 cm is interesting. And it appears to be related to the existence of medieval and modern economic forest. For the High Middle Ages and modern times it is necessary to take into account the artificial water flow regulation relating to the creation of ponds and further modifications of the artificial watercourse.

7. Conclusion

In the sediments of the valley floodplain of the Unanovka stream a significant part of the Holocene has been captured (5211-5008 BC to present). The sedimentary record is incomplete because of the facies characteristics of an alluvial environment, but it is still an important source of palaeological information on the development of the basin. The exponential increase in sediment accumulation reflects well the growing human impact and changes in sand and dust grain size fraction is probably related to changes in landuse (forest logging, plowing). This human impact is also mirrored in the increased magnetic susceptibility values due to the increasing anthropogenic pollution of topsoil.

In the Neolithic, forest environments with shrubs were captured, cereals appeared at the end of the Neolithic or in Eneolithic. The slow transition from gravel to organic-rich dust sediment - transition of dust fractions can be evidence of the oldest agricultural activity. Possible explanations include a change in the facies area of the riverbed, natural sedimentation, regime change from the old to the middle Holocene, when there is a full development of forest vegetation and forest soil pedogenesis. In early Eneolithic, there was an increase in cereal and signs of deforestation. In subsequent periods until the Iron Age we see gradual changes. In the Bronze Age expansion corresponds with nitrophilous vegetation in the macroremains record.

From the Roman period until the Migration period in the microregion the archaeological evidence of human habitation disappears. In the palaeoenvironmental proxy data we do not note any significant changes. The increase in pine (a pioneer tree species) may indicate overgrowing of abandoned land, or rather the exploitation and degradation of the forest. Due to the length of transport of pine palynomorphs we can not say how wide the area of this development is responsible. Based on other indicators, change is hard to perceive. In the early Middle Ages, there was a place below the site of "Starý Zamek" of moist floodplain with a transition to Ruderals. Dating is based on a radiocarbon dating corresponding to the late Hillfort period. Trees and shrubs disappear and a high phosphate concentration (which does not correlate to the maximum organic matter) indicates intense human activity. Sedimentological record indicates high erosion. Everything indicates a high degree of anthropogenic activity in this period, which corresponds with new archaeological data (evidence of settlement activities).

The High Middle Ages and the modern period is characterized by a high degree of erosion of upper soil levels and loess soil. This is probably connected with the tillage in the basin, or economic use of the forest.

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Conclusion

I studied vegetation and environmental changes in the Lateglacial period and early Holocene using palynology in concert with other sedimentary analyses. Localities in regions that have traditionally been neglected by palynological research were selected for the study. The objectives of my work were to (a) obtain palynological records from regions that have been largely forgotten by researchers in my field; (b) compare regional variability of the environment; and (c) take advantage of combining palynology and sedimentary analyses, an approach that is still undervalued in the Czech Republic.

I focused on contrasting localities representing the diversity of the Czech and Slovak Republics. The work is partly a revision of historical studies from the Elbe region (Hrabanovská černava, Losert 1940) and the Danube region (Šúr, Kinzler 1936), but other, previously unknown paleobotanical localities were also included (Late-Glacial meanders of the Elbe near the village of Chrást or the locality Černé jezero Lake – Moraine in the Šumava Mts).

In my studies, I attempted to exploit the methodical potential of geochemical analyses. By applying these methods and combining them with analyses of the paleobotanical record, it is possible to reconstruct changes of the local environment and also of the wider area. In conjunction with magnetic susceptibility and loss on ignition (LOI), it is possible to examine the extent of erosion, which is an important measure for estimating the degree of canopy compactness. Another useful tool for interpreting lithologically complex situations is micromorphology. It makes it possible to study postdeposition changes in detail and thus obtain a new type of information. The advantages of exploiting the possibilities of these methods in connection with palynology have not yet been fully recognized in the Czech Republic.

The locality Chrást (Petr et al. In press) in central Bohemia is the only pollen profile which documents the conditions in the Lateglacial floodplain of a large river in the Czech Republic. The paleoecological potential of the floodplain environment has not yet been entirely appreciated, probably because it requires a slightly different approach than a lithologically simple peatbog. This is also the reason why appropriate attention has still not been paid to the glacial floodplain of the Elbe. Nothing had been known about its vegetation, for example. Geomorphological changes of the river course are explained in the paper by their correlation with global changes. The lithology of the profile also documents highly complex sedimentary and taphonomical conditions of the floodplain environment at the turn of the Glacial and Holocene periods. Here it is possible to demonstrate the utility of sedimentary analyses without which the interpretation of the lithology and postdepositional processes would not have been possible. An absence of pollen does not translate into an absence of paleoecological information.

A comparison of results from the localities Chrást (Petr et al. in press) and Hrabanovská černava (Petr 2005) shows fundamental habitat contrasts of the Elbe region in the Lateglacial period. A forest grew in the surroundings of the floodplain, but the nearby lowland was covered by a continental steppe with a dominance of *Artemisia* and *Helianemum*. This indicates a spatial distribution of habitats and the possibilities for populations of species to spread and survive in the Lateglacial.

Montane glaciation created a different type of environment at the end of the Glacial period. A study of the locality Černé jezero Lake – moraine (Vočadlová et al. submited) documents in detail the process of deglaciation of the Šumava Mts. It indicates that montane glaciation was very limited in its area and that it sensitively reacted to climatic oscillations. An interpretation of the log indicates that a frost barren was maintained even after the retreat of the glacier, where intensive cryogenic weathering and erosion did not permit the existence of a core continuous vegetation cover. Eolean erosion was also significant, as documented by the sedimentary record in the profile Černé jezero Lake – moraine, where a dust fraction is lodged in the sediment.

The Černé jezero Lake – moraine profile also shows that the Šumava Mts got completely forested as late as around 8,200 BP, when the treeline reached the highest elevations. The evidence is not only paleobotanical but also geochemical. At this time, influx of inorganic material into the water body due to water and wind erosion ceased. It has repeatedly been documented that broadleaved woody species (*Ulmus*, *Tilia*, *Quercus* and *Corylus*) occurred at higher elevations then than today. Their share in the pollen spectrum is markedly higher than in subrecent samples. It is, however, necessary to consider the large altitudinal gradients in the surroundings of the Černé jezero Lake. Beech in the Šumava Mts spread early (around 7,200 BP) compared to the Czech Basin itself, and the profile thus holds evidence of one of European Holocene migration routes (Margi et al 2006).

The locality Šúr (Petr et al. submited) provides the only dated palynological record from Western Pannonia. Previous knowledge and notions about the vegetation of western Slovakia are based mainly on historical studies of E. Krippel (1986). The locality holds evidence of a large vanished lake, a marked increase of its trophic level in the Holocene and formation of a subhalophilous environment. Our results indicate a similarity of the locality to Tisza River Region and, conversely, differences from localities west and north of the Carpathian Arch.

Our results from the Bohemian lowland and the Danube region create a different impression of rapid closing of the forest canopy and existence of dark forests (with a strongly closed canopy) in the early Holocene. Discussions have hitherto revolved around the existence of primary non-forested land and a dark forest. This is trivial in light of published findings because such a contrast almost did not occur. Further considerations will require focusing on resolving the details of the relationship between non-forested land and sparse woodlands, which facilitated the survival of many light-loving species. The common style of thinking in terms of environmental gradients and vegetation continuums is usually a mere substitute for the former thinking in terms of discontinuities. That there is a gradual transition between forests and non-forested land has been known for a long time. This fact got, however, obscured by emphasis on the two opposing extremes, that is, non-forested land and a dense forest.

In the profile Chrást (Petr et al. in press), I avoided an interpretation involving a hypothesis concerning the fashionable topic of northern glacial refugia of woody plants. The presence of solitary pollen grains of mesophilous woody species in the Lateglacial does not mean much in itself. The Glacial period was windy, which facilitated long-distance pollen transport. Diffuse vegetation of the Glacial period had lower pollen production, so solitary pollen grains from other regions are prominent in the pollen spectrum. Until we have evidence suggesting otherwise (e.g., macroremains), long-distance transport and redeposition offer a much more probable explanation than a hypothetical reconstruction of glacial refugia in climatically unfavourable regions. The pollen taphonomy is also closely related to the occurrence of pollen of exotic woody plants that are long extinct in central Europe. A high degree of erosion in the Glacial period caused redeposition of pollen from the Older Pleistocene or Tertiary, which is recorded in the sedimentary log.

Results from the locality Šúr (Petr et al. submited) lead to scepticism towards the notion of so-called initial forest charring (Peške 1987), which is often presumed to be practised by the first settlers. That is to say, Neolithic settlers found the landscape in the Danube region to be covered by a forest so open and diffuse that they did not have to char it. The palynological record does not contain evidence of an impact of prehistoric farmers or any earlier Mesolithic colonization. At the locality Santovka (Petr et al. 2012), linear pottery was discovered directly in the sediment, but the pollen record nevertheless does not change at all from the beginning of the Holocene to the Eneolithic. The population density was definitely higher than in previous Mesolithic colonizations but still relatively low compared to subsequent periods. Only at the turn of the Younger Neolithic and Eneolithic, gradual vegetation changes and, most importantly, the onset of erosion took place. Pollen of cereal crops first appeared in pollen profiles from the western Danube region as late as the turn of the Eneolithic and the Bronze Age.

Another conclusion drawn from the profile Šúr (Petr et al. submited) concerns a comparison of the pollen log with conditions in NW Europe. In the Pannonian Lowland, the proportion of *Artemisia* and Chenopodiaceae pollen remains practically unchanged in the Lateglacial and Holocene. This is a difference between the Czech Basin and NW Europe, where it consistently reflects the beginning of the Holocene and later increases under human influence. Areas affected by the most recent glaciation differ in their natural conditions from the Danube region, of course. This is why interpretations of pollen spectra and so-called secondary anthropogenic indicators from NW Europe (Behre 1986) cannot be applied in the Danube region. *Artemisia* is a natural component of these large-scale vegetation types. Also important is the relatively low proportion of pollen of grasses, which is the same or even lower than that of *Artemisia* pollen. This also supports the open character of the vegetation. Analogous is the situation concerning the AP/NAP ratio, which remains unchanged during the turn of the Glacial and Holocene periods. The composition of woody vegetation changes fundamentally, however. Automatic application of the same rules when interpreting pollen spectra across the entire continent (Behre 1981, 1986) is therefore problematic; natural and vegetation conditions vary.

A detailed analysis of the profile Černé jezero Lake – moraine (Očadlová et al. submited) indicates shading of the locality and a decline in local diversity with the appearance of fir and local expansion of spruce and beech. This points to a general trend of closing of the forest in the second half of the Holocene. Another factor determining environmental change besides the spruce and beech expansion itself is pedogenesis, which is also partly related to the expansion.

The analyses of the flood sediment of Těšetička River (Petřík et al. submited) shows gradual human impact on alluvial environment during Holocene. The erosion and accumulation of wash deposits began in Eneolitic period and maximum has in modern time.

Evidence of environmental changes at the end of the Glacial and beginning of the Holocene in Czechia and Slovakia is still only fragmentary. Accurate dating is paramount for mutually correlating localities and intercepting regional variability. The main shortcoming of paleoecological research in the Czech Republic is the absence of a detailed paleoclimatic record from the Lateglacial and Holocene, be it from biological proxy data or the isotope record.

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Curriculum Vitae

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Grant projects

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