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Middle Age paleoecological and paleoclimatological reconstruction in the Carpathian Basin

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Abstract—Three programs of medieval environmental history research of fourteen sites was undertaken between 1998 and 2008 as part of the "*Evolution of the Hungarian mires, peats and marshes*", "*Environment history of Hungary*", and "*Geoarcheological investigations of Hungary*" projects. This present study was to demonstrate the facilities of paleoecological and paleoclimatological investigations (pollen, macrofossil, sediment works) completed on the core sequence of the Nádas Lake at Nagybárkány (Hungary). The Nádas Lake at Nagybárkány is a small peat-bog in the eastern Cserhát Mountains. The formation of the lake can be traced back to the late Glacial. The sediments deposited in the lakebed provide a record of climatic and hydrologic changes. A higher water level could be demonstrated from the late Glacial to the mid-Holocene, when the reed-beds covered a small area only. This was followed by a hiatus spanning about 5000 years, caused by the deepening of the lakebed during the Imperial Age, around 20–50 AD. The water level decreased and the water quality was more eutrophic. A reed-bed evolved around the lake. Paludification started with a bulrush floating mat phase at the close of the Middle Age, ca. 1300 AD. The initiation of the *Sphagnum*-bog underwent similar phases as in the other Hungarian peat-bogs. Although some anthropogenic disturbances can be reconstructed in the development of the peatland, some climatic effects and authogenic processes might be separated by paleoecological analyses.

Key-words: peatland development, macrofossils, pollen, geochemistry, paleoclimate, Holocene

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1. Introduction

The application of macrofossil analysis to peat and lacustrine deposits enables to identify long-term vegetation changes in aquatic ecosystems. The composition of aquatic plant communities is largely influenced by the hydrological conditions prevailing in the basin harboring them. These, on the other hand, are highly prone to centennial-scale fluctuations in the climate. Former studies aimed at deciphering past climatic conditions via detailed analysis of peatland deposits primarily focused on the investigation of *Sphagnum*-peats of so-called ombrotrophic peatlands (*Barber et al.*, 2000; *Barber* and *Langdon*, 2001; *Barber* and *Charman*, 2005; *Mauquoy* and *Barber*, 1999). Due to various methodological problems, high-resolution quantitative macrofossil studies on the eutrophic peatlands of continental Europe were generally lacking so far. A slight modification of the method proposed by *Barber et al*. (1994) enabled us to retrieve proxy-climate data from the eutrophic peatlands of continental areas as well (*Jakab et al*., 2004).

The total number of *Sphagnum* occurrences hardly exceeds 50, and in the central driest areas of the Great Hungarian Plain they are completely absent. Only sporadic *Sphagnum*-bogs are known in the country with a total number well below 20, most of them being extremely small with an area of a mere couple ha. Real raised bogs are completely missing. The majority of *Sphagnum*-bogs is restricted to the western parts of the country enjoying oceanic climatic influences, and to those of the areas of the Northern Mountains and the northern part of the Great Hungarian Plain, enjoying montane-type climatic influences of the Carpathians (*Boros*, 1968; *Szurdoki* and *Nagy*, 2002).

The present paper is discussing the findings regarding the development of small eutropic peat-bog from northern Hungary. Autogenic succession processes, climatic conditions, and anthropogenic influences largely contributed to creating the modern view of the referred peatland. Other aim was to put the reconstructed anthropogenic impacts and their changes to the context of the settlement strategies and landscape usages in the central parts of the Carpathian Basin.

Besides the radiocarbon-dated (Table 1) results (Tables 2–5) presenting some similarities and differences between local strategies in adopting and using marginal landscapes, this project will contribute to future research in Hungary on similar topics. In order to shed light onto the interrelations of vegetation changes and climate change, the model of *Davis et al*. (2001, 2003) was adopted in our work (Table 6). In our model the plants inferred from the palynological and plant macrofossil records were assigned to groups of plant functional types (*Prentice et al.*, 1998; *Peyron et al.*, 1998).

2. Study site

The Nádas Lake (360 m a.s.l.) at Nagybárkány lies on the northern side of Mt. Hármas-Határhegy, rising to a height of 516 m in the eastern Cserhát Mountains (*Fig. 1*). There are two other lakebeds in its vicinity, but these are smaller than the Nádas Lake. The lakebed has an elongated, north-west oriented form, with a strongly narrowing extension in the south. Its length is roughly 100 m, its greatest width is 40 m, and it covers an area of roughly 2000 m^2. The narrowing section is about 5 –10 m wide. Accumulation in the catchment basin of the lake started in the late Glacial, when a mass movement (exactly rotation landslide) process was formed on the slope of the Miocene sandy and silty sediment covered land surface. A slump hollow formed in the source area between the landslide toe, and the scarp which was filled up by water forming a small round-form lake. This mass movement process is characteristic in the analyzed region. The annual rainfall is between 600 –700 mm. The origin of the peat-bog's water is ombrotrophic and topogenic. There is not any visible watercourse in the drainage area.

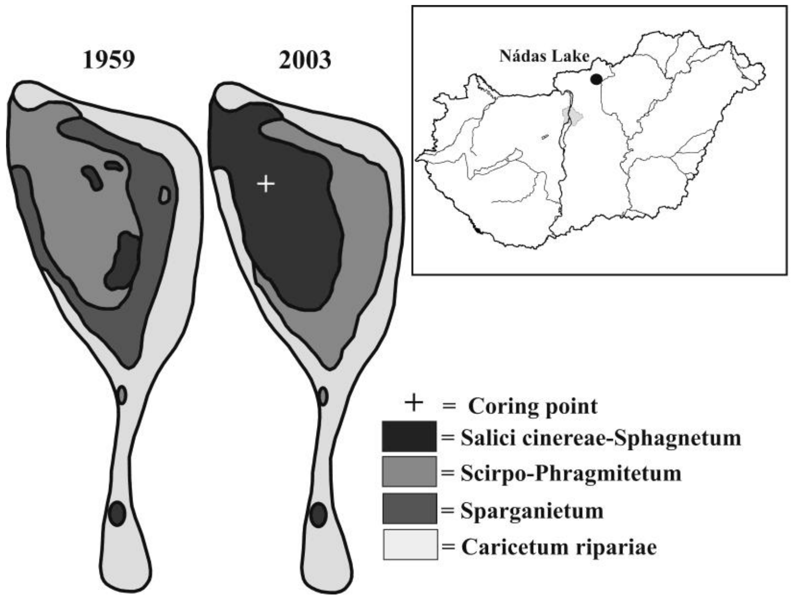

Fig. 1. Site location of the Nádas Lake and core location on the vegetation map in 1959 (after *Máthé* and *Kovács* (1959)) and in 2003 *Jakab-Sümegi* (2005).

The lakebed is fringed by a sessile oak forest. Three plant communities can be distinguished in the recent bog (*Fig. 1*). The central part of the bog is covered with Sphagnum willow swamp (*Salici cinereae-Sphagnetum recurvi*). This community is rather poor in species; it is characterized by a dominance of *Salix cinerea* and a carpet of *Sphagnum squarrosum*. This association is rather rare in Hungary, occurring in the well watered, undrained valleys of the Great Hungarian Plain and the Northern Mountains, as well as in smaller local hollows. The willow swamp is fringed by reed-beds (*Scirpo-Phragmitetum*), except on the western side. The reed-beds are similarly poor in species; the presence of *Lythrum salicaria*, *Lycopus europaeus*, and *Utricularia vulgaris* can be noted. Tall sedge communities (*Caricetum ripariae*) line the reed-beds. These communities are dominated by *Carex riparia*.

3. Methods

Overlapping cores were extracted using a Russian corer conforming to the general practice in quaternary paleoenvironmental studies. The samples submitted to lithological analyses were identical with the ones used for the paleobotanical, macrobotanical, and radiocarbon analyses. Results of pollen analyses of the peat-bog sequence were presented in *Juhász*, (2005) and *Juhász et al*. (2004).

The sampling of the 340-cm-deep, undisturbed sedimentary sequences from basin of the Nádas Lake was carried out using a 5-cm-diameter Russian type corer. The main lithostratigraphic features of the sedimentary sequence were determined and analyzed. For the description of the cores, the internationally accepted system and symbols of *Troels-Smith* method developed for unconsolidated sediments were adopted (*Troels-Smith*, 1955).

Radiocarbon dating of the sequence was obtained by both bulk and AMS (accelerator mass spectrometry) analyses. Four bulk samples of sediment were analyzed for radiocarbon ages at the Nuclear Research Centre of the Hungarian Academy of Sciences, Debrecen, Hungary, and one sample of plant macrofossils was analyzed for AMS date at the radiocarbon dating facility in Poznan, Poland. In order to allow comparison with other archaeological data, the dates were calibrated using the Oxcal v.3.9 calibration program (*Bronk Ramsey*, 2001), using atmospheric data of *Stuiver et al.* (1998). The original dates are indicated as uncal BP, while the calibrated dates are indicated as cal BC, cal BP, or cal AD (*Table 1)*. Depth-age modeling and determination of the age of the samples were constructed by using radiocarbon data and sedimentation rate (*Bennett*, 1994; *Valanus*, 2008).

The core was divided into 4 cm samples. The organic content of the core samples was estimated by loss-on-ignition at 550 °C for 5 hours and the carbonate content by the further loss-on-ignition at 900 °C for 5 hours (*Dean*, 1974). The inorganic content was further analyzed using the sequential extraction method. *Mackereth* (1966) was the first to recognize the potential of geochemical investigations on the sediments of the catchment basin for the purpose of environmental reconstructions in his review of bulk chemical analyses on deposits from the Lake District. The application of bulk analysis, however, is quite problematic since it does not shed light unequivocally onto the origin of the chemical constituents (*Engström* and *Wright*, 1984). Mackereth' work was later enhanced by researchers working on the combination of chemical analyses with palynological investigations.

Table 1. Radiocarbon dates for the lake Nádas at Nagybárkány. Calibrated with Radiocarbon Calibration Program 4.4.2

Sample number	Depth (cm)	Sediment type	$\delta^{13}C$(PDB) $\pm$ 0.2 [‰]	^{14}C age (uncal BP)	cal AD/BC (2 σ)
deb-11110	NB-45	Peat	–28.02	100% ± 0.40 pM ^{14}C	1950–1960 cal AD
deb-11098	NB-100	Peat	–27.73	740 ± 60	1230–1300 cal AD
deb-11009	NB-180	Peat	–28.49	1600 ± 60	400–540 cal AD
deb-11100	NB-250	Charcoal	–27.52	6090 ± 60	4956–5146 cal BC
Beta-194559	NB-280	Charcoal	–24.90	8050 ± 40	6875–7061 cal BC

A new, so-called sequential extraction method (*Dániel*, 2004) with a long established history in the analysis of geochemical composition of lacustrine sediments was adopted in our work. From the full procedure, the step of water extraction for unseparated samples was sufficient to suit our analytical needs. As it was shown by previous works (*Dániel*, 2004), the most important paleo-hydrological and paleoecological data originate from water extraction samples. Distilled water was purified using a Millipore 5 Plus water purification system for water extraction samples. 100 ml distilled and purified water was added to 1.0 g sample and was shaken for 1 hour (*Dániel*, 2004), and then the water extract elements of Na, K, Ca, Mg, Fe were analyzed using a Perkin-Elmer AAS spectrometer. The results from the geochemical analyses are plotted against depth. Statistical procedures were used to zone the data. Principal components analyses computed on correlation matrices were preformed after logarithmic transformation of the geochemical data (*Rollinson*, 1993). The geochemical zones were identified by cluster analysis of principal components (*Dowdeswell*, 1982) using squared Euclidean distance and Ward aggregation method.

For the description of macrofossils, we used a modified version of the QLCMA technique (semi-quantitative quadrat and leaf-count macrofossil analysis technique) of *Barber et al.* (1994). Organic remains from peat and lacustrine sediments rich in organic matter can be divided into two major groups. Some remains can be identified with lower ranking taxa (specific peat components), while others cannot be identified using this approach (non-specific peat components). The most important specific peat components are seeds, fruits, sporogons, mosses, rhizomes, and epidermis (e.g., *Carex* species), leaf epidermis, other tissues and organs (hairs, tracheids, etc.), insect remains, and Ostracoda shells. The identification of herbaceous plant tissues was based on the procedure described by *Jakab* and *Sümegi* (2004). We defined the amount of peat components on the 1 cm^3 level, and the amount of seeds on the 3 cm^3 level. The samples were washed through a sieve with a 300 μm mesh size.

Concentration levels were determined by adding a known amount of indicator grains (0.5 g poppy seed, ca. 960 pieces) and by counting the poppy seeds and the remains using a stereo microscope in ten 10 mm by 10 mm quadrates in a Petri dish. Similarly to mosses, rhizomes can only be identified with a light microscope.

We removed a hundred monocotyledon remains and mounted them in water on microscopic slides for determining the percentages of individual taxa and of Monocot. undiff. The values for different moss species and UBF were determined using a similar procedure. We used the Psimpoll (*Bennett*, 1992) and Syn-Tax (*Podani*, 1993) programmes for plotting the analytical results.

4. Results

4.1. Chronology and sediment stratigraphy

Coring was carried out in the north-western part of the bog, now occupied by a willow swamp (*Fig. 1*). We found peat down to a depth of 110 cm, with an underlying water pocket (floating mat) down to 130 cm. Between 130 – 300 cm, we found peat and peat-mud with varying organic content. Between 300 – 340 cm, there was a silty lacustrine sediment layer (*Table 1*). The radiocarbon dates indicate a hiatus of roughly 4400 years (from 4970 BC to ca. 20 – 50 AD) between 248 – 240 cm, meaning that we have no data of any kind for this period. The results of the radiocarbon measurements analyses of the sequence described in this study are shown in *Table 2*.

Table 2. The lithological description of the sequence of Nádas Lake (*Jakab* and *Sümegi*, 2005)

Depth (cm)	***Troel-Smith* (1955) system**	**Description**
0 – 40	Tb4 (Sphag.)	*Sphagnum* peat
40 – 110	Dg2Th1Tb1(Sphag.)	*Sphagnum* peat mixed with limus detritus, made up mostly of *Phragmites* (40 – 80 cm) and *Typha* rhizomes (80 – 100 cm)
110 – 130	–	Water
130 – 134	Dg2Tb1Th1	Burnt, charcoal rich peat layer with *Phragmites* rhizomes
134 – 255	Ld3Sh1 Tb + (Sphag.)Th + Tl+	Dark brown eutrophic lacustrine deposits (clayey silt) with varying organic content, large amount of wood fragments at 225 cm
255 – 277	As3Ld1 Th + Gs + (min.)	Pale yellow, brownish-grey slightly laminated silty clay with yellow spots
277–295	Ld3Sh1Tb + (Sphag.)Th + Gs + (min.)	Brownish-grey and pale yellow clayey silt with yellow spots
295 – 300	As3Ld1Gs + (min.)	Transitional layer
300 – 340	As3Ag1Gs + (min.)	Greenish-grey, clayey silt with frost marks (oligotrophic lacustrine deposists)

4.2. Geochemistry

A distinctive elemental and lithological stratigraphy was identified in the studied core sequence, which can serve as a potential record of paleohydrological and paleoecological history of the catchment basin of the Nádas Lake. According to the retrieved geochemical data (*Majkut*, 2009), 6 geochemical zones (*Table 3*) developed in the sediment profile of the core at Nagybárkány (*Fig. 2*).

Table 3. The geochemical zones and results from core sequence of the Nádas Lake (based on *Majkut* (2009))

Zone	cm	cal BP years	Geochemical changes
NBC-1	340 – 280	15,260 – 8800 late Glacial and early Holocene	The lake basin is characterized by the deposition of non-calcareous and low-organic content sediment. This sediment was predominantly inorganic (90 – 95%) and contained a high amount of water soluble Fe and K
NBC-2	280 – 240	8800 – 6000 early Holocene	The inorganic content (80 – 90%) decreased and there was a gradual increase in carbonate (5%) and organic (10 – 15%) content. The water soluble Fe, K content decreased, while the level of water soluble Ca, Mg input prior to this increase, indicating that the transformation of the vegetation continued and deciduous forest spread around the lake basin
NBC-3	240 – 190	2000 – 1500 Antiquity	There is a sudden upward decrease in the inorganic content of the deposits from the depth of 240 cm upwards, with an increase of the organic matter from the previous 10 – 15% to 70 – 80%. Elements to increase the level of included water soluble Ca and Mg suggest authigenic changes within the catchment (*Dániel*, 2004).
NBC-4	190 – 130	1500 – 700 Dark Age and early Middle Age	There is a gradual decrease in the organic content and water soluble Ca, Mg content accompanied by an increase in the inorganic content with water soluble Na content between 190 – 130 cm of the core profile. Previous studies (*Dániel*, 2004) have indicated that an increase of the abundance of these elements is indicative of both physical and chemical weatherings associated with soil erosion and human impact
NBC-5	110 – 40	700 – 0 late Middle Age and Industrial Age	A gradual increase in the organic content indicates decreasing soil erosion and human influences around the lake catchment basin. The water soluble Na, K, Ca, Mg content increased gradually in this zone. The observed composition of these elements may refer to the development of a floating mat, or a moss blanket on the water surface
NBC-6	40 – 0	Last 50 years	There is a rapid increase in the amount of water soluble Ca, Mg, K, and Na, as well as the organic content in this zone with peak values in the entire profile. According to the observed chemical composition of this zone, the emergence of a closed peat layer with mosses and the formation of a small peat-bog could have been inferred for the last 50 years

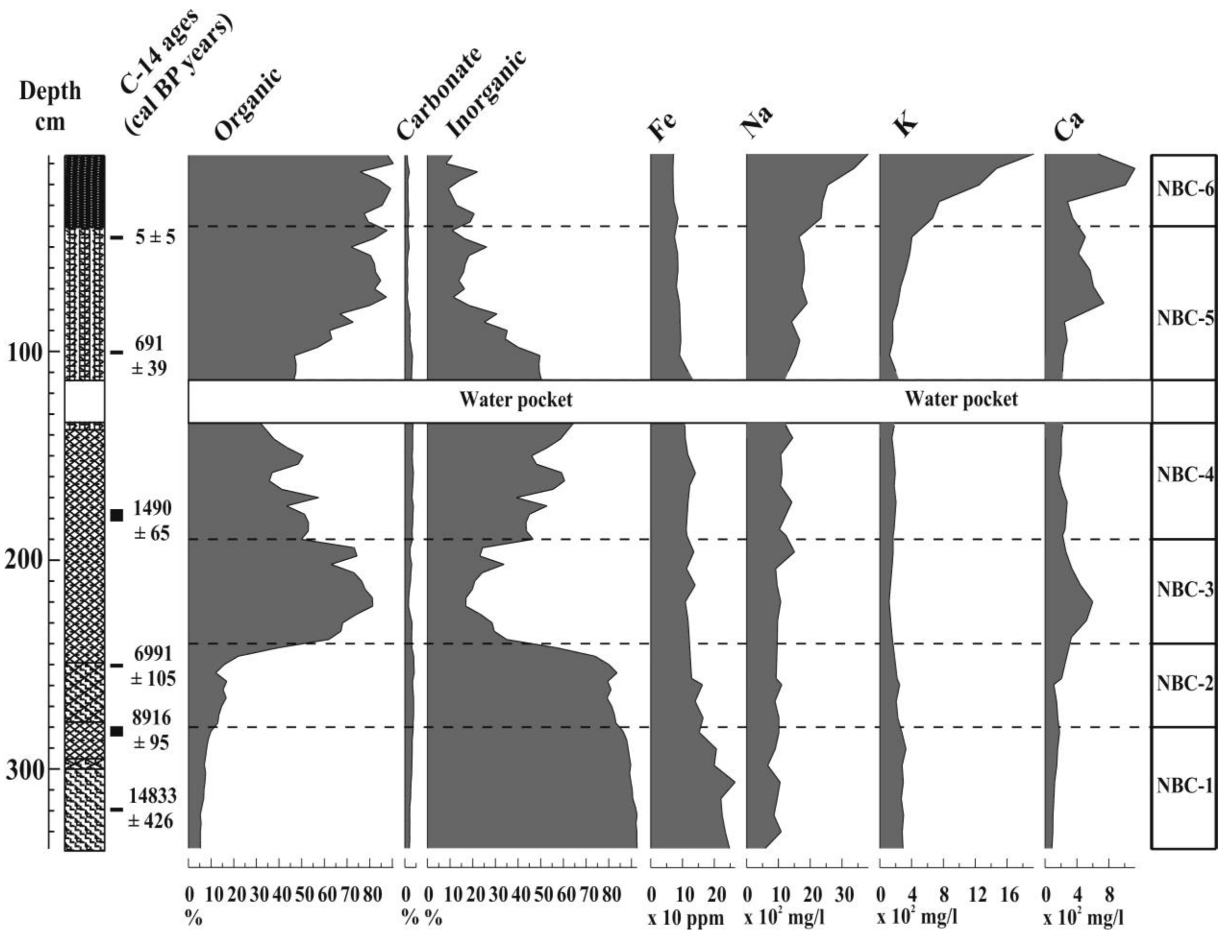

Fig. 2. Results of geochemical analyses (*Majkut,* 2009).

4.3. Macrofossils

The macrofossil zones are shown in *Table 4*. The profile was divided into nine zones on the basis of the analyses. The distribution of 15 most important peat components in the studied samples was evaluated using multivariate statistical methods in order to elucidate the major ecological, hydrological gradients of the individual macrofossil zones (*Jakab* and *Sümegi*, 2005). The ordination of variables (peat components) and objects (sediment samples) are depicted in *Figs. 3* and *4*.

Table 4. Macrobotanical zones and results from core sequence of Nádas Lake (based on *Jakab* and *Sümegi* (2005))

Zone	cm	cal BP years	Macrobotanical changes
NBM-1	340 –288	15,260 – 10,000 late Glacial and early Holocene	The macrofossil concentration was rather low in the lower silty sediment which is poor in organic matter, suggesting high water level, oligo-mesotrophic water quality, and low vegetation cover. A narrow belt or patches of reed-beds probably lined the lakebed

Table 4 (continued)

Zone	cm	cal BP years	Macrobotanical changes
NBM-2	288 –272	10,000 – 8000 early Holocene	The macrofossil concentration increased from 288 cm and reflected lower water level and mesotrophic water quality. The reed-bed at the edge of the lakebed probably formed a continuous belt by this period
NBM-3	272–247	8000 – 6000 mid-Holocene	The macrofossil concentration and the number of *Phragmites* decreased at 270 cm, marshland and bog species disappeared, suggesting a rise in the water level. In the second part of the zone, after 7000 cal BP, the macrofossil concentrations and the amount of *Phragmites* again increased, parallel to the renewed appearance of various *Sphagna* and moss species. These changes reflect another decrease in the water level and the spread of wetland vegetation
NBM-4	247–193	2000 – 1500 Antiquity	The radiocarbon measurements of the sediment samples between 187–176 cm indicated a hiatus of roughly 4400 years at the beginning of the zone. The extrapolation of the measurements suggest that this sediment hiatus developed around 2000 cal BP, during the Imperial Age, when the area was probably settled by Celtic man, who probably deepened the bog which had evolved by then
NBM-5	193 –103	1500 – 700 Dark Age and early Middle Age	The concentration of *Phragmites* rhizomes was quite high at the beginning of the zone, but declined continuously, parallel to the spread of *Typha*. The transition is marked by the lakebed’s brief desiccation at 160 cm, with the significant increase of *Sphagnum squarrosum* peat-moss. The water quality was meso-eutrophic, changing to eutrophic from 160 cm. Between 130–110 cm there was a water pocket
NBM-6	103 –78	700 – 400 late Middle Age	The macrofossil concentration in this zone was extremely high. Many trees fell into the lakebed. The charcoal concentration also shows high values, reflecting the intensive exploitation of the environment. Thus, this zone represents the lake/bog transition
NBM-7	78 – 68	400 – 200 late Middle Age	A genuine floating mat phase
NBM-8	58 –33	200 – 0 Industrial Age	A *Sphagnum* bog (*Phragmiti communis-Sphagnetum*) developed in consequence of oligotrophication in the sampling area
NBM-9	33 – 0	Last 50 years	The *Sphagnum*-bog is replaced by a *Sphagnum* willow swamp in the last zone

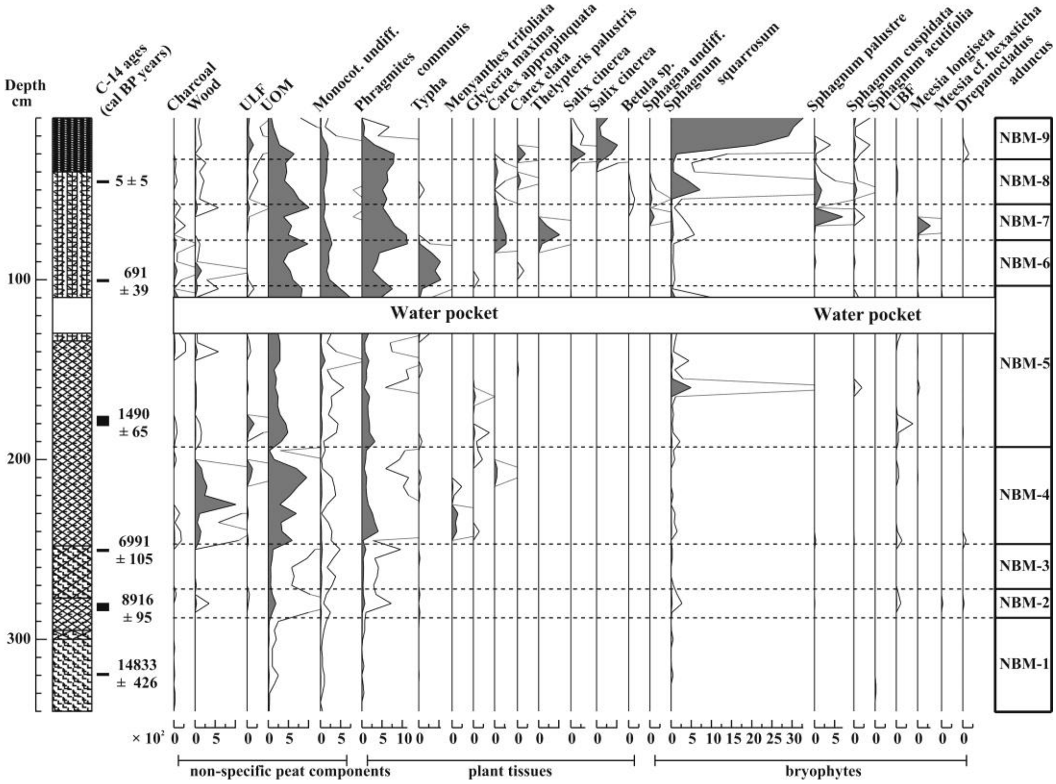

Fig. 3. Fossil plant tissues, mosses (pc cm^{-3}), and seeds (pc cm^{-3}) from Nádas Lake at Nagybárkány (*Jakab* and *Sümegi*, 2005).

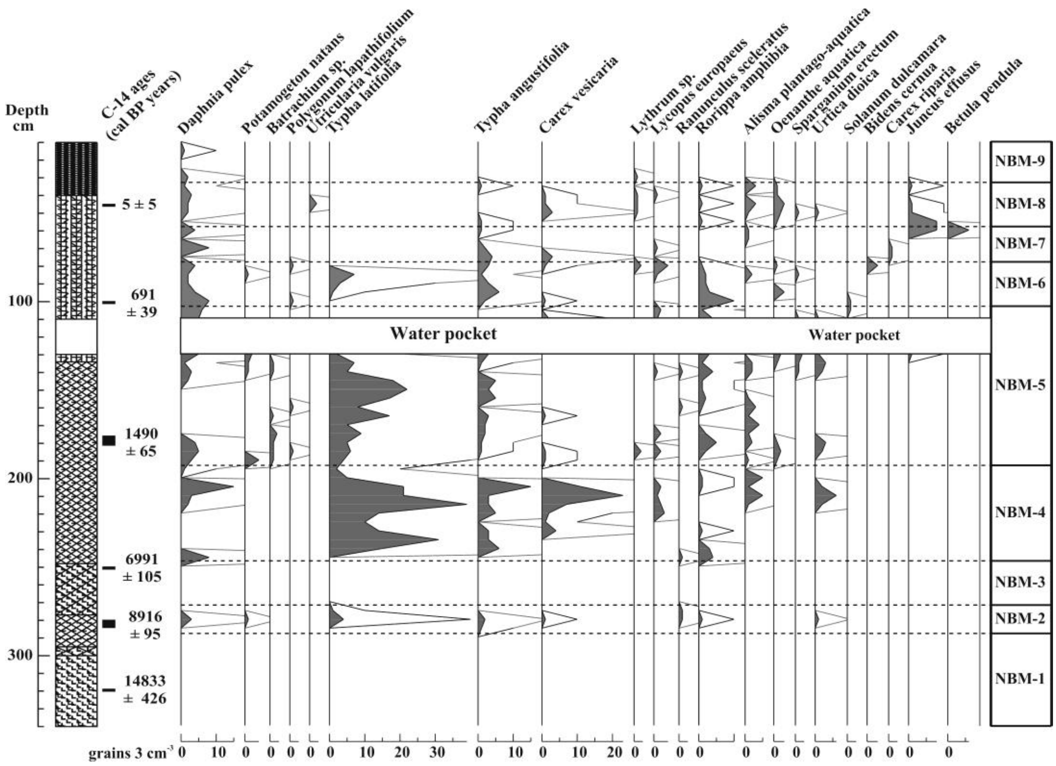

Fig. 4. Fossil plant tissues, mosses (pc cm^{-3}), and seeds (pc cm^{-3}) from the Nádas Lake at Nagybárkány (*Jakab* and *Sümegi*, 2005).

4.4. Pollen analysis

Samples taken between the depths of 340 and 0 cm yielded material suitable for evaluation. A summary of pollen analytical results is depicted in *Fig. 5*. *Table 5* shows the pollen zones of the lake Nádas.

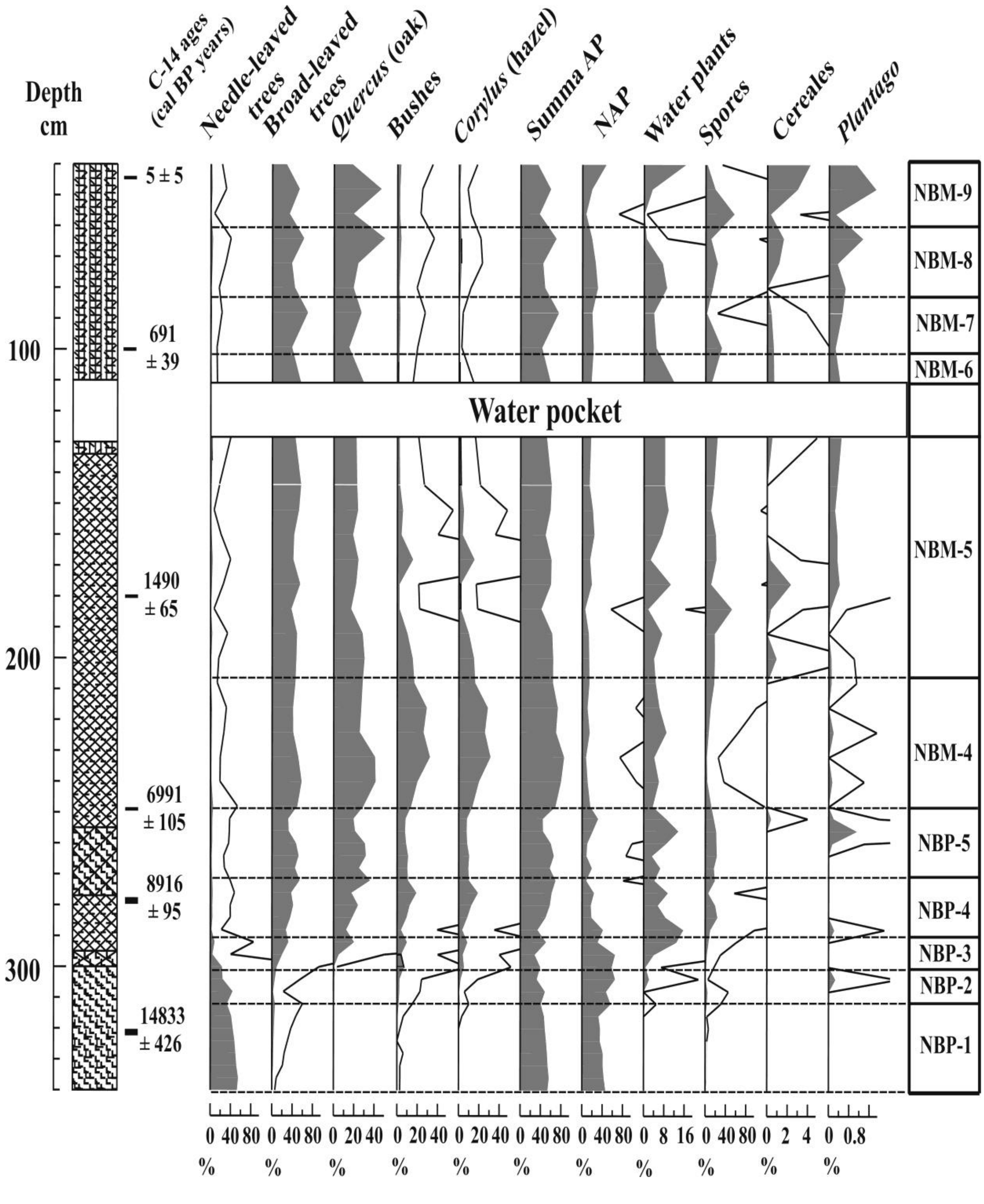

Fig. 5. Pollen zones and results from core sequence of Nádas Lake (based on *Juhász* (2005) and *Juhász et al.* (2004) (selected taxa)).

Table 5. Pollen zones and results from core sequence of Nádas Lake (based on *Juhász* (2005) and *Juhász et al*. (2004))

Zone	**cm**	**cal BP years**	**Pollen composition changes**
NBP-1	340 –312	15,260 – 12,000 late Glacial	During the late Glacial, the surrounding hill slopes were covered by a mixed taiga vegetation with scattered patches of forest and steppe
NBP-2	312–304	12,000 – 10,000 transition	Open mixed taiga forest developed within *Pinus, Picea, Betula, Juniperus, Quercus* trees and *Corylus* scrub
NBP-3	304 –292	10,000 – 9000 early Holocene	A species-rich mixed oak woodland appears early in this zone. There is a major decrease in the amount of pine at the beginning of the zone
NBP-4	292–272	9000 – 8000 early Holocene	A rapid spreading of *Fagus* and *Ulmus* can be traced within the newly developed mixed oak woodland accompanied by a gradual retreat of coniferous and steppe elements. The arboreal flora is dominated by oak and hazel with minor amounts of conifers and birch
NBP-5	272–248	8000 – 6000 mid-Holocene	The dominant elements of the flora in this zone are oak and hazel together with beech. Elm comprises the minor component of the flora. Evidence of the first human impacts was found in this zone. Selective logging of the woodlands is responsible for the change in the forest
NBP-6	248 –192	2000 – 1600 Antiquity	In this zone, a mixed oak woodland was reestablished containing elements of hazelnut and scattered stands of *Fagus* and *Carpinus*. However, this woodland is characterized by a more closed canopy than the one present in the previous zone
NBP-7	192–136	1600 – 1000 Migration (Dark) Age	Besides the general dominance of oak, there is a sudden increase in the proportion of beech and hornbeam. The increased abundance of NAPs marks the gradual opening of the canopy from about 168 cm upwards. The presence of numerous weeds and cereals marks an intensive human activity in the analyzed area
NBP-8	104 –72	900 – 300 Middle Age	The pollen profile points to the development of a closed canopy woodland with such dominant elements as *Salix* (40%) and *Quercus* (30 – 40%), together with *Fagus* and *Carpinus*. Other arboreal pollen (AP) types are rare. The presence of numerous weeds (*Plantago lanceolata* and *Centaurea cyanus*) and cereals marks an intensified human activity in the area
NBP-9	72–40	300 – 0 Industrial Age	The top of the pollen profile by *Juhász* (2005) is characterized by the development of an altered closed oak woodland with a presence of such AP species as beech and *Carpinus*
NBP-10	40 –0	Last 50 years	Every 0.8 cm interval was analyzed for pollen. The pollen composition suggests forest regeneration process started around the peat-bog system

4.5. *Paleoecological zones*

According to the retrieved sedimentological, geochemical, pollen, and macrobotanical data, 6 paleoecological evolution phases developed in the sediment profile of the core at the lake Nádas (*Fig. 6*).

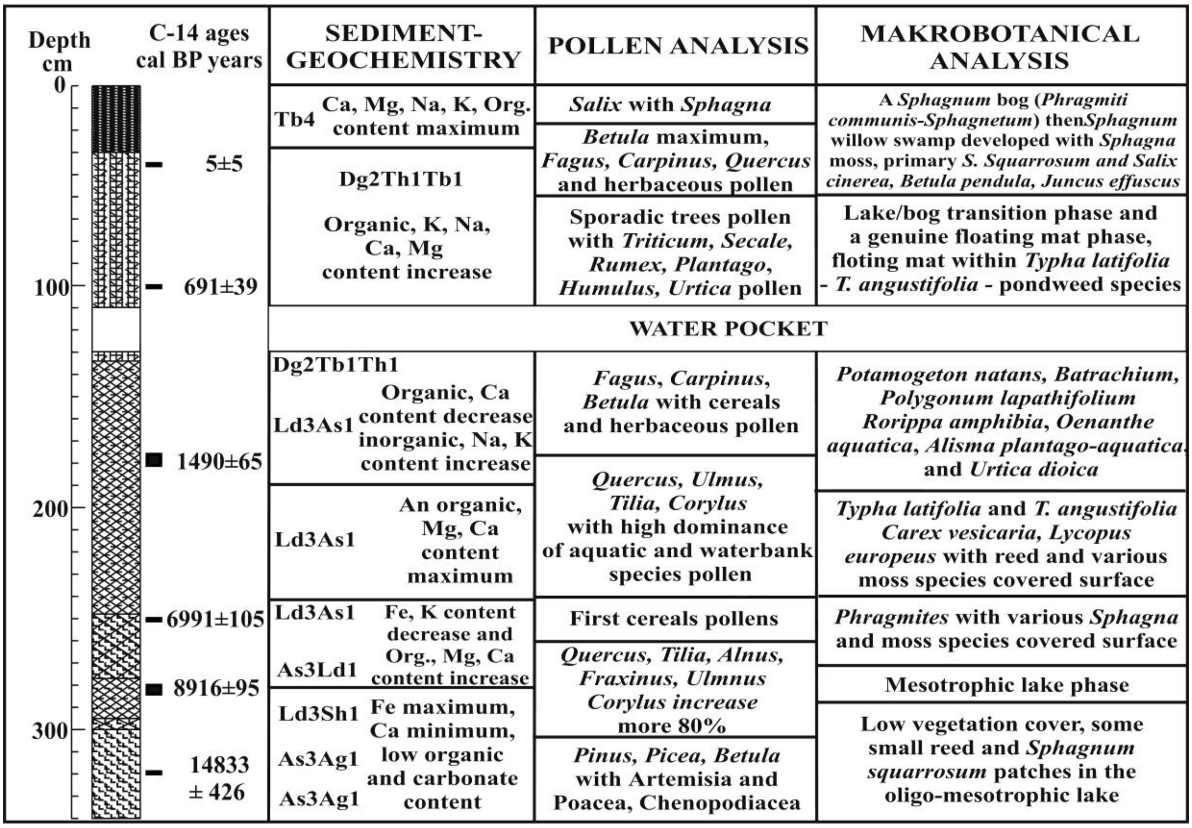

Fig. 6. Results of sedimentological, geochemical, pollen, and macrobotanical analyses.

4.5.1. *The first paleoecological phase, from late Glacial to early Holocene periods*

The lake base sediment is characterized by the deposition of non-calcareous and low-organic content sediment during the late Glacial and early Holocene periods. This sediment was predominantly inorganic (90 – 95%) and contained a high concentration of the water soluble Fe and K, and low concentration of water soluble Ca and Na.

The macrofossil concentration was rather low in the lower silty sediment which is poor in organic matter, suggesting high water level, oligo-mesotrophic water quality, and low vegetation cover. A narrow belt or patches of reed-beds probably lined the lakebed. The radiocarbon measurements indicated that this zone evolved at the time of the late Glacial up to the Pleistocene/Holocene transition. Rough peat-moss, *Sphagnum squarrosum*, a characteristic feature of the bog's recent vegetation, was already present at this time, even if in minimal amounts. The presence of peat-moss belonging to the *Acutifolia* section is noteworthy, coming from the damp soil of the surrounding coniferous forests.

During the late glacial and up until 10,000 cal BC, a coniferous forest steppe of Scots pine, spruce, and birch (*Pinus, Picea, Betula*) with several steppe elements surrounded the Nádas Lake at Nagybárkány. Pollen from the trees accounted for > 50 – 60% of the total pollen with the remaining percentage composed of steppe elements such as the grasses (Gramineae), Chenopodiaceae, and *Artemisia*. The pollen compositions suggest that a cool climate phase developed around the catchment basin of Nádas Lake during the last phase of the Ice Age. Between 10,000 – 7000 cal BC, a dramatic change developed in the late-glacial boreal, type forest around the lake. There was a rapid decline in all dominant needle-leaved trees (*Pinus, Picea*) and an increase in the deciduous woodland elements. This deciduous woodland was composed of *Quercus, Tilia, Fraxinus, Alnus, Ulmus,* and *Corylus* and occurred for more 80% of the total pollen. This early postglacial diverse deciduous forest then persisted until anthropogenic activity effected the woodland at about 6000 cal BC. This pollen composition change indicates that a drastic climatic change developed during the early postglacial phase and the relative warm – rainy climatic Holocene climate was stabilized in the analyzed region.

4.5.2. The second paleoecological phase, mid-Holocene period

Up to the mid-Holocene, the inorganic content (80 – 90%) decreased and there was a gradual increase in carbonate (about 5%) and organic (10 –15%) content. The water soluble Fe, K content decreased, while the level of water soluble Ca, Mg input prior to this increase indicates that the transformation of the vegetation continued and deciduous forest elements spread around the lake basin.

The macrofossil concentration increased from 288 cm. The number of *Phragmites communis* rhizomes and *Sphagnum squarrosum* leaves increased. *Typha angustifolia* and *Typha latifolia* made their appearance, together with the seeds of plants typical for reed-beds (*Ranunculus sceleratus, Rorippa amphibia, Alisma plantago-aquatica*) and *Daphnia* ephippiums. Bryophytes include the peatmoss *Sphagnum palustre* and other various mosses (*Drepanocladus aducus*, *Meesia* cf. *hexasticha*). The macrofossils reflect lower water level and mesotrophic water quality. The reed-bed at the edge of the lakebed probably formed a continuous belt by this period. The macrofossil concentration and the number of *Phragmites* decreased at 270 cm, and marshland and bog species disappeared, suggesting a rise in water level. In the second part of this zone, after 7000 cal BP, the macrofossil concentrations and the amount of *Phragmites* again increased, parallel to the renewed appearance of various *Sphagna* (*Sphagnum squarrosum, S. cuspidata, S. palustre*) and moss species

(*Drepanocladus aducus*). These changes reflect another decrease in the water level and the spread of wetland vegetation.

At approximately 5500 cal BC, the structure of the woodland altered once again with a large decline in the woodland pollen diversity, parallel with an increase of open gorund herbaceous types and an occurrence of cereal pollen. This change usually associated with anthropogenic activity. These results are consistent with archaeological data that has indicated development of Liner Pottery Culture within the Carpathian Basin at this time (*Kalicz* and *Makkay*, 1977). Some localities of this culture can be found around the analyzed region (*Bácsmegi* and *Fábián*, 2005).

4.5.3. The third paleoecological phase, Imperial Age

There is a sudden upward decrease in the inorganic content of the deposits from the depth of 240 cm upwards, with an increase of the organic matter from the previous 10 – 15% to 70 – 80%. Elements to increase the level of included water soluble Ca and Mg suggest authigenic changes within the catchment (*Dániel*, 2004). Probably Ca, Mg acceptor water plants, such as *Typha* and *Phragmites* colonized the analyzed catchment basin and the increase of the content water soluble Ca, Mg originated from the remains of these plants.

The macrofossil concentration suddenly increased at the beginning of the zone, with strikingly high UOM values, indicating an eutrophic marshland environment. The *Phragmites* cover expanded significantly over the lakebed. The zone contained high amounts of the leaf sheat epidermis of bogbean (*Menyanthes trifoliata*), which probably grew at the edge of the reed-bed facing the open water or in hollows. This section of the zone contained *Sphagnum squarrosum*. Reed declined in the second half of the zone, parallel to the expansion of bulrush (*Typha latifolia* and *Typha angustifolia*). This period is characterized by *Carex vesicaria* and various moss species (*Amblystegium serpens, Calliergonella cuspidata, Drepanocladus aduncus*). *Daphnia* ephippiums occurred in high numbers, and the spread of eutrophic marshland species, such as *Lycopus europaeus, Rorippa amphibia, Alisma plantago-aquatica*, and *Urtica dioica* could be noted. The macrofossils indicate lower water level and meso-eutrophic conditions at the beginning of the zone, and eutrophic conditions from ca. 1700 cal BP.

The radiocarbon measurements of the sediment samples between 187–176 cm indicated a hiatus of roughly 5000 years at the beginning of the zone. The extrapolation of the measurements suggest that this sediment hiatus developed around 1700 cal BP, during the Imperial Age, when the area was probably settled by Celtic or/and German groups, who probably deepened the peat-bog, which had evolved by then.

The closing of the forest canopy can be linked to the sudden increase of hazel (*Corylus*) from 15 to 30% and to the constantly high values of oak

(*Quercus*) in the first part of the zone. This is followed by the decline of hazel, while lime (*Tilia*) and elm (*Ulmus*) maintain a continuous presence, parallel to the re-appearance of *Fagus* and *Carpinus* at the end of the zone. The herbaceous vegetation has very low values, with a low amount of pollen grains. However, almost all taxa of the previous zone are present, even if only sporadically, but only grasses (Poaceae) and mugwort (*Artemisia*) have a continuous curve. Typical species of the wet zones, such as *Ranunculus*, *Lysimachia*, Apiaceae, can also be noted. The most important change in the local vegetation is the disappearance of *Sphagnum* moss with a very sharp decrease in the species of the earlier bogland vegetation, such as *Typha/Sparganium*, the Pteridophytes with Monolete spores (*Thelyptheris palustris*) and aquatic species (*Nuphar*, *Butomus*, *Potamogeton*).

4.5.4. The forth paleoecological phase, Migration Age

There is a gradual decrease in the organic content and water soluble Ca, Mg content accompanied by an increase in the inorganic content with water soluble Na content between 190 –130 cm of the core profile. Previous studies (*Mackereth*, 1966; *Engström* and *Whright*, 1984; *Dániel*, 2004) have indicated that an increase of the abundance of these elements is indicative of both physical and chemical weatherings associated with soil erosion and human impact. The increase of the water soluble Na may indicate a drop in lake level as well during this phase.

The macrofossil concentration declined slightly in this zone. The concentration of *Phragmites* rhizomes was relatively low. Various pondweed species (*Potamogeton natans*, *Batrachium sp.*, *Polygonum lapathifolium*) made their appearance, suggesting a relatively higher water level. *Sparganium erectum* became typical. The reed-bed was quite species rich, with species such as *Lycopus europaeus*, *Lythrum* sp., *Ranunculus sceleratus*, *Rorippa amphibia*, *Alisma plantago-aquatica*, *Oenanthe aquatica*, and *Urtica dioica*.

The concentration of *Phragmites* rhizomes was quite high at the beginning of the zone, but declined continuously, parallel to the spread of *Typha*. The transition is marked by the lakebed's brief desiccation at 160 cm, with the significant increase of *Sphagnum squarrosum* peat-moss. The water quality was meso-eutrophic, changing to eutrophic from 160 cm. Between 130 –110 cm there was a water pocket. Between 110 –100 cm, the number of *Phragmites* rhizomes increased significantly, suggesting that the extent of the open water diminished and that reed-beds also covered the sampling location. *Typha* (rhizome) appeared at the sampling location, although to a lesser degree only. The peak of *Rorippa amphibia* similarly indicates the decrease of the water level.

This zone is characterized by the opening up of the forest canopy and the increase of herbaceous elements. *Quercus* shows relatively constant values throughout the zone, while *Tilia* and *Ulmus* decline to very low values, parallel to the sudden rise of beech (*Fagus*) and hornbeam (*Carpinus*) at the beginning of the zone. *Betula* develops again in the forest with a constant level, except for a temporary minimum at 168 cm, while *Corylus* has a temporary maximum, followed by a decline to its previous level. *Alnus*, the typical taxa for the marginal zone of the peat-bog, is continuously present with low values, while *Fraxinus* shows a sporadic presence. Agricultural activity is reflected by the presence of cereals, *Plantago lanceolata*, *Centaurea cyanus*, and some nitrophilous taxa (*Urtica*) in this zone.

4.5.5. The fifth paleoecological phase, from Middle Age until 20th century AD

A gradual increase in the organic content indicates decreasing soil erosion and human influences around the lake catchment basin. The water soluble Na, K, Ca, Mg content increased gradually in this zone. The observed composition of these elements may refer to the development of a floating mat, or a moss blanket on the water surface.

The macrofossil concentration in this zone was extremely high. Many trees fell into the lakebed. The charcoal concentration also shows high values, reflecting the intensive exploitation of the environment. The expansion of bulrush at the sampling location can be noted (increase of *Typha* rhizomes), and the proportion of *Typha angustifolia* was higher than previously. *Typha angustifolia* gradually replaces *Typha latifolia*, indicating paludification and higher water level. This zone can be regarded as the first stage in the development of the present-day bog, when its central part was covered by floating bulrush mat at the expense of pondweed communities. It seems that the reed-bed broke loose from the sediment in consequence of rising water levels, leading to the formation of a floating mat. As a result of intensive oligotrophication, a floating reed swamp (*Phragmitetum communis thelypteridetosum*), then a *Sphagnum* bog (*Phragmiti communis-Sphagnetum*) developed in the sampling location with *Carex riparia* and *Carex appropinquata*. The zone is characterized by abrupt changes, reflecting further oligotrophication. There is a large-scale increase in marsh fern (*Thelypteris palustris*), which later decreases, parallel to the expansion of a rare moss, *Meesia longiseta*. Following the decline of the latter, the values of peat-mosses, especially of *Sphagnum palustris*, *Sphagnum squarrosum* increases. The high values of *Juncus effusus* are also characteristic for this zone.

According to the pollen composition (*Juhász*, 2005), this zone is characterized by a relatively closed vegetation cover. *Salix* is the dominant taxon, accounting for 40% of the total pollens. *Quercus* has high values too and shows a rise parallel to the decline of willow. Other tree taxa show a sporadic presence, except for beech (*Fagus*) and hornbeam (*Carpinus*), which are present with minor, but continuous curves, together with *Betula* and *Corylus*. Anthropogenic taxa are also present: the pollen grains of *Plantago lanceolata*, *Rumex*, and cereals (*Triticum* and also *Secale*) were identified. Cyperaceae, *Typha/Sparganium*, and aquatic species (*Lemna*, *Potamogeton*, *Butomus*) are present sporadically. The closing up of the forest canopy can be noted, with a dominance of *Quercus* and *Betula*.

4.5.6. The sixth paleoecological phase, 20th century

There is a rapid increase in the amount of water soluble Ca, Mg, K, and Na, as well as the organic content in this zone with peak values in the entire profile. According to the observed chemical composition of this zone, the emergence of a closed peat layer with mosses and the formation of a small peat-bog could have been inferred for the last 50 years.

The uppermost section of the pollen sequence is also dominated by oak, with some beech and hornbeam. Willow (*Salix*) is present and rises towards the end of the zone; the herbaceous vegetation (Poaceae and anthropogenic taxa) increases and dominates the landscape. The *Sphagnum*-bog is replaced by a *Sphagnum* willow swamp in the last zone. The recent expansion of *Salix cinerea* could be noted in the area (see *Fig. 1*). The number of reed species and reed-beds decreases, parallel to the increase of wood remains (wood, ULF). *Salix cinerea* remains (leaves, roots) are quite frequent. The values of *Sphagnum squarrosum* increase significantly.

Plantago lanceolata, Cerealia, *Urtica*, and *Rumex* have relatively high values. *Phragmites*, *Typha/Sparganium* are present in the local vegetation, together with *Thelypteris palustris*, although *Sphagnum* moss has lower values than in the previous zones. The very end of the pollen sequence was dated to 0 ± 60 uncalBP (1955 +/– 5 calAD), indicating a strong human impact on the vegetation cover, with high proportions of cereals, *Rumex*, and *Plantago lanceolata* among the herbaceous taxa. The size of the oak forest decreases and willow re-appears.

5. Discussion

5.1. Initial pond phase (late Glacial to mid-Holocene: 15,000 – 5000 cal BC yr)

The first phase of the analyzed region development, lasting until the mid-Holocene, was determined by relatively stable trophic conditions and smaller fluctuations in the water level. The water level somewhat decreased at ca. 6800 cal BC and the start of peat-bog initiation can be noted, probably in consequence of the onset of a warmer and drier climate. Species referring to paludification like *Sphagnum squarrosum* and *S. palustre* also turn up here. On the testimony of the pollen profiles (*Juhász et al.* 2004), this phase coincided with the appearance of thermophilous species rich oak forests. The water level again rose at 6000 cal BC and decreased after 5000 cal BC, enabling the expansion of reed-beds.

Between 15,000 – 5000 cal BC, inputs of K and Mg into the basin suggest that erosion of the slopes surrounding the lake basin was occurring and trophic conditions of the formed lake was oligotrophic (*Mackereth,* 1966; *Engström* and *Whright*, 1984; *Engström* and *Hansen*, 1985). The high content of water soluble Fe suggests that a combination of acidic silicate rich bedrock, coniferous trees and cool late Glacial climatic conditions resulted in podzol soil formation around the catchment basin. The deposited lacustrine sediments embedded minor pebbles as well till around 6000 cal BP in varying quantities. These must indicate abrasion of the shore in the lack of a closed reed belt.

According to the findings of geochemical analysis, the early Holocene lacustrine phase differed significantly from the previous pond stage in sedimentary, chemical composition and temperature conditions. While the earlier, late Glacial and lateglacial/postglacial transition lake environment can be characterized by sedimentation in a cold and oligotrophic water lacking Ca content and low vegetation cover, the early Holocene paleohydrological stage can be described as being relatively rich in Ca, with high carbonate and organic content and with a vegetation typical of easily warming water. The amount of Ca increased from about 100 to 200 ppm. Changes in the chemical composition refer to intensified erosion around the catchment basin and the transformation of the late Glacial oligotrophic lake into an open mesotropic lake phase. The increasing level of overland soil erosion into the catchment basin must have developed under increasing human impacts (e.g., woodland grazing). As shown by archeological data (*Bácsmegi*, 2005; *Bácsmegi* and *Fábián*, 2005), Neolithic Age communities settled around the analyzed region between 5500 –5000 cal BC. These prehistoric human communities transformed their forested environment to open surface for arables and pasturelands. This type of human disturbance might trigger intensified soil erosion into the catchment basin.

5.2. Climate-driven mire phase (late Holocene: 0 –1300 cal AD)

Abrupt geochemical changes indicate the emergence of a sedimentary hiatus in the catchment basin. It seems to us that this geological layer discordance formed by human impact. Results of the radiocarbon measurements are presented in *Table 1,* from which a sedimentary hiatus is apparent between 187–176 cm. This hiatus associated with a thin layer of burnt macrocharcoals. This, and a subsequent change in lacustrine stratigraphy from mesotrophic lake to reed peat show ca. 4000 years difference in age between adjacent samples. According to radiocarbon and sedimentological data of the core profile, this event coincides with a peat cutting in the Imperial Age when Barbarian groups (Celts, German tribes) occurred around the lake catchment basin (*Vaday,* 2005). Probably, one of these antique tribes cleaned the analyzed pond around 20-30 cal AD (*Figs. 5* and *6*). Then, after this cleaning procedure, a mass of water plants covered the artificially transformed pond surface (*Fig. 6*).

The *Phragmites* concentration in the sediment decreased during warmer periods in the Imperial Age and Middle Ages, parallel with an increase of *Typha* seeds and *Daphnia ephippia*. This reflects a competitive situation, characterized by alternating dominances of reed and bulrush in the lakebed. Reed and bulrush are both competitive species under favorable conditions.

In the pollen record, this phase is characterized by the opening up of the forest canopy and the increase of herbaceous elements (*Juhász*, 2005). It would appear that during periods of greater solar activity, the lake received more light, in part owing to the retreat of species forming higher and more closed forest canopy, like *Fagus* or *Carpinus*.

In order to shed light onto the interrelations of vegetation changes and climate change, the model of *Davis et al.* (2001, 2003) was adopted in our work. According to this model, some climatic changes, drier, wetter and warmer (*Table 6*), and cooler phases developed during last 2000 years (*Figs. 7* and *8*). One of the most important warmer climatic phases formed in the Imperial Age, then in the late Migration Age, and early Middle Age. The lake is fringed by high, steep slopes in the south and south-east, from where the high trees cast a shadow over the greater part of the lake. The expansion of phyto-planktons at the time of greater solar activity is indicated by an increase of *Daphnia* feeding on them. The expansion of phytoplankton leads to the development of looser sediments, encouraging the spread of *Typha*. The beginning and close of the Medieval Warm Period saw the maximum of solar activity (*Bradley et al*., 2003). The end of this warm period at about 1250 AD was marked by the so-called medieval solar activity maximum, which caused serious droughts in Europe and North America. The sudden expansion of *Sphagnum squarrosum* can be noted at the time of the two maximums. *Phragmites* and *Typha* both declined at around 800 AD, suggesting the brief desiccation of the bed, when peat-moss temporarily covered the entire lakebed .

In the pollen record at ca. 600 cal AD, *Cyperaceae* and aquatic species (*Nuphar*, *Nymphea*, *Lemna*, *Butomus*) have a temporary minimum as well (*Juhász*, 2005). The water level decreased for a longer period of time around 1200–1300 cal AD, enabling the expansion of the reed-bed over the lake's entire surface and causing the reduction of open water. According to the geochemical data between 500–1300 cal AD, a drier and maybe a warmer phase formed (*Fig. 4*). The increase of the water soluble Na content shows that a decrease of the pond water level might have developed during this phase.

The referred period was coeval with one of the major crisis periods of medieval Hungary, the invasion of Mongolian tribes dated between 1241 and 1242. From the written record we do know that some chronicle writers blamed the Mongolian invasion of the country on the severe cold weather, while others related it to the unusual droughts hampering Europe during the summers of the 13th century. *Barber et al.* (2000) declared this period as the driest of the past 2000 years in the history of Europe. In Hungary, the extremely cold winter of

1241 was devastating regarding the political and economic fate of the country, when the river Danube was completely frozen enabling the Mongol tribes to safely cross the river and destroy the settlements of Transdanubia as well. As *Kiss* (2000, 2003) clearly stated, the controversies lying in the contrast of the extremely cold winters and summer droughts can easily be resolved. A complete freezing of the river Danube was not an unusual event in Hungary preceding the river regulations on the one hand. On the other hand, the summer droughts which might have struck Hungary as well at the time must have reinforced the devastating effects of famine attributable to the war itself as well. This warm and dry weather must have contributed to a complete desiccation of the Nádas Lake of Nagybárkány, when reed coverage must have extended to the entire lacustrine basin.

Table 6. Climatic parameters changes according to the pollen-based paleoclimatic reconstruction (used by pollen data based paleoclimatic reconstruciton methods of *Davis et al.* (2001))

Climatic parameters/Age AD	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**	**1000-1100**
MTCO (ºC) The mean temperature of the coldest month	–2.0	–1.8	–2.1	–2.7	–3.0	–2.2	–1.9	–1.8	–1.9	–1.8
MTWA (ºC) The mean temperature of the warmest month	+19.5	+19.7	+19.6	+19.5	+19.2	+19.7	+19.6	+19.8	+19.7	+19.7
TANN (ºC) Annual temperature	+ 9.0	+ 9.2	+ 9.1	+ 8.9	+ 8.9	+ 9.2	+9.3	+9.4	+9.2	+ 9.5
PANN (mm) Annula precipitation	610	620	650	600	680	660	620	630	620	550
Continentality (ºC) MTCO - MTWA	21.5	21.5	21.6	22.0	22.2	21.9	21.5	21.6	21.6	21.5
Water level of the pound based on macrobotanical data	low	low	rel. high	lowest	high	high	rel. low	rel. high	low	lowest
Climatic parameters/Age AD	**1100-1200**	**1200-1300**	**1300-1400**	**1400-1500**	**1500-1600**	**1600-1700**	**1700-1800**	**1800-1900**	**1900-2000**	**today**
MTCO (ºC) The mean temperature of the coldest month	–2.5	–1.8	–2.2	–3.0	–2.2	–3.3	–3.5	–3.9	–3.6	–3.5
MTWA (ºC) The mean temperature of the warmest month	+19.2	+19.9	+19.4	+18.5	+19.7	+18.2	+18.5	+19.0	+19.1	+ 19.0
TANN (ºC) Annual temperature	+ 9.2	+ 9.6	+ 9.2	+ 8.8	+ 9.2	+8.3	+8.5	+8.2	+ 8.7	+ 8.8
PANN (mm) Annula precipitation	570	550	600	620	600	650	650	650	660	620
Continentality (ºC) MTCO – MTWA	21.7	21.7	21.6	21.5	21.9	21.5	22.0	22.9	22.7	22.5
Water level of the pound based on macrobotanical data	low	lowest	low	rel. high	low	high	high	high	highest	**regu-lated**

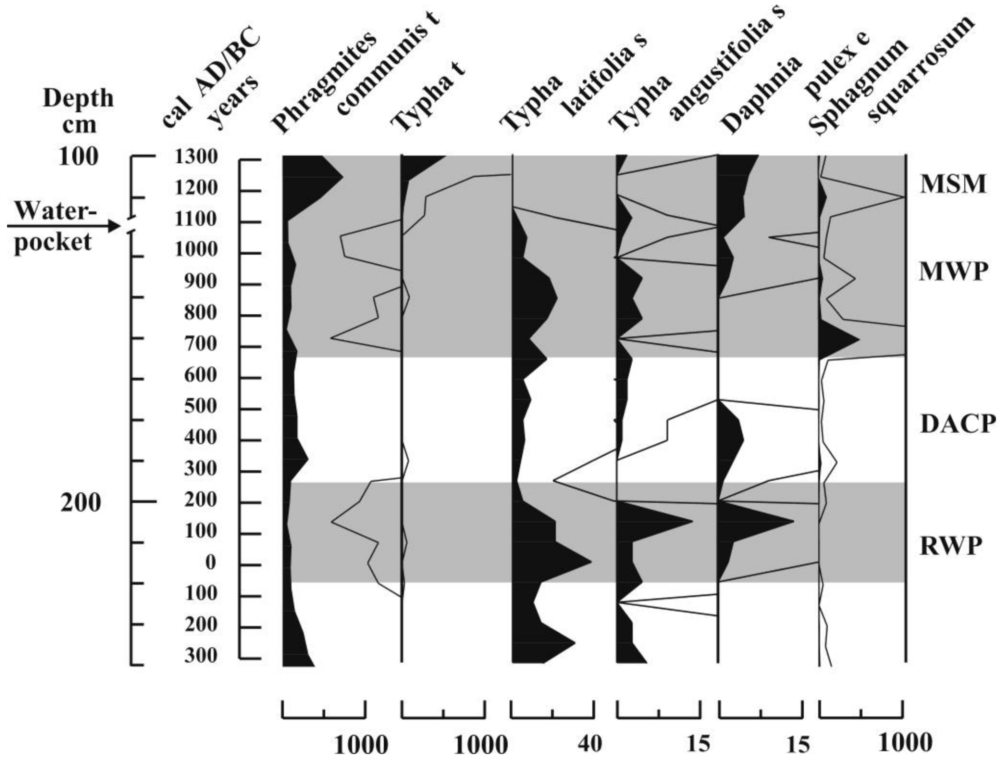

Fig. 7. Trophic fluctuations at the Nádas Lake between 330 BC and 1300 AD. The grey areas indicate periods with a warmer climate (MSM: medieval solar activity maximum; MWP: medieval warm period; DACP: Dark Ages cold period; RWP: Roman Age warm period; the interbedded water layer between 130 –110 cm has been omitted).

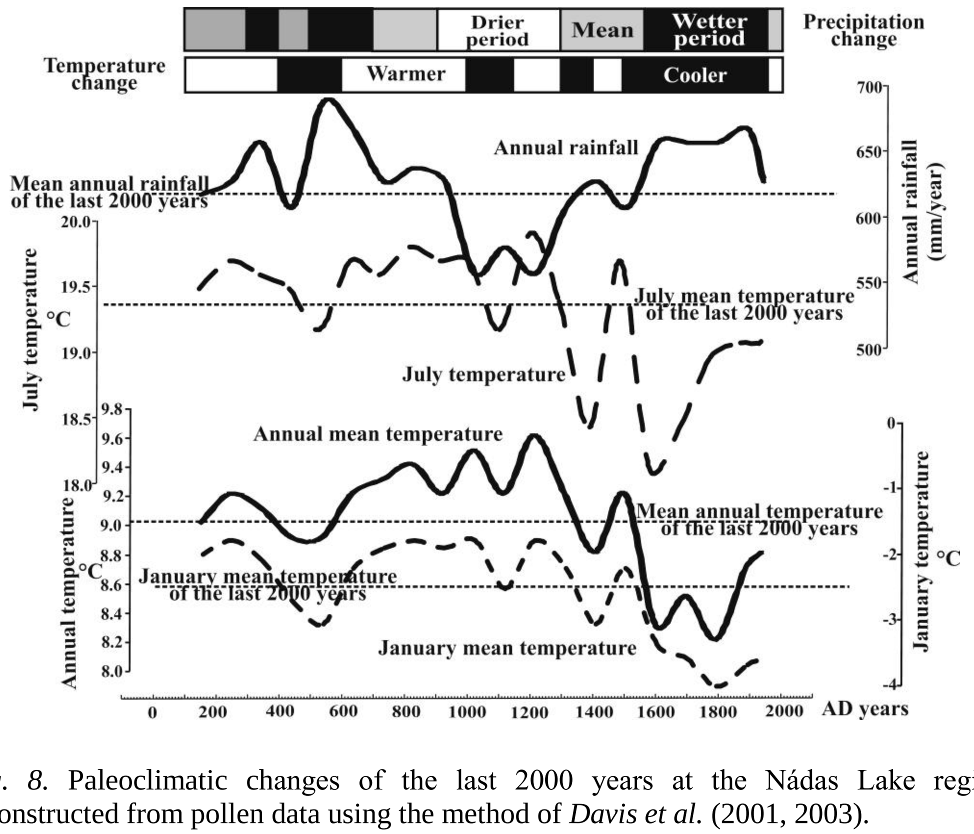

Fig. 8. Paleoclimatic changes of the last 2000 years at the Nádas Lake region reconstructed from pollen data using the method of *Davis et al.* (2001, 2003).

In the next part of the profile, there is major depositional hiatus spanning about 4400 – 4700 years. This must have emerged during the terminal part of the Iron Age, beginning of the Imperial Age around 20 –30 AD, preserving the signs of immense human impact. According to the available archeological record from the wider surroundings of the site, the area must have been controlled by Celtic herds at the time. The remains of Late Iron Age fortresses near Mátraszőlős and Kerekbikk are clear proof (*Vaday*, 2005). The area of Nádas Lake at Nagybárkány, which was a peatland at the time of the referred period, must have been systematically exploited by Celtic tribes. Peat must have been utilized in various forms ranging from fuel to litter, similarly to modern day utilizations observable in many parts of rural Ireland or Scotland (*Seymour*, 1984). An additional alternative might have been the use of the newly created ditches, which were the side-effects of peat mining, as water cisterns or reservoirs. Signs of similar activities could have been attested by Celtic tribes in the case of the Mohos Marshland at Kelemér and the Nyíres marshland of Csaroda for the periods of the late Iron Age – early Imperial Age (*Willis et al.*, 1998; *Sümegi*, 1999).

Some proxies from the referred period indicate a warming climate with perhaps a slight aridification, as seen by a concomitant increase in the amount of hazel, elm, and oak pollen grains accompanied by a retreat of lime (*Fig. 5*). In the light of this paleoenvironmental information one may assume, that the initiating peat exploitation and the artificial creation of cisterns must have been a feedback for this climatic change. Nevertheless, these activities might have been triggered by other factors as well, like a significant population growth or the foundation of a new settlement in the vicinity, not to mention a serious increase in livestock. The large proportions of macro- and micro-charcoal particles identified in the profile refer to intentional deforestation via burning, resulting in new open areas suitable for animal farming. These impacts can generally be connected to foundations of new settlements or the initiating construction of fortified settlements, around which woodland clearance was inevitable for defensive reasons (*Figs. 5* and *6*).

In the following part of the profile corresponding to the terminal part of Antiquity and the opening of the Age of Great Migrations, there is a gradual deceleration in the accumulation of organic matter in a continuously increasing trend, which was followed by alternating sudden increases and drops (*Fig. 2*). The growth period is characterized by an increase in Ca, followed by similar rises in Fe and Na. Nevertheless, when there is an increase in Fe and Na in the deposits, the ratio of Ca reaches a low. In the first part of the referred zone, there is an extremely rapid increase in the proportion of hazel pollen grains parallel with high values for oak pollen grains. Conversely, this is accompanied by a decrease in the amount of elm pollen grains and reed fragments preserved in the sediments. Afterwards, there is a very rapid decrease in the amount of oak pollen grains, reaching about two-third of their original value. Parallel with this phenomenon, large amounts of arboreal organic matter and unidentifiable organic matter appear in the deposits, accompanied by an increase in dissolved Ca as well. In the following part, oak seems to witness a slow recovery with a sudden increase in hazel pollen grains displaying a slow decrease afterwards till the end of the referred zone. All these biotic and chemical proxies seem to refer to rapid and very intensive human activities in the area. The large-scale rapid drop in oak pollen grains accompanied by an advent of lime and elm in the profile refers to selective deforestation, which must have been targeted the wood raw material itself as an ideal construction material and was not focusing on creating open areas for livestock primarily.

If the amount of available wood is proportional to changes seen in the pollen record, then one must assume a one-third decrease in the natural oak woodlands as a result of selective deforestation during the referred period, which is a very high number. Former environmental historical works speculated about the use of exploited wood in creating artificial objects within the lakebed or the exploited peatland area. This model assumes the construction of wood walls within the lakebed itself to give support to the newly formed cisterns, which seems plausible. Nevertheless, as it is seen from hard data depicted on the diagrams of *Figs. 5* and *6*, the majority of the oak stands logged down were 150-year-old at least, with a predicted volume of 800 m^3/hectar, assuming an annual growth of 8 m^3, which is a standard in forest management. This much log following the removal of branches and slicing by saw must have provided about 360 m^3 timber. The relatively small size and large proportion of retrieved timber remains call for the use of saw. If the logs were sawed into 10 cm thick, 30 cm wide and 1.5 m long timber pieces, ideal for construction of supporting walls, then for this purpose in case of a lakebed with a perimeter of 300 m, a volume of 45 m^3 timber must have been sufficient. As seen from the archeological record saw was known and utilized by late Iron Age Celtic tribes as well (*Caselli*, 1981).

The referred amount of timber could have been retrieved from an area of 1/8 hectars alone. Making predictions about the spatial extension of areas affected by logging is not an easy task. Nevertheless, the small size of the studied catchment basin (less than 100 m) and the origin of the preserved pollen grains in the deposits may help us to solve this conundrum. According to the findings of modern palynological studies in catchment basins, when the size of the basin is below 100 meters, 90% of the preserved pollen grains are of local origin with a small proportion of extralocal pollen grains (*Fig. 5*). As the largest radius of the studied catchment basin of Nádas Lake is well below this limit value, this might be rather promising in solving the above mentioned question. According to our model, the areas affected by deforestation during the referred period must have covered a radius of 300 m around the lake, reaching a maximum area of 20–30 hectars. This would suit both the spatial needs and the raw material demands of a smaller settlement with log houses and orchards, meadows, etc. As it is seen in the archeological record (*Bácsmegi* and *Guba*, 2007), people of the settlement must have been composed of Celtic groups surviving German, Dacian, and Roman attacks showing affinities to newly arriving German tribes as well. Moreover, based on the available absolute dates, the emerging settlement at the terminal part of the 4th and beginning of the 5th centuries AD might have been linked to the first appearance of Hun tribes in Central Europe, triggering the movement of lowland people to highland areas offering more safety.

After the formation of the settlement, the early period of the Age of Great Migrations (between the turn of the 4th–5th centuries AD and the terminal part of the 6th century AD) was characterized by a slow increase in the amount of oak pollen grains accompanied by the uniform accumulation of wood remains and a slow decrease in dissolved Ca in the deposits. All these imply the emergence of planned woodland management and the influences of a human group with a well-established economy for about two centuries. The use of oak woodlands in animal fodder and husbandry was a well-known established agricultural method offering efficient, cost-effective, and risk-free solutions in contrast to growing plants in arables used as fodder. Acorn has a relatively high nutrition value, with a high annual production rate of 15 tons/hectar, enabling efficient and cost-effective animal husbandry without the need of fodder plant production. As it can be seen in the pollen diagram (*Fig.5*), there is a minor peak of cereals at 200 cm corresponding to the opening of the 5th century AD, which further corroborates the permanent presence of human settlements and activities in the study area.

The next prominent change in the profile is observable at the depths of 190 and 130 cm corresponding to the period between the 6th and 9th centuries AD (*Fig. 6*). This zone is characterized by a decrease in organic and increase in inorganic components of the deposits (*Fig. 6*). The geochemical parameters also tend to be constant lacking any sudden transformations or outliers. These changes must have been triggered by a gradual retreat of reed fringing the lakebed. Nevertheless, the large amounts of wood remains as well as flue-ash in the initial part of the zone, as well as the inferred decrease in the amount of oak, hazel, lime, and elm pollen grains may indicate a smaller deforestation activity.

The presence of buttercups, known to carry toxics, can be clearly attested during the second half of the Age of Great Migrations. An increase of these plants may indicate the appearance of large livestock grazing meadows besides the survival of woodland grazing. The peak in the pollen ration of buttercups was noticed at a depth of 160 cm, followed by a gradual decrease, which must be attributed to an aridification of the climate on the one hand. On the other hand, a decrease in the importance of animal husbandry may be assumed as well. Based on the available plant macrofossils, this period is characterized by a decrease in the area of the peatland, which must be attributed to drier climatic endowments (*Figs. 7, 8*). This transformation, however, was by no means drastic, as peat-mosses managed to survive in the area, suffering only a minor decrease. Peat-mosses are capable to thrive in areas of the Carpathian Basin, where the rate of average annual rainfall is above 550 mm. So we may assume a similar value for the referred period in our study area, corroborated by results of pollen analysis as well (*Fig. 8*), assuming a rainfall value of 630 – 650 mm for the period between the 6th and 9th centuries. This value is well above the average of the past two millennia (620 mm).

Conversely, as it is clearly observable in the paleoclimate diagram based on pollen data (*Fig. 5*), the referred period is characterized by elevated mean annual, January, and July temperatures. Thus, as a result of higher temperatures, evaporation must have been higher as well during the second half of the Age of Great Migrations, between the 6th and 9th centuries. As a result of the elevated evaporation rate, drier conditions must have emerged with varying intensities related to micro-morphological and geographical setting. Conversely, the higher 100-year-long environmental historical data do not refer to such a drastic climatic change during the collapse of the Avar Empire, which might be blamed for its fall, e.g., famine following an extremely dry period. This question becomes even more exciting, when our data from the referred period of the Late Age of Great Migrations is compared with those for the periods of the Hungarian Conquest, the Arpadian Age, the late Middle Ages, or the New Age.

At a depth of 144 cm there is a rapid and considerable increase in the amount of willow pollen grains, overlain by layers embedding large proportions of wood remains, flue-ash, and burnt peatland mud. This overlying horizon is characterized by a drop in willow pollen grains implying a rapid burnt-down of the area of the peatland. The advent of acidic, toxic plants and those tolerating treading as seen in the pollen record during this horizon refers to an increasing importance of animal husbandry, implying human origin of the transformation. This horizon was dated to the 10th century, possibly marking a large demand for meat produce as a result of higher population densities following the foundation of the Hungarian state. In the zone between 130 and 110 cm there is an aquatic horizon implying the emergence of floating mats in the area (*Fig. 6*). The hollow stem of reed leaning over the lakebed must have served as a natural raft for successive plant generations, providing them habitat and sufficient nutrition, enabling the emergence of floating mats. The thickness of this layered plant complex may reach such proportions, which enables the advent of trees onto the mats as well as time passes, as was the case of Nádas Lake as well.

Based on chronometric data, the emergence of floating mats must be dated between the 11th and 16th centuries, seen in the continuous and steady increase in organic components and the advent of reed, willow, and bulrush to the area connected to the natural succession of the marshland. Nevertheless, two ash and wood remain peaks in this part of the profile can clearly be correlated with a significant drop in the amount of oak pollen grains. The ash peaks correspond to drops in reed fragments implying the development of natural or artificial fires in the reed zone fringing the lakebed. The second ash peak at 96 cm with a parallel increase in the ratio of weed and cereal pollen grains indicate a larger deforestation again attributable to mixed agriculture of crop cultivation and animal husbandry in the area. As shown by the archeological record (*Zatykó*, 2005), this period was characterized by multiple periods of plot shifts, deserting population, and revivals.

The first written record of the settlement of Nagybárkány can be dated to this period at around 1220, when it was the property of the Zách clade. The climate is characterized by natural cycles with a temperature maximum and a precipitation minimum during the 13th century. This climatic transformation resulted in real dry conditions yielding the extermination of peat-mosses from the area of the lake. Peat-mosses managed to conquer the lakebed only during the 16th century. When pollen-based paleoclimatic data for the 8th and 13th centuries are compared, it becomes clear that the 13th century transformations are much more pronounced. The aridity index must have been 4 times of that inferred for the 8th century as a result of the elevated temperatures and a drastic drop of annual rainfall. Yet as it was recorded in the written historical documents, the 13th century collapse of the Hungarian Kingdom were by no means the outcome of environmental changes, but rather political ones; the military defeat of the Hungarian troops by the Mongol tribes. The inland political fights and restructuring of the feudal social and political system is explained by historians by not the extreme dry conditions characterizing the period, but rather the loss of royal power, financial problems, and the collapse of the traditional latifundium system.

Conversely, several authors emphasize the role of extreme dry climate in the collapse of the Avar Empire and the resulting inland political tensions in a period, when the aridity index was much lower, relatively negligible compared to the 13th century conditions. Some papers postulated a „*devastating drought*" accompanied by famine waves which must have affected „*the warrior nation of the half-nomadic Avars*" (*Rácz*, 2008, pp. 54–55). Conversely, the statement according to which „*the more drought tolerant Slavic tribes could have been better suited to eliminate the hardships of draughts by withdrawing near oak woodlands and using acorn as fodder in the hard times*" (*Rácz*, 2008), was turned down by our paleoenvironmental data from the Nádas Lake, as this type of landscape use was present since the Age of Great Migrations in the area. Thus, this type of landscape economy must have emerged preceding the arrival of the Slavs to the area. Our paleoenvironmental data also calls for the re-evaluation of postulations made regarding the collapse of the Avar Empire. Since social processes and disturbances can only be linked to natural catastrophes if and only if there were such catastrophes in the referred area during the referred period. Based on our data, this problem must be treated with great caution, as highly different climatic conditions must have emerged in the area than stated by numerous recent paleoenvironmental studies (*Magny et al*., 2008).

In contrast to the previous periods, the one starting from the 16th century till today is characterized by intensified rainfall and cooler conditions, resulting in a thriving of peatland conditions in the area of the Nádas Lake at Nagybárkány. The floating mats were turned into peatmossy reeds and willow peatland. This is the period when the highest organic content (around 80 – 85%) was recorded. Nevertheless, several inorganic peaks are observable as well reflecting soil erosion from the neighboring areas as a result of recurring deforestation activities. These transformations are observable at a regular centennial scale, which can be tracked to intentional forest management. Numerous ash peaks are observable in the lower part of the zone coinciding with a halt in the expansion of reed-beds. The continuous presence of weed, buttercup, and plantain pollen grains in the record refer to permanent human activities in the area and continuous disturbances. The most dynamic advent of peat-mosses is observable in the most recent periods attributable to a deserting population in the area.

5.3. Autogenous peat-bog phase (after 1300 cal BP)

The development of the present-day bog and the commencement of peat accumulation can be dated to the end of the early Middle Age. At around 1300 AD, the number of *Typha* rhizomes increases significantly, indicating a rise in the water level and the formation of a floating mat. The hydroseries of the bog was from this point on characterized by autogenic processes, with a tendency towards a gradual oligotrophication.

Based on detailed phytogeographical studies, floating mats of *Phragmites* and *Typha* are frequent components of lake shore vegetation in Hungary. The first signs of peat-bog formation from these floating mats can be seen in a massive expansion of *Thelypteris palustris*. As time goes by, peat-mosses also turn up on the mats (*Borhidi* and *Balogh*, 1970; *Balogh*, 2000a, b). Based on the paleobotanical investigations, the bog development passed through phases characterized by *Typha* → *Thelypteris palustris* → *Meesia longiseta* → *Sphagnum* spp.. This development shares numerous similarities with the formation of two other *Sphagnum*-bogs at the Csaroda–Báb Lake (*Jakab* and *Magyari*, 2000) and Kelemér-Nagy-Mohos (*Magyari et al.*, 2001), suggesting some sort of regularity in the formation of Hungarian *Sphagnum*-bogs. *Meesia longiseta* preceding the expansion of *Sphagna* is highly interesting. The taxon *Meesia longiseta* is a unique component of the flora of the Carpathian Basin with a single occurrence recorded in Hungary from 1885 (*Boros*, 1968). According to *Hall* (1979), the appearance of *Meesia longiseta* can be linked to a distinct phase of wetland succession, characterized by the transformation of the brown moss sedge floating mat into acidic *Sphagnum*-bog. This species was observed during the secondary succession of abandoned lakes used for retting hemp. *Odgaard* (1988) reported the same for *Meesia triquetra*.

Representatives of *Sphagna* seemed to have appeared in similar quantities during the middle part of the 17th century as today, followed by a complete drop till 0 BP. Surprisingly, the taxon *Sphagnum palustre*, indicating mesotrophic conditions, was present in the largest numbers. In the pollen record *Sphagnum* reaches a maximum peak at 70%, at the same time (*Juhász*, 2005). This expansion of *Sphagnum* coincides with the coldest period of the Little Ice Age (*Rácz*, 2001), which was also the coldest time of the past 2000 years (*Fig. 7*). The Little Ice Age dates from the middle part of the 16th till the middle part of the 19th centuries (*Bradley et al.*, 2003). The most significant cooling is put to the terminal part of the 16th century, when a major drop in the average temperatures is traceable across entire Europe (*Pfister*, 1999; *Pfister* and *Brázdil*, 1999).

As shown by archeological data (*Zatykó*, 2005), the traditional Medieval Age settlement system collapsed followed by the emergence of unpopulated areas in the analyzed region during the Ottoman occupation and scattered farmstead-like settlements from the 16th century onwards. The geochemical composition and the increasing amount of charcoal indicate that the human disturbance decreased around the analyzed catchment basin in the 18th century. According to the pollen analytical data, human impact on the vegetation became more intensive (*Juhász*, 2005). There was a rapid decrease in the amount of *Sphagnum palustre* preferring mesotrophic conditions (*Daniels* and *Eddy*, 1985). A rapid expansion of *Juncus effusus* indicates eutrophication, and the quick spread of weeds. Forest management, accompanied by increased soil erosion in the study area resulted in an enrichment of plant type nutrients on the marsh. The steady expansion of *Sphagnum squarrosum* refers to the emergence of an acidophil but eutrophic peatland in the area. *Sphagnum squarrosum* relatively tolerant to high Ca, bicarbonate levels, and pH (*Clymo*, 1973), and in mineral rich habitat with a high nutrient supply grow very fast (*Kooijman*, 1993). The expanding beds of *Sphagnum squarrosum* are capable of capturing and accumulating Ca via ion exchange (*Anschutz* and *Gessner*, 1954; *Clymo*, 1963; *Kooijman*, 1993). The recorded Ca content of the embedding sediments seems to display a strong correlation with the amount of peat-moss, which is a clear sign of the excellent Ca ion bonding capacity of peat-moss. Reed is also capable of accumulating Ca in its rhizomes similarly to peat-mosses (*Kovács et al.*, 1978; *Penksza et al.*, 1994; *Podani et al.*, 1979; *Tóth* and *Szabó*, 1958).

A smaller drop in the water-level can be dated to the turn of the 15th –16th centuries, reflected by the expansion of green algae and the retreat of alder, and the rise of aquatic species and reed. A secondary reforestation following forest clearance is reflected by the expansion of hornbeam around 1500. A slight rise in the water-level and a gradual reforestation can be noted during the Ottoman period. The warmer and drier climate observed at the paleoecological sites from 9th to 14th centuries coincides with the so-called Medieval Warm Period (MWP) in Europe, which is supposed to have been characterized by a warmer and wetter climate (*Lamb*, 1977). The opening of this period can be placed between the 9th and 11th centuries with differences regarding the applied analytical methods, sources of dating, and regions (*Bradley et al*., 2003). On the contrary to the widely accepted idea of the warmer and wetter climate of MWP, in the cases of 14 Hungarian paleoecological sites, drier climate can be noted, in spite of high amount of precipitation. It appears that the increasing evapotranspiration, following the higher temperature led to a drier climate and a drop in the water-level of the lakes. These results concerning medieval (pre-15th-century) climatic processes are among the first data derived from the medieval layer of a sediment core extracted at the Hungarian sites and call the attention to the great importance of regional studies in order to refine further the local variations of climate conditions.

6. Conclusions

The development of the bog can be divided into three main phases in the light of macrofossil analysis. The first phase spanned the late Glacial to the mid-Holocene layers. The trophic conditions in this phase were oligo-mesotrophic and mesotrophic. The water level was high, although with minor fluctuations. A hiatus of roughly 4400 years can be noted in the sediment after this phase, owing to peat-cutting during the Imperial Age. The water level decreased slightly, the trophic conditions became eutrophic, and the lake was fringed by macrophyte vegetation. This period was characterized by the fluctuation of the lake's trophic conditions. This phase can be dated to the late Holocene, lasting until the end of the early Middle Age, at the beginning of the 14th century. The last phase, spanning the period up to the present, saw the paludification of the lake and the cessation of the open water surface.

The hydroseries was characterized by autogenic processes, with taxa *Thelypteris palusris* and *Meesia longiseta* playing a key role. Peat-mosses appeared in the same quantities during the coldest period of the Little Ice Age dated to the middle part of the 17th century as today. The subsequent periods saw a temporary decrease in their amounts. Forest management, accompanied by increased soil erosion in the study area resulted in an enrichment of plant type nutrients on the marsh during the past 200 years. The steady expansion of *Sphagnum squarrosum* refers to the emergence of an acidophil but eutrophic peatland in the area. Based on our findings, changes in the paleohydrology and aquatic vegetation of the bog were mainly driven by climatic changes and autogenic processes. Recurring human influences have also significantly modified the natural path of succession in the studied area.

7. Summary

The profile of the Nádas Lake at Nagybárkány speaks about continuous sedimentation from the Paleolithic till the opening of the Copper Age. Then during the opening of the Imperial Period, a major depositional hiatus emerged in the deposits attributable to the creation of a water reservoir system by Celtic tribes in the lakebed. This initiated a secondary succession which enabled us to make inferences about the environmental historical evolution of the area for the past two millennia at a scale of centuries alone. With the help of paleoecological and geological data, a better reconstruction of climatic fluctuations was made from the Imperial Age up to modern times. As it was shown by our data, one must exercise caution in interpreting the correlations of environmental and social crises, e.g., in the case of the fall of the Avar Empire. An objective and correct approach is the careful and most elaborate utilization of available paleoenvironmental data from the area of the Carpathian Basin.

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