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Holocene palaeohydrology and environmental history in the South Harghita Mountains, Romania

Holocén hidrológiai és környezeti változások a romániai Dél-Hargita-hegységben

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(11 ábra, 4 táblázat)

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Tárgyszavak: holocén, paleoökológia, Szent Anna-tó, Románia

Összefoglalás

A tanulmány az erdélyi Csomád-hegycsoport fiatal krátertavának, a Szent Anna-tónak a holocén üledékfeldolgozását tárgyalja. Pollen, növényi makrofosszília, szilíciumvázas alga- és nyomelemvizsgálatok segítségével rekonstruáltuk a holocén környezetváltozásokat és a tó vízszintjének ingadozásait. Vizsgálataink alapján a kráterben mintegy 9800 és 8800 kal. BP évek közt sekély oligotróf tó alakult ki, melyet 8800 évvel ezelőtt a vízszint csökkenését követően tőzegmohaláp nőtt be. A szárazföldi vegetációban a mogyoró (*Corylus avellana*) dominanciája jellemezte ezt az időszakot. A diatóma- és makroflóra változásai alapján 7050 évtől a tó vízszintje fokozatos emelkedésnek indult és egészen 5500 évig sekély, vízimohákban gazdag oligotróf tavi állapot alakult ki. 5500 évvel ezelőtt a vízsszint jelentős emelkedése egybeesett a szárazföldi vegetációban a gyertyán (*Carpinus betulus*) terjedésével. A vízszint emelkedését a tó produktivitásának növekedése és gazdag makrofiton vegetáció kialakulása kísérte. A holocén folyamán a legmélyebb tavi állapot a bükk (*Fagus sylvatica*) dominanciájával egyidőben, kb. 2700 és 700 évek közt alakult ki. A tópartot a makrofosszília vizsgálatok alapján a kora-holocéntől kezdődően lucfenyves (*Picea abies*) erdősáv borította mely függetlenül a zonális erdőtársulások változásaitól mindvégig fennmaradt a tómedence hűvös mikroklímájának köszönhetően.

Abstract

In this study we present the results of a multi-proxy investigation carried out on the sediment of a crater-lake – Saint Ana (Szent Anna-tó) – located in the Harghita Mts in the middle range of the East Carpathians in Romania. Pollen, plant macrofossil, siliceous algae and trace element analyses were used to reconstruct Holocene environmental and water-depth changes. Reconstruction of the Holocene lake-

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level changes was based on the diatom and plant macrofossil records. According to these, the water depth showed considerable fluctuation during the Holocene, in most cases occurring coincidentally with the terrestrial vegetation changes. It is significant that, low water depths characterised the early Holocene until ca. 8800 cal yr, when the open water became overgrown with vegetation and the lake turned into a *Sphagnum* bog. From ca. 7050 cal yr BP the water depth grew gradually and shallow water conditions prevailed until ca. 5550 cal yr BP, when a marked increase was detected and this was accompanied by increasing productivity. The highest lake-levels were found between 2700 and 700 cal yr BP. The geochemical record points to the thermal stratification of the lake in this period. The early Holocene terrestrial vegetation of the area was characterised by *Ulmus – Fraxinus* forests that were replaced by *Corylus* at ca. 8800 cal yr BP. This was followed by the re-expansion of *Fraxinus, Quercus* and *Tilia* and the spread of *Carpinus betulus* from ca. 7500 cal yr BP. The formation of a forest belt dominated by *Carpinus betulus* was dated to 5500 cal yr BP, while the two-step expansion of *Fagus sylvatica* took place between 3700 and 3300 cal yr BP. From 3300 cal yr BP *Fagus sylvatica* became the dominant canopy tree in the forests around the lake. Joint interpretation of the terrestrial pollen and plant macrofossil records also highlights the difference between the lakeshore and hillslope vegetation throughout the Holocene. The persistence of the lakeshore *Picea abies* forest belt can be explained by the cooler and moister microclimate of the basin, leading to thermal inversion. The geochemical record shows high Fe and Mn concentrations between 8150–6600 cal yr BP; from which reducing soil conditions and an oxygen rich sedimentary environment have been inferred. Following the increase in lake-level at 7050 cal yr BP, a gradually increasing amount of P was deposited in the lake pointing to increasing productivity.

Introduction

In the past couple of years, several high-resolution, radiocarbon-dated pollen diagrams were published with reference to the East and South Carpathians in Romania. These studies pointed to diversified Late Glacial and Holocene vegetation development along altitudinal and latitudinal gradients (Fărcaş et al. 1999, 2003; Rösch & Fischer 2000; Wohlfarth et al. 2001; Björkman et al. 2002a, b; Bodnariuc et al. 2002; Tantau et al. 2003; Feurdean & Bennike 2004; Feurdean 2005). While the Late Glacial and Holocene vegetation phases are well known, very few studies have dealt with the climatic fluctuations and hydrological changes within the Holocene. There have been attempts at high-resolution Holocene palaeoclimate reconstruction using speleothelm stable-isotope records (Onac et al. 2002; Tamas 2003 and Constantin 2003 cited in Feurdean 2004, Kern et al. 2003) and testate amoebae from peat bogs (Schnitchen et al. 2002, 2003). Most recently, Feurdean and Bennike (2004) published pollen and plant macrofossil data based on Late Glacial and Holocene palaeoclimate reconstruction for NW Romania. These data suggest that in the southern and northern parts of the Romanian Carpathians different temperature regimes prevailed during the Holocene. Furthermore, the Early Holocene climatic reversals of the North-Atlantic palaeo-records can also be traced in NW Romania (Feurdean & Bennike 2004). The testate amoebae records point to a marked increase in precipitation from 2800 cal yr BP (Schnitchen et al. 2002, 2003).

Although small, closed lake basins are popular objects of palaeoenvironmental research (Lotter 2003), and occur in a large number in the East Carpathians, so far little interest has been shown towards to them (eg. Diaconeasa & Mitroescu 1987). This is true in spite of the great variety of techniques that can be used to obtain palaeoecological reconstruction from lake sediments (Last & Smol 2001; Smol et al. 2001). In this study we present the results of a multi-proxy investigation carried out on the sediment of a crater-lake – Saint Ana – located in the Harghita Mts in the middle range of the East Carpathians in Romania (*Fig. 1*). Pollen, plant macrofossil, siliceous algae and trace element analyses were used to reconstruct Holocene environmental and water-depth changes. Our aim was to investigate the relationship between terrestrial vegetation, water depth fluctuation and soil development. In particular, the environmental changes which occurred during the transition from *Fagus sylvatica* to *Carpinus betulus* dominated forests have been given special attention.

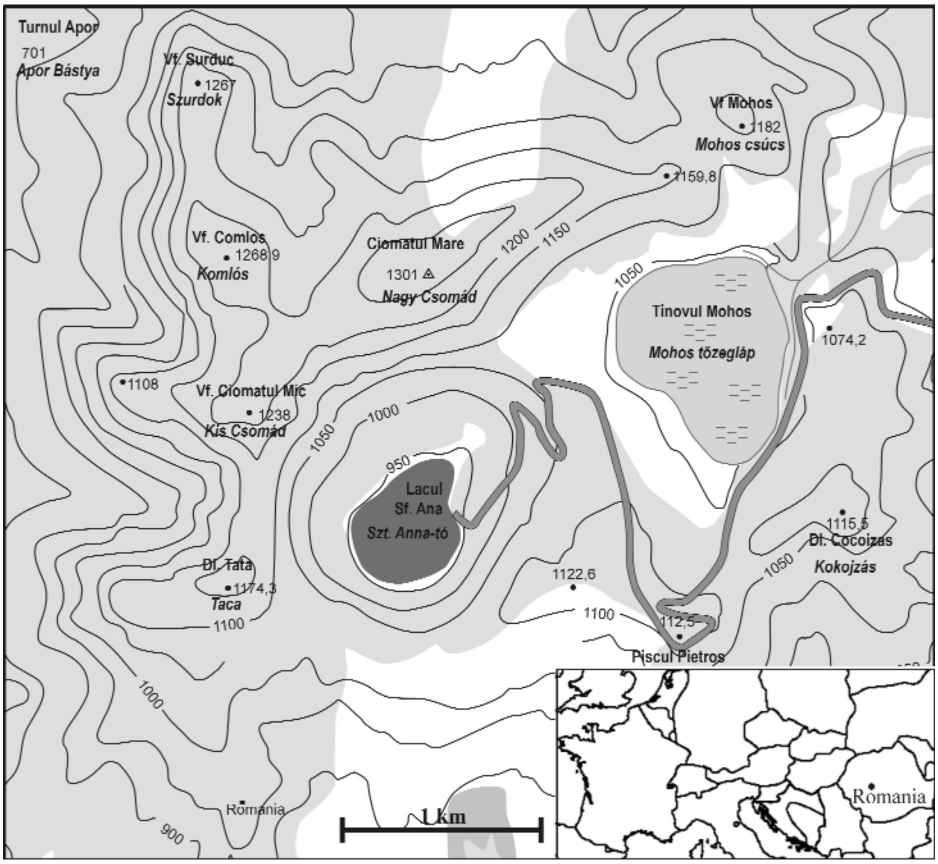


Fig. 1 Location of the study site in Europe and topographic map of the Ciomatu Massif showing the location of Lake Saint Ana. The grey-shaded area denotes closed forest and white colouring indicates grazed meadows

1. ábra. A mintavételi terület helyzete Európában és a Csomád hegycsoport topográfiai térképe a Szent Anna-tóval. A szürkével árnyalt területek zárt erdővel borítottak, míg a fehér háttér legelőket jelöl.

Study area

Lake Saint Ana (Szent Anna-tó) is a young crater lake in the Ciomatu Massif (Csomád-hegycsoport) of the Harghita Mountains (Hargita-hegység) (SZAKÁCS & SEGHEDI 1995). It is located 3 km SE of Baile Tusnad (Tusnádfürdő), in the vicinity of the peaks Ciomatul Mic (Kis-csomád) and Ciomatul Mare (Nagy-csomád, *Fig. 1*).

The water in the lake is quite clear, but tourist guides often exaggerate when they describe the lake as the cleanest water-body in the world (Kristó 1994). This is due to the lack of underground and riverine water inflows; the lake is fed only by rainwater and run-off from the surrounding slopes (Pál 2000, 2001). Lake Saint Ana is situated at 950 m asl, while the crater rim is 120–350 m above it. The perimeter of the lake is 1.75 km and the largest diameter 650 m (*Fig. 2*). The catchment area is 2.15 km^2. The area of the lake decreased rapidly at the beginning of the last century; in 1909 it was 0.214 km^2, in 1957 0.195 km^2, while in 2000 it was only 0.193 km^2 (Kristó 1995, Pál 2000). The water depth has also decreased; in 1869 Orbán (1869) recorded 12.5 m, in 1909 Gelei (1909) measured it to be 8.3 m, while in 2000 the deepest point was 6.0 m (Pál 2000). During winter the lake is covered by thick ice. According to Pál's measurement (2001), the average thickness of the ice cover in January is 73 cm. The lake water is characterised by seasonal fluctuation in pH; in the summer months pH ranges 6–6.4, while in autumn and spring it is 4.2–4.5.

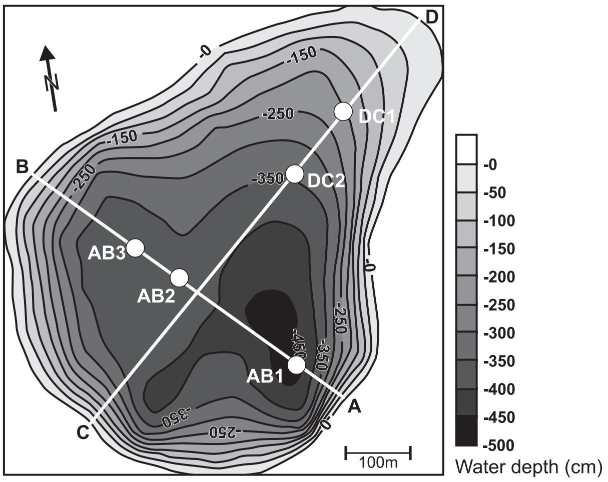


Fig. 2 Core locations and bathymetric map of Lake Saint Ana. Note that the recorded depths on the bathymetric map are based on sondage echograms. Due to the presence of a ca. 1 m thick gelatinous stratum consisting of organic matter above the surface consolidated sediment, the echograms underestimate the depth of the lake (Pál 2001)

2. ábra. A Szent Anna-tó batimetriai térképe a fúráspontok helyzetével. A térkép által jelölt vízmélységek szonda echogramok alapján becsültek. A konszolidált üledék felett lebegő zselatinszerű szerves anyag miatt az echogramok kb. 1 méterrel alulbecsülik a vízmélységet

The geology of the Ciumatu Massif was influenced by volcanic activity along the inner arch of the Eastern Carpathians; this activity abated during the Late Tertiary and Quaternary (Juvigné et al. 1994; Szakács & Seghedi 1995; Moriya et al. 1996; Karátson 1999). However, post-volcanic activity is still present in the forms of mineral water springs, and carbon dioxide and hydrogen sulphide gas-flows (*mofettas* and *solfataras*). Ciomatu is a single volcano with two craters: the well-preserved Saint Ana and the older, more eroded, breached Mohos (*Fig. 1*). The base rock of the mountain comprises sandstone and conglomerate (flysch formation). This base was covered by a number of lava domes and, finally, by pyroclastic deposits of amphibole biotite dacite magma. The age of Lake Saint Ana, which was formed subsequent to the last eruption, is uncertain. The earliest eruption of the crater has been dated at 10 to 35–42 ka BP, using charcoal from the eruption material (Juvigné et al. 1994), and charcoal and paleosoil (Moriya et al. 1996).

The climate is continental-temperate. The height of the mountain (1301 m) and the frost retention in the Tusnad Gorge (*Fig. 1*) are the main factors that determine the climate in the Ciomatu Massif. The January mean temperature is around –5°C.

The warmest month is July; the mean temperature in Baile Tusnad is 18 °C, while in the vicinity of Lake Saint Ana it is 15 °C. Annual precipitation is around 800 mm (KRISTÓ 1995). An important characteristic of the Tusnad Gorge is thermal inversion which results in the reverse order of the vegetation belts; deciduous forests of *Fagus sylvatica* are normally located above *Picea abies* forests. According to the observation of SHUR (1858), Lake Saint Ana was surrounded by dense *Picea abies* forest in the middle of the 19th century. *Picea* trees were in contact with the lake water, while on the slopes *Fagus sylvatia* formed a forest area with the scattered occurrence of *Abies alba*. In 1929, NYÁRÁDY also reported a dense *Picea*-forest, but only a few metres distance from the lakeshore. On the hillslopes he only found *Picea abies*, *Juniperus communis, Pinus sylvestris* and scattered *Fagus sylvatica.* His observations are probably related to the extensive forest fire at the beginning of the 20th century (NYÁRÁDY 1929). Today the slopes around the lake are covered again by dense *Fagus sylvatica* forest and in some places *Picea abies* extends upslope well into the *Fagus* stands. In the shallow NE corner of the lake a "floating fen" has developed (*Fig.* 2). Its extent has increased in the last couple of years (PÁL 2000). The matrix of the floating mat is formed by *Carex rostrata* and *C. lasiocarpa. Sphagnum* species and *Lysimachia thyrsifolia* appear on this mat. Botanical reports indicate that the extent of the floating mat and the occurrence of more nutrient-demanding aquatic and telmatic macrophytes have changed dramatically over the last two centuries. For example, SHUR in 1858 reported the occurrence of *Pedicularis palustris, Utricularia vulgaris* and *Phragmites australis.* However, SHUR's observations were questioned by NYÁRÁDY (1929) and BOROS (1943) since they failed to find these taxa on the lakeshore floating fen.

Methods

The lake was bored in the summer of 2001. Sediment profiles were obtained from a boat using a 7 cm diameter Livingstone piston corer with a chamber length of 100 cm (WRIGHT 1967). Borings were made along two transects (*Fig.* 2). At the location of core SZA-AB3 boring started at a water depth of 600 cm and reached 1023 cm. In spite of repeated efforts, no further sediment could be retrieved and thus it ended with a sharp boundary. This study will discuss core SZA-AB3.

In the laboratory, core sections were sub-sampled at every 4 cm for loss-on-ignition and elemental analyses, and at 4 to 8 cm for pollen and diatom analyses using a volumetric subsampler. Plant macrofossil samples were obtained by sieving 2–4 cm thick half-core sediment slices using a 300 mm sieve. Sample volume ranged between 10–21 cm^3. For the determination of the organic content of the sediment the loss-on-ignition technique was used following DEAN (1974). Total organic carbon (TOC) was determined for 30 samples using the Rock Eval pyrolysis method (ESPITALIE et al. 1985).

For the elemental analyses 1 cm^3 of dried samples were digested with 65% nitric-acid and 25% hydrogen-peroxide using the technique of BENGTSSON & ENELL (1986). This procedure enables the extraction of the loosely-bound cations derived from the surface of the clastic mineral and organic components of the sediment (ENGSTROM & WRIGHT 1984). Acid-soluble concentrations were measured by inductively-coupled plasma atomic emission spectrometry (ICP-AES).

Samples for siliceous microfossil analysis were treated with hot 30% hydrogen peroxide and sulphuric acid, after which the residues were embedded in Zrax. For light microscope analysis LEICA DM LB2 was used (100 HCX PLAN APO). Scanning electron microscopy was performed with a Hitachi S-2600N. The nomenclature of KRAMMER & LANGE-BERTALOT (1986–1991) was followed, as well as the volumes of Diatoms of Europe (KRAMMER 2000, LANGE-BERTALOT 2001), and LANGE-BERTALOT & METZELTIN (1996). The *Eunotia* taxa were checked following PETERSEN (1950) and ALLES et al. (1991). Approximately 300 diatom valves were counted at each level. The percentage ratio of diatoms to *Chrysophycean* cysts follows SMOL (1985). Environmental variables, the pH and the epilimnetic total phosphorous (TP), were inferred using diatom-water chemistry transfer functions. Training sets from the European Diatom Database (EDDI) were compared to the fossil assemblages, and in this way 44 species were selected for further analysis (>95% of total diatom). Environmental reconstructions were made by locally-weighted averaging (LWWA; JUGGINGS 1991). The number of common species between the best-performing training set and fossil samples were 25 for pH and 18 for TP. Further details of the multivariate calibration are given in BUCZKÓ et al. (in prep).

Pretreatment for pollen analysis followed the standard chemical process described by BERGLUND & RALSKA-JASIEWICZOWA (1986). 1 cm^3 sediment samples were processed and microfossil concentrations were determined using *Lycopodium* tablets (STOCKMARR 1971). Pollen identifications are based on the descriptions and identifiation keys given in MOORE et al. (1992). Counting was continued until a terrestrial pollen sum of 500 was attained. The main pollen sum (M) includes trees, shrubs, dwarf shrubs and terrestrial herbs. Taxonomic nomenclature follows the pollen taxon list of the European Pollen Database.

Plant macrofossil analysis was carried out using the modified version (JAKAB et al. 2004a, b) of the semi-quantitative quadrate and leaf-count macrofossil analysis technique (BARBER et al. 1994). For the identification of herbaceous plant tissues the textbook of JAKAB & SÜMEGI (2004) was used. To obtain concentrations for the macrofossil components, a known amount of marker grains (0.5 g poppy seeds, ca. 960 pieces) were added to the samples. In the diagrams, the total number of seeds relates to 20 cm^3 ofsediment, while other macrofossil components are expressed as concentrations (piece cm^{-3}).

Numerical and multivariate analyses were performed using PSIMPOLL 3.00 (BENNETT 1992), SYN-TAX 5.0 (PODANI 1993), and SPSS (NORUSIS 1990).

The pollen, plant macrofossil and siliceous microfossil diagrams have been zoned using optimal splitting by information content (BIRKS & GORDON 1985). The element-concentration diagram was zoned by clustering the principal component sample scores (see below).

Results

Sediment stratigraphy and radiocarbon chronology

Sediment colour was recorded in the field followed by a more detailed textural analysis in the laboratory. Based on these observations four stratigraphic units were distinguished (*Table 1*).

Table1 Lithological description of core SZA-AB3, Lake Saint Ana, Romania. The notation after the lithological description follows the key of TROELS-SMITH (1955)

1. táblázat Az SZA-AB3 fúrásszelvény rétegtani leírása. Szent-Anna tó, Románia. A nevezéktan és szimbolikus jelölések TROELS-SMITH (1955) munkája alapján

Depth (cm)	Lithological characteristics
1023–1016	Dark brown lake sediment (gyttja) rich in plant macrofossils and Caldocera remains; Ld^{2}Tb^{1}Th^{1}Dg$^+$As$^+$
1016–980	Dark brown peaty lake sediment rich in *Sphagnum*-leaves; *Acer* sp. seed at 1014 cm; Tb^{2}Ld^{1}Th^{1}Dg$^+$Dh$^+$As$^+$
980–960	Dark brown lake sediment rich in macrofossils; abundant moss leaves, predominantly *Warnstorfia fluitans; Eriophorum vaginatum* remains Ld^{2}Dg^{1}Tb^{1}Th$^+$Dh$^+$As$^+$
960–600	Mid brown gyttja with Cladocera remains and occasional plant macrofossils; Ld^{3}Dg^{1}Tb$^+$Th$^+$Dh$^+$As$^+$

Radiocarbon measurements were done on five bulk sediment samples in the Laboratory of Environmental Sciences, Atomki, Hungary (HERTELENDI et al. 1989). Despite the given pollen stratigraphy, the measured radiocarbon ages were older than expected (*Table 2*); moreover, the ^{14}C date near the sediment surface was much older (2040±70 yr BP). Therefore, the presence of old, ^{14}C-depleted carbon (OLDFIELD et al. 1997) was suspected. In an attempt to resolve the problem, a search was carried out for datable terrestrial plant macrofossils in the sediment. Five macrofossil samples were selected and AMS ^{14}C dated in the Poznan Radiocarbon Laboratory (*Table 2*). The results of these datings were stratigraphically coherent and, as is obvious from *Fig. 3*, they were considerably younger than the nearest bulk sediment ^{14}C dates. However, the age offset of the bulk sediment and macrofossil dates was quite variable. Furthermore, it seems that the core-bottom bulk sediment radiocarbon date is not affected by ^{14}C-depleted carbon, as it falls on the extrapolated age-depth line (*Fig. 3*). It was noticed that this sample showed a low δ^{13}C value, pointing to a predominantly terrestrial origin of the dated material (BJÖRCK et al. 1998).

The origin of the old carbon in the sediment has not yet been investigated. CO_2 upwellings were reported from the crater by GELEI (1909). Therefore, it can be suggested that these could have been the source of old carbon in the lake ecosystem. Taken up by photosynthetic algae, the ^{14}C-depleted CO_2 passes through the aquatic food chain, and this can lead to anomalously old ages when measured by radiocarbon. A similar phenomenon was found by HUNTLEY et al. (1999) in Italian crater lakes. In such cases, the reliable determination of ages could only be obtained from terrestrial macrofossils.

Table 2 Results of the ^{14}C measurements, core SZA-AB3, lake Saint Ana, Romania. All dates were converted into calendar years BP using the INTCAL98 dataset of STUVIER et al. (1998) and the CALIB v.4.4.2 program

2. táblázat. A ^{14}C mérések eredményei. SZA-AB3 fúrás, Szent-Anna tó, Románia. A koradatokat az INTCAL98 kalibrációs adatsort (STUVIER et al. 1998) felhasználva kalibráltuk a CALIB v.4.4.2 számítógépes szoftver segítségével

Laboratory code	Dated material	Method of ^{14}C measurement	Depth below water surface (cm)	δ^{13}C(PDB) ± 0,15[‰]	^{14}C ages BP	Calibrated BP age ranges (1σ)
deb–11316	bulk sediment	bulk	625–630	–24,16	2040±70	1923–2066
deb–11341	bulk sediment	bulk	730–740	–26,34	1860±60	1715–1834
deb–11342	bulk sediment	bulk	825–830	–24,96	5200±90	5889–6002
deb–11318	bulk sediment	bulk	925–930	–26,48	4610±90	5275–5469
deb–11317	bulk sediment	bulk	1020–1026	–28,68	8460±110	9710–9950
Poz–9981	*Fagus* sp. budscale, leaf fragments	AMS	720–725	–	1185±30	1062–1141
Poz–9980	*Fagus* sp. budscale, leaf fragments	AMS	870–874	–	2970±35	3077–3131
Poz–9979	*Picea abies* seed	AMS	908–910	–	3475±30	3691–3728 3790–3825
Poz–9978	*Picea abies* seed	AMS	958–960	–	4830±40	5579–5606 5486–5512
Poz–9976	*Acer* seed	AMS	1012–1014	–	8050±50	8977–9029

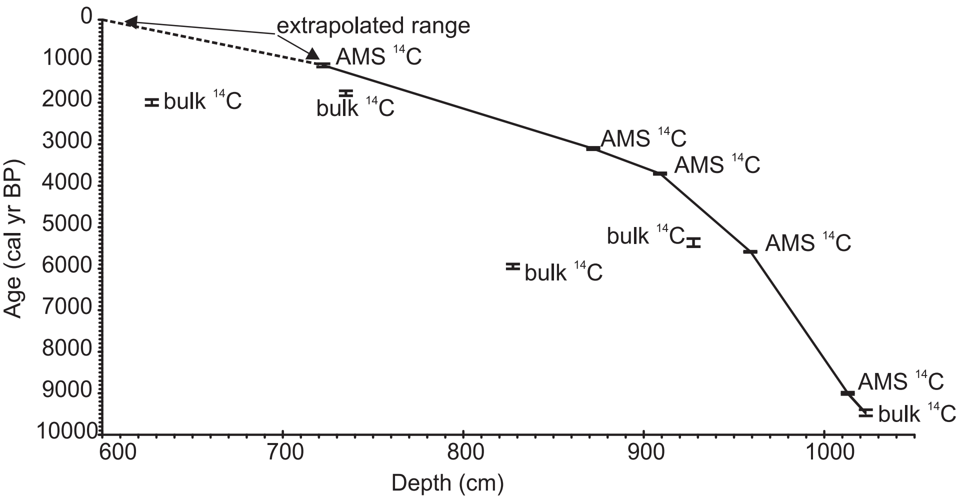


Fig. 3 Calibrated radiocarbon age ranges (1σ) and suggested age-depth curve for core SZA-AB3 (Lake Saint Ana). Note that both bulk sediment and terrestrial macrofossil based AMS ^{14}C dates are shown, but only the AMS ^{14}C dates were used in constructing the age-depth curve. All dates were converted into calendar years BP using the INTCAL98 dataset of STUVIER et al. (1998) and the CALIB v.4.4.2 program. See also Table 2

3. ábra. Kalibrált radiokarbon időtartományok (1σ) és az SZA-AB3 üledékszelvényre alkalmazott kor/mélység függvény (Szent-Anna tó). Az ábrán a teljes üledéken és a szárazföldi makrofosszíliákon végzett AMS radiokarbon mérések eredményeit egyaránt feltüntettük, a korskála számításában viszont csak az utóbbiakat vettük figyelembe. A radiokarbon adatokat a STUVIER et al. (1998) által közölt INTCAL98 adatsor felhasználásával kalibráltuk a CALIB v.4.4.2 program alkalmazásával. Lásd még 2. táblázat

The age-depth model was established by linear interpolation between the terrestrial macrofossil dates (*Fig. 3*). Sedimentation rates are shown in *Table 3*. The bottom part of the core, between 960–1026 cm, is characterised by very low values (0.12–0.15 mm yr^{-1}); the sedimentation rate increases gradually between 960–725 cm (from 0.15 to 0.75 mm yr^{-1}), and attains the highest values in the top 80 cm of the core (1.08 mm yr^{-1}).

Table 3 Sediment accumulation rates for core SZA-AB3, Saint Ana Lake, Romania

3. táblázat Az ülepedési ráta változásai a Szent Anna-tó (Románia) SZA-AB3 fúrásszelvényében

Depth range (cm)	Sedimentation rate (mm/yr)
1026 1014	0.12
1014–960	0.15
960 910	0.27
910–874	0.61
874 725	0.75
725–600	1.08

Chemical stratigraphy

Element concentrations were measured between 1000–600 cm. The results of the analyses are presented in *Fig. 4*. To evaluate changes in the diagram, data were subjected to principal component analysis following logarithmic transformation (*Table 4*). The resultant first four principal components explained 81.7% of the total variance. The distribution of the explained variance between these components was relatively even (23.7, 23.2, 21.2 and 13.6%). This suggests that although several

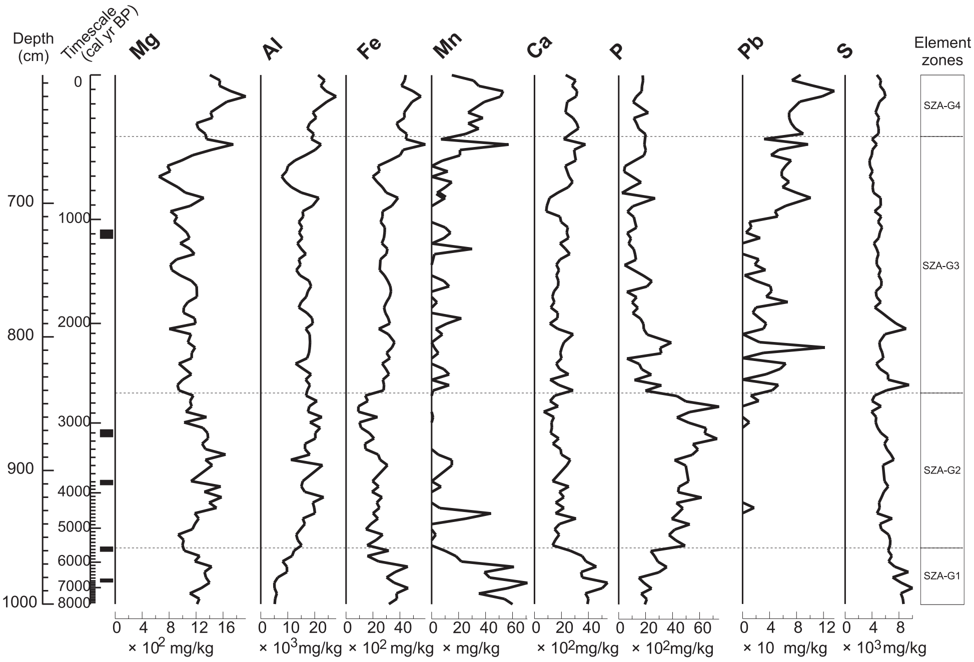


Fig. 4 Frequency distribution of selected trace elements in core SZA-AB3, Lake Saint Ana. Note thedifferent scales

4. ábra A fontosabb nyomelemek koncentrációváltozásai az SZA-AB3 üledékszelvényben, Szent Anna-tó. Figyelem! A koncentrációskálák az egyes elemek esetében eltérnek

Table 4 Results of the Principal component analysis. Data were log transformed before the analysis. Significant eigenvalues for the first four principal components are highlighted

4. táblázat A főkomponens analízis eredményei. Az adatokat logaritmikus transzformációnak vetettük alá a főkomponens analízist megelőzően. A szignifikáns főkomponens értékeket kiemeltük

Element	PCA1	PCA2	PCA3	PCA4
Li	**0.9406**	-0.1345	0.0094	0.0730
Cu	**0.9314**	0.1513	0.1359	0.1247
V	**0.8327**	0.2952	0.0685	0.2557
P	**0.5495**	0.3967	-0.4099	0.4644
Sr	0.1584	**0.8439**	0.1492	0.1184
Pb	-0.1440	**-0.8194**	0.2957	-0.1648
K	0.5075	**-0.7185**	0.0913	0.2323
Al	0.0927	**-0.6384**	-0.3663	0.5723
S	0.2828	**0.6244**	0.3133	0.1056
Mn	0.2243	0.0557	**0.8661**	0.1514
Ca	0.0723	0.3360	**0.8462**	0.0514
Fe	-0.1792	-0.3287	**0.8234**	0.1871
Mg	0.2324	0.0270	0.2708	**0.8495**
Ba	0.1808	0.2054	0.4495	**0.6197**

elements or elemental groups showed variability throughout the sequence, there was not an element or elemental group with a decisively high variability. By clustering these components and plotting the results according to depth, five groups were distinguished (*Fig. 5*). These show clear stratigraphic separation with the exception of groups 3 and 4. Between 842 and 650 cm (2700–440 cal yr BP), samples appear randomly in groups 3 or 4 suggesting alteration between two states. Using the results of these statistical analyses the chemical diagram was divided into four zones (*Fig. 4*).

The chemical record is characterised by a significant negative correlation between Al and organic content (r^2 = –0.82) indicating the attachment of Al to inorganic sediment components, i.e. clastic silicate minerals. Concentration changes of Al in the sediment therefore indicate changes in soil erosion/hillslope inwash (Engstrom & Wright 1984). S concentrations are high in the sediment and this can be connected to high organic content and lake productivity. The highest S concentrations were measured in SZA-G1 (8000–5500 cal yr BP; 1000–958 cm). This zone is also characterised by high Ca, Sr, Fe, Mn, Mg and low Al, K and P values. Taking into account the particularly high organic content (75–88%; *Fig. 4*), we can assume that Ca, Sr and partly Mg are bound to organic substances. High Fe and Mn concentrations suggest reduction of soils in the catchment, and an oxygen rich environment in the sediment surface; the latter resulted in the precipitation of iron and manganese oxides (Mackereth 1966). Above 972 cm (6400 cal yr BP), the respective concentrations of Mn, Fe and Mg decline, while those of Al and P increase. Taking into account the coincident decline in organic content (*Fig. 4*), we can infer increasing inorganic inwash from the surrounding slopes. The second geochemical zone (SZA-G2; 5500– 2700 cal yr BP; 958–842 cm) is characterised by gradually increasing Al and P concentrations. Fe displayed a small-scale decrease, while Mn fluctuated immensely with peak values (936– 932cm: 4730–4600; 896–892cm: 3500– 3430 cal yr BP) followed by non-detectable concentrations (*Fig. 4*). The increase in P can probably be con-nected to the change in the composition of the sediment; *Sphagnum*-peat was replaced by organic lake sediment at around 960 cm (*Table 2*). The increase in Al also correlates with the increasing water depth (see below) and points to gradually increasing inorganic inwash. The third zone (SZA-G3; 2700–420 cal yr BP; 842–650 cm) commenced with a sharp decline in *P* and coincident increases in Fe and Mn. In addition, Pb is detectable in the sediment above 842 cm and without interruption. The cluster analysis indicated oscillation between two distinctive element-compositions (*Fig. 5*). The concentration curves of Fe and Mg in this zone run parallel with Al, thus suggesting that Fe and Mg are predominately bound to silicate minerals. This is also confirmed by the molar ratios of Al:Fe. These show nearly constant values above 840 cm (2700 cal yr BP), while below 840 cm molar ratios fluctuate considerably (*Fig. 11*). Increasing Pb content in the sedimentary profiles is often interpreted as representing atmospheric accumulation (Boyle 2001). The sharp increase at 2700 cal yr BP (840 cm), therefore most likely indicates a boost in metallurgy from the Iron Age. The upper part of the third zone, between 707–695 cm (960–510 cal yr BP) is characterised by episodic increases in Mg, Al and Fe followed by steep declines (*Fig. 4*). The concentration minima of these elements couple with organic content maxima. The same cycle occurs repeatedly further up in the sequence (*Fig. 4*). Tese processes can be interpreted as soil erosion leading to nutrient enrichment and eutrophication in the lake. The fourth zone (SZA-G4: 650–600 cm; 420–0 cal yr BP) is characterised by general increases in Al, Fe and Mn that are superimposed by the above mentioned erosion cycles.

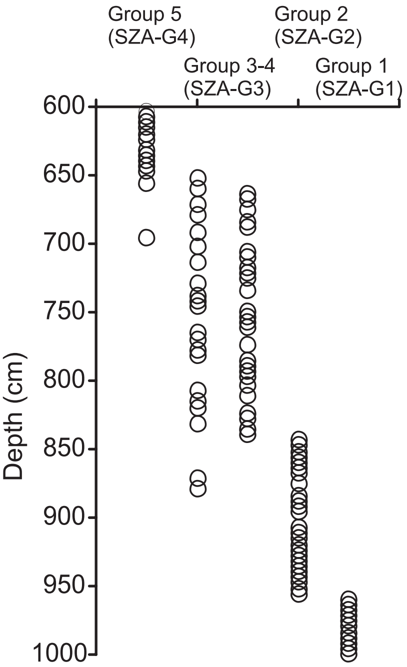


Fig. 5 Results of the cluster analysis made on the component scores of the first four principal components. Trace element concentrations were log transformed before PCA. See also Table 4

5. ábra A nyomelem adatsor első négy főkomponens értékein végzett klaszter analízis eredményei. A nyomelem koncentrációkat a főkomponens analízist megelőzően logaritmikus transzformációnak vetettük alá. Lásd még 4. táblázat

Pollen analysis – terrestrial vegetation development

For the reconstruction of the terrestrial vegetation development, the percentage pollen and macrofossil diagrams were used (*Figs 6a, b, c, 8*). On the basis of these records, the slopes around the lake were covered by mixed *Ulmus* and *Fraxinus excelsior* forests between 9830–8800 cal yr BP (1023–1010 cm; SZA–P1) with *Quercus*, *Tilia* and *Corylus* as admixtures. On the basis of the dominant tree species low-built mesic forest stands can be inferred. Although in the pollen spectra *Picea* shows low percentages, its abundant macroremains in the sediment indicate the growth of *Picea abies* on the lakeshore (*Fig. 6a, 8*) together with *Acer* sp. (*Fig. 7*), and point to the wetter and cooler microclimate of the lake basin. This feature of the vegetation zonation can be connected to a thermal inversion, as is present in the area today; our data suggest its prevalence during the Early Holocene. Towards the end of this phase, from ca. 9000 cal yr BP, *Corylus* started to spread in the forest. The second pollen zone (1010–989 cm; 8800–7500 cal yr BP) is characterised by a further increase in *Corylus* and declining *Fraxinus*, *Ulmus*, *Quercus* and *Tilia* pollen percentages. On the basis of these details the development of *Corylus* dominated forests can be inferred. *Corylus* attained dominance by ca. 7600 cal yr BP (995 cm). The changing character of the forest is also suggested by the occurrence of thermophil shrubs, such as *Euonymus* and *Viburnum*. Increasing pollen percentages and high macrofossil concentrations of *Picea abies* provide evidence for the persistence and possible expansion of the lakeshore *Picea* forest belt. *Picea* probably also grew on the peat bog that occupied most of the basin in this phase (see below). High pollen concentrations, especially during the *Corylus* maximum (ca. 7600 cal yr BP), suggest extremely low sediment accumulation. The third pollen zone (989–957 cm; 7500–5500 cal yr BP) indicates the expansion of *Carpinus betulus*. From 7500 cal yr BP (989 cm) the abundance of mesophil broad-leaved trees (*Fraxinus*, *Tilia*, *Quercus* and *Ulmus*) increases gradually in the pollen diagram which suggests the resurgence of the mixed broad-leaved forests. The lakeshore *Picea* belt receded and *Alnus* probably advanced at the expense of *Picea*, although no macrofossils were found in the sediment. From ca. 6100 cal yr BP, *Picea* expanded again, and *Carpinus* spread rapidly in the mixed deciduous forest. On the whole, this phase is characterised by gradual change in the forest composition. Another element showing changes comprises the terrestrial pollen concentrations that declined from 1.7×106 to 9.51×105 grains cm^{-3} between 7400–6350 cal yr BP (987– 971 cm). A similar trend can be seen in the organic content (*Fig. 6c*) that declined from 80 to 75%. By 5500 cal yr BP, *Carpinus betulus* became the major forest tree and between ca. 5250 and 3300 cal yr BP high pollen percentages point to the development of a distinctive forest belt formed by *Carpinus betulus* (SZA-P4; 957– 886 cm; 5500-3300 cal yr BP). *Picea* pollen percentages were high through this phase and its macrofossils are also present in the sediment, suggesting the continued presence of the lakeshore *Picea* stands. On the basis of the high pollen percentages, it can be assumed that *Picea* expanded uphill and probably mixed with *Carpinus betulus* in this phase. Between 4700–4200 cal yr BP (935–923 cm) several disturbance-indicator herbaceous plants appeared (e.g. *Rumex acetosella/acetosa, Plantago major/media*) with concomitant declines in the organic content and the occurrence of macrocharcoal in the sediment (*Fig. 6b* and *8*). In addition, *Betula* begaan to increase from ca. 4200 cal yr BP, suggesting that secondary forest

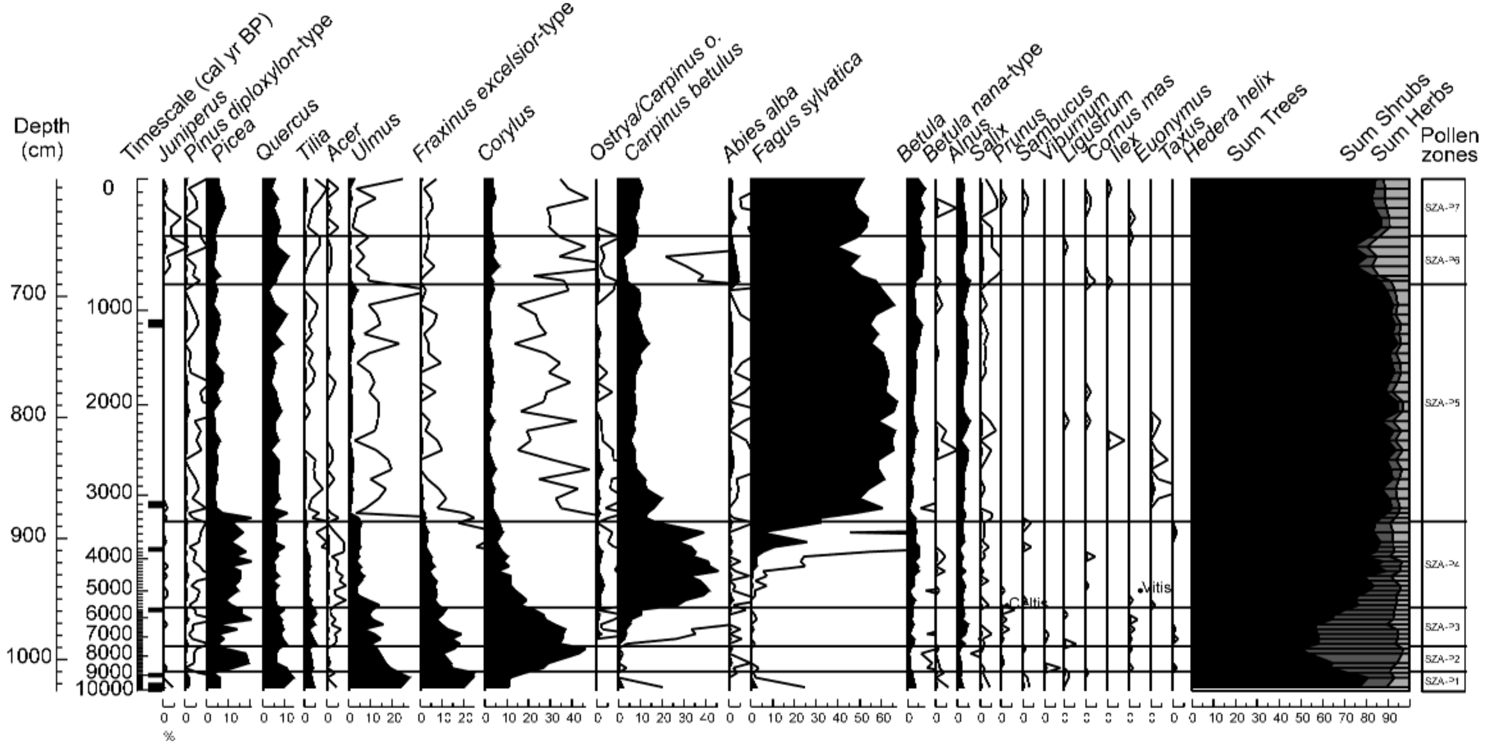


Fig. 6a Percentage pollen diagram from Lake Saint Ana (core SZA-AB3) with selected arboreal pollen types. Both depth and timescales are shown on the left Lines without filling are exaggerated (x10).

6a. ábra. A Szent Anna-tó százalékos pollen diagramja a legfontosabb fásszárú pollentípusokkal (SZA-AB3 fúrás). A diagram mélység és időskála mentén ábrázolja a változásokat. A segédvonalak (kitöltetlen háttér) 10-el felszorzott százalékos értékeket jelölnek.

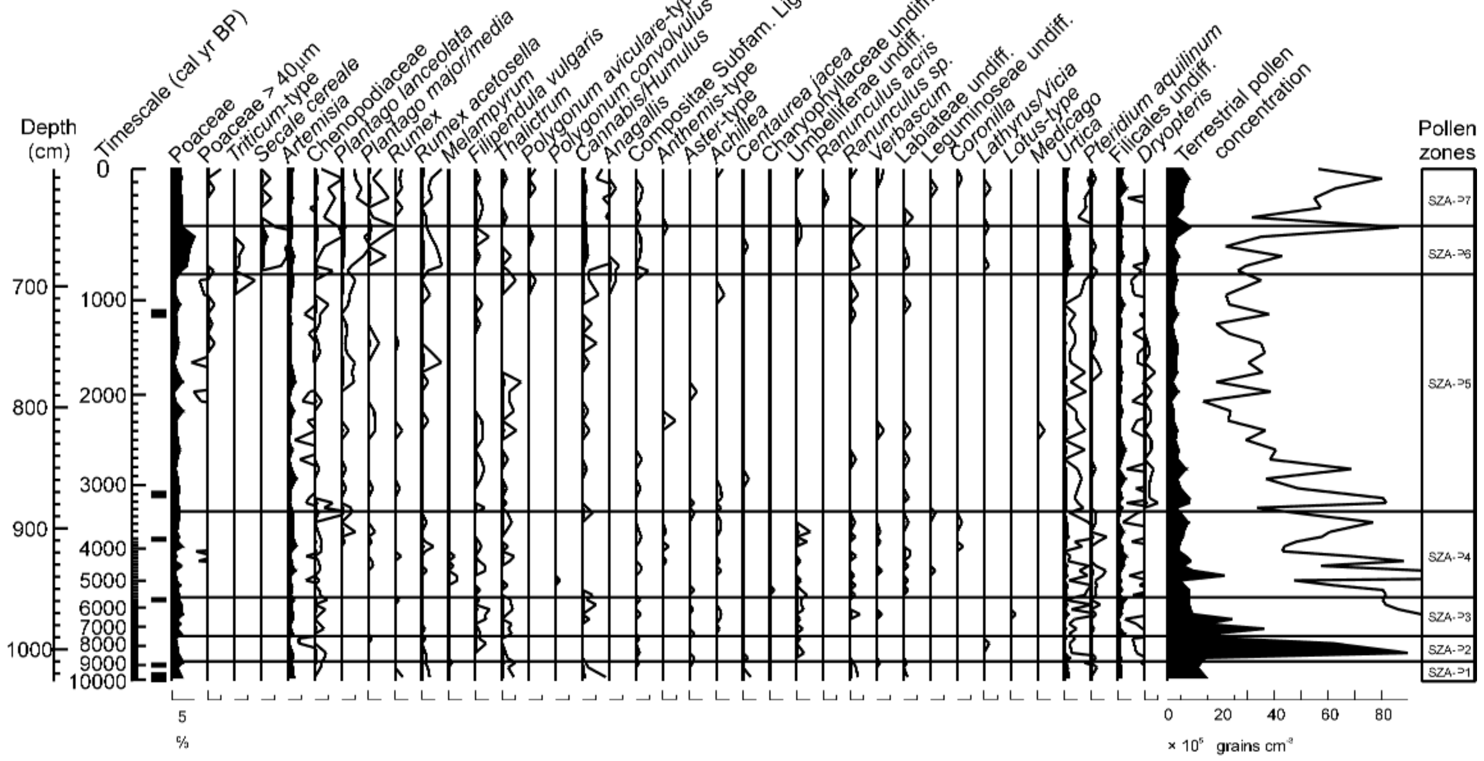


Fig. 6b Percentage pollen diagram from Lake Saint Ana (core SZA-AB3 core) with selected herbaceous pollen types. Both depth and timescale are shown on the left. Lines without filling are exaggerated (x10)

6b. ábra A Szent Anna-tó százalékos pollen diagramja a legfontosabb lágyszárú pollentípusokkal (SZA-AB3 fúrás). A diagram mélység és időskála mentén ábrázolja a változásokat. A segédvonalak (kitöltetlen háttér) 10-el felszorzott százalékos értékeket jelölnek.

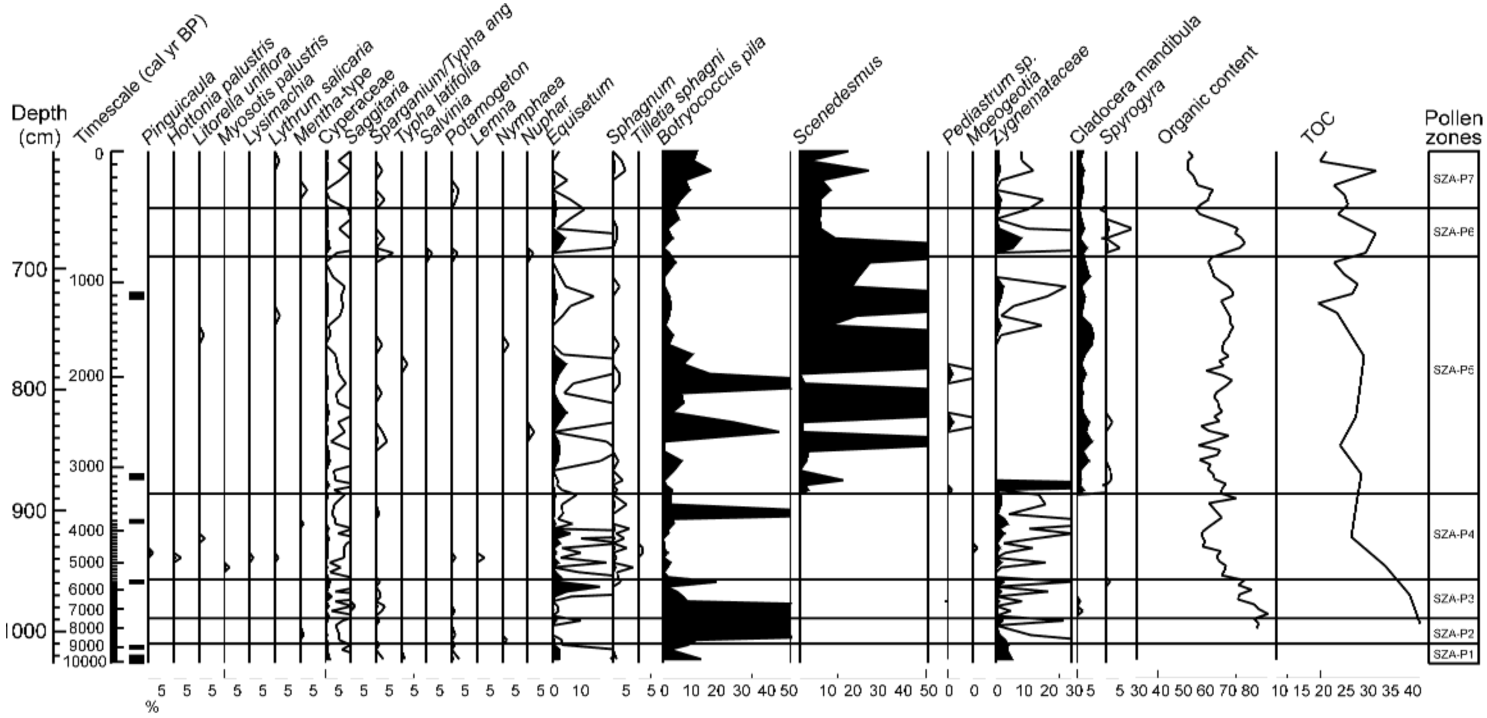


Fig. 6c Percentage pollen diagram from Lake Saint Ana (core SZA-AB3) with selected wetland and aquatic pollen types and algae. Both depth and timescale are shown on the left. On the right sediment organic content (measured by LOI) and total organic carbon (TOC) and local pollen assemblage zones (SZA-P1-7) are displayed. Lines without filling are exaggerated (x10)

6c. ábra A Szent Anna-tó százalékos pollen diagramja a legfontosabb vízi és mocsári pollen-, spóra- és algataxonokkal (SZA-AB3 fúrás). A diagram mélység és időskála mentén ábrázolja a változásokat. A diagram jobb oldalán a szerves anyag tartalom (izzítási veszteség alapján számított), teljes szerves széntartalom (TOC) görbéi, valamint a lokálisan előforduló pollenegyüttes zónák (SZA-P1-7) szerepelnek. A segédvonalak (kitöltetlen háttér) 10-el felszorzott százalékos értékeket jelölnek.

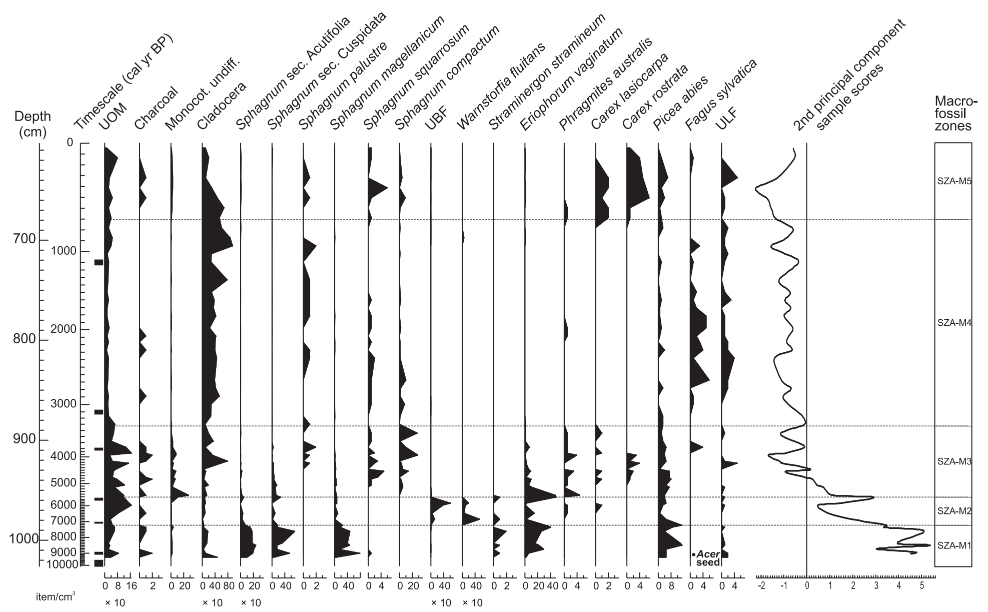


Fig. 7 Macrofossil concentration diagram for SZA-AB3, Lake Saint Ana with selected macrofossil remains presented on depth and calibrated BP age scales. UOM: unidentifiable organic matter; UBF: unidentifiable bryophyte fragment; ULF: unidentifiable leaf fragment; Monocot. undiff.: unidentifiable monocotyledon remains

7. ábra A Szent Anna-tó SZA-AB3 fúrás makrofosszília koncentráció diagramja, mely a legfontosabb makromaradványokat ábrázolja mélység- és korskála mentén. UOM: szerves törmelék; UBF: azonosíthatatlan mohamaradvány; ULF: azonosíthatatlan levél töredék; Monocot. undiff.: azonosíthatatlan egyszikű maradvány

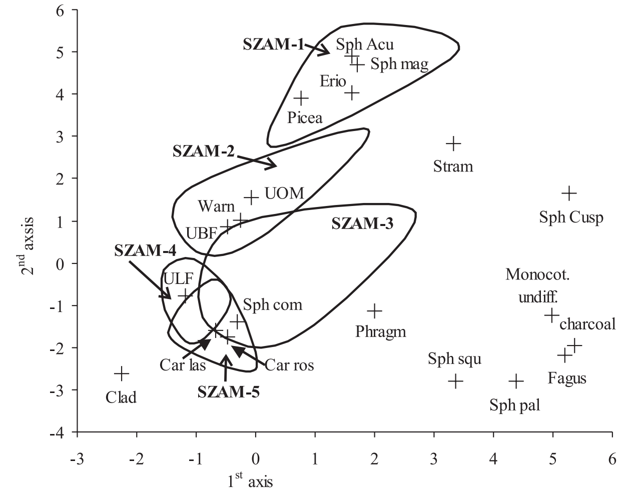


Fig. 8 PCA biplot showing the position of the macrofossil zones and taxon scores together. The macrofossil zones are spread along the second principal component axis that is identified as a hydrological gradient from peat bog (represented by high positive scores for *Sphagnum* sec. *Acutifolia*, *Sphagnum magellanicum* and *Eriophorum vaginatum*) to deep water (represented by high negative scores for *Cladocera* and the lake marginal floating fen formed by *Carex rostrata* and *C. lasiocarpa*)

8. ábra A minta és taxon főkomponens értékek együttes szórásdiagramja. A makrofosszília zónák a második főkomponens mentén rendeződnek, mely egyben hidrológiai gradiensként is értelmezhető. A gradiens a tőzegmohaláp irányából (a Sphagnum sec. Acutifolia, Sphagnum magellanicum és Eriophorum vaginatum magas pozitív értékeivel jellemzhető) a mélyvízi tó felé halad (a Cladocera maradványok és a tóparti úszóláp fajainak, mint pl. Carex rostrata és C. lasiocarpa, erősen negatív értékeivel jellemezhető).

succession followed the forest disturbance. These processes point to low-intensity human impact around the lake. *Fagus sylvatica* appeared locally around 3700 cal yr BP, when an increase in its pollen frequency was accompanied by the occurrence of its macroremains in the sediment (*Fig. 6a, b* and 8). On the basis of the accompanying changes in the pollen diagram, it appears that the temporary spread of *Fagus sylvatica* was facilitated by forest disturbance. The fifth pollen zone (886–690 cm; 3300–800 cal yr BP) commenced with a sharp increase in *Fagus* pollen. The replacement of *Carpinus* by *Fagus* also affected the mesophil broad-leaved trees – *Ulmus*, *Fraxinus excelsior*, *Tilia* and *Quercus;* these all declined to background level around 3300 cal yr BP. *Carpinus betulus* remained relatively abundant until ca. 3150 cal yr BP. This was probably related to the occurrence of some disturbance-indicator herbaceous pollen types (e.g. *Chenopodiaceae* and *Plantago lanceolata*; see *Fig. 6 a* and *b*), pointing to low intensity human impact. *Taxus* pollen was present between 3000–2200 cal yr BP (867– 803 cm). The overall expansion of *Fagus*, together with the occurrence of *Taxus*, imply decreasing continentality and mild winters. *Fagus sylvatica* extended down the lakeshore by ca. 2700 cal yr BP, from which date its macrofossils appear in the sediment together with *Picea abies*. The *Picea* belt around the margin of the lake was probably partially replaced by *Fagus* in this phase. The first distinct forest clearance can be traced in the pollen diagram around 1100 cal yr BP (723 cm: *Carpinus*, *Fagus*, *Alnus* and *Betula* decline). At this point soil erosion and temporary nutrient enrichment can also be inferred from changes in the organic content, elemental composition and aquatic vegetation (*Fig. 4* and *6c*). For example, note the occurrence of *Nuphar* and *Nymphaea* pollen (*Fig. 6c*).

In the sixth pollen zone (690–650 cm; 800–440 cal yr BP), a decrease in the forest is attested by the declining arboreal pollen frequencies. Forest clearance initially affected the respective tree populations of hillslope *Fagus*, *Carpinus* and *Quercus.* In the forest openings, *Betula*, *Juniperus* and *Abies alba* appeared, followed later by *Fagus*. The occurrence of cereal pollen together with the increasing diversity of herbaceous pollen types indicate intensified disturbance such as grazing, forest felling, and hay cutting in this period. In the lakeshore vegetation *Fagus* disappeared while *Picea* became more abundant. This inference is based on the change in the macrofossil composition; note, however, that *Picea* pollen did not increase coincidentally. The final vegetation phase commenced ca. 440 cal yr BP (SZA–P7; 650–600 cm; 440–0 cal yr BP) with the spread of *Fagus* and *Picea abies*. Although the area covered by forest increased at this time, disturbance-indicator herbaceous plants were present throughout the pase e.g. *Plantago lanceolata, Chenopodiaceae, Rumex acetosella, Polygonum aviculare*) together with macrocharcoal. The diversity of the arboreal flora also increased, especially shrubs – e.g. *Sambucus, Juniperus, Cornus mas, Euonymus.* The greater abundance of shrubs suggests that there was persistent forest disturbance.

Macrofossil analysis – stages of the wetland succession

The results of the macrofossil analysis are shown in *Figs 7, 8*. The 20 most frequent components shown in *Fig. 7* were subjected to principal component analysis (PCA) in order to investigate the ecological and hydrological characteristics of the macrofossil zones. Ordination of the variables (macrofossil components) and objects (sediment samples) resulted in a biplot (*Fig. 8*) in which the sediment samples are clearly spread along the 2nd principal component axis. Lower values are shown by open-water taxa such as *Cladocera*. In the vicinity of the latter are sediment samples which were examined in order to record high water depths. Higher values along the 2nd PC axis are represented by typical *Sphagnum*-bog macrofossil components such as *Sphagnum magellanicum*, *Sphagnum* sec. *Cuspidata* and *Eriophorum vaginatum*. Near to these are sediment samples which were used to record low water depths. In between are typical shallow-water species and sediment samples that are characterised by their abundance (*Warnstorfia fluitans*, U.B.F.: unidentifiable bryophyte fragments). The stratigraphic plot of the component scores for the 2nd principal component is also shown along the macrofossil diagram (*Fig. 7*). In light of the PCA biplot it has been assumed that this reflects changes in the water depth. Using binary splitting on the basis of information content (BIRKS & GORDON 1985), the macrofossil diagram was divided into 5 zones.

The bottom sediment sample (1017 cm: ca. 9300 cal yr BP) shows the dominance of Cladoceran remains (mainly *Bosmina* sp.) from which shallow water conditions can be inferred. Above 1013 cm (SZA-M1: 1017–982 cm; 9350–7050 cal yr BP) *Sphagnum*-bog species (*Sphagnum magellanicum, Sphagnum sec. Acutifolia, S. sec. Cuspidata, Eriophorum vaginatum, Straminergon stramineum* and *Polytrichum strictum*) gain dominance and the number of Cladoceran remains decreases. The pollen slides above 1003 cm (ca. 8400 cal yr BP) are characterised by large quantities of *Botryococcus pila* alga (*Fig. 6c*). On the basis of these results it can be assumed that the shallow lake present in the crater before 9000 cal yr BP was overgrown with a *Sphagnum*-bog. Only in the deepest part of the former lake can we assume the persistence of open water (i.e. bog pools rich in *Botryococcus pila*; KOMÁREK & JANKOVSKÁ 2001). At 982 cm (SZA-M2: 982–956 cm; 7050–5500 cal yr BP) the quantity of the remains of *Sphagnum* and *Eriophorum* decreased in the sediment, but this was counterbalanced by an increase in a shallow water moss species, *Warnstorfia fluitans*. At the same time, the quantity of Cladoceran remains also increased, and between 972 and 974 cm (ca. 6500 cal yr BP) the macroremains of eutrophic mire plants – *Phragmites australis* and *Carex elata* – were found in the sediment. The wetland microfossil assemblages (*Fig. 6c*) also suggests at the presence of meso-eutrophic mire plants, such as *Saggitaria* and *Typha angustifolia*. These data point to increasing water depth and pH in SZA-M2. In the shallow north-eastern part of the basin the increase in the water depth probably initiated the formation of a *Phragmitetum* swamp and tall herb, fen vegetation. The third macrofossil zone (SZAM-3: 956–887 cm; 5500–3350 cal yr BP) is characterised by the abundance of heavily decomposed organic fragments (U.O.M.: unidentifiable organic matter). This indicates high macrophyte production and an oxygen rich sedimentary environment. In the lower part of the zone, between 956 and 954 cm (ca. 5450 cal yr BP), the quantity of *Eriophorum vaginatum* increased temporarily, suggesting a decrease in water depth. A coincident increase in organic content also supports this inference (*Fig. 6c*). This was followed by an increase in *Phragmites australis* and *Sphagnum* species. Among them, *Sphagnum compactum* var. *squarrosum* is a rare submerged moss of mountain lakes. Recently it was found in Lake Bucura in the Romanian Carpathians (PLĂMADĂ

1998). Above 939 cm (ca. 4850 cal yr BP) *Carex rostrata* and C. *lasiocarpa* also appeared. A considerable increase in water depth is suggested by the increasing quantity of Cladoceran remains from 923 cm (ca. 4250 cal yr BP). Complemented by the wetland microfossil record – *Potamogeton, Hottonia palustris, Lemna* – it can be inferred that an extensive, shallow, open water body existed with rich submerged and floating aquatic vegetation, as well as the presence of a lake-marginal *Phragmitetum* swamp. According to the hydrological reconstruction (see PCA results on *Fig. 7*) the increasing trend in the water depth in the upper part of the zone was interrupted twice in this zone: at 931 cm (ca. 4500 cal yr BP) and between 913 and 907 cm (ca. 3860–3680 cal yr BP). The first coincide with the occurrence of disturbance-indicator herbs; while the second was coeval with a decline in arboreal pollen percentages, suggesting human-induced water depth fluctuation. The fourth zone (SZA-M4: 887–680 cm; 3350–700 cal yr BP) commenced with a repeated increase in Cladoceran remains and a marked decline in the concentration of organic detritus (U.O.M.). An important change was the overall decrease of the macroremains as compared to the previous zones. The aquatic microflora changed at 883 cm (3300 cal yr BP). An increase in *Scenedesmus* green algae took place, accompanied by the occurrence of Cladoceran mandible fragments (as shown on the pollen slides – *Fig. 6c*). The matrix of the sediment was formed by *Scenedesmus* cell walls. These changes imply a considerable increase in water depth. During the Holocene the water depth must have been at its highest in this phase. A remarkable feature of this zone is the periodic replacement of *Scenedesmus* by *Botryococcus pil*a at 835 cm and 795 cm that may indicate temporary water depth declines or the expansion of the lakeshore *Sphagnum* carpet. In the fifth zone (SZA-M5: 680–603 cm; 700–0 cal yr BP) the macrofossil composition changed coincidentally with the terrestrial pollen assemblages. *Warnstorfia fluitans* occurred temporarily, followed by *Phragmites australis* and the species of the present floating fen association of the lakeshore (*Carex rostrata, C. lasiocarpa, Sphagnum squarrosum, S. palustre*). The micro-fossil assemblages indicate a gradual increase in *Botryococcus pila* and *Cyperaceae*. All these changes suggest a small decrease in water depth and the eutrophication which entailed the formation of the floating fen vegetation on the margin of the lake.

Siliceous algae

Two groups of siliceous algae were investigated: diatoms and chrysophycean stomatocysts. The latter were tallied but the cyst-types were not identified. Therefore, in *Fig. 9* only total stomatocyst frequencies are shown. Most diatom species identified in the sediment are acidobiontic or acidophilous and they are characteristic for oligo-dystrophic water. Euplanktonic diatoms were represented by *Asterionella ralfsii* and *Stenopterobia delicatissima*. In addition, the tychoplanktonic *Tabellaria flocculosa* was abundant in several samples. This species can occur in the plankton and benthos as well. The most diverse and abundant genera were *Pinnularia* and *Eunotia*. The description of the results below concentrates on species with distinct ecological indicator values. For a more detailed review of the diatom flora see BUCZKÓ et al. (in prep).

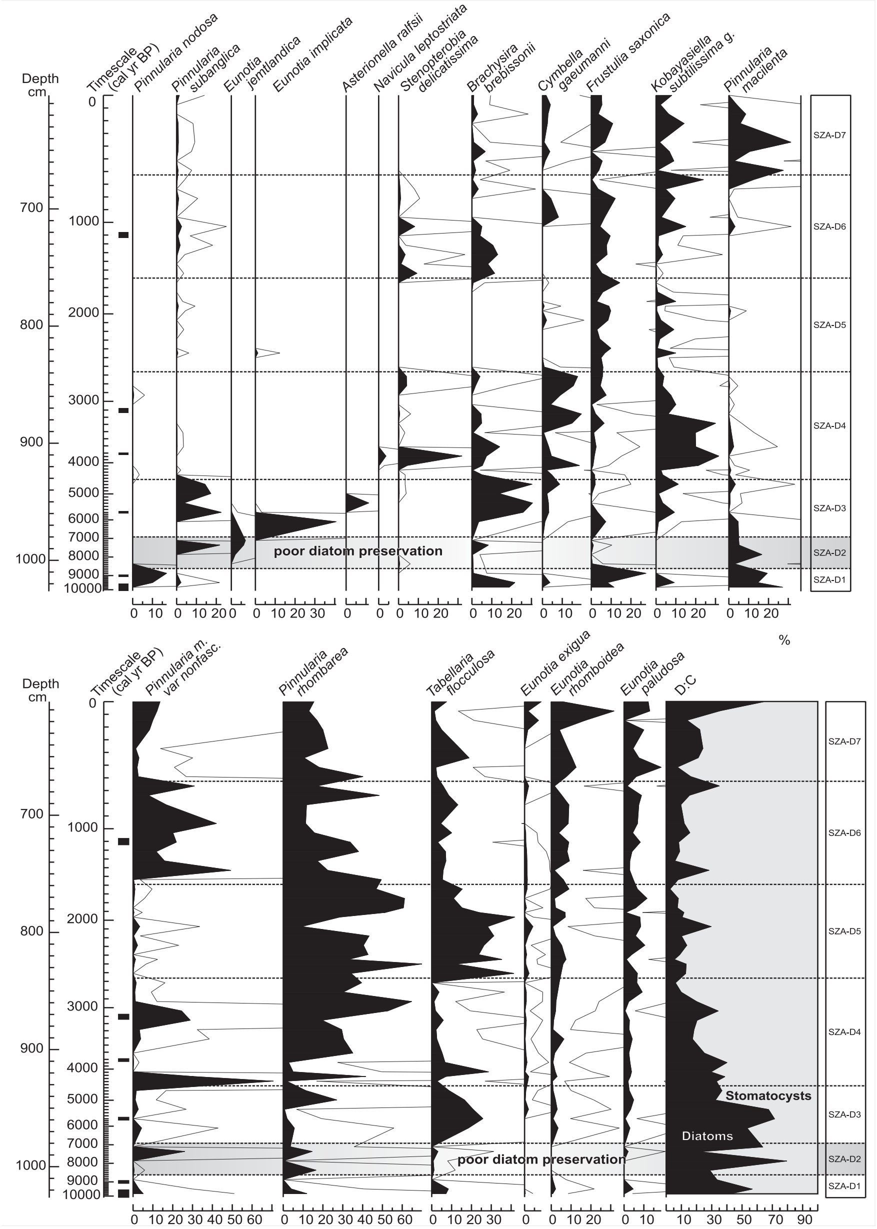


Fig. 9 Diatom abundance diagram of selected species expressed as a percentage of the total diatoms. Core SZA-AB3, Lake Saint Ana. Lines without filling are exaggerated (x10). Here abbreviated species names are given in full for the *Pinnularia microstauron* var. *nonfasciculata* and *Kobayasiella subtilissima* groups. D:C stands for Chrysophycean stomatocyst abundances relative to diatoms

9. ábra A kovamoszatvázak százalékos eloszlása a Szent Anna-tó üledékében (SZA-AB3 fúrás). A segédvonalak (kitöltetlen háttér) 10-el felszorzott százalékos értékeket jelölnek. Rövidített taxonnevek: Pinnularia microstauron var. nonfasciculata és Kobayasiella subtilissima csoport. D:C = A Chrysophyta sztomatociszták kovamoszatokra vonatkoztatott relatív gyakorisága

The lowermost zone of the diagram (SZA-D1; 9830–8800 cal yr BP; 1023–1010 cm) is characterised by acidophilous species: *Pinnularia macilenta, Brachysira brebissonii, Eunotia paludosa* and *E. exigua*. High humic acid concentrations are indicated by *Frustulia saxonica*. Oligotrophic conditions are suggested by *Cymbella gauemannii*. Today this species is abundant in *Sphagnum*-bogs and bog pools in N Europe and the Alps (KRAMMER & LANGE-BERTALOT 1986). Also characteristic is the occurrence of *Pinnularia nodosa*; this is a species which indicates low pH (<5.5) and *Sphagnum*-bogs (KRAMMER & LANGE-BERTALOT 1986). The relative abundance of diatoms (D) to chrysophycean cysts (C) – that is, the D:C ratio – is around 40%, pointing to mesotrophic conditions and/or low water depth (SMOL 1985). These results confirm the existence of a Sphagnum bog in the basin between 9830 and 8800 cal yr BP. Above 1007 cm (8600 cal yr BP) diatom valves are heavily damaged, being partially dissolved and fragmented. Therefore, only limited inferences can be made with respect to the environmental conditions between ca. 8800– 6900 cal yr BP (SZA-D2; 1010–980 cm). On the basis of the species composition (e.g. *Pinnularia, Frustulia*), it can be assumed that the water remained acidic. The most characteristic species is *Eunotia jemtlandica* which is described as a variant of *Eunotia monodon* (KRAMMER & LANGE-BERTALOT 1986) and indicates oligo-dystrophic water. Poor preservation of the diatoms suggests temporary desiccation of the bog pool, diatom dissolution triggered by organic acids,and oxic conditions at the sediment surface (LAWSON et al. 1978; BENNETT et al. 1991; GELL et al. 1994). Any of these factors or their combination can lead to the dissolution of the valves. D:C values are high in this zone – 80% – suggesting mesotrophic conditions. An interesting feature of the proxy-records is the coincidence of the poorly preserved diatom layers with the maxima of *Botryococcus pila* (*Fig. 6c*). According to KOMÁREK & JANKOVSKÁ (2001) and JANKOVSKÁ (2001) the presence of *Botryococcus pila* indicates that there was dystrophic water in small peaty lakes. Its good quantity can possibly be correlated with the poor preservation of the diatoms. The oil compounds stored by these algae break up and produce organic acids during decay, and in turn this triggers the dissolution of siliceous compounds. In this phase, the calculated sediment accumulation rates were very low (0.15 mm/yr). Furthermore, the pollen concentration maximum at 1003 cm (ca. 8400 cal yr BP) suggests the temporary stagnation of the sediment accumulation and so provides further evidence for the temporary desiccation of the lake basin caused by diatoms. Diatom preservation improves considerably above 980 cm (6900 cal yr BP). This level marks the onset of the third zone (SZA-D3; 6900–4550 cal yr BP). Both *Brachisera brebissonii* and *Tabellaria flocculosa* increase; the latter indicates a gradual increase in the water depth. This zone was divided into 3 subzones on the basis of frequent species composition changes (see *Fig. 9*). In addition to the increase in *T. flocculosa*, SZA-D3/a (6900–5450 cal yr BP; 980–955 cm) is characterised by the abundance of *Eunotia implicata*. This species indicates acidic water and low nutrient content. In SZA-D3/b (5450–5000 cal yr BP; 955–943 cm) a further water depth increase is suggested by the occurrence of *Asterionella ralfsii*. This euplanktonic species is abundant in acidic lakes and is a well-known indicator-organism of pH changes (GENSEMER et al. 1995). The maximum frequency of *T. flocculosa* is also attained in SZA-D3/b, in agreement with the inferred water depth increase. D:C values decrease in this subzone (20–40%) suggesting a shift from mesotrophic to oligo/mesotrophic conditions. In SZA-D3/c (5000–4550 cal yr BP; 943–931 cm) *Asterionella ralfsii* disappears. There is a decrease in *Tabellaria flocculosa* which is counterbalanced by an increase in *Pinnularia subanglica*. All these changes point to a decreasing water depth.

The fourth zone (SZA-D4; 4550–2650 cal yr BP; 931–839 cm) is characterised by swift changes in the diatom flora. *Pinnularia rhombarea* still dominates, but its abundance fluctuates considerably within the zone, occasionally giving place to other taxa. SZA-D4 was divided into four subzones. In SZA-D4/a (4550–4200 cal yr BP; 931–923 cm) a low water depth can be assumed due to the abundance of *Pinnularia microstauron* var. *nonfasciata*; the latter is a species characteristic of *Sphagnum*-bogs (KRAMMER 2000). SZA-D4/b (4200–3800 cal yr BP; 923–911 cm) is characterised by the dominance of *Tabellaria flocculosa* and decreasing D:C values; both species suggest an increase in water depth and enhanced oligotrophy. Boreal and alpine species are also better represented (*Cymbella gauemanni, Kobayasiella subtilissima*). In SZA-D4/c (3800–3600 cal yr BP; 911–903 cm) *Stenopterobia delicatissima* attains its maximum presence (40%) and also characteristic is *Navicula leptostriata*; both indicate high humic acid concentrations and greater water depth. SZA-D4/d (3600–2650 cal yr BP; 903–839 cm) is characterised by an increase in the abundance of *Pinnularia rhombarea*. In addition, several *Kobayasiella* species appear and replace each other. All known species of the *Kobayasiella* genus are characteristic of oligotrophic or dystrophic water bodies (VANHOUTTE et al. 2004); their high amplitude fluctuation suggests frequently changing environmental conditions. The higher abundance of chrysophycean cysts points to increasing oligotrophy.

A significant increase in the water depth can be inferred around 2650 cal yr BP (839 cm), when the presence of *Tabellaria flocculosa* increases and attains the highest values in the sequence (23%). This marks the onset of the fifth zone (SZA-D5; 2650–1600 cal yr BP; 839–759 cm). In addition to *T. flocculosa, Pinnularia rhombarea* is also abundant in this zone. D:C values are very low (10%) suggesting a low trophic level. *Frustulia saxonica* and *Eunotia paludosa* are also well represented, and probably indicate the presence of a lakeshore *Sphagnum*-mire. On the basis of the diatom flora, the lake was at its deepest in this phase. Around 1600 cal yr BP, *T. flocculasa* declined markedly, while *Pinnularia microstuaron* var. *nonfasciata* increased. This change denotes the beginning of SZA-D6 (1600–650 cal yr BP; 759–671 cm) and points to decreasing water depth. This inference is also supported by the increasing abundance of *Frustulia saxonica* and *Brachiseira brebissonii*. D:C values, however, remain low suggesting oligotrophy. The uppermost zone, SZA-D7 (650–0 cal yr BP; 671–603 cm) is characterised by the dominance of *P. rhombarea* and *P. macilenta. Eunotia rhomboidea* and *E. paludosa* are also abundant and together with the *Pinnularia* species suggest an increase in the lakeshore *Sphagnum*-carpet and probably a further water-level decline. In recent decades, Lake Saint Ana has become a tourist attraction with bathers in the summer months. This is clearly reflected in the declining abundance of chrysophycean cysts which indicates nutrient enrichment and thus a shift to mesotrophic conditions.

Discussion

In this section an attempt is made to achieve a synthesis of the various environmental proxy records. In particular, an examination is made of the extent to which the recorded environmental changes are coincident. A consistent and comparable zonation scheme of all stratigraphies may help to distinguish between phases of stability and phases of change (BIRKS & GORDON 1985). If the zone boundaries of different proxies coincide, it can be assumed that a substantial and overriding change in a major environmental factor was the common cause. Zone boundaries which only occur in individual proxies may be the result of the passing of a threshold which was only important for that individual proxy and may thus signify environmental change at a lower level. The numerical zonations of all the proxies are shown on *Fig. 10*, together with the major inferences (BIRKS & GORDON 1985).

Reconstruction of the Holocene water depth changes in Lake Saint Ana

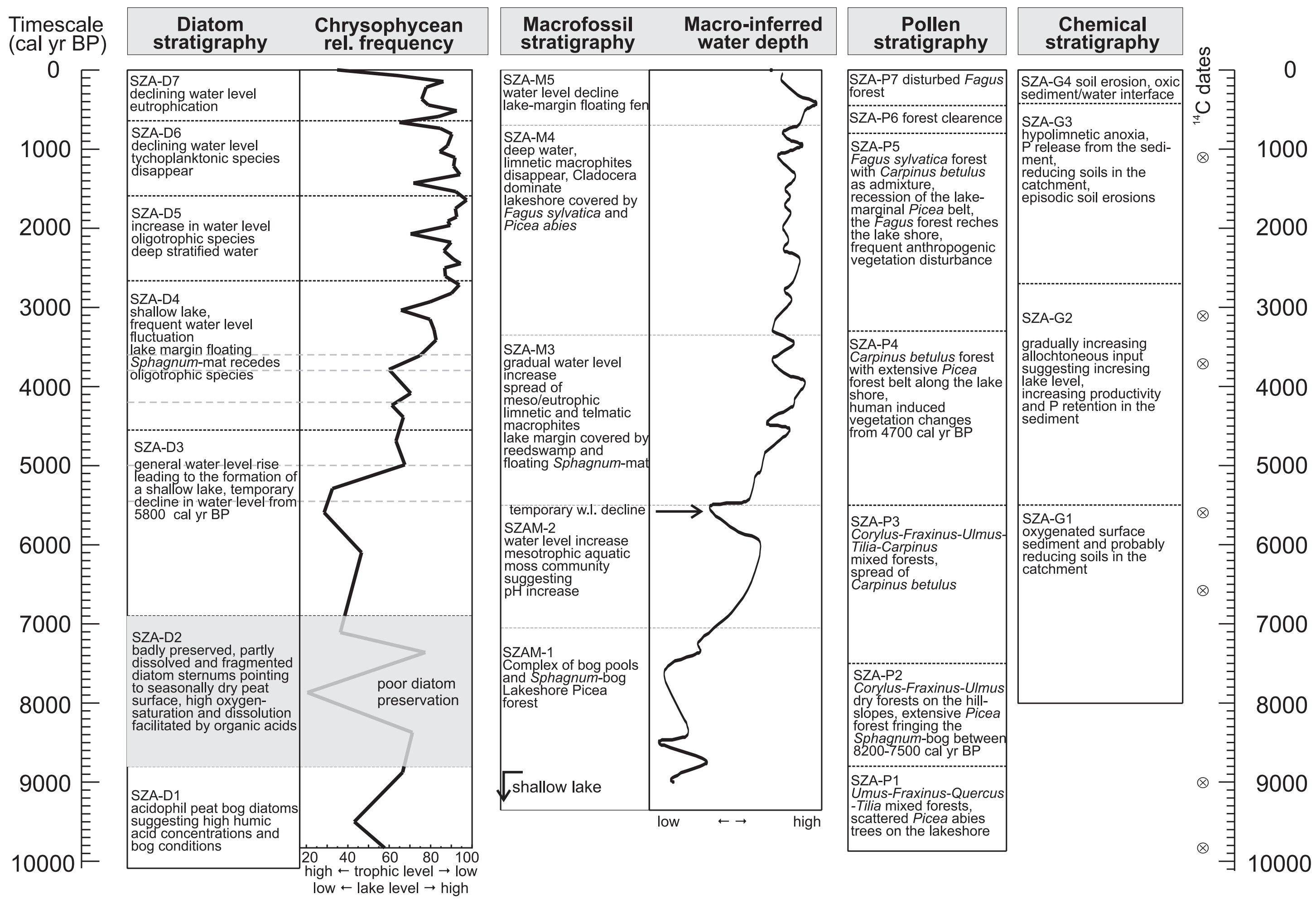
For the reconstruction of the water depth changes the results of the diatom, D:C ratio and macrofossil analyses were used. In the case of the diatoms, a water depth increase was inferred from the spread of tycho- and euplanktonic species, whilst a decreasing water depth was indicated by the expansion of benthic/littoral species (*Fig. 11*). In addition, changes in the relative abundance of Chrysophycean stomatocysts were taken to represent changes in the trophic status and also in the water depth. In lakes such as Saint Ana an increase in the water depth (and volume) will inevitably lead to the decrease of available nutrients and this in turn would trigger the spread of planktonic chrysophyceans (SMOL 1985). For the macrofossil record, the stratigraphic plot of the 2nd principal component was used to infer water depth changes (*Fig. 10*). Here, low values indicate an increase in the water depth, and vice versa.

9830–8800 cal yr BP – shallow lake and Sphagnum-bog

At the core location, the numerous Cladoceran remains point to the presence of a puddle in the middle of the crater. This was surrounded by *Sphagnum*-bog. The high humic acid concentration of the water and the acidophilus bog conditions suggested by the diatoms are in good agreement with the abundant macroremains of *Sphagnum* and *Eriophorum vaginatum*.

8800–7050 cal yr BP – Sphagnum-bog and bog pools

The decrease of Cladoceran remains and the alteration of the diatom flora suggest a decrease in water depth. The two records are offset by ca. 200 years. The compositional change of the macrofossil record at 9000 cal yr BP (*Fig. 10*) is followed by the damage and partial dissolution of the diatom frustules from ca. 8800 cal yr BP. The oxidative surface conditionsindicated by the presence of diatoms and the possible temporary drying out of the bog pools (BENNETT et al. 1991) are also coincident with a major terrestrial vegetation change, i.e. the spread of *Corylus avellana*. Since the lake basin is fed exclusively by rainwater, the reconstructed water depth decrease can most likely be connected to a regional climate change, i.e. a decrease in available moisture during the vegetation season.


Timescale (cal yr BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Diatom stratigraphy
SZA-D7
declining water level
eutrophication
SZA-D6
declining water level
tychoplanktonic species disappear
SZA-D5
increase in water level
oligotrophic species
deep stratified water
SZA-D4
shallow lake,
frequent water level fluctuation
lake margin floating *Sphagnum*-mat recedes
oligotrophic species
SZA-D3
general water level rise leading to the formation of a shallow lake, temporary decline in water level from 5800 cal yr BP
SZA-D2
badly preserved, partly dissolved and fragmented diatom sternums pointing to seasonally dry peat surface, high oxygen-saturation and dissolution facilitated by organic acids
SZA-D1
acidophil peat bog diatoms suggesting high humic acid concentrations and bog conditions
Chrysophycean rel. frequency
poor diatom preservation
20 40 60 80 100
high ← trophic level → low
low ← lake level → high
Macrofossil stratigraphy
SZA-M5
water level decline
lake-margin floating fen
SZA-M4
deep water,
limnetic macrophites disappear, Cladocera dominate
lakeshore covered by *Fagus sylvatica* and *Picea abies*
SZA-M3
gradual water level increase
spread of meso/eutrophic limnetic and telmatic macrophites
lake margin covered by reedswamp and floating *Sphagnum*-mat
temporary w.l. decline
SZAM-2
water level increase
mesotrophic aquatic moss community suggesting pH increase
SZAM-1
Complex of bog pools and *Sphagnum*-bog
Lakeshore Picea forest
shallow lake
Macro-inferred water depth
low ←→ high
Pollen stratigraphy
SZA-P7 disturbed *Fagus* forest
SZA-P6 forest clearence
SZA-P5
Fagus sylvatica forest with *Carpinus betulus* as admixture,
recession of the lake-marginal *Picea* belt,
the *Fagus* forest reches the lake shore,
frequent anthropogenic vegetation disturbance
SZA-P4
Carpinus betulus forest with extensive *Picea* forest belt along the lake shore,
human induced vegetation changes from 4700 cal yr BP
SZA-P3
Corylus-Fraxinus-Ulmus-Tilia-Carpinus mixed forests,
spread of *Carpinus betulus*
SZA-P2
Corylus-Fraxinus-Ulmus dry forests on the hill-slopes, extensive *Picea* forest fringing the *Sphagnum*-bog between 8200-7500 cal yr BP
SZA-P1
Umus-Fraxinus-Quercus-Tilia mixed forests, scattered *Picea* abies trees on the lakeshore
Chemical stratigraphy
SZA-G4 soil erosion, oxic sediment/water interface
SZA-G3
hypolimnetic anoxia,
P release from the sediment,
reducing soils in the catchment,
episodic soil erosions
SZA-G2
gradually increasing allochtoneous input suggesting incresing lake level,
increasing productivity and P retention in the sediment
SZA-G1
oxygenated surface sediment and probably reducing soils in the catchment
^{14}C dates
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

7050–5800 cal yr BP – shallow mesotrophic lake with a gradual water depth increase

Both the diatom and macro records denote an increase in the water depth, but due to the slightly different position of the zone boundaries, there is a ca. 150 years delay in the diatom record (6900 cal yr BP). Also delayed is the decline of *Botryococcus pila*, at 6800 cal yr BP, and the decrease in organic content (*Fig. 11*), both stressing that the increase in the water depth was gradual. The trophic status of the water also increased in this phase. There is no coincident change in the terrestrial vegetation; there was a change about 300 years earlier with the decline of *Corylus* and the repeated spread of mesophilous trees. However, 6800 cal yr BP does mark the spread of *Carpinus betulus* in the forests dominated by *Corylus–Fraxinus–Ulmus* (*Fig. 11*), and on the basis of this it can be assumed that the reconstructed gradual increase in the lake depth can be correlated with a change in the macroclimate.

5800–5500 cal yr BP – water depth decline or increase? Temporary widening of the lake marginal Sphagnum-mat

The macrofossil record signals a short-term decrease in the water depth around 5800 cal yr BP (*Fig. 10*), although statistically significant zone boundaries were not found. This change is also apparent in the siliceous microfossil record. The relative abundance of chrysophycean stomatocysts decreases temporarily together with the tychoplanctonic *T. flocculosa* (*Figs 10, 11*).

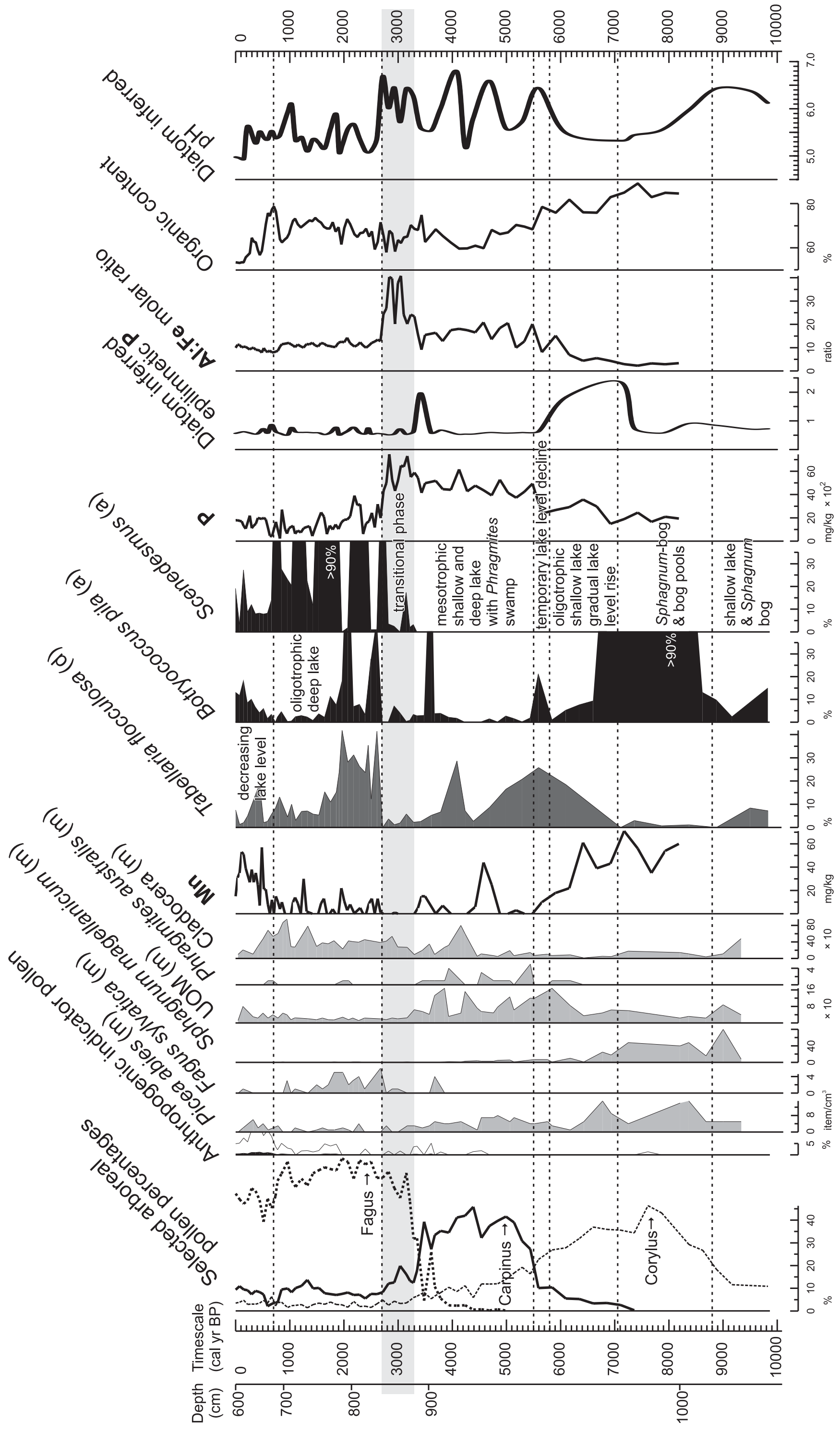
5500–2700 cal yr BP – mesotrophic shallow and deep lake phase

All three proxies – diatom, D:C ratio, macrofossil – denote a swift water depth increase between 5550 and 5250 cal yr BP with statistically significant zone boundaries in the pollen, macrofossil and chemical records. In the diatom record the occurrence of the euplanktonic *Asterionella ralfsii* also indicates an increase in water depth (*Fig. 10*). Due to its low frequency, this part of SZA-D3 could only be differentiated as an ecologically important subzone. The inferred water depth increase is coincident with a significant (10%) decrease in the organic content of the sediment (*Fig. 11*). Moreover, the maximal coverage of *Carpinus betulus* on the slopes surrounding the lake also commenced at 5500 cal yr BP, suggesting a climate-induced environmental change, i.e. an increase in the available moisture in the growing season.

Between 5000 and 2700 cal yr BP the diatom, macrofossil and chemical records indicate several fluctuations in the water depth (see the Mn peaks and coincident *Tabellaria flocculosa* minima on *Fig. 11*) and this can probably be connected to short-term anthropogenic disturbances as evidenced by the pollen record (*Fig. 11*).

←*Fig. 10* Summary of the diatom, macrofossil, pollen and chemical stratigraphies with inferences for the Holocene water depth changes, forest development and catchment/within lake processes. Core SZA-AB3, Lake Saint Ana, Romania

10. ábra A kovamoszat, makrofosszília, pollen és nyomelem sztratigráfiák összefoglaló ábrája. Az ábra következtetéseket tartalmaz a holocén vízmélységváltozásokra, erdőtörténeti fázisokra és az üledékgyűjtőben/tóban végbement kémiai változásokra vonatkozóan. SZA-AB3 fúrás, Szent Anna-tó, Románia


Depth (cm)
Timescale (cal yr BP)
Selected arboreal pollen percentages
Antropogenic indicator pollen
Picea abies (m)
Fagus sylvatica (m)
Sphagnum magellanicum (m)
UOM (m)
Phragmites australis (m)
Cladocera (m)
Mn
Tabellaria flocculosa (d)
Botryococcus pila (a)
Scenedesmus (a)
P
Diatom inferred epilimnetic P
Al:Fe molar ratio
Organic content
Diatom inferred pH
600
700
800
900
1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Fagus →
Carpinus →
Corylus→
decreasing lake level
oligotrophic deep lake
>90%
transitional phase
mesotrophic shallow and deep lake with Phragmites swamp
temporary lake level decline
oligotrophic shallow lake gradual lake level rise
Sphagnum-bog & bog pools
>90%
shallow lake & Sphagnum bog
%
item/cm³
× 10
mg/kg
mg/kg × 10²
ratio
5.0
6.0
7.0

2700–700 cal yr BP – oligotrophic deep lake phase

During the *Carpinus/Fagus* forest change (ca. 3300 cal yr BP), aquatic organisms experienced diversified reactions. The macrofossil composition of the sediment changed coincidentally with the terrestrial vegetation, but this does not imply any significant increase in water depth (*Fig. 10*). The diatom flora, on the other hand, indicates a marked increase in the water depth at 2700 cal yr BP, i.e. 500 years later than the forest change. In the microfossil record, *Scenedesmus* remains first appeared around 3300 cal yr BP; however, they only occurred *en masse* from *ca.* 2700 cal yr BP (*Fig. 11*). *Scenedesmus* species are planktonic and their occurrence in the sedimentary records usually indicates increasing water depth (VORREN et al. 1988). It is noteworthy that the relative abundance of *Scenedesmus* fluctuated considerably between 2700 and 700 cal yr BP, and it occurred antagonistically with *Botryococcus pila*. This process was also accompanied by fluctuations of the organic content (*Fig. 11*). Comparing these changes with the pollen record, they cannot unequivocally be connected to anthropogenic disturbance (*Fig. 11*); it is clear, however, that the aquatic environment changed frequently even within this relatively stable deep-water phase. The coincidence of the major zone boundaries around 3300 and 2700 cal yr BP suggests that the reconstructed water depth increase was invoked by a major environmental change between 3300 and 2700 cal yr BP. From these data a considerable increase in precipitation can be inferred around 2700 cal yr BP.

At 1600 cal yr BP the diatom flora suggests a decrease in the water depth (*Figs 10, 11*). The small-scale increase of the D:C ratio also supports this notion, but there is no coincident change in the macrofossil and chemical records. In the terrestrial vegetation, the relative abundance of *Carpinus betulus* increases around 1600 cal yr BP, together with anthropogenic indicators; therefore, the forest change can probably be related to human disturbance. The first clearly anthropogenic forest clearance and soil erosion was detected between ca. 1050 and 900 cal yr BP. From this date changes in the macrofossil and diatom records indicate human induced eutrophication and related water depth decreases.

←*Fig. 11* Selected palaeo-proxies plotted against a calibrated BP timescale. Core SZA-AB3, Lake Saint Ana, Romania. Note the different scales. UOM: unidentifiable organic matter; (p):pollen; (m): macrofossil; (d): diatom; (a): algal remains. To estimate total epilimnetic P and pH from diatoms, the training dataset in the EDDI database was used. Water chemistry parameters were obtained by comparing the fossil and recent diatom assemblages using the transfer function (LWWA). Details of this technique are given by BIRKS (1998) and JUGGINGS (2001). Details of the analysis are given in BUCZKÓ et al. (in prep). Dashed lines indicate the reconstructed water depth phases

11. ábra A legfontosabb őskörnyezeti proxi-adatok kalibrált időskála mentén. SZA-AB3 fúrás, Szent Anna-tó, Románia. UOM: szerves törmelék; (p): pollen; (m): makrofosszília; (d) kovamoszat; (a): algamaradvány. Az epilimnetikus foszfortratalom változásainak rekonstrukciójához a fosszilis kovamoszat adatsort használtuk fel. A fosszilis spektrumokat az EDDI adatbázisban szereplő modern mintákkal vetettük össze transzfer funkciók alkalmazásával (LWWA). A mószer részletes leírását lásd BIRKS (1998) és JUGGINGS (2001) munkáiban. A statisztikai analízis részleteit BUCZKÓ et al. (in prep) tanulmánya tartalmazza. A szaggatott vonalak a rekonstruált vízménység-fázisokat jelölik

700–0 cal yr BP – oligotrophic lake phase

Both the diatom and the macrofossil records denote decreasing water depth and an increasing trophic status from 700 cal yr BP.

Relationship between chemical composition, water depth, terrestrial vegetation and diatom-based environmental reconstruction

Element concentrations were measured above 1000 cm (ca. 8150 cal yr BP); therefore, comparison with other proxies can only be made above this level. The interpretation of the chemical diagram is complicated by the collective measurement of the different sediment components (ENGSTROM & WRIGHT 1984); in addition to the allochtonous organic matter and inorganic clastic particles, the followind – among others –have to be considered: autochthonous organic material (e.g. macrophytes and algae), dust precipitation and dissolved ions from soil solutions. From the diatom and macrofossil records it is clear that Lake Saint Ana was a low pH, oligo-mesotrophic water body both in its lake and mire phases. Today, the dissolved ion content of the water is very low (GELEI 1909, Péter SOMAY pers comm.). In the formation of the sediment an important role is played by allochtonous organic material (leaves, pollen),this beeing due to overhanging trees. Taking into account these factors, changes in the chemical composition of the sediment have most likely been triggered by one of the following processes: 1) soil change in the catchment area; 2) changes in the aquatic/wetland flora and fauna; and 3) changes in the redox condition at the sediment/water interface.

If the chemical record is considered in light of the above relationships and together with the terrestrial vegetation and water depth records, it can be said that between 8150 and 6600 cal yr BP the high Mn and Fe content-based inference of an oxidative sedimentary environment and reducing soil conditions is good in agreement with the reconstructed *Sphagnum*-bog and extensive *Picea abies* forest. The abundance of *Picea* on the lakeshore persisted until ca. 6600 cal yr BP (see the macro curve in *Fig. 11*). It is known from recent experiments that *Picea* needles can cause acidification in the soil and this leads to the reduction and mobilisation of the Fe and Mn compounds (ROTHE et al. 2002; HAGEN-THORN et al. 2004). The diatom-inferred pH is also in agreement with these inferences; it shows consistently low values of around 5.5.

During the decline of the respective Fe and Mn concentrations, around 6600 cal yr BP, there was also a temporary decrease in the quantity of *Picea* macrofossils (*Fig. 11*), whilst the water depth increased. The decrease in the organic content indicates that there was an accelerated clastic input. At the same time, there was a massive increase in sedimentary *P*, coincident with the expansion of *Carpinus betulus* and the occurrence of *Phragmites australis* macrofossils (*Fig. 11*). Note also that diatom-inferred epilimnetic *P* declined at the same time along with an increase in pH (*Fig. 11*). Taking into account the results of several other sedimentary phosphorous studies (for summaries see LERMAN 1978; ENGSTROM & WRIGHT 1984; GIBSON 1997), it seems likely that the increased concentration of P in the sediment can be connected to the increasing productivity of the lake and the intense accumulation of P-rich macrophytes between 6600 and 3300 cal yr BP. The applied technique does not make it possible us to determine in what form it is present in the sediment, but the lack of correlation with the traditionally clastic elements (Al, K) suggests that it is bound to organic compounds, and most likely originates from the lakeshore *Phragmites*-swamp.

Between 3300 and 2700 cal yr BP several marked changes took place in the chemical record: the concentration of Fe decreased, Mn disappeared, whilst sedimentary P increased further (*Figs 5* and *11*). At the same time, the abundance of *Picea* decreased on the lakeshore and *Fagus sylvatica* became dominant on the uphill forest. However, the macrofossil record contained only a very few *Fagus* macro-remains. The water depth increased slightly but with considerable fluctuation (see the Chrysophycean frequency and PCA curves in *Fig. 10*). In the sediment, the Al:Fe molar ratio increased above 30 in several samples suggesting intense Fe reduction and dissolution at the sediment/water interface. Given the inferred Fe reduction, it is very difficult to interpret the increasing quantity of P. Note also that the diatom-inferred epilimnetic P shows a peak around 3400 cal yr BP – that is, it preceded the sedimentary *P* rise. This infers an accelerated *P* input and availability in the lake, probably in connection with the ongoing terrestrial and aquatic vegetation change (for example note the coincident disappearance of *Phragmites australis*). As pointed out in several studies (GIBSON 1997; BOYLE 2001), anoxic conditions at the sediment/water interface favour the dissolution of P, but here the opposite trend was found. This is only conceivable if the *P* molecules were bound to organic substances at the time of deposition and thus could not be released. Therefore the increasing concentration can probably be interpreted as a result of slackening decomposition, most likely in relation to the redox changes at the sediment/water interface. The possibility of a further increase in lake productivity was not considedred, because both the macrofossil and diatom records provided evidence against this (*Fig. 11*).

From 2700 cal yr BP P concentrations declined steeply, whilst Fe and Mn increased slightly. In addition, between 2700 and 600 cal yr BP, several elements – Mn, Li, K, V, Cu – showed high-amplitude fluctuation (*Fig. 4*), whilst the diatom-inferred pH indicated the acidification of the lake water. For the interpretation of these changes it is important to note that 2700 cal yr BP marks a large increase in the water depth and the establishment of a thick *Fagus sylvatica* forest on the lakeshore. The *P* decline could be explained by several mechanisms: (1) decreasing input from the catchment area; (2) increased mobilisation of P due to enhanced bacterial decomposition and seasonal anoxia at the sediment/water interface; and (3) the increased volume of the water in which the unchanged influx of allochtonous P became diluted. These latter two mechanisms seem to have acted together since, beside the inferred oligotrophy of the lake, there were several algal blooms which suggest periodic increases in the phytoplankton productivity (*Fig. 11*). In the background of the periodic Fe and Mn increases it is assumed that there was an increasing allochtonous input. From 2700 cal yr BP, the concentration curves of Fe and Mn show a positive correlation with Al (see molar ratios on *Fig. 11*), suggesting that these elements arrived into the lake by clastic inwash. Their concentration changes in the sediment ant this reflects the intensity of the soil erosion in this period.

The frequent changes in the concentration of several elements from 2700 cal yr BP can probably be connected with the establishment of the dimictic thermal stratification of the lake (LERMAN 1978). In the case of small lakes like Saint Ana, it is possible to calculate the water depth at which the lake becomes stratified. Using RAGOTZKIE's (1978) formula and the present perimeter of the lake, the position of the thermocline is estimated at 5–5.3 m. Although measurements have not yet been made on the possible existence of a thermocline, it seems unlikely that the lake is stratified today, since the largest water depth is 6 m, and this is limited to a very small area (*Fig. 2*). Nonetheless, if the measured maximal water depth in the 17th century (12 m) is considered and the calculated increase in the perimeter of the lake is taken into account (ca. 1.9–2 km using 3D digital basin-elevation model; see PÁL 2001), the position of the thermocline can be estimated at 5.65 m – i.e. the lake was certainly stratified at that time. Around 2700 cal yr BP the lake level increased to well above the 19th century level, and therefore it is feasible to assume that the lake became stratified in this period.

Regional pattern of lake-level change during the Holocene

Recent syntheses of Holocene lake-level records by HARRISON et al. (1996) and MAGNY et al. (2002) focus on the NW, Baltic, Mediterranean and central zones of Europe, but there is no discussion about SE Europe, including Hungary, Romania and Bulgaria. Except for Lake Balaton in western Hungary (CSERNY 1993, 2002; CSERNY & NAGY-BODOR 2000), this area appears blank on the lake data source maps (MAGNY et al. 2002) and this signifies to the paucity of available Holocene lake-level records in this region.

In NW Romania, the pollen and plant macrofossil-based palaeohydrological reconstruction of FEURDEAN & BENNIKE (2004) suggests that around 8600 cal yr BP synchronous changes in two peat bogs (Steregoiu and Preluca Tiganului) took place, these being associated with drier conditions. The authors argue that regionally and climatically driven changes occurred. In Lake Saint Ana, the first decrease in the water depth was dated to ca. 8800 cal yr BP – that is, about 200 years earlier – but still within error of dating with respect to the NW Romanian records. In Poland, STARKEL et al. (1996) found higher lake-levels between 9500 and 8600 cal yr BP, in agreement with the higher lake-level phase in Lake Saint Ana. In the Vistula Valley, ca. 8600 cal yr BP there was a considerable decline in lake-levels (STARKEL et al. 1996). A lengthy dry phase was also established in the lowland areas of S and NW Hungary, this being on the basis of the plant macrofossil records (Császártöltés, Szélmező Mire). JAKAB et al. (2004b) and JAKAB (2005) recorded drier mire conditions from 9000 cal yr BP at Szélmező and from 8500 cal yr BP at Császártöltés. In both places the dry period was followed by increasing water depths around 4400 cal yr BP. In the Szigliget Basin of Lake Balaton, high lake levels were recorded at 8400 cal yr BP, but subsequently the lake level decreased gradually until ca. 7600 cal yr BP (JAKAB 2005; JAKAB et al. 2005). It can be concluded that a large number of palaeo-records in the region suggest lower water depths and so drier conditions probably commenced around 8600 cal yr BP. In this respect, the 200 years deviation of the records referring to Saint Ana might be attributable to the uncertainty of the radiocarbon timescale in this part of the core. Note that pollen concentration varies considerably between 9000 and 5500 cal yr BP, these being two endpoints of the interpolated age range (*Fig. 3*). This suggests varying sediment accumulation rates.

The moderate lake-level rise from ca. 7050 cal yr BP in Saint Ana is also detectable in Lake Balaton (JAKAB et al. 2005), while in the NW Romanian peat bogs, a two-step return to cooler and moister conditions was shown by FEURDEAN (2005) from ca. 8000 and 6800 cal yr BP. Furthermore, climatic signals recorded by oxygen isotopes in a stalagmite in NW Romania indicated a cooler period between 7100 and 6800 cal yr BP (ONAC et al. 2002). These data are in sharp contrast with the Western Mediterranean, where the Early Holocene was generally moister (HARRISON et al. 1996; MAGNY et al. 2002). In contrast, the Carpathian Region was characterised by a more complex climate regime, with dry conditions between ca. 8600 and 7100 cal yr BP, followed by a gradual increase in the regional lake-levels; this indicates that there was available moisture from ca. 7100–7000 cal yr BP.

The moderate increase in the lake-level of Saint Ana between 7050–5500 cal yr BP, punctuated by short-term decreases (*Fig. 10* and *11*), was followed by a marked increase around 5500 cal yr BP. It is worth mentioning that Lake Balaton also displayed a considerable lake-level rise at the same time and attained its largest surface area (CSERNY & NAGY-BODOR 2000; TULLNER & CSERNY 2003; JAKAB 2005; JAKAB et al. 2005; SÜMEGI et al. in press). Withespect to the terrestrial vegetation *Fagus*, *Tilia* and *Carpinus* spread. Around Lake Saint Ana, *Carpinus betulus* had attained maximum abundance by 5500 cal yr BP. In contrast with these records, in NW Romania FEURDEAN (2005) inferred warmer and possibly drier conditions between 5750–4800 cal yr BP, his assumptions resting on the basis of the lower frequency of wetland indicator pollen taxa and lower peat accumulation rates. The accompanying terrestrial vegetation change – i.e. expansion of *Carpinus betulus* and *Fagus sylvatica* – however, corresponds with the Saint Ana pollen record, suggesting a regional and so probably climatically driven vegetation change.

A further substantial lake-level rise ca. 2700 cal yr BP resulted in the stratification of the water in Lake Saint Ana. A synchronous change took place in NW Romania, where increasing mire surface wetness was demonstrated from ca. 2800 cal yr BP using testate amoebae and peat humification records (SCHNITCHEN et al. 2003; in press). In the Gutin Mountains BJÖRKMAN et al. (2002a, b) noted the development of open fen vegetation along with the expansion of *Fagus sylvatica* after 3400 cal yr BP. In Hungary, several lake basins showed renewed sediment accumulation from ca. 3000 cal yr BP following early and mid-Holocene hiatuses – e.g. Lake Baláta near Szenta (JAKAB 2005, JUHÁSZ 2005) and Lake Nádas near Nagybárkány (JAKAB 2005; JAKAB & SÜMEGI 2006). On the whole these data suggest increasing moisture availability in the Romanian Carpathians and the adjoining Carpathian basin from ca. 3400 cal yr BP, with maximum moisture availability occurring around 2700–2800 cal yr BP.

Conclusions

From the above discussion the following conclusions can be made concerning the Holocene environmental history of Lake Saint Ana:

The early Holocene *Ulmus–Fraxinus* forests of the hillslopes around the lake were replaced by *Corylus* ca. 8800 cal yr BP, followed by the re-expansion of *Fraxinus*, *Quercus* and *Tilia* and the spread of *Carpinus betulus* from ca. 7500 cal yr BP. The formation of a forest belt dominated by *Carpinus betulus* was dated to 5500 cal yr BP, while the two-step expansion of *Fagus sylvatica* took place between 3700 and 3300 cal yr BP. From 3300 cal yr BP *Fagus sylvatica* became the dominant canopy tree in the forests around the lake.

Joint interpretation of the terrestrial pollen and plant macrofossil records also highlighted the difference between the lakeshore and hillslope vegetation throughout the Holocene. The persistence of the lakeshore *Picea abies* belt can be explained by the cooler and moister microclimate of the basin; the latter led to thermal inversion.

The reconstruction of the Holocene lake-level changes was based on the diatom and plant macrofossil records. According to these, the water depth showed considerable fluctuation during the Holocene and in most cases this was coincidental with the terrestrial vegetation changes. This is significant that low water depths characterised the early Holocene until ca. 8800 cal yr when the open water became overgrown by a raised bog. From ca. 7050 cal yr BP the water depth increased gradually and shallow water conditions prevailed until ca. 5500 cal yr BP, when a marked increase was detected, accompanied by increasing trophic status. The highest lake-levels were found between 2700 and 700 cal yr BP. The geochemical record pointed to the thermal stratification of the lake in this period.

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References

Alles, E., Nörpel-Schempp, M. & Lange-Bertalot, H. 1991: Zur Systematik und Ökologie charakteristischer Eunotia-Arten (Bacillariophyceae) in elektrolyt-armren Bachoberläufen. – *Nova Hedwigia* **53**, 171–214.

Barber, K. E., Chambers, E. M., Maddy, D. & Brew, J. 1994: A sensitive high-resolution record of the Holocene climatic change from a raised bog in northern England. – *The Holocene* **4**, 198–205.

Bengtsson, L. & Enell, M. 1986: Chemical analysis. – In: Berglund, B. E. (ed.): Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons, Chichester. 423–451.

Bennett, K. D. 1992: PSIMPOLL: A quickBasic program that generates PostScript page description of pollen diagrams. – *INQUA Commission for the study of the Holocene: working group on data handling methods newsletter* 8, 11–12.

Bennett, P. C., Siegel, D. I., Hill, B. M. & Glaser, P. H. 1991: Fate of silicate in a peat bog. – *Geology* **19**, 328–331.

Berglund, B. E. & Ralska-Jasiewiczowa, M. 1986: Pollen analysis and pollen diagrams. – In: Berglund B. E. (ed.): Handbook of palaeoecology and palaeohydrology. John Wiley and Sons, New York. 455–479.

Birks, H. J. B. 1998: Numerical tools in palaeolimnology – Progress, potentialities, and problems. – *Journal of Palaeolimnology* **20**, 307–332.

Birks, H. J. B. & Gordon, A. D. 1985: Numerical methods in Quaternary Pollen Analysis. – Academic Press, London, 317 p.

Björck, S., Bennike, O., Possnert, G., Wohlfarth, B. & Digerfeldt, G. 1998: A high-resolution ^{14}C dated sediment sequence from southwest Sweden: age comparisons between different components of the sediment. – *Journal of Quaternary Science* **13**, 85–89.

Björkman, L., Feurdean, A., Cinthioa, K., Wohlfarth, B. & Possnert, G. 2002a: Lateglacial and early Holocene vegetation development in the Gutaiului Mountains, northwestern Romania. – *Quaternary Science Reviews* **21**, 1039–1059.

Björkman, L., Feurdean, A. & Wohlfarth, B. 2002b: Late-Glacial and Holocene forest dynamics at Steregoiu in the Gutaiului Mountains, Northwest Romania. – *Review of Palaeobotany and Palynology* **25/14**, 1–33.

Bodnariuc, A., Bouchette, A., Dedoubat, J. J., Otto, T., Fontugne, M. & Jalut, G. 2002: Holocene vegetational history of the Apuseni mountains, central Romania. – *Quaternary Science Reviews* **21**, 1465–1488.

Boros, Á. 1943: A Kukojszás vagy Mohos-tó és a Szentanna tó lápja. – *Debreceni Szemle* **12**, 113–115.

Boyle, J. F. 2001: Inorganic geochemical methods in paleolimnology. – In: Last, W. M. & Smol, J. P. (ed.): Tracking Environmental Change Using lake Sediments. Volume 2. Physical and Geochemical Methods. Kluwer Academic Publishers, London, 83–141.

Buczkó, K., Magyari, E. K., Schnitchen, Cs. & Braun, M., Jakab, G. (in prep): Diatom-inferred Holocene hydrological changes in the carter lake of Saint Ana, Harghita Mountains, Romania. – *Journal of Palaeolimnology*.

Cserny, T. 1993: Lake Balaton, Hungary. – In: Gierlowski-Kordesch, E. & Kelts, K. (eds): A Global Geological Record of Lake Basins, Cambridge University Press. 397–401.

Cserny, T. 2002: A balatoni negyedidőszaki üledékek kutatási eredményei. – *Földtani Közlöny* **132/különszám**, 193–213.

Cserny, T. & Nagy-Bodor, E. 2000: Limnogeology of Lake Balaton (Hungary). – In: Gierlowski-Kordesch, E. H. & Kelts, K. R. (eds): Lake basins though space and time: AAPG Studies in Geology, 605–618.

Dean, W. E. Jr. 1974: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparisons with other methods. – *Journal of Sedimentary Petrology* **44**, 242–248.

Diaconeasa, B. & Mitroescu, S. 1987: Analize polen in Mlastina „Taul Fara Fund", Jud. Alba. – *Contributii Botanice, Cluj-Napoca*, **69–74**.

Engstrom, D. R. & Wright, H. E. 1984: Chemical stratigraphy of lake sediments as a record of environmental change. – In: Haworth, E. Y. & Lund, J. W. G. (eds): Lake Sediments and Environmental History. Leichester University Press, Leichester; University of Minnesota Press, Minneapolis. 11–67.

Espitalie, J., Deroo, G. & Marquis, F. 1985: Rock-Eval Pyrolysis and its Applications. – *Institut Français du Pétrole. Geologie* No. 27299, 72 p.

Fărcas, S., de Beaulieu, J.L., Reille, M., Coldea, G., Diaconeasa, B., Goslar, T. & Jull, T. 1999: First ^{14}C datings of lateglacial and holocene pollen sequences from the Romanian carpathians. – *Comptes Rendues de l'Academie des Sciences de Paris, Sciences de la Vie* **322**, 799–807.

Fărcas, S., Tantău, I. & Bodnariuc, A. 2003: The Holocene human presence in Romanian Carpathians, revealed by the palynological analysis. – *Würzburger Geographische Manuskripte* **63**, 113–130.

Feurdean, A. 2004: Palaeoenvironment in north-western Romania during the last 15,000 years. – PhD Thesis in Quaternary Geology No. 3, Department of Physical Geography and Quaternary Geology, Stockholm University. 47 p.

Feurdean, A. 2005: Holocene forest dynamics in northwestern Romania. – *The Holocene* **15/30**, 435–446.

Feurdean, A. & Bennike, O. 2004: Late Quaternary palaeoecological and palaeoclimatological reconstruction in the Gutaiului Mountains, northwest Romania. – *Journal of Quaternary Science* **19/8**, 809–827.

Gelei, J. 1909: A Szent Anna-tó. – *Földrajzi Közlemények* **47**, 177–201.

Gell, P., Barker, P., DeDeckker, P., Last, W. & Jelicic, L. 1994: The Holocene history of West Basin Lake, Victoria, Australia; chemical changes based on fossil biota and sediment mineralogy. – *Journal of Palaeolimnology* **12**, 235–258.

Gensemer, R. W., Smith, R. E. H. & Duthie, H. C. 1995: Interactions of pH and aluminium on cell length reduction in Asterionella ralfsii var. americana. In: Korner. & Marino, D. & Mostresor, M. (eds.): Proceedings of the 13th International Diatom Symposium. Biopress Limited Bristol. 39–46.

Gibson, C. E. 1997: The Dynamics of Phosphorous in Freshwater and Marine Environments. – In: Tunney, H., Carton, O. T., Brookes, P. C. & Johnston, A. E. (ed.): Phosphorous Loss from Soil to Water. CAB international, Wallingford, UK. 119–149.

Harrison, S. P., Yu, Ge. & Tarasov, P. E. 1996: Late Quaternary Lake-Level Record from Northern Eurasia. – *Quaternary Research* **45**, 138–159.

Hagen-Thorn, A., Callesen, I., Armolaitis, K. & Nihlgard, B. 2004: The impact of six European tree species on the chemistry of mineral topsoil in forest plantations on former agricultural land. – *Forest Ecology and Management* **195**, 373–384.

Hertelendi, E., Csongor, É., Záborszky, L., Molnár, J., Gál, J., Györffy, M. & Nagy, S. 1989: A counter system for high precision ^{14}C dating. – *Radiocarbon* **34/3**, 833–839.

Huntley, B., Watts, W.A., Allen, J. R. M. & Zolitschka, B. 1999: Palaeoclimate, chronology and vegetation history of the Weichselian Late-glacial: comparative analysis of data from three cores at Lago Grande di Monticchio, southern Italy. – *Quaternary Science Reviews* **18**, 945–960.

Jakab, G. 2005: Növényi makrofosszília vizsgálati módszerek kidolgozása negyedidőszaki üledékek paleobotanikai leírására. – PhD Dolgozat Szegedi Tudományegyetem Földtani és Őslénytani Tanszék, Szeged. 119 p.

Jakab, G. & Sümegi, P. 2004: A lágyszárú növények tőzegben található maradványainak határozója mikroszkópikus bélyegek alapján. – *Kitaibelia* **9/1**, 93–129.

Jakab, G. & Sümegi, P. 2006: A nagybárkányi Nádas-tó kialakulása a makrofosszília vizsgálatok alapján (Cserhát, Észak-Magyarország). – *Kitaibelia* **11/1** (in press).

Jakab, G., Sümegi, P. & Magyari, E. 2004a: A new quantitative method for the palaeobotanical description of Late Quaternary organic sediments. – *Antaeus* **27**, 181–211.

Jakab, G., Sümegi, P. & Magyari, E. 2004b: A new paleobotanical method for the description of Late Quaterary organic sediments (Mire-development pathways and paleoclimatic record from S Hungary). – *Acta Geologica Hungarica* **47/4**, 373–409.

Jakab, G., Sümegi, P. & Szántó, Zs. 2005: Késő-glaciális és holocén vízszintingadozások a Szigligeti-öbölben (Balaton) makrofosszília vizsgálatok eredményei alapján. – *Földtani Közlöny* **136/3,** 405–432.

Jankovská, V. 2001: Vegetation development in the W part of the Giant Mts. during the Holocene (Panèava Rašelinište Mire – palaeoecological research). – *Opera Corcontica* **8**, 8–17.

Juggings, S. 2001: The European Diatom Database, User Guide, Version 1.0. 72 p.

Juhász, I. E. 2005: Late-Holocene vegetation history of Baláta Lake, Kaszópuszta. The palynological results. – In: Juhász, I. E. Zatykó, Cs. & Sümegi, P. (ed.): Environmental History of Transdanubia. British Archaeological Report, Central European Series, 3. (in press).

Juvigné, E., Gewelt, M., Gilot, E., Hurtgen, C., Seghedi, I., Szakács, A., Gábris, Gy., Hadnagy, Á. & Horváth, E. 1994: Une éruption vieille d'environ 10700 ans (^{14}C) dans les Carpates orientales (Roumanie). – *Isotopic Geochemistry. C.R. Acad. Sci. Paris, t.* **318**, série II, 1233–1238.

Karátson, D. 1999: Erosion of primary volcanic depressions in the Inner Carpathian Volcanic Chain. – *Zeitschrift für Geomorphologie* Suppl.-Bd. **114**, 49–62.

Kern, Z., Fórizs, I., Kázmér, M., Nagy, B. & Szántó, Zs. 2003: Preliminary results in dendroclimatological and isotope studies at Ghetarul Focul viu, Bihor Mts, Romania, EuroDendro 2003 – *Conference of the European Working Group for Dendrochronology, Abstracts, Obergurgl*, p. 45.

Komárek, J. & Jankovská, V. 2001: Review of the Green Algal Genus Pediastrum; Implication for Pollenanalytical Research. – *Bibliotheca Phycologica* **108**. Berlin-Stuttgart. 127 pp.

Krammer, K. 2000: The genus Pinnularia. – In: Lange-Bertalot, H. (ed.): Diatoms of Europe 1. A.R.G. Gantner Verlag K. G. 703 p.

KRAMMER, K. & LANGE-BERTALOT, H. 1986–1991: Süsswasserflora von Mitteleuropa. – Bacillariophyceae 1–4. Gustav FISCHER Verlag, Stuttgart, Jena, 876, 611, 576, 437 p.

KRISTÓ, A. 1994: A Csomád Hegycsoport. – *Környezetkultúra* **4**, 1–17.

KRISTÓ, A. 1995: A Csomád hegycsoport. A Szent Anna-tó természetvédelmi területe. – In: PAPP, Á. & SZÍJÁRTÓ, I. (eds): KRISTÓ András emlékére, Balaton Akadémia Könyvek 13, Vörösberény, Budapest. 38–45.

LANGE-BERTALOT, H. 2001: Navicula sensu stricto 10 Genera separated from Navicula sensu lato Frustulia. – In: LANGE-BERTALOT, H. (ed.): Diatoms of Europe 2. A.R.G. Gantner Verlag K.G. 526 p.

LANGE-BERTALOT, H. & METZELTIN, D. 1996: Indicators of Oligotrophy. – In: LANGE-BERTALOT, H. (ed.): Iconographia Diatomologica 2. Koeltz Scentific books. 390 p.

LAST, W. M. & SMOL, J. P. (eds.) 2001: Tracking Environmental Change Using lake Sediments. Volume 2. Physical and Geochemical Methods. Kluwer Academic Publishers, London, 504 p.

LAWSON, D. S., HURD, D. C. & PANKRATZ, H. S. 1978: Silica dissolution rates of decomposing phytoplankton assemblages at various temperatures. – *American Journal of Science* **278**, 1373–1393.

LERMAN, A. (Ed.) 1978: Lakes: Chemistry, Geology, Physics. – Springer-Verlag, New York. 363 p.

LOTTER, A. F. 2003: Multi-Proxy Climatic Reconstructions. – In: MACKAY, A. W., BATTARBEE, R. W., BIRKS, H. J. B. & OLDFIELD, F. (eds.): Global change in the Holocene. Arnold, London. 373–383.

MACKERETH, F. J. H. 1966: Some chemical observations on post-glacial lake sediments. – *Philosophical Transactions of the Royal Society of London B* **250**, 165–213.

MAGNY, M., MIRAMOT, C. & SIVAN, O. 2002: Assessment of the impact of climate and anthropogenic factors on Holocene Mediterranean vegetation in Europe on the basis of palaeohydrological records. – *Palaeogeography, Palaeoclimatology, Palaeoecology* **186**, 47–59.

MOORE, P. D., WEBB, J. A. & COLLINSON, M. E. 1992: Pollen analysis. Second edition. – Blackwell Scientific Publications. Oxford, 216 p.

MORIYA, I., OKUNO, M., NAKAMURA, T., ONO, K., SZAKÁCS, A. & SEGHEDI, I. 1996: Radiocarbon ages of charcoal fragments from the pumice flow deposit of the last eruption of Ciomadul volcano, Romania. – *Summaries of Researches using AMS at Nagoya University* **7**, 255.

NORUSIS, M. J. 1990: SPSS/PC+ Advanced Statistics 4.0 for IBM PC/XT/AT and PS/2. – SPSS Inc. Chicago. 647p.

NYÁRÁDI, E. Gy. 1929: A vizek és vízben bővelkedő talajok növényzetéről a Hargitában. – In: CSUTAK, V. (ed.): Emlékkönyv a Székely Nemzeti Múzeum 50 éves jubileumára. A Székely Nemzeti Múzeum Kiadása. Minerova Irodalmi és Nyomdai Műintézet Részvénytársaság, Sepsiszentgyörgy. 557–615.

OLDFIELD, F., CROOKS, P. R. J., HARKNESS, D. D. & PETERSON, G. 1997: AMS radiocarbon dating of organic fractions from varved lake sediments: an empirical test of reliability. – *Journal of Palaeolimnology* **18**, 87–91.

ONAC, B. P., CONSTANTIN, S., LUNDBERG, J. & LAURITZEN, S. E. 2002: Isotopic climate record in a Holocene stalagmite from Ursilor Cave (Romania). – *Journal of Quaternary Science* **17**, 319–27.

ORBÁN, B. 1869: Szent Anna-tava. – A Székelyföld leírása. Háromszék. 3. kötet, Európai Idő Kiadó. 72–75.

PÁL, Z. 2000: A Szent Anna Tó: következtetések a tó mélységét és feltöltődésést illetően. – *Collegicum Geographicum* **1**, 65–74.

PÁL, Z. 2001: A Szent Anna Tó batimetriája. – *Collegicum Geographicum* **2**, 73–78.

PETERSEN, J. B. 1950: Observations on some small species of Eunotia. – *Dansk Botanisk Arkiv* **14**, 1–19.

PLĀMADĀ, E. 1998: Flora Briologicā a Romāniei, Vol. I. Fasc. 1. – Presa Universitarā Clujanā, 230 p.

PODANI, J. 1993: SYN-TAX 5.0: Computer programs for multivariate data analysis in ecology and systematics. – *Abstracta Botanica* **17**, 289–302.

RAGOTZKIE, R. A. 1978: Heat Budgets of Lakes. – In: LERMAN, A. (ed.): Lakes: Chemistry, Geology, Physics. Springer-Verlag, New York, 1–19.

ROTHE, A., HUBER, C., KREUTZER, K. & WEIS, W. 2002: Deposition and soil leaching in stands of Norway spruce and European beech: results from the Höglward research in comparison with other European case studies. – *Plant Soil* **240**, 33–45.

RÖSCH, M. & FISCHER, E. 2000: A radiocarbon dated Holocene profile from the Banat mountains (Southwestern Carpathians, Romania). – *Flora* **195**, 277–286.

SCHNITCHEN, Cs., MAGYARI, E. & GRIGORSZKY, I. 2002: Egy erdélyi tőzegmoholáp mikropaleontológiai vizsgálata Testacea fajok alapján (Micropaleonthological observations on a Sphagnum moss in East Carpathian region). – *Hidrológiai Közlöny* **82**, 105–108.

SCHNITCHEN, Cs., MAGYARI, E., TÓTHMÉRÉSZ, B., GRIGORSZKY, I. & BRAUN, M. 2003: Micropaleontological observations on a Sphagnum bog in East Carpathian region – testate amoebae (Rhizopoda: Testacea) and their potential use for reconstruction of micro- and macroclimatic changes. – *Hydrobiologia* **506–509 (1–3)**, 45–49.

SCHNITCHEN, C., CHARMAN, D.J., MAGYARI, E., SZURDOKI, E., BRAUN, M., GRIGORSZKY, I., TÓTHMÉRÉSZ, B., MOLNÁR, M. & SZÁNTÓ, Zs. in press: Reconstructing hydrological variability from testate amoebae analysis in Carpathian peatlands. – *Journal of Palaeolimnology*.

SCHUR, F. 1858: Der südliche Hochgebirgs-Zug Siebenbürgens in botanish-geographisher Beziehung. – *Österreichische Botanische Zeitschrift* **8**, 393–407.

SMOL, J. P. 1985: The ratio of diatom frustules to chrysophycean statospores: a useful paleolimnological index. – *Hydrobiologia* **123**, 199–208.

SMOL, J. P., BIRKS, J. B. & LAST, W. M. (ed.) 2001: Tracking Environmental Change Using lake Sediments. – Volume 3. Terrestrial, Algal and Siliceous Indicators. Kluwer Academic Publishers, London, 371 p.

STARKEL, L., KALICKI, T., KRAPIEC, M., SOJA, R., GÊBICA, P. & CZYZOWSKA, E. 1996: Hydrological changes of valley floor in the Upper Vistula Basin during the Late Vistulian and Holocene. – *Geographical Studies* Spec. Iss. **9**, 7–128.

STOCKMARR, J. 1971: Tablets with spores used in absolute pollen analysis. – *Pollen et Spores* **13**, 614–621.

STUIVER, M., REIMER, P. J., BARD, E., BECK, J. W., BURR, G. S., HUGHEN, K. A., KROMER, B., MCCORMAC, F. G., VAN DER PLICHT, J. & SPURK, M. 1998: INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. – *Radiocarbon* **40**, 1041–1083.

SÜMEGI, P., ILON, G., JUHÁSZ, I. E. & JAKAB, G. (in press) Mezőlak – Szélmező tőzegláp geoarcheológiai vizsgálatának eredményei. – In: JUHÁSZ, I. E., ZATYKÓ, Cs. & SÜMEGI, P. (ed.) *Environmental History of Transdanubia, Varia Archaeologica Hungarica* XVIII, Budapest (in press)

SZAKÁCS, S. & SEGHEDI, I. 1995: The Calimani-Gurghiu-Harghita volcanic chain: volcanological features. – *Acta Vulcanologica* **7/2**, 145–153.

TANTAU, I., REILLE, M, DE BEAULIEU, J. L., FĂRCAS, S., GOSLAR, T. & PATERNE, M. 2003: Vegetation history in the eastern Romanian Carpathians: pollen analysis of two sequences from the Mohos crater. – *Vegetation History and Archaeobotany* **12**, 113–125.

TROELS-SMITH, J. 1955: Karakterisering af lose jordater. — *Danmarks Geologiske Undersogelse ser. IV* **10**, 1–53.

TULLNER, T. & CSERNY, T. 2003: New aspects of lake-level changes: Lake Balaton, Hungary. – *Acta Geologica Hungarica*, **46/2**, 215–238.

VANHOUTTE, K., VERLEYEN, E., VYVERMAN, W., CHEPURNOV, V. & SABBE, K. 2004: The freshwater diatom genus Kobayasiella (Bacillariophyta) in Tasmania, Australia. – *Australian Systematic Botany* **17/5**, 483–496.

VORREN, T., VORREN, K. D., ALM, T., GULLIKSEN, S. & LØVLIE, R. 1988: The last deglaciation (20,000 to 11,000 B.P.) on Andøya, northern Norway. – *Boreas* **17**, 41–77.

WOHLFARTH, B., HANNON, G., FEURDEAN, A., GHERGARIC, L., ONAC, B.P. & POSSNERT, G. 2001: Reconstruction of climatic and environmental changes in NW Romania during the early part of the last deglaciation (15,000–13,600 cal years BP). – *Quaternary Science Reviews* **20**, 1897–1914.

WRIGHT, H. E. 1967: A square rod piston sampler for lake sediments. – *Journal of Sedimentary Petrology* **37**, 975–976.

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