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Vegetation development in the Lake Miłkowskie area, north-eastern Poland, from the Plenivistulian to the late Holocene

AGNIESZKA WACNIK

W. Szafer Institute of Botany, Polish Academy of Sciences, Lubicz 46, 31-512 Kraków, Poland, a.wacnik@botany.pl

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ABSTRACT. Pollen and fossil green algae studies of bottom sediments from Lake Miłkowskie provide new data about the post-glacial history of terrestrial and lacustrine vegetation in the Great Mazurian Lake District region. The studied basin is a small gully lake filled up with sediments almost 25 m thick, which were partly annually laminated. This paper describes the events and stages of plant cover development from the Plenivistulian ca. 16 600 cal. BP, when the sediment deposition process began, until the younger Holocene ca. 3800 cal. BP. Special attention is paid to Late Glacial palynostratigraphy which is poorly known so far. Detailed radiocarbon chronology has made it possible to determine the age of particular phenomena, which is especially important in the context of sedimentological gaps present in the Late Glacial section. The studied profile is the longest pollen record of post-glacial evolution of vegetation in north-east Poland. Pollen analysis, for example, revealed the local presence of *Larix* since the Plenivistulian; the early dominance of *Hippophaë rhamnoides* ca. 14 400–14 200 cal. BP; the early immigration of tree birches (confirmed by macrofossil remains) and the establishment of woodland at ca. 14 200–14 150 cal. BP; the rapid opening up of the landscape and intensive development of juniper at ca. 12 600–12 000 cal. BP and the late migration of spruce ca. 3900 cal. BP.

Palaeoalgological studies showed a close correlation among climate, sediment type and fossil green algae taxonomic composition.

KEY WORDS: vegetation history, post-glacial tree migration, fossil green algae, palynology, laminated lake sediments, radiocarbon chronology, Mazurian Lake District, NE Poland

INTRODUCTION

Young-glacial relief with numerous lakes and peat bogs makes the Great Mazurian Lake District a promising area for palynological investigation. Despite the accessibility of material suitable for pollen analysis, the post-glacial vegetation history of this area is not adequately known. There is, in particular, an incomplete knowledge of the Late Glacial development of lacustrine and terrestrial vegetation and a lack of detailed chronology for the recognized phenomena. The present studies at Lake Miłkowskie are focused mainly on these two aspects, as well as on reconstruction of selected green algae succession in the water body in response to climate and lake evolution.

The history of palynological studies in NE Poland was recently summarised by Kupryjanowicz (2008). The high potential of this area was recognized by palynologists in the 1930s when studies of past vegetation changes were initiated (e.g. Knoblauch 1931, Gross 1935). Studies on the history of kettle holes were started by Stasiak in 1958. She analysed bottom sediments in several lakes, e.g. Kruklin, Tałty, Mamry and from the marginal part of Lake Mikołajskie (Stasiak 1963, 1967). In later years she analysed more profiles, but the data remained unpublished. Far more detailed pollen and macrofossil studies of sediments from the central part of Lake

Mikołajskie were carried out by Ralska-Jasiewiczowa (1966). This was the first full study of the Late Glacial and Holocene vegetational development of the area. Up to the present time it has been the reference site for the eastern part of the Mazurian Lake District, despite the lack of a detailed chronology (Ralska-Jasiewiczowa 1989, Ralska-Jasiewiczowa & Latałowa 1996).

In the 1990s, in connection with archaeological excavations of a para-Neolithic Zedmar culture site at Dudka (Gumiński 1995, 1999), pollen analyses of a few samples of Holocene sediments were done (Nalepka 1995), supplemented by studies wood, charcoal and macroremains (Gumiński & Michniewicz 2003). Palynological analyses were also performed at Nietlice (Kupryjanowicz 2002) and Lake Dgał Wielki (Filbrandt-Czaja 2000) at the initiative of archaeologists with the aim of studying the natural context of the settlement. Recently studies of the profiles from Szczepanki in the Staświńskie Meadows (Wacnik & Ralska-Jasiewiczowa 2008), from Lake Wojnowo (Wacnik 2009), Lake Jędzelek (Karczewski et al. 2007), and the area of the Skaliska syncline (Pochocka-Szwarc et al. 2008) have been started.

A very interesting feature of Lake Miłkowskie is the presence of a long sequence (25 m) of partly annually laminated bottom sediments, deposited discontinuously from ca. 16 600 cal. BP. In Poland varved lake sediments have been palynologically studied at Lake Gościąż in central Poland and Perespilno in central-east Poland (Ralska-Jasiewiczowa et al. 1998b, Goslar et al. 1999, 2000). Also, elsewhere in Europe, fine resolution interdisciplinary studies of such type of sediments are not common (e.g. Lotter 1999, Tinner & Lotter 2001, Litt et al. 2001, Veski et al. 2004, Tiljander et al. 2008). Lake Miłkowskie is the first site in north-eastern Poland with a well recognized chronology for its Late Glacial part, partly based on varve counting (Czernik 2004, 2009). In the last few years 14 lakes with laminated sediments or traces of lamination have been reported from northern Poland (Tylmann et al. 2006), and some of them are being studied now.

This paper is based on a PhD Thesis (Wacnik 2003).

CHARACTERISTICS OF THE STUDIED REGION

GEOMORPHOLOGY

According to the physico-geographic regionalisation of Poland (Kondracki 2000), the Mazurian Lake District is the westernmost macroregion of the Eastern Baltic Lake Districts. It covers altogether an area of 13 180 km^2 and can be divided into 7 mesoregions. The Great Mazurian Lake District is one of them and is located in a depression between the Mrągowo Lake District to the west and the Ełk Lake District to the east. It borders the Węgorapa District to the north and the Mazurian Plain to the south. Its limit is determined by marginal forms (moraines, kames) of the Pomeranian phase of the Vistula glaciation. The system of marginal forms is rather consistent as they make a range of minor lobes surrounding the depressions formed after dead ice. As to the geomorphology, the region is located between the 1st and 7th morainic ranges. The mosaic sculpture rich in hills is the result of glacier activity. The absolute range in height between the highest peak of the Piłackie Hills (218.5 m a.s.l.) and the water level in the lake system is 102 m, and while if we include the lake depth it is ca. 150 m (Kondracki 1972).

In the Miłki region, during the time of glacier standstill in the Pomeranian phase, rows of channel lakes were formed among which Lake Miłkowskie also belongs. During the recession of ice to the west from Miłki a glacial valley arose, draining water from the Lake Niegocin region towards Lake Śniardwy. Most probably the depression of the valleys was filled with blocks of dead ice, which, after melting, formed Lake Jagodne. The succeeding stages of deglaciation were accompanied by sedimentation of loams and sands in the lake basins (Szumiński & Liskowski 1993).

GEOLOGY

The geological substratum was formed by a Mazury-Podlasie anticline of the East-European platform. The Precambrian rocks occur here at a depth of several hundred metres. They are covered with Palaeo- and Mesozoic marine sediments (Kondracki 2000). The geological data achieved from drillings show substantial hypsometric differences in the pre-Quaternary surface in the study region and variation in the geological structure of that surface. Its elements are locally upper Cretaceous (Maastricht) as well as Tertiary (Palaeocene, Oligocene, Eocene, Miocene, or even Pliocene) formations. The Pleistocene sediments in the central part of the Mazurian Lake District attain the greatest thickness observed in Poland, in places up to 250 m. The thickness of Quaternary formations is substantially greater in the northern part of the region (to the north of Giżycko and Kętrzyn), by ca. 150–200 m. The substratum there is formed by Palaeogene or Upper Cretaceous sediments. In the sediment profile in this region the main part is boulder clay. In the central and southern parts of the Mazurian Lake District the Palaeogene formations are mostly covered with Neogene sediments, the thickness of Quaternary sediments is not greater than 50–100 m and sandy and gravel-sandy series mostly play the dominant role. Thicker Quaternary formations similar to those from the northern region can be found locally along meridional erosional valleys, prominent in the pre-Quaternary relief of the terrain. The main feature of this type is a meridian depression situated along the line Kolno-Pisz-Orzysz-Giżycko with lateral branches, e.g. in the region of Kętrzyn, Bisztynek and Bartoszyce (Słowański 1971, 1981). The principal part of the Pleistocene stratigraphy in the Mazurian Lake District consists of boulder clays of the older Sanian glacial, the red mud complex of the Wilga glaciation, the lake and swamp deposits of the Masovian interglacial and boulder clays of the younger stadial of the Oder glaciation. Fourteen levels of boulder clays of different age have been distinguished. They correspond probably to the stadials of eight glaciations. Some deposits accumulated during seven interglacials have palynological documentation (Lisicki 1996, 1997) and form one of the stratotype areas for the glacial Pleistocene of Europe (Lisicki 1996). The results of such investigations made possible estimation of ice movement directions during the Narew and San glaciations from the Scandinavian Mountains during the Nida, Wilga, Liwiec and Warta glaciations from the northern part of Botnian Gulf and during Oder and Vistula glaciations from northern Finland (Lisicki 1997).

CLIMATE

The Great Mazurian Lake District is, apart from the mountainous areas, one of the coldest climatic regions of Poland, characterized by long, cold winters (about 130 days with frost). Snow cover persists for 90 to 110 days on average. Ice cover the lakes persists for 3–4 months. The growing period lasts for 180–190 days. Mean monthly air temperatures vary from -4.5°C in January to 17.5°C in July (the mean annual temperature is 6.5°C). Mean annual rainfall ranges from 550 to 600 mm and locally even up to 700 mm (Starkel 1999, Woś 1999).

SOILS

The soils of the Mazurian Lake District form a complex of zonal brown soil, leached soil and semihydrogenic as well as hydrogenic soils. In the northern part brown soils are dominant. In the south rusty, podzolized soils occur with some podzols prevailing, whereas brown soils are rather sporadic. In the depressions along rivers and in the vicinity of lakes hydrogenic and semihydrogenic soils (peat, gyttja soils and others) are prevalent. Brown soils are mostly situated in the areas of hill moraines. They are formed of boulder clay, though sometimes clay, sand, dusty deposits, or loam occur (Bednarek & Prusinkiewicz 1999).

LAKES

The Great Mazurian Lake District is characterized by many lake basins covering 350 km^2 (about 20% of the District area) of which the largest are Śniardwy (113.8 km^2), Mamry (105 km^2), and Niegocin (27.8 km^2). They are situated in the terminal depressions of small glacier lobes separated by moraine ridges (Kondracki 1988). Some of them are connected by canals to form a system of lakes with a constant water level at 116 m a.s.l. At 50.8 m Lake Tałty is the deepest while Lake Miłkowskie occupies part of the Lake Niegocin basin. River systems are poorly developed.

The southern part of the region is situated in the Vistula River basin and the northern part in the Pregoła River catchment area (Kondracki 1994, 2000).

PLANT COVER

The vegetation of the Mazurian Lake District is considered to be quite well-known.

Investigations of the plant cover began in the 19th century and at the beginning of 20th. They were continued after World War II by scientists based at the Olsztyn centre (Korniak 1968, Olesiński & Korniak 1980, Polakowski 1961, 1962, 1963, 1985, Polakowski et al. 1976, 1979, 1980a, b, 1985).

The western parts of the area are included within the natural range of *Fagus sylvatica* and *Acer pseudoplatanus* and show some features of an Atlantic climate. In the eastern and southern parts the marked influence of a continental climate is apparent, creating good conditions for the development of spruce and, in the southern part, of pinewoods (Jutrzenka-Trzebiatowski 1999).

The present vegetation is very rich both floristically and phytosociologically. Various types of coniferous and mixed woodland of the *Dicrano-Pinion* and *Piceion abietis* alliances on sandy soils and dry oak-lime-hornbeam woodland of the *Carpinion betuli* alliance on morainic areas are the prevailing forest communities (Matuszkiewicz 2001).

Mixed forest are the communities dominate on moderately fertile sites which occur mostly in morainic areas. In addition to *Pinus sylvestris*, *Carpinus betulus*, *Picea abies*, and *Quercus robur* occur there. The understorey is rich with *Corylus avellana*, *Frangula alnus*, and *Juniperus communis* the most important species. The herb layer is also well-developed. Slightly moist pine forest with some birch, aspen and spruce occurs in poorer habitats. Juniper is the most important constituent of the brushwood in which also occur some sporadic rowans, oaks, and, in moist places, spruce. In the herb layer *Vaccinium myrtillus* is dominant while *Vaccinium vitis-idaea*, sometimes with *Calluna vulgaris*, occurs in drier places. Deciduous woodland in the areas beyond the natural range of *Fagus* and *Acer pseudoplatanus* are rich in tree species with *Quercus robur*, *Carpinus betulus*, *Tilia cordata*, *Acer platanoides*, *Betula pendula*, and *Populus tremula*. In fertile deciduous woodland, and especially eutrophic carr *Fraxinus excelsior*, *Ulmus glabra*, *U. laevis*, *U. minor*, *Salix alba*, *S. fragilis*, *Populus alba*, *P. nigra*, and, locally, *Alnus glutinosa*, are frequent. In the wooded margins of lakes and rivers, and also in depressions, *Alnus glutinosa* is the dominant tree (Jutrzenka-Trzebiatowski 1999). The whole Mazurian Lake District is characterized by the presence of boreal species from the northern part of the moderate zone of the Euro-Siberian area. Such species, together with central-European ones, dominate in the flora. Most are rather common plants, although there are some rare and relict species such as *Aquilegia vulgaris*, *Pulsatilla patens*, *P. pratensis*, *Anemone sylvestris*, and *Silene tatarica* (Polakowski et al. 1979, Polakowski 1985). The glacial relicts *Rubus chamaemorus*, *Chamaedaphne calyculata*, *Salix lapponum*, and *Betula humilis* also occur. In the area 67 associations and communities have been described (Polakowski et al. 1976). The lacustrine flora is zonal according to depth. The most deeply submerged vegetation consists mainly of the genera *Chara* and *Potamogeton*, accompanied by *Elodea canadensis*, *Myriophyllum spicatum*, *Ceratophyllum demersum*, and *Fontinalis antipyretica*. It grows on the lake bottom down to a depth of several metres, depending on water transparency. Plants of the next zone occur at depths of 2.5–3.5 m, principally *Potamogeton*, *Myriophyllum*, *Lemna minor*, *Nymphaea alba*, and *Nuphar lutea*. Towards the lake margins, at 1.5–2.0 m depths, we can find inshore vegetation composed of *Schoenoplectus lacustris*, *Phragmites australis*, *Typha angustifolia*, and *Carex* species (Polakowski et al. 1980a, Polakowski 1985).

The most widespread plant associations are *Scirpo-Phragmitetum* with dominant *Phragmites australis* and *Caricetum rostratae* with dominant *Carex rostrata*, *C. pseudocyperus*, *C. vesicaria*, and *Lysimachia thyrsiflora* (Polakowski et al. 1980b, Polakowski 1985).

A substantial part of the landscape is devoted to agriculture and settlement where a synanthrophic flora of ruderals and arable weeds occurs.

SITE DESCRIPTION

Lake Miłkowskie formerly the Wobel See, Milkener See, 53°56′N, 21°50′E, is an eutrophic, meromictic water body with a surface area of 23.7 hectares situated in the Miłki village (Fig. 1) ca. 15 km south-east of Giżycko (Wacnik 2009). The area is lowland with some glacial and fluvioglacial hills (Starkel 1999). During the glacier standstill of the Pomeranian phase of the Vistula glaciation gullies developed which gave rise to the present-day gully lakes. One of them is Lake Miłkowskie, set in a hollow surrounded by morainic hills (Szumiński & Liskowski

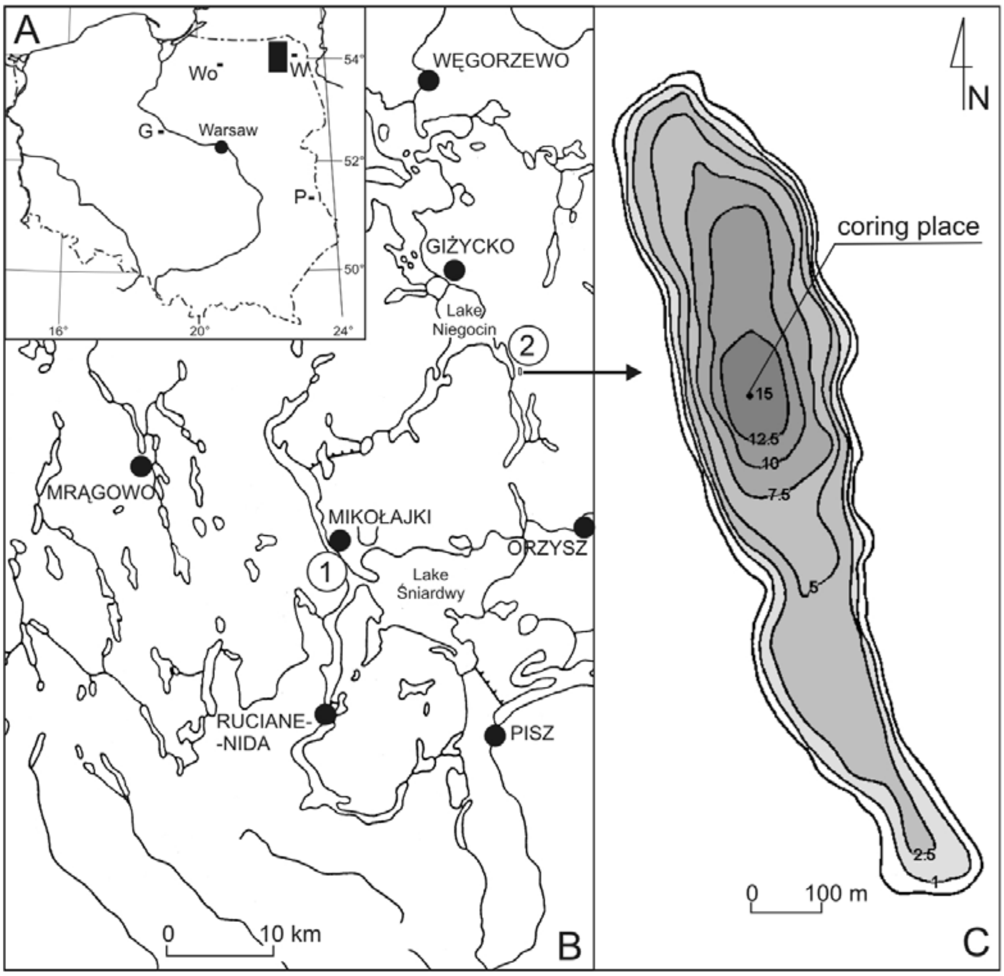

Fig. 1. The area under study; **A**. Location of the studied area and main palynological reference sites mentioned in the text; **G** – Lake Gościąż, **P** – Lake Perespilno, **Wo** –Woryty, **W** – Lake Wigry; **B**. Location of Lake Miłkowskie in the eastern part of the Great Mazurian Lake District; **1** – Lake Mikołajskie, **2** – Lake Miłkowskie; **C**. Bathymetry of Lake Miłkowskie (after R. Tatur 1993) with indication of where corings were made

1993). In shape the lake approximates to an elongated ellipse whose major axis is about 1280 m long and runs north-south. Its greatest depth is 15 m with a mean of 4.2 m (Choiński 1991). Lake Miłkowskie falls within the catchment area of Lake Niegocin. On both its eastern and western sides an escarpment plunges steeply down to the water surface. The slopes leading to its northern and southern margins are gentler. On its eastern side the lake adjoins farm buildings and the Giżycko-Orzysz road. On the others it is bordered mostly by arable fields and meadows. The location of the lake has resulted in its strong eutrophication. Nowadays, after closure of a creamary which was the main source of contamination, the water quality is improving.

The Miłki area is highly deforested with average woodland cover only about 10%. That which remains belongs to the associations *Ribeso nigri-Alnetum* and *Salicetum pentandro-cinereae*. Additionally, half a kilometre from the lake shore there is a small pine plantation. Studies of the present-day vegetation show the predominance of cultivated fields accompanied by weed communities of the alliances *Aperion spicae-venti* and *Polygono-Chenopodion*. Meadows and pastures of the class Molinio-Arrhenatheretea cover extensive areas around the lake. Meadows of the alliance *Arrenatherion* are present on the tops and slopes of hills, while wet meadows of the association *Angelico-Cirsietum oleracei* occupy low lying areas (Zarzyka-Ryszka pers. comm.).

PREVIOUS PALAEOBOTANICAL STUDIES OF THE LAKE MIŁKOWSKIE DEPOSITS

In the 1980s monitoring of the Mazurian Lakes resulted in the coring of the bottom sediments of several dozen lakes, Lake Miłkowskie among them, to find those particularly useful for detailed palaeoecological studies. The basic aim of this work was to select the best lake for analysis of changes in the natural environment by human activities during historical times (Tatur 1986). In the majority of lakes the uppermost, anthropogenic layer of laminated sediment was up to 0.5 m thick and its half-liquid consistency was not good for preserving undisturbed stratification. Lake Miłkowskie was an exception with 3.5 m thick anthropogenic layer. The annual laminations found there, were rather thick, making it possible to realise detailed chronological palaeolimnological studies (A. Tatur per. comm., R. Tatur 1993).

Following the corings in 1984 and 1988 the depth and character of the lake-bottom deposits were studied. Over the succeeding years lithostratigraphical studies of the whole profile and analyses of selected chemical elements and compounds in its uppermost part were carried out by researchers from the Institute of Ecology, Polish Academy of Sciences led by A. Tatur (A. Tatur 1986, 1987, and unpubl. R. Tatur 1993). In 1993 R. Tatur performed the first pollen analyses of the 4.5 m thick upper part of the core, deposited in historical times. In 1997 expert palynological studies were performed from the whole profile (Wacnik 2003). These indicated that the accumulation of bottom sediments began earlier than the Allerød interstadial and provided information about the accumulation rates and history of changes in the local vegetation. Because of the unique character of the sediments, showing fairly regular laminations and the time frames of sediment deposition, the decision was made to continue the interdisciplinary studies.

CORING AND SEDIMENT DESCRIPTION

The sediment from the bottom of the lake was taken in a core from the area where it was thickest in the deepest part of the lake (water depth 15 m, Fig. 1). The twin cores M2-M3/98 and M4/98, 1 m apart, were collected using a Więckowski piston corer fastened to a floating platform stabilized by ropes. The collected cores were rather compact even in their uppermost part. Gases which, in the uppermost part of profiles, normally result in the necessity of freezing for structure protection were only weakly liberated. The cored sequence was 24.97 m long.

A photographic record of the cores was made and later used for the correlation of sediments from the twin cores. In this way continuity of deposition and the designation of the depth where possible hiatuses in sedimentation may have occurred were analysed (Czernik 2004, 2009). Then samples for palaeobotanical, chronological and geochemical studies were taken.

The top 2 m long core sections contained sediment from the borehole walls reworked during sampling. These mixed sections were recognised by correlation with the corresponding sections of the twin cores, confirmed by pollen analysis, and then rejected. This procedure was the cause of 'technical' gaps in the pollen diagram which are not real hiatuses in the sediment. The bottom part of the profile (2497–2253 cm) contained silty sand and gravels overlain by sandy silt intercalated with sand layers. These series were covered by coarse detritus with thin sand layers (2253–2134 cm). The next part of the profile (2134–1416 cm) was composed of gyttja with sporadic sand layers. The major part of the lake sediment displayed regular laminations, fading or disturbed in places to varying degrees.

MATERIAL AND METHODS

POLLEN AND GREEN ALGAE ANALYSIS

Samples for palynological investigations of 1 cm^2 size, comprising 10 pairs of laminae, were collected from the segments displaying regular lamination. From the remaining parts of the cores samples of 1 cm^3 volume were taken every 3–4 cm. A standard chemical preparation of 10% HCl, 10% KOH, 40% HF was used and acetolysis and mounting in glycerine (Erdtman 1960) was carried out. To estimate sporomorph concentration *Lycopodium* tablets were added (Stockmarr 1971, Berglund & Ralska-Jasiewiczowa 1986). All pollen and spores were identified on at least two slides using keys (e.g. Moore et al. 1991, Reille 1992, 1995, 1998, Stuchlik 1994) and the reference collection of modern pollen slides at the W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

On average 900 grains of tree and shrub pollen were determined as well as all accompanying pollen grains of herbaceous plants and spores. In the bottom part the number of counted sporomorphs was reduced to 250 of arboreal pollen because of the very low concentrations.

During pollen analysis a substantial number of one-celled as well as colonial green algae were found. An attempt was made to discover their succession in the lake with the aim of obtaining additional ecological information, particularly about the environmental conditions in the accumulation basin.

Determination of selected green algae was made by use of keys and taxonomic descriptions contained in publications such as Komárek & Fott (1983), Komárek & Marvan (1992), Jankovská & Komárek (2000), and Komárek & Jankovská (2001).

GRAPHICAL PRESENTATION OF RESULTS

The results are presented as percentage pollen diagrams prepared with POLPAL for Windows software (Walanus & Nalepka 1999). The samples have been plotted on a depth scale. The percentage value of each pollen taxon has been calculated in relation to the total of tree, shrub (AP) and herbaceous plant pollen (NAP), excluding that of local plants, limnophytes and telmatophytes, as well as the spores of Pteridophyta, *Sphagnum* and redeposited Tertiary sporomorphs. Frequency of the excluded taxa were counted in relation to the total sum. The same procedure was applied in the determination of non-pollen palynomorphs frequency.

The algal remains of *Pediastrum*, *Botryococcus*, *Coelastrum*, *Scenedesmus*, and *Tetraedron* were counted on one microscope slide, and then their proportion were calculated in relation to the total pollen sum. In the case of the massive presence of *Tetraedron*, its numbers were counted on only half a slide.

The sequence of pollen taxa in the diagrams has been based on both their affiliation to ecological groups (Berglund & Ralska-Jasiewiczowa 1986), as well as on the stratigraphical order of their appearance in the pollen spectra.

CHRONOLOGY

Chronology was based on the results of AMS ^{14}C datings of plant remains (macrofossils of terrestrial plants, fragments of aquatic plants, pteridophytes and mosses), and was supported by dates interpolated from other pollen profiles mainly from Woryty (Pawlikowski et al. 1982), Dudka (Nalepka 1995), and Szczepanki (Wacnik & Ralska-Jasiewiczowa 2008, Madeja et al. 2009). The chronology of the Late Glacial part follows the depth-age model constructed by Czernik (2004, 2009). All radiocarbon dates used in the text are calibrated years BP (Tab. 1). For calibration Calib 5.0.2 software was used (Stuiver & Reimer 1993, Stuiver et al. 2005).

REDEPOSITED SPOROMORPHS

The taxonomic composition of the pollen spectra in the bottom part of profile M4/98 (2497–2294 cm) revealed a substantial admixture of redeposited material. The bottom sediments formed from sandy-silty fluvioglacial material contained the highest admixture of redeposited sporomorphs (ca. 20%) in parallel with the lowest general frequency of pollen in the profile. From 2294 cm upwards the content of secondary sporomorphs gradually declined. Sediment analysis showed a corresponding decline in its density, a rise in organic matter content, lamination disturbance and a change of deposit type into gyttja with intercalations of glacial sandy muds or silty sands (A. Tatur pers. comm.). Above 2253 cm rebedded sporomorphs occurred only sporadically while at the same time the pollen frequency rose and the contribution and taxonomic diversity of green algae increased.

Table 1. Lake Miłkowskie. Results of AMS ^{14}C datings

Depth from the lake bottom surface [cm]	Laboratory code	Uncalibrated age BP	Calibrated age BP (2σ certainty, the highest data probability only)	Dated material
1613.6–1614.3	Poz-843	5060±45	5710–5913	fragments of leaf nervature
1649.0–1649.6	Poz-846	5660±60	6308–6567	fragments of leaf nervature
1851.5–1852.4	Poz-842	8130±110	8715–9334	fragments of leaf nervature
1869.0–1872.8	*Poz-845	8160±60	8997–9288	*Alnus* seedcoat
2147–2149	*GdA-103	10 290±100	11 699–12 404	*Betula* sect. *Albae* fruit, fruit scale; *Pinus sylvestris* periderm
2164–2168	*GdA-104	10 870±80	12 758–12 971	*Betula* sect. *Albae* fruit, fruit scale; *Pinus sylvestris* periderm; *Carex* fruit
2222–2228	*GdA-106	11 190±90	12 924–13 240	*Betula* sect. *Albae* fruit, fruit scale; *Pinus sylvestris* periderm
2228–2232	*GdA-107	11 620±80	13 296–13 668	*Betula* sect. *Albae* fruit, fruit scale; *Pinus sylvestris* periderm; *Carex* fruit
2236–2240	*GdA-109	12 240+360/–350	13 400–15 230	*Betula* sect. *Albae* fruit, fruit scale; *Pinus sylvestris* periderm; *Carex* fruit
2250–2252	*Poz-28540	12 500±60	14 230–14 962	*Betula* sect. *Albae* fruit, fruit scale; *Carex* fruit
2280–2285	*GdA-113	12 380±80	14 074–14 846	moss twigs and leaves
2300–2308	*GdA-114	12 550±160	14 113–15 176	*Equisetum* sp. Rhizome fragments
2353–2357	*GdA-124	13 970+110/–100	16 199–17 078	*Carex* sp. fruit
2408–2413	*GdA-135	13 760±90	15 996–16 821	Characeae oogonia
2423–2433	*GdA-137	13 960±100	16 204–17 052	Characeae oogonia

* selected data obtained by J. Czernik (2009). For further information see Czernik (2004)

Within the redeposited taxa two basic groups could be identified. The first was composed of Tertiary taxa, e.g.: Taxodiaceae/Cupressaceae (*Inaperturopollenites* sp.), *Sequoia* (*Sequoiapollenites* sp.), *Castanea*/ *Castanopsis* (*Castaneoideaepolis* sp.), *Liquidambar* (*Preiporopollenites* sp.), *Nyssa* (*Nyssapollenites* sp.), *Quercoidites henrici*, *Engelhardia* (*Engelhardtiopollenites* sp.), *Rhus* (*Rhuspollenites* sp.), and Cyrillaceae/ Clethraceae (*Tricolporopollenites megaexactus*). The second group consisted of taxa common in deposits of different age both Quaternary and Tertiary, such as *Alnus*, *Carpinus*, *Tilia*, *Ulmus*, *Quercus*, *Picea*, *Abies*, and *Corylus*. These taxa could not occur in the pre-Allerød part of the Vistulian Late Glacial in north-eastern Poland because of the climatic conditions. To this group could also be included some problematic taxa such as *Pinus sylvestris*, *Betula*, and *Pinus haploxylon* type. The provenance of these pollen taxa (long distance transport, redeposition, local sources) is difficult to estimate.

THE SOURCE OF POLLEN CONTAMINATION

The contaminations noted, especially in the sediment section older then 14 250 cal. BP, are probably, primary character, which means that they came into existence during the deposition of the sediments and are not connected with the fieldwork methods. The evidence for this is provided by the substantial representation of exotic taxa known from Tertiary deposits, the connection between the occurrence of redeposition and the kind of sediment and by the lack of rebedded taxa in the younger part of the profile. Rebedded pollen disappear almost completely in the Allerød part of the profile when the plant cover became denser. Tertiary sediments of the similar age to the redeposited pollen have been recorded in the deep corings several dozen kilometres to the north and west of Miłki where they form the geological background (Lisicki 1996, Lisicki & Winter 1999). Several standstill phases during the glacier recession left rows of front moraines, among others, along the line running parallel to the north-eastern banks of lakes Wojnowo and Miłkowskie. The boulder clay forming them, comprising Quaternary and Tertiary matter, possibly with some pieces of older rocks, should be treated as the probable source of redeposition in the pollen spectra. Through water erosion, fine fractions of sediments of different age were transported and accumulated within the lake basin as sand and silt during the first phase of lake formation, when the plant cover was sparse. In the samples from sandy or silty sediments the contamination by exotic taxa is much higher then elswhere.

POLLEN STRATIGRAPHY

The percentage pollen diagram of the Lake Miłkowskie sediment has been divided into 13 (L PAZ) local pollen assemblage zones (Tab. 2). The delimitation of the zones was based on the taxonomic composition and percentage values of the main or characteristic taxa recorded in the pollen spectra and supported by ConSlink numerical analyses.

The name of any particular zone was assigned on the basis of those taxa which were characteristic or represented in the greatest abundance.

RESULTS OF FOSSIL GREEN ALGAE ANALYSES

Nine phases of marked change in the taxonomic composition as well as in the frequency of green algae (indicated with consecutive letters of the alphabet) were distinguished (Tab. 3).

HISTORY OF THE LOCAL VEGETATION

STAGE I: OPEN LANDSCAPE WITH STEPPE AND TUNDRA-LIKE COMMUNITIES, PIONEER VEGETATION

Zone Mł1 *Pinus sylvestris-Sphagnum* (ca. 16 600–16 400 cal. BP)

The palynological data reveal a situation typical for a periglacial environment during the initial stage of melting of dead ice and basin formation (Fig. 2). Intensive erosional processes taking place in the area uncovered by the retreating glacier were probably the reason for sediment contamination with redeposited sporomorphs. The analogous presence of rebedded material was observed not only during the Late Glacial part of the Vistulian, but also in the older Pleistocene glaciations (Ralska-Jasiewiczowa 1966, Mamakowa 1989, Granoszewski 2003). The AMS ^{14}C datings, as well as the preliminary results of counting the rather thick laminae (ca. 1 cm), provide evidence of the intense accumulation of silty-sandy deposits, probably from 16 600 till 16 300 cal. BP (Czernik 2004, 2009). Rapid sediment deposition is associated with the lowest concentration of sporomorphs in the whole profile and is one of the main causes of it. The vegetation should therefore be regarded as substantially contaminated because of the high redeposition and the low totals of counted palynomorphs.

The vegetational cover was of pioneer in character and, as can be expected, developed in the form of patches which did not provide any closed cover. The lake shores were not protected against slope erosion. The vegetation was treeless with a small, but gradually increasing shrub representation. The most important elements of the flora were heliophilous herbs,

Table 2. Lake Miłkowskie. Description of local pollen assemblage zones (L PAZ)

L PAZ	Name	Depth [cm]	Description of pollen spectra
Mł1	*Pinus-Sphagnum*	2459–2349	Relatively high contribution of AP (from 59% to 72%). The dominance of *Pinus sylvestris* (66.3%) and *Betula* (35%). Several percentage frequency of *Salix* (5.4%). Shrubs represented by *Betula nana* type (4.2%), and single finds of *Rubus arcticus* type, *Juniperus*, *Hippophaë*, and *Salix polaris* type. Regular presence of *Empetrum* and *Calluna*. Among herbs the highest number of Poaceae (22.4%), *Artemisia* (12.1%), Cyperaceae (6.7%), Chenopodiaceae (3.2%), and *Bupleurum*. The sporadic identification of *Astragalus* type, *Gypsophila* type, *Helianthemum canum* type, and *H. nummularium* type. The single pollen grains of limnophytes, such as *Potamogeton*, *Typha angustifolia* type, and *Myriophyllum verticillatum*. Numerous sporophytes *Equisetum*, Filicales monolete, *Botrychium*, and *Sphagnum*. *Selaginella selaginoides* spores present in 2 samples. High content of rebedded palynomorphs like: *Alnus*, *Quercus*, *Corylus*, *Picea*, *Ulmus*, *Carpinus*, *Sequoia* (*Sequoiapollenites* sp.), *Nyssa* (*Nyssapollenites* sp.), *Liquidambar* (*Preiporopollenites* sp.), Taxodiaceae/Cupressaceae (*Inaperturopollenites* sp.). The upper limit: rise of *Betula*, drop of *Pinus sylvestris*, beginning of *Juniperus* curve. Pollen concentration: the lowest in the whole profile with high number of corroded pollen grains
	Subzone Mł1a *Betula-Artemisia*	2459–2414	The zone is devided into 2 subzones: a – dominance of *Betula* pollen. Decline tendency of *Pinus sylvestris*. The high contribution of NAP especially *Artemisia*, Poaceae, and Cyperaceae. Chenopodiaceae, and *Helianthemum canum* type form continuous curves. High value of *Bupleurum* (5.1%). The upper limit: rapid rise of *Pinus sylvestris*, synchronous decline of *Betula* and *Artemisia* curves
	Subzone Mł1b *Pinus*	2414–2349	b – dominance of *Pinus sylvestris*. Rise of *Salix* with two short-lasting peaks. Appearance of *Larix*. High frequency of *Betula nana* type. Single grains of *Salix polaris* type, *Ephedra fragilis* type, and *Hippophaë*. Decline of NAP contribution. *Artemisia*, Poaceae, and Cyperaceae still dominant. Regular presence of *Gypsophila* type, *Astragalus* type, *Aster* type, and Brassicaceae
Mł2	*Betula nana-Juniperus-Artemisia*	2349–2324	Strong decrease of *Pinus sylvestris*. High values of *Betula* pollen with short-lasting peak (40.6%) in the bottom part of zone. Continuous curve of *Salix* undiff. (7.3%), *Betula nana* type (6.9%), and *Juniperus* (3.1%). Presence of *Larix*. Single *Hippophaë*, *Rubus arcticus* type, *Calluna*, and *Ephedra distachya* type pollen. Almost continuous curve of *Empetrum.* Rise of NAP. Domination of Poaceae (21.1%). Strong increase of *Artemisia* (14.2%), slight rise of Cyperaceae as well as Chenopodiaceae. Systematically present *Bupleurum*, *Astragalus* type, *Helianthemum canum* type, and *Thalictrum*. Low contribution of limnophytes represented by *Potamogeton* and *Typha angustifolia* type. *Selaginella selaginoides* registered in the bottom sample. High number of rebedded pollen. The upper limit: rise of *Pinus sylvestris*, and synchronous decline of *Juniperus*, *Artemisia* and Cyperaceae frequencies. Pollen concentration: very low
Mł3	*Pinus-Salix*	2324–2289	The high contribution of AP (75%). The most numerous *Pinus* (45%) and *Betula* (38.5%). The continuous curves form *Salix* (7.3%), *Betula nana* type (max. 3.5%), *Juniperus* (2.1%), and in the upper part also *Hippophaë*. Sporadical presence of *Larix.* Lower values of NAP, consequently dominated by Poaceae, Cyperaceae, *Artemisia*, and Chenopodiaceae. Systematically noted Brassicaceae, *Gypsophila* type, Rubiaceae, and *Thalictrum*. Among limnophytes *Potamogeton*, and *Myriophyllum verticillatum*. Decrease of redeposited palynomorphs. The upper limit: rise of *Hippophaë*, *Salix*, and *Artemisia* values. Pollen concentration: very low
Mł4	*Betula nana-Hippophaë-Salix*	2289–2250	The highest contribution of *Hippophaë* (up to 8%). Significant increase of *Betula nana* type pollen (7.5%). Substantial decline of *Pinus sylvestris* (36.7%) and *Betula* (31.7%). Relatively high and stable *Salix* curve (8.6%). Appearance of *Populus*. Sporadic presence of *Larix*, *Salix pentandra* type, *Calluna*, and *Empetrum*. Among NAP rise of *Artemisia* and Cyperaceae. Percentage values of Poaceae oscillate between 4% and 12%. Regularly Chenopodiaceae, *Gypsophila* type, *Helianthemum*, Brassicaceae, *Filipendula*, *Rumex acetosella* type, and *Thalictrum*. Presence of *Myriophyllum verticillatum* in the upper part of zone. Almost continuous presence of *Equisetum* and *Sphagnum* spores. The majority of redeposited taxa disappear. The upper limit: rapid rise of *Betula*, accompanying declines of *Pinus sylvestris*, *Hippophaë*, and *Betula nana* type. Pollen concentration: very low, rises only in the upper part

Table 2. Continued

L PAZ	Name	Depth [cm]	Description of pollen spectra
Mł5	*Betula-Salix pentandra-* Poaceae	2250–2235	Increase of AP (85%). Dominant *Betula* with high double culmination (65.1%). Low frequency of *Pinus sylvestris* (32.7%). Continuous low-percentage curve of *Salix pentandra* type (2.5%), *Betula nana* type (1.5%), *Salix* (4.8%), and *Juniperus* (3.7%). Presence of *Salix polaris* type and *Larix*. Disappearance of *Hippophaë* in the uppermost part. Considerable frequency of herbs, mainly Poaceae (13.6%), *Artemisia* (1.9%), Cyperaceae (3.8%), and Chenopodiaceae. Sporadically *Dryas octopetala*, *Gypsophila* type, *Helianthemum canum* type, *H. nummularium* type, *Potentilla* type, Rubiaceae, and *Ranunculus acris* type. Single pollen grains of limnophytes: *Potamogeton*, *Myriophyllum verticillatum*, and *Sparganium* type. Appearance of *Typha latifolia* in the uppermost sample. Pteridophyta represented by spores of Filicales monolete, *Equisetum*, *Botrychium*, *Dryopteris filix-mas*, and *Thelypteris palustris*. Small number of rebedded pollen. The upper limit: rise in *Pinus* values, decline of *Betula*, *Salix*, and NAP. Pollen concentration: rapid increase
Mł6	*Pinus–Betula*	2235–2136	Characteristic high frequency of *Pinus sylvestris* (69.3%). Its curve forms 3 peaks, corresponding with depressions in *Betula* curve. Stable high amount of AP (mean ca. 90%). Gradual fall of *Betula* (43.8%) frequency. Single *Larix*, *Populus*, and *Salix pentandra* type. Shrubs represented by *Betula nana* type, *Juniperus*, *Salix polaris* type, and *Rubus arcticus* type. Low contribution of herbs (NAP). Poaceae (8.2%), Cyperaceae (3.8%), *Artemisia* (4.6%), Chenopodiaceae (1.7%), and *Filipendula* (below 1%) form continuous curves. Regularly registered Rubiaceae, *Rumex acetosella* type, *Thalictrum*, Apiaceae, and *Urtica*. More numerous *Typha latifolia* and limnophytes *Potamogeton*, *Myriophyllum verticillatum*, and *Nuphar*. *Sphagnum* forms again a continuous curve at the upper part of zone. The upper limit: decline of *Pinus* and rapid rise of *Juniperus* frequency. Pollen concentration: relatively high, but oscillating
Mł7	*Juniperus*-NAP	2136–2034	Characteristic rapid rise and the highest participation of *Juniperus* (46.4 %), as well as synchronous decline of *Pinus sylvestris* (31.7%). Decrease of tree pollen contribution (min. 33%). Generaly low frequency of *Betula* with rise in the upper part up to 38.1%. Considerable participation of *Salix* undiff., *Betula nana* type, and *Populus*. Single *Larix*, *Pinus haploxylon* type, *Salix pentandra* type, *Rubus arcticus* type, *Empetrum*, and *Ephedra* (*E. fragilis* type and *E. distachya* type). Increase of herbs importance, particularly of *Artemisia*, Poaceae, Cyperaceae, Chenopodiaceae, and *Filipendula*. In the top part *Helianthemum canum* type forms continuous curve. Regularly *Anthemis* type, *Aster* type, *Gypsophila* type, Rubiaceae, *Rumex acetosella* type, *Thalictrum*, and Apiaceae. Presence of *Typha latifolia*, *Sparganium* type, *Phragmites*, *Potamogeton*, *Myriophyllum verticillatum*, and *Nuphar*. The upper limit: rapid rise of *Betula* and considerable fall of *Juniperus*. Pollen concentration: moderate. The zone is devided into 2 subzones:
	Subzone Mł7a *Juniperus-Artemisia*	2136–2047	a - the highest frequency of *Juniperus* (46.4%), low percentage continuous curve of *Salix* (2.7%), and nearly continuous curve of *Larix*. Regularly present *Salix polaris* type and *Rubus arcticus* type. Single rebedded pollen. The upper limit: decline of *Juniperus* number from 32.6% to 12%.
	Subzone Mł7b *Betula-Juniperus*	2047–2034	b - gradual rise of *Betula*, *Populus*, and substantial participation of *Pinus sylvestris. Betula nana* type forms short-lasting peak (4.8%)
Mł8	*Betula-Pinus*	2034–1913	Dominant *Betula* (76.7%) and *Pinus* (39.9%). Substantial *Populus* (3.9%). Rise of *Ulmus* (4.2%), and *Corylus* in the upper part. Systematical decrease of *Juniperus* and *Salix* (1.2%). Sporadically *Larix* and *Betula nana* type. Single *Dryas octopetala* type, *Ephedra* (incl. *E. dystachia* and *E. fragilis*), and *Empetrum nigrum*. Decreasing tendency of Poaceae (10.5%), Cyperaceae (3.7%), *Artemisia* (1.4%). Continuous curve of *Filipendula* (below 1%). Chenopodiaceae frequent (0.6%) at the beginning of zone, then sporadic. Regular *Sparganium* type, *Nymphaea alba*, and *Potamogeton*. Decrease of *Equisetum.* The upper limit: before an increase of *Corylus* values and just after the *Pinus* decrease. Pollen concentration: oscillating from very low to very high. This zone is divided into 3 subzones:

Table 2. Continued

L PAZ	Name	Depth [cm]	Description of pollen spectra
	Subzone Mł8a *Betula-Pinus-Juniperus*	2034–2011	a - *Juniperus* (4.6%) and high proportion of herbs (up to 20%). The upper limit: decrease of *Juniperus*, *Betula nana* type, and NAP.
	Subzone Mł8b *Betula-Pinus-Populus*	2011–1990	b - the highest *Betula* content and low *Pinus sylvestris*. Fall of NAP. Frequent *Dryopteris filix-mas* and *Thelypteris palustris*. The upper limit: drop of *Betula* and increase of *Pinus*.
	Subzone Mł8c *Pinus-Betula-Populus*	1990–1913	c - high values of *Pinus* (39.9%). Sharp rise of *Corylus* up to 8.9% at the top. Significant *Populus* (5.7%). Stable, relatively high content of *Ulmus* (4.2%). Continuous curve of *Quercus* and *Fraxinus* in the upper part. Re-appearance of *Calluna vulgaris*. Frequent *Urtica*, *Humulus*, and Apiaceae. *Typha latifolia* and *Nymphaea alba* appear several times. Stable amount of Filicales monolete (0.1–1%)
Mł9	*Corylus-Ulmus*	1913–1865	Very high values of *Corylus* (30%). Slow rise of *Ulmus* (8.3%). Decrease of *Pinus* (39.3%), *Betula* (45%). Slight reduction of *Populus*. Low, continuous curve of *Quercus* and *Salix*. Beginning of *Alnus* curve and systematic presence of *Tilia*, *Fraxinus*, *Carpinus*, and *Sambucus nigra* type pollen. Among NAP the most frequent Poaceae (3.3%), Cyperaceae (1.3%), *Artemisia*, Cichorioideae, Rubiaceae, *Filipendula*, and *Urtica*. The upper limit: increase of *Alnus* and *Tilia*. Pollen concentration: moderate
Mł10	*Alnus-Tilia-Ulmus* (*Corylus*)	1865–1805	Rapid rise of *Alnus* (21.6%) and fast fall of *Corylus* (from 27% to 9%). Decrease of *Pinus* (35.6%) and *Betula* (28%). Rise of *Ulmus* (8%) and *Tilia* (6.5%). Slow increase of *Quercus* (2.8%) and *Fraxinus* (0.6%). Regularly *Carpinus*, *Salix*, and *Populus*. Appearance of *Hedera helix* and *Viscum album*. Systematically *Calluna*. Small decrease of herbs (average 4%). Beginning of *Pteridium aquilinum* curve. The upper limit: increase of *Tilia*, *Ulmus*, *Quercus*, and decrease of *Betula*. Pollen concentration: high
Mł11	*Ulmus-Tilia-Alnus* (*Quercus*)	1805–1613	High values of *Ulmus* (12%), *Tilia* (11%), and *Alnus* (25.5%). Distinct increase of *Quercus* (7.8%) and *Fraxinus* (6.4%). Strong oscillations of *Corylus* (37.9%). Farther falls of *Pinus* and *Betula*. Frequent *Carpinus* and *Populus*. Almost continuous presence of *Salix*, and regular *Acer*, *Populus*, *Juniperus*, *Sambucus nigra* type, *Frangula*, *Viscum*, *Hedera*, and *Calluna*. Single *Vitis vinifera* pollen. In the bottom part herbs are quite numerous (8%), than decrease. Reduction of Poaceae, Cyperaceae, and regular appearance of *Artemisia*, *Filipendula*, *Urtica*, and Chenopodiaceae. Almost continuous presence of *Pteridium aquilinum*. Frequent Filicales monolete, *Thelypteris palustris*, *Potamogeton* and *Nuphar*. The upper limit: fall of *Ulmus* and synchronous rise of *Quercus*. Pollen concentration: low to moderate, with rising tendency
Mł12	*Quercus-Ulmus*	1613–1449	The maximum values of *Quercus* (17.8%). High content of *Corylus* (21.4%), *Alnus* (stable content around 23% with short depression), *Ulmus* (8.9%), and *Fraxinus* (6.9%). Slow decrease of *Tilia* (8%–4%). Rise of *Carpinus* (1.5%). Discontinuous curve of *Picea*. Low amount of *Pinus* and *Betula*. Systematically *Populus*, *Acer*, *Fagus*, and *Salix*. Presence of human indicators e.g. Cerealia and *Plantago lanceolata*. Fall of NAP to the minimum values. Regularly *Calluna*, Poaceae, *Artemisia*, *Filipendula*, *Urtica*. Almost constant presence of *Pteridium aquilinum*. Limno- and telmatophytes represented mostly by *Potamogeton*, *Phragmites*, *Nymphaea*, *Nuphar*, and *Thelypteris palustris*. The upper limit: sharp increase of *Corylus*, decrease of *Ulmus*, *Tilia*, and *Quercus*. Pollen concentration: moderate and oscillating
Mł13	*Corylus-Quercus-Alnus*	1449–1416	High *Corylus* with short pick (35%) coincidentally with sharp *Ulmus* fall (from 6.6% to 2.4% and than to 1.3% at the top) and depression of *Pinus* (by 5%), *Betula* (by 7%), and *Tilia* (by 2%). High amounts of *Quercus* (16.6%), *Alnus* (26.7%), stable *Fraxinus* (ca. 3%), *Pinus* (ca. 13%), slow rise of *Carpinus* (1.1–4%), and *Picea* (0.4–2.1%). Regularly *Sambucus* and *Frangula alnus*. Less frequent *Calluna*. Slight increase of NAP, including human indicators e.g. Poaceae (2.7%), Cyperaceae, *Artemisia*, *Plantago lanceolata*, *P. major*, *Rumex acetosella* type, and Cerealia. Pollen concentration: high, but falls to moderate at the top

Table 3. Lake Miłkowskie. Description of algal zones

Name of green-algae zone	Depth [cm]	Description
Zone A	2459–2257	The highest in the profile participation of *Botryococcus*, with predominance of *B. pila*. *Pediastrum* represented mostly by *P. kawraiskyi*, and sporadically by *P. integrum*, *P. boryanum* var. *boryanum*, and *P. boryanum* var. *longicorne*. At the depth of 2303–2304 cm presence of Characeae oogonia
Zone B	2257–2235	Decline of *Botryococcus* values. Beginning of continuous curves of *Tetraedron* at the bottom of zone, and *Scenedesmus* slightly later. Systematic presence of *P. integrum*, *P. boryanum* var. *boryanum*, and *P. duplex* var. *rugulosum*. More often *P. boryanum* var. *longicorne*, and single individuals of *P. angulosum*, *P. kawraiskyi*, and *Coelastrum reticulatum*
Zone C	2235–2115	Stable low frequency of *Botryococcus*. The highest representation of *Pediastrum* genus (20%), especially *P. integrum*, *P. boryanum* var. *boryanum*, and *P. duplex* var. *rugulosum*. Single finds of *P. boryanum* var. *perforatum/cornutum*. After fast increase at the beginning and achieving the maximum, *Tetraedron* and *Scenedesmus* show the tendency to decline in the top samples.
Zone D	2115–2046	Limitation of green-algae frequency except of *Pediastrum kawraiskyi*
Zone E	2046–1990	The renewed rise of algae participation, particularly rapid in case of: *Tetraedron*, *Scenedesmus*, and *Botryococcus* (especially *B. pila*). Small increase of *Pediastrum integrum*, *P. boryanum* var. *longicorne*, and *P. boryanum* var. *boryanum*. In the top a general declining tendency of all green-algae
Zone F	1990–1858	Low number of *Pediastrum* represented mostly by coenobia of *Pediastrum integrum*, *P. duplex* var. *rugulosum*, *P. boryanum* var. *longicorne*, *P. boryanum* var. *boryanum*, and single of *P. angulosum*, *P. boryanum* var. *perforatum/cornutum*. Presence of *Coelastrum reticulatum*. Considerable limitation of *Tetraedron*, *Scenedesmus*, and *Botryococcus*
Zone G	1858–1736	Increase of *Tetraedron*, *Botryococcus* (*B. pila*, *B. neglectus*), and *Scenedesmus*. The highest participation of *Tetraedron* (60%) in the upper part of zone. Higher frequency of *Pediastrum*, particularly of *P. boryanum* var. *boryanum* and *P. integrum*. Appearance of new taxa *P. simplex* and *P. duplex* var. *duplex/gracillimum*. Short-lasting, high peak of *Coelastrum reticulatum*
Zone H	1736–1675	Quick decline of *Tetraedron*, *Botryococcus*, and *Scenedesmus*. Moderately low frequencies of other green-algae representants
Zone I	1675–1407	Strong increase of *Tetraedron*, *Coelastrum* (*C. reticulatum*, *C. polychordum*), and slight of *Botryococcus* (*B. pila*, *B. neglectus*). Rapid oscillations of *Tetraedron* values (between 2% and 41%). Several peaks of *Coelastrum* (20%). Increase of *Scenedesmus*. Relatively rare representants of *Pediastrum*, mostly: *P. boryanum* var. *boryanum*, *P. boryanum* var. *longicorne*, *P. duplex* var. *duplex/gracillimum*, and *P. integrum*

while the plant communities formed a mosaic whose varied composition was related to the local edaphic conditions. Damp places were covered by sedge and tundra communities consisting of *Salix*, *Betula nana*, *Empetrum*, *Thalictrum*, *Ranunculus flammula*, *Selaginella selaginoides*, *Equisetum*, and *Sphagnum*. On the dry surfaces of morainic hills open pioneer communities composed of Poaceae, Chenopodiaceae, *Helianthemum canum*, *H. nummularium*, *Astragalus* and sporadic *Rumex acetosella*, *Plantago media*, *Sanguisorba officinalis*, and *Botrychium* occurred. On the acid areas, poor in nutrients, *Betula nana*, *Empetrum* and possibly *Botrychium* developed. Well represented in dry places were *Artemisia*, *Gypsophila*, *Bupleurum*, and possibly also *Armeria* and *Ephedra fragilis*. In the steppe-like communities species of e.g. Brassicaceae, Cichorioideae, *Aster* type, *Anthemis* type and *Saxifraga oppositifolia* (growing on rocky outcrops, mostly calcareous) may also have been present. Sporadically *Rubus arcticus* and *Vaccinium* may also have been present. A high proportion of steppe taxa indicates cold continental climatic conditions (e.g. Demske et al. 2005, Kupryjanowicz 2008). The consistent contribution of *Pinus haploxylon* type (incl. also *Pinus cembra*) is probably an effect of pollen redeposition and long distance transport. *Juniperus* pollen probably came similarly but from the shorter distances. At a depth of 2407 cm a change in the palynological record becomes apparent, marked by a rise in *Pinus sylvestris* frequency. This phenomenon may have resulted from increased transport of pollen from greater distances in the open area, probably as a consequence of a short-lived approach of the northern tree limit towards the site. The lack of any macrofossils of terrestrial plants suggests that the high values of tree pollen should be treated as the summary effect of long distance pollen transport from the south and its redeposition from older sediments, especially in the context of such a high proportion of Tertiary palynomorphs. The results obtained would seem to indicate that at that time Lake Miłkowskie was a shallow expanse of open water. Supporting evidence is the presence of limno- and telmatophytes consisting of *Potamogeton*, *Myriophyllum verticillatum*, *Typha angustifolia*, and/or *Sparganium* as well as green algae, especially representatives of the genera *Botryococcus*, *Pediastrum* and sporadically, *Tetraedron*. Among the macrofossils single mosses and Characeae (oogonia) were identified (Fig. 3). In the Lake Mikołajskie sediments Characeae were also noted in the initial phase of lake formation (Ralska-Jasiewiczowa 1966) and were associated with silty-sandy sediments similar to those in Lake Miłkowskie, but of younger age. *Chara* species are today an important component of plant communities at the bottom of the Mazurian lakes. They are considered to be pioneer taxa opening vegetation succesion in the littoral zone (Polakowski et al. 1980a). The lake margins were locally covered with peat, as is shown by the considerable proportion of Cyperaceae, *Sphagnum*, and *Equisetum*. Regular *Sphagnum* occurrence is associated with saturated soil, which may have resulted from the presence of permafrost.

The occurrence of *Betula nana* indicates that the maximum temperature of the coldest month was below 0°C and the minimum mean July temperature was around 7°C. The presence of *Selaginella selaginoides* suggests that the mean temperature of the warmest month was below 17°C (optimum temperature for its occurrence is 10–14°C), while *Sanguisorba officinalis* suggests that the mean minimum July temperature was 9–10°C (Kolstrup 1980, Tobolski 1991, Granoszewski 2003, Isarin & Bohncke 1999).

Zone Mł2 *Betula nana-Juniperus-Artemisia* (ca. 16 400–15 500 cal. BP)

The character of the vegetation remained similar and *Juniperus* occurred in the shrub tundra. The slightly higher pollen percentages and the presence of a *Betula nana* fruit scale in the sediment indicate that species occurrence in the immediate vicinity of the lake. Plant cover was rather sparse, as it is shown by the presence of rebedded sporomorphs and the lake bottom deposits composed of sandy silt.

The Cyperaceae, dominant in damp places, were common and abundant also in other sites, showing a broader distribution pattern (Latałowa et al. 2004). Within the sedge communities *Cirsium*, *Thalictrum*, and *Filipendula*, as well as other representatives of the Rosaceae, may have grown. On unstable soils *Ephedra distachya* and *Armeria* occurred. The importance of trees declined simultaneously with the considerable increase in herb representation. The distance separating the studied site from the woodland communities possibly increased as an effect of cold climatic fluctuations. Grass communities developed in drier habitats. The greatest incidence of *Artemisia* and the regular presence of *Gypsophila*, *Helianthemum canum*, *H. nummularium*, Chenopodiaceae, *Astragalus*, and *Bupleurum* suggest the dominance of a grass-steppe formation in the vicinity.

The occurrence of plants associated with the lake (or its shore) such as *Potamogeton*, *Typha angustifolia* and/or *Sparganium*, *Equisetum*, and *Sphagnum* increased considerably. The sedimentation rate declined substantially as a consequence of reduced erosion associated with the increasing stabilisation of plant cover around the lake.

STAGE II: STEPPE-TUNDRA-LIKE FORMATION WITH LARCH, EXPANSION OF *SALIX*

Zone Mł3 *Pinus-Salix* (ca. 15 500–14 400 cal. BP)

The proportions of *Betula* and *Pinus sylvestris* pollen increased, suggesting a shortening of the distance between the lake region and the northern forest limit caused by a rapid amelioration of the climatic conditions (e.g. Rasmussen et al. 2008). The landscape in the vicinity of the lake was still open. *Larix* was a component of the steppe-tundra formations. Larch, like *Pinus sylvestris*, *P. cembra*, *Betula*, and probably *Picea*, most probably survived in the Carpathians throughout the whole Vistulian time from the last interglacial, enabling it to expand rapidly northwards in the favourable continental climate of the Late Glacial (Mamakowa & Starkel 1977, Ralska-Jasiewiczowa 1980, Starkel 1988, Wacnik et al. 2004, Jankovská & Pokorný 2008).

Around Lake Miłkowskie the basic type of

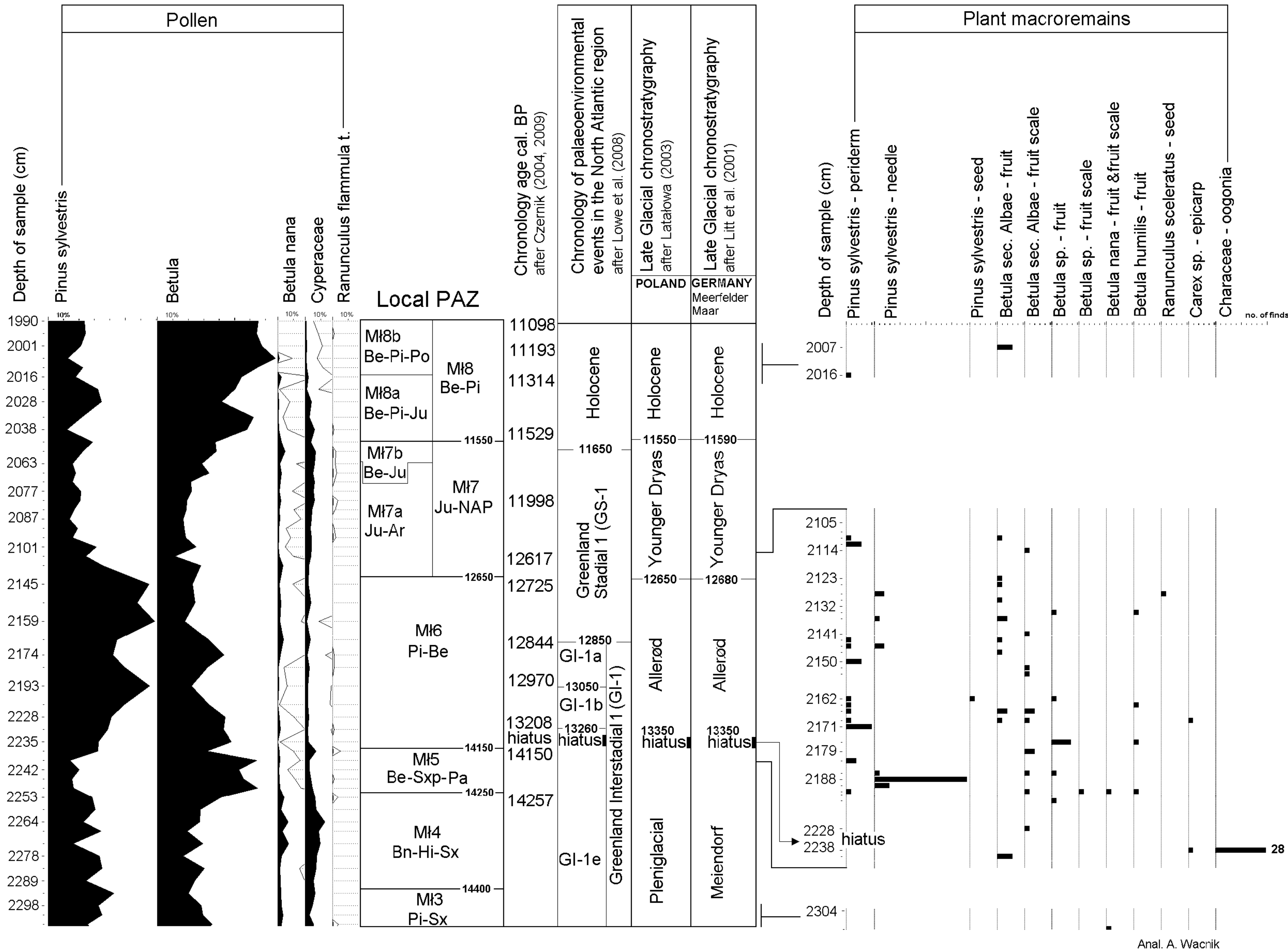

Fig. 3. Plant macrofossils diagram and selected pollen curves from the Late Glacial part of the Lake Miłkowskie deposits

vegetation was a mosaic of steppe-tundra-like formations rich in plant species. They formed a rather dense cover, but there were also small areas of exposed mineral soil. In higher sandy places pioneer herbaceous vegetation composed of Poaceae, Chenopodiaceae, *Artemisia*, *Helianthemum* and *Rumex acetosa*, with *Juniperus* and *Hippophaë rhamnoides*, developed. The importance of herbs diminished, especially that of *Artemisia*, although the high diversity of taxa continued. In the shrub tundra the amount of *Salix*, *Betula nana*, and *Empetrum* increased significantly. The areas of sedge communities contracted slightly. Brassicaceae, Asteraceae (*Aster* type, *Anthemis* type, Cichorioideae), Rubiaceae, *Mentha*, *Ranunculus flammula* or *R. repens*, *Thalictrum*, and *Urtica* grew in these communities. In the lake marginal zone, which included swamps in places, communities with *Equisetum*, Polypodiaceae, and *Sphagnum* developed. In the lake itself *Myriophyllum verticillatum* and *Potamogeton*, as well as single green algae, still occurred.

STAGE III: THE DEVELOPMENT OF A DENSE PLANT COVER, EXPANSION OF SEA-BUCKTHORN, MIGRATION OF TREE BIRCHES

Zone Mł4 *Betula nana-Hippophaë-Salix* (ca. 14 400–14 250 cal. BP)

A slight reduction in *Pinus sylvestris* and *Betula* pollen accompanied by an expansion of that of herbaceous plants was probably an effect of deteriorating of climate.

A change in sediment type to a peaty silt was noted from the bottom of the zone. The local vegetation had an open character with single groups of trees and considerable numbers of shrubs. The composition of communities varied according to the type of soil. The groups of trees were mostly made up of *Betula*, *Larix*, and *Populus*. The continued high representation of *Pinus sylvestris* pollen was a consequence of transport from the surroundings. The local presence of tree birches was not confirmed by macrofossils, but it should be remembered that the analysed samples were of very small volume. Macrofossils identified as *Betula tortuosa* (fruits and scales), *B. pubescens* (fruits and scales), *B.* sec. *Albae* (fruits and leaves) were found in synchronous sediments from Lake Mikołajskie (Ralska-Jasiewiczowa 1966). Numerous fruits of *Betula* sec. *Albae* were found at Witów in central Poland (Wasylikowa 1964). Analyses performed by Kupryjanowicz (2000) at Stare Biele from the region of the Białostocka Plateau showed that *Betula pubescens* and *B. pendula* (macrofossils) were quite important at that time, forming groups of park trees, open birch forest or as constituents of pine-birch forest (needles of *Pinus sylvestris* were also found).

Damp habitats were occupied by sedge communities and shrub tundra. This type of habitat must have been common as is shown by the peak occurrence of *Betula nana*, a high representation of *Salix* and Cyperaceae, the regular presence of *Thalictrum* and, at the beginning of the zone, also *Filipendula*, *Mentha*, *Valeriana*, and *Urtica*. The maximum presence of dwarf birch in the younger part of the zone coincided with a great expansion of *Hippophaë*. It could be the equivalent of the *Betula nana* shrub stage found in Lake Mikołajskie (numerous nutlets, fruit scales and leaves) which according to Ralska-Jasiewiczowa (1966), was a reaction to climate amelioration and preceded the expansion of tree birches.

In the vegetation surrounding Lake Miłkowskie *Hippophaë rhamnoides* was unusually abundant (Krupiński et al. 2004). Its presence in the sediment as pollen and hairs suggests that it was a very important element in the plant cover. Its proportion increased gradually, reaching a peak in the middle of the zone, later declining rapidly. Similar changes were observed in the profile from Lake Mikołajskie where, despite a decline in pollen contribution its hairs were present up to the end of the continuous pollen curve, providing evidence of the local presence of this shrub (Ralska-Jasiewiczowa 1966). Short-lived phases of a high incidence of *Hippophaë* have been observed in many Late Glacial pollen diagrams from Poland and have been included by various authors in different chronozones: Oldest Dryas–Witów (Wasylikowa 1964), Oldest Dryas and Bølling–Lake Gościąż (Ralska-Jasiewiczowa et al. 1998a), Bølling and Older Dryas–Łukcze (Bałaga 1990), and Older Dryas –Lake Mikołajskie (Ralska-Jasiewiczowa 1966). In each case the high *Hippophaë* number preceded the development of woodland, so could, in some sense, be regarded as indicating a small distance between the lake and the forest limit (Krupiński et al. 2004). Sea-buckthorn was a component of pioneer heliophilous communities developing at the forest edges on rather poor carboniferous soils (Kolstrup 1980). It could grow in drier habitats, accompanied by *Juniperus*, *Calluna vulgaris*, *Ephedra distachya*, Chenopodiaceae, Poaceae, *Artemisia*, *Gypsophila*, *Helianthemum*, *Bupleurum*, and *Rumex acetosella*. *Hippophaë* probably formed dense thickets on unstable soils. Its local presence (as well as that of *Myriophyllum verticillatum*) suggests a mean July temperature of at least 11–12°C (Kolstrup 1980, Paus 1992, Isarin & Bohncke 1999).

The gradual lessening in importance of *Empetrum* and *Calluna* suggests, a decline in soil acidity. The density of plant cover increased as is shown by a consequent disappearance of redeposited palynomorphs in the sediment. As the zone declined the representation of Cyperaceae, *Equisetum*, and ferns (Filicales monolete) diminished, while *Sphagnum* and Bryales (spores and macrofossils) disappeared completely. These plants grow in moist or even swampy habitats, not only in the shore zone, but also in adjoining areas. Limnophytes were represented only by *Myriophyllum verticillatum* and marsh plants just by *Schoenoplectus*.

In the transitional section between zones Mł4 and Mł5, above 2253 cm, an intercalation of silty sand occurred and at a depth of 2243 cm thick lamination began. The arrangement of particular layers was somewhat oblique (laminae of different thicknesses approaching one another at different angles). Higher still an insert of olive- grey silty sand was found, covered with an approximately 15 cm thick layer of peat-like sediments (2237–2222 cm). These features probably show the final stages of the melting of dead ice (Błaszkiewicz 2005).

STAGE IV: THE DEVELOPMENT OF BIRCH WOODLAND

Zone Mł5 *Betula-Salix pentandra*-Poaceae

(ca. 14 250–14 150 cal. BP)

The lake surroundings were overgrown with forest communities dominated by birch, with a small incidence of larch. The high frequency of *Betula* in the case of Lake Miłkowskie has been dated at ca. 14 150–14 250 cal. BP (Fig. 4). A similar phase has been observed in other profiles from this region and interpreted (without proper confirmation by radiocarbon dating) as the beginning of the Allerød interstadial (Gross 1937a,b, 1938, Stasiak 1963, Ralska-Jasiewiczowa 1966, Ralska-Jasiewiczowa et al. 2004a). In the context of the present studies the age of birch expansion in the Great Mazurian Lake District needs to be reconsidered. In central Poland the "*Betula* phase" has been noted earlier at ca. 14 450 cal. BP (Ralska-Jasiewiczowa et al. 1999, Goslar et al. 1999, 2000, Czernik 2004, 2009).

With the increasing density of woodland the heliophilous *Hippophaë* was gradually eliminated. At the same time the area of grassland became more and more restricted. Grass-sedge communities with *Salix* sp., *S. pentandra*, *Betula nana*, and *Populus* occurred in damp places along lake shores and streams. *Dryas octopetala* also appeared in the communities indicating the presence locally of carbonates in the soil. Open communities of herbaceous plants, e.g. Poaceae, *Artemisia*, *Gypsophila*, *Helianthemum*, *Astragalus*, and *Juniperus* shrubs which had previously grown in drier habitats became restricted. There was an increase in the taxonomic diversity of cryptogams. The presence of plants characteristic for the lake shore zone was confirmed by single pollen grains of *Typha angustifolia* and/or *Sparganium*, *Thelypteris palustris*, and *Typha latifolia*, the last appearing for the first time due to climatic amelioration. It requires a minimum mean July temperature of at least 13°C (Isarin & Bohncke 1999).

The continued presence of *Potamogeton* and *Myriophyllum verticillatum* in the deposits confirm the existence of communities of plants rooted in the lake bottom. The rapid development of green algae from the genera *Tetraedron*, *Scenedesmus* and *Pediastrum*, accompanied by a decline in *Botryococcus pila* may suggest a change in the trophic state of the lake.

Transition between zones Mł5 and Mł6, problematic aspects

After the radical limitation of *Betula* at the top of zone Mł5 an increase in the contribution of *Pinus sylvestris* was observed. It confirms the ongoing process of reafforestation. The pioneer birch forest was replaced by pine. The expansion of *Pinus sylvestris* around Lake Miłkowskie was preceded in the pollen diagram by a "transitional phase" (2238–2233 cm) indicated primarily by fluctuations in the frequency of basic forest taxa and also *Salix* sp., *Betula nana*, and Poaceae. As a consequence of the reduced incidence of *Betula*, and despite

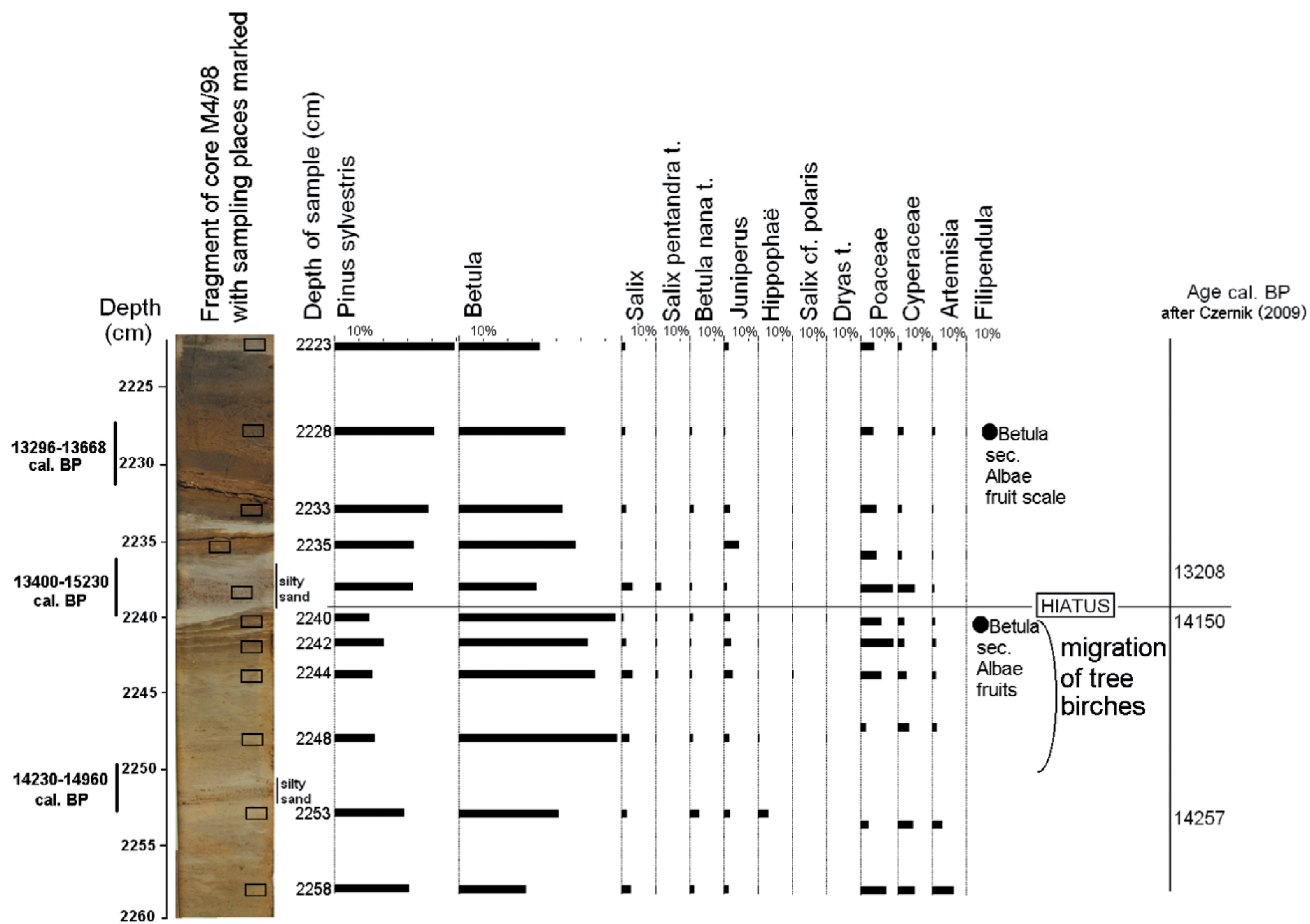

Fig. 4. Changes in pollen composition and lithology accompanying tree birch migration into the Lake Miłkowskie area. Sections of the core and simplified pollen diagram

increasing values of *Salix* including *S. polaris* and *S. pentandra*, the importance of trees and shrubs generally declined. The representation of herbs from the Poaceae and Cyperaceae together with *Gypsophila* was higher, suggesting a decrease in forest density. Considerable fluctuations in the representation of algae were also apparent. These changes slightly proceded the brief increase in the importance of *Juniperus* and the start of a stable *Filipendula* presence.

The changes in the taxonomic composition of communities may reflect a cool oscillation of the climate which caused a transitional opening up of forest (e.g. Berglund 1966).

The results of radiocarbon datings supported by the twin-core correlation point to the lack of sediments between ca. 14 200 and ca. 13 200 cal. BP.

It is worth mentioning that the simultaneous occurrences of a herb maximum and a *Betula* minimum noted in the pollen sequence from Meerfelder Maar (Germany), and to some degree in Hämelsee and Usselo/De Borchert (The Netherlands), were correlated with the Gerzensee oscillation ca. 13 000–12 900 cal. BP (van Geel et al. 1989, Merkt & Müller 1999, Stebich 1999, Litt et al. 2003). However, in the case of Lake Miłkowskie these changes occurred earlier – ca. 13 200 cal. BP.

STAGE V: THE DEVELOPMENT OF DENSE PINE-BIRCH WOODLAND

Zone Mł6 *Pinus–Betula* (ca. 14 150–12 650 cal. BP)

The immediate vicinity of the lake was overgrown with thick pine-birch woodland. This is confirmed by their high pollen values as well as by finds of *Pinus sylvestris* macrofossils (needles, short shoots, fragments of bark and seed), and *Betula* sect. *Albae* (*B. pubescens* and *B. tortuosa* as nutlets and scales). To begin with birch-pine forest was dominant, but later was replaced by pine-birch forest. Towards the end of the zone pine dominated forest with only a small contribution of birch prevailed. The maximum incidence of pine was dated at ca. 12 800–12 750 cal. BP. At that time *Larix* and *Populus* formed an admixture in woodland and *Dryopteris filix-mas* was present in the herb layer. Damp habitats favoured the development of communities with different species of *Salix*, *Populus tremula*, and in places also *Betula*. Locally these may have taken the form of willow carr. Poaceae, Cyperaceae, *Thalictrum*, *Filipendula*, *Mentha*, *Caltha*, *Humulus lupulus*, and *Urtica* would be associated with such habitats. Only in this zone of the Late Glacial was *Filipendula* noted in all the analysed spectra. Dry open places, and gaps in the forest were occupied by herb communities composed of *Artemisia*, *Bupleurum*, Chenopodiaceae, *Rumex acetosella*, *Rhinanthus*, and *Botrychium* with *Juniperus* shrubs. In the swampy lakeside places *Betula nana*, *Salix polaris*, *Selaginella selaginoides*, and *Sphagnum* still remained. At the lake margins *Polygonum amphibium* and *Equisetum* grew, while in reedswamp communities with *Typha latifolia* sporadic *Sparganium* and/or *Typha angustifolia*, probably *Schoenoplectus* and *Thelypteris palustris* also developed. Communities from the class Potametea with *Potamogeton*, *Myriophyllum verticillatum*, and *Ceratophyllum* spread in the basin. Macrophyte communities became enriched for the first time with *Nuphar* and in the water body itself a rapid development of green algae, especially *Scenedesmus* and *Tetraedron*, was observed.

STAGE VI: THE DEVELOPMENT OF OPEN PINE-BIRCH WOODLAND WITH A HIGH REPRESENTATION OF JUNIPER

Zone Mł7 *Juniperus*-NAP (ca. 12 650–11 550 cal. BP)

In the bottom of the zone the sediments changed into irregularly laminated silts with inserts of sand. A rapid reduction in the tree cover occurred with the pine-birch forest becoming more open. That trees grew around the lake was confirmed by the presence of pine needles and fragments of bark, scales and nutlets of birch from *Betula* sect. *Albae* (*B. pubescens*). We may assume that the vegetation was of a park character with groups of pine, tree birch and larch. The frequency of *Larix* increased slightly. The dry open habitats in the surroundings of the lake and probably down to also on its shores, were occupied by *Juniperus* shrub. Rapid juniper expansion was common at that time, not only in the Polish pollen profiles (e.g. Okuniewska-Nowaczyk et al. 2004), but in those of other nearby countries as well, such as Germany (e.g. Litt et al. 2001), Denmark (e.g. Odgaard 1994), Sweden (e.g. Berglund et al. 2008) and Lithuania (e.g.

Stančikaitė et al. 2002). Among the dwarf shrubs *Rubus arcticus* occurred regularly.

An interesting feature was a systematic presence of *Picea* pollen, especially in the context of early finds of spruce macro-remains in NE Poland. At the Stare Biele site *Picea* needles have been identified in the sediment of the Older Dryas, confirming its local presence in fertile, damp habitats (Kupryjanowicz 2000). The regular presence of spruce pollen has been observed in the Younger Dryas part of pollen profiles from the region, e.g. Lake Staświńskie (Wacnik & Ralska-Jasiewiczowa 2008), Sejny (Szwarczewski & Kupryjanowicz 2008), Lake Tałty (Stasiak 1967), and Niecka Skaliska (Pochocka-Szwarc et al. 2008). Very high *Picea* values were found contemporarily in the sediments of Lake Dolgoye in Belarus (>50%) (Zernitskaya et al. 2001). It seems that in the case of Lake Miłkowskie, the presence of *Picea* pollen was a direct consequence of its open woodland surroundings which permitted increased regional pollen transport, maybe from the south, or east (Obidowicz et al. 2004, Latałowa & van der Knaap 2006, Tollefsrud et al. 2008).

Large areas around Lake Miłkowskie were occupied by herb communities containing a high proportion of steppe plants with *Artemisia*, Poaceae, and Chenopodiaceae codominant. The frequency of *Gypsophila*, *Helianthemum canum*, *Ephedra* (*E. distachya* and *E. fragilis*), and *Rumex acetosella* increased. *Bupleurum* and *Astragalus* appeared again and representatives as of subfamilies of the Asteraceae as well as the Cichorioideae were recorded more often. Herb taxonomic diversity rose, with many taxa, such as *Centaurea nigra*, *Veronica*, *Trollius*, and *Pleurospermum austriacum* appearing for the first time. In damp areas stands with *Betula nana*, *Salix* (*Salix* undiff., *S. pentandra* and *S. polaris*), and *Populus* cf. *tremula* occurred locally, accompanied by such herbs as Cyperaceae, *Rhynchospora*, *Thalictrum*, *Filipendula*, *Ranunculus flammula*, *R. sceleratus* (seed), and *Lychnis*, plus members of the Rubiaceae and Apiaceae. Locally *Equisetum* (maybe *E. fluviatile*), Bryales (fragments of stems), and *Sphagnum* grew there. The regular presence of *Phragmites* pollen type confirms the occurrence of reed stands from the Phragmitetea class. In addition to species of the Cyperaceae, *Typha latifolia*, *Sparganium* and/or *Typha angustifolia*, and *Menyanthes trifoliata* were present. The inshore shallow-water vegetation included representatives of the Potametea class, *Potamogeton*, *Nuphar*, *Myriophyllum verticillatum*, and *Hottonia palustris*.

The character of the local vegetation shows two distinct phases of successive change. In the older part the woodland became more open, shrub representation increased and *Larix* decreased. In the younger part there occurred synchronously a decline in the frequency of *Juniperus*, and increases in *Betula nana*, other *Betula*, *Populus*, and *Filipendula*. A gradual confraction of open areas took place (decline of NAP values, mostly *Artemisia*, Cyperaceae and Poaceae). Changes similar to those in the higher plants also occurred in the algal flora. In the older part of the zone most green algae declined in frequency, apart from the repeated rise of *Pediastrum kawraiskyi*, a species associated with cold water lakes. The results of analyses from the younger phase were completely different. Then, simultaneously with the disappearance of stable presence of *Pediastrum kawraiskyi*, occurred a rapid expansion of *Scenedesmus*, *Tetraedron*, and *Pediastrum integrum*.

The nature of the vegetation in the longer lasting older phase (Mł7a), suggests deteriorating conditions as a consequence of the cooler and drier climate. In the younger part of the zone (Mł7b) temperatures rose. In parallel with the development of open communities disturbances in the sedimentation were observed. The cooler phase record was interrupted by erosion which resulted in a sediment gap in profile M4/98 (complemented by sediments from the second core M2-M3/98) and insertions of sand. Deposition of laminated gyttja restarted from a depth of 2042 cm.

A possibly incomplete sediment section of the Younger Dryas deposits has been reported from Lake Wigry (Kupryjanowicz 2007). Sand insertions also appeared at the beginning of the Younger Dryas at about 12 585 cal. BP, in the sediments of Lake Gościąż (Ralska-Jasiewiczowa et al. 1998b).

The bipartite nature of the Younger Dryas has been observed just as many times in Poland (Zachowicz et al. 1982, Bałaga 1990, Ralska-Jasiewiczowa & van Geel 1992) as it had been in north-western Europe (e.g. Berglund et al. 1994, Vanenberghe 1995, Renssen 2001). During the coldest period the estimated mean July temperature was around 13°C in northern Poland. This phase was followed by warming with a temperature rise of 1–2°C (Isarin & Bohncke 1999).

In the Lake Gościąż, the longer cool phase was specified as clearly moister and milder (Ralska-Jasiewiczowa et al. 1998a). A detailed reconstruction of the climatic changes at the Younger Dryas/Preboreal transition revealed the first phase of major warming between 11 520 and 11 500 cal. BP, with a dry climate due to lower winter precipitation. It was followed by a second phase of warming and higher humidity (11 500–11 460 cal. BP), the latter persisting throughout the summer seasons (Ralska-Jasiewiczowa et al. 2003b).

STAGE VII: THE RESTORATION OF BIRCH-PINE WOODLAND

Zone Mł8 *Betula-Pinus* (ca. 11 550–10 200 cal. BP)

Alongside the amelioration of the climate at the beginning of the Holocene, renewed development of woodland communities composed of taxa which had survived *in situ* during the coolness of the Younger Dryas (Greenland Stadial 1) took place in the vicinity of the lake (Fig. 5). Pioneer birch and pine-birch woodland with *Populus* (probably *Populus tremula*, identified from macro-remains in sediments of similar age in Lake Mikołajskie (Ralska-Jasiewiczowa 1966) and occasional *Larix* developed. The increase in *Ulmus* pollen values from ca. 11 050 cal. BP suggests the occurrence of isolated elm trees near the lake. In the Lake Mikołajskie area elm was present from ca. 10 700 cal. BP (9450±100 ^{14}C BP, Ralska-Jasiewiczowa unpubl.). Around Lakes Staświńskie and Wigry elm reached 2–3% in the upper part of the Preboreal chronozone, higher than the *Betula* maximun and slightly ahead of *Corylus* (Kupryjanowicz 2007, Wacnik & Ralska-Jasiewiczowa 2008). In the littoral zone of the lake *Equisetum* was growing together with *Sparganium* and/or *Typha angustifolia*, *T. latifolia*, *Schoenoplectus*, and *Scirpus*, forming stands of reed swamp. The presence of *Potamogeton* confirms the development of aquatic vegetation rooted in the lake bottom, characteristic for the Potametea class (Polakowski et al. 1980a). At the same time a rapid expansion of algal growth took place, initially mostly of *Tetraedron*, but later also of *Scenedesmus* and *Botryococcus*. Among the representatives of *Pediastrum* the frequency of *P. boryanum* var. *boryanum*, *P. boryanum* var. *longicorne* and *P. integrum* decreased, while that of *P. duplex* var. *rugulosum* increased. A rapid increase in the incidence of *Tetraedron*, making the beginning of the Holocene, was noted in the profiles from Lake Gościąż. It is a very good climatic indicator because it reacts quite quickly to a warming of the climate (Ralska-Jasiewiczowa et al. 2003b).

Subzone Mł8a *Betula-Pinus-Juniperus* (ca. 11 550–11 300 cal. BP). First to form was pioneer woodland dominated by *Betula* but with increasing amounts of *Pinus sylvestris.* That the forest was open is shown by the high incidence of juniper shrubs and herbs: Poaceae, *Artemisia*, Chenopodiaceae, *Rumex acetosella* type (including both *R. acetosella* and *R. tenuifolius*), Apiaceae and *Thalictrum.* In dry places scattered Late Glacial heliophytes such as *Dryas octopetala*, *Ephedra fragilis*, *Pleurospermum austriacum*, *Saxifraga oppositifolia*, and *Helianthemum* survived. On the lake margins carr, with *Salix*, *Populus* cf. *tremula*, and sporadically, *Empetrum nigrum*, may have occurred. Wet habitats were also suitable for Cyperaceae, *Filipendula*, *Urtica*, *Sparganium*, and/or *Typha angustifolia.*

This zone may be correlated with the bottom of zone G1/87-4 *Betula-Populus-Ulmus* from Lake Gościąż whose sedimentation took place between 11 500 and 11 300 cal. BP.

Subzone Mł8b *Betula-Pinus-Populus* (ca. 11 300–11 050 cal. BP). This period saw the maximum spread of birch in the Holocene (Fig. 6). In Poland it was observed throughout the entire eastern lake districts and Mazovian Lowland (Ralska-Jasiewiczowa et al. 2004a). A similar phenomenon has been reported from other European countries (e.g. Behre 1978, Björck et al. 1997, Bos 2001, Berglund et al. 2008) and interpreted as a reaction to a short climatic oscillation. The Preboreal oscillation has been described for example in Germany (ca. 10 900–10 750 cal. BP) as colder and temporarily wetter (Bos & Urz 2003) and in the Swiss Alps (ca. 10 900–10 350 cal. BP) as a cold and humid phase (Haas et al. 1998). In Poland the Youngest Dryas has been described in several pollen records from the northof the country (Latałowa 1982, 1988, Pawlikowski et al. 1982). In the case of Lake Miłkowskie the

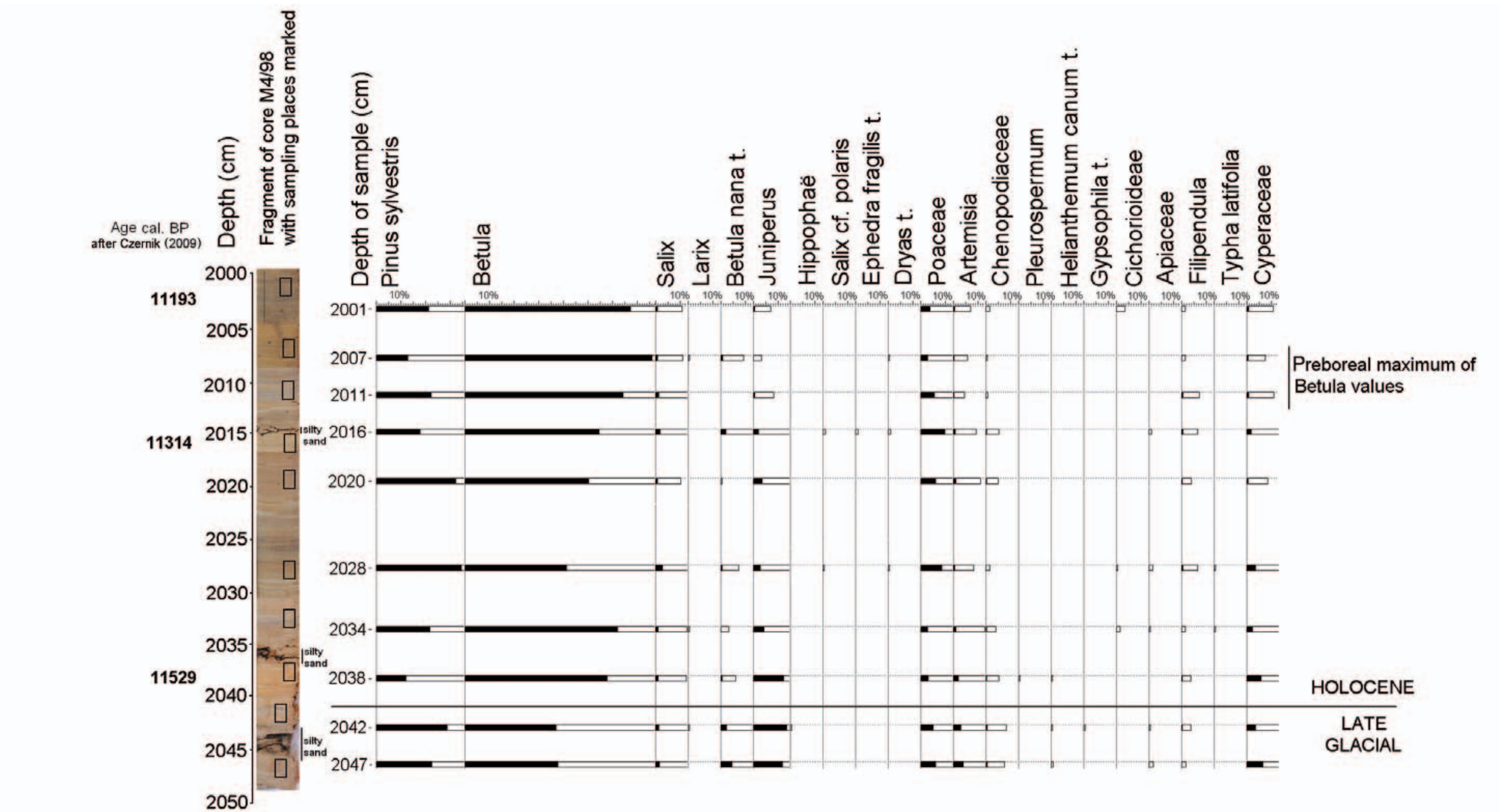

Fig. 6. Changes in pollen composition and lithology at the beginning of the Holocene. Pollen data showing the re-establishement of birch woodland at the onset of the Preboreal period

sharp increase of *Betula* which coincided with a decrease in *Filipendula* as well as the disappearance of *Typha angustifolia* and/or *Sparganium*, and *Typha latifolia* could indicate such a short cooling of the climate.

Birch and birch-pine woodlands with *Populus* (cf. *tremula*) were dominant at that time. Possibly some of them resembled present-day swampy *Betula pubescens* birch woodlands. Numerous macro-remains of *Betula pubescens* (scales, nutlets) were identified in the analogous section of the profile from Lake Mikołajskie (Ralska-Jasiewiczowa 1966). Nowadays communities of this type occur in the Mazurian Lake District in undrained shallow synclines in the ground moraine (Jutrzenka-Trzebiatowski 1999). The significant percentage of pollen of *Populus* (*P.* cf. *alba* or *P.* cf. *nigra*) and *Salix* strongly suggests the presence of carr.

In forest gaps and in the outskirts, on the dry south facing slopes of morainic hills, stands of steppe-like communities with *Juniperus*, *Artemisia*, Chenopodiaceae and representatives of e.g. the Poaceae and Cichorioideae still remained. On the lake shores some tall herb taxa associated with places possessing a high water table, such as *Sparganium* and/or *Typha angustifolia*, *Schoenoplectus*, and *Scheuchzeria*, constituting reed swamp vegetation, as well as Cyperaceae, *Filipendula*, *Valeriana*, and *Thalictrum* may have grown. Additionally, in the marshes, stands of communities with *Thelypteris palustris* and *Equisetum* (maybe *E. fluviatile*) occurred in places. The aquatic vegetation with floating leaves contained, in addition to *Nuphar*, *Nymphaea alba* for the first time. In the lake shallows species of *Potamogeton* also occurred. A new alga taxon, *Coelastrum reticulatum*, appeared. The numbers of other alga species were somewhat restricted, especially those of *Tetraedron* and *Scenedesmus*.

This subzone may be correlated with part of the G1/87-4 *Betula-Populus-Ulmus* zone from Lake Gościąż dated at 11 300–10 800 cal. BP.

Subzone Mł8c *Pinus-Betula-Populus* (ca. 10 750–10 200 cal. BP). A rapid increase in the importance of *Pinus sylvestris* was accompanied by a decline of *Betula* in the woodland. Various types of pine-birch forest with some aspen were widespread at this time over much of Poland. The importance of *Ulmus* and *Corylus avellana* gradually increased, especially at the time of possible climate warming, reported from Lake Mikołajskie between ca. 10 350 and 10 200 cal. BP (Ralska-Jasiewiczowa (1989). Hazel was an important component of the understorey where also might have grown *Sorbus*, *Prunus*, *Frangula alnus*, *Rosa*, *Rubus*, and *Sambucus nigra*. Particularly at the beginning of the zone, juniper could have been a local component of the understorey in conifer communities (finally fading out at its decline). In the pine forest herb layer, as well as ferns, some grass species, *Rumex acetosella* and *Calluna vulgaris* could have grown in dry places. The composition of *Salix* and *Populus* carr gradually changed as inward migration of *Ulmus* occurred on fertile ssoils. Additionally *Humulus lupulus* and *Urtica* could grow where it was slightly damp. The low representation of *Quercus* and *Fraxinus* may suggest that these genera no longer grew in the immediate vicinity, although the distance between the lake and their range limit was not large. The sporadic *Alnus*, *Tilia* and *Picea* pollen owed their presence to transport from further away. A likely source of *Alnus* was suggested by the results of palynological investigations from Knyszyńska Forest where it was rather numerous (together with elm), at least from the Preboreal maximum of *Betula*. Single *Alnus* trees grew at Stare Biele area as early as the Younger Dryas (Kupryjanowicz 2000). The poorly represented herbs, associated with different types of community, were characterised by the domination of Poaceae, Cyperaceae, Asteraceae (*Aster* type, Cichorioideae), and *Artemisia*. Reed swamp stands with *Schoenoplectus*, *Cladium mariscus*, *Sparganium*, and/or *Typha angustifolia* and *Typha latifolia* made up a mosaic of communities occupying the lake inshore zone. In places where the shores were covered by peat, stands with representatives of the Cyperaceae as well as *Thelypteris palustris*, *Equisetum*, and *Sphagnum* occurred. The macrophytes composition, of *Nymphaea alba*, *Nuphar*, and *Potamogeton* was supplemented by *Ceratophyllum* (identified as leaf-spines).

Among algae the single coenobia of *Pediastrum angulosum* and *P. boryanym* var. *perforatum*/*cornutum* appeared.

Subzone Mł8c may be correlated with the zone W6 from Woryty (Pawlikowski et al. 1982) and with the older part of zone G1/87-5 *Pinus-Betula-Ulmus-Corylus* from Gościąż

(Ralska-Jasiewiczowa et al. 1998) whose age was defined to be ca. 10 800–10 200 cal. BP.

STAGE VIII: THE FORMATION OF MIXED WOODLAND, EXPANSION OF HAZEL, ELM AND ALDER

Zone Mł9 *Corylus-Ulmus* (ca. 10 200–9100 cal. BP)

The lake surroundings were almost entirely wooded, still mostly by pine-birch forest with *Populus*. Single oak trees may have appeared. The contribution of oak was below 2% and a ≥2% frequency is generally accepted as evidence of its local presence (Huntley & Birks 1983). It was a time of rapid oak migration northwards, reaching Scandinavia and northern Belarus by ca. 8900 cal. BP (Brewer et al. 2002). In floodplain communities *Alnus* may have occurred, together with such constant components as *Ulmus*, *Salix*, and *Populus*. At this time (as a result of the expansion of the new genera) a fresh type of multispecies carr woodland could have formed. Forest similar to present-day elm carr with some alder, with *Corylus avellana* and *Sambucus nigra* in the understorey, could have grown on fertile soils. In its herb layer and other wet places grew Cyperaceae, *Filipendula*, *Humulus lupulus*, *Urtica*, *Mentha*, and *Ranunculus flammula*.

Hazel became abundant at the forest margins, in gaps and in the understorey, as well as on sunny slopes, because it could outcompete birch and pine. It is accepted that a ≥25% contribution of *Corylus* pollen provides convincing evidence of its forest-forming role. *Corylus*, overcoming competition from other deciduous trees, probably also occupied low lying places around the lake. A corresponding phase of high *Corylus* incidence has been noted as in numerous European pollen diagrams in addition to those from Poland (Huntley & Birks 1983, Ralska-Jasiewiczowa et al. 2004b). It is conventionally accepted that this phase was the result of hazel's widespread presence in the understorey, although the possibility of its having become a forest dominant, of which there is no present-day equivalent, has also been discussed (Huntley & Birks 1983, Gardner 1999, Tallantire 2002). Accompanying hazel in the understorey were small quantities of *Sorbus*, *Rosa*, *Sambucus nigra*, *Rubus*, and *Rhamnus*. The join presence of *Corylus avellana* and *Ulmus* indicates long but not very hot summers with high effective humidity (Dahl 1998, Heikkilä & Seppä 2003). *Calluna vulgaris* was present in the herb layer of woodland together with representatives of the Poaceae, Rubiaceae, Rosaceae, Caryophyllaceae (*Dianthus*, *Silene*), Apiaceae, Cichorioideae, *Artemisia*, and *Rumex acetosella*.

It was a period of high water level in the lakes (Ralska-Jasiewiczowa & Latałowa 1996, Gumiński 2008). Two wet phases in the peat bogs occurred at the beginning and end of the zone (Żurek & Pazdur 1999).

STAGE IX: OPTIMAL DEVELOPMENT OF MULTISPECIOUS WOODLAND

Zone Mł10 *Alnus-Tilia-Ulmus* (*Corylus*) (ca. 9100–8600 cal. BP)

Pine woodland with birch was still common, especially on dry morainic hills. Stands of mixed deciduous forest with *Ulmus*, *Tilia cordata*, and *Quercus* and a rich understorey, consisting mainly of *Corylus*, developed on slightly moist and fertile soils. The increased shading was a likely reason for a gradual decrease in the amount of *Corylus* or for a decline in its pollen production. High water levels in lakes and fens were reported locally.

The competitive attributes of *Alnus* such as very rapid growth in the first few years of its life, the resistance against moderate shading, particularly when young, the ability of its root system to develop on heavy, moist soils and its light demands lower than those of *Betula* and *Salix*, favoured its rapid migration (Białobok 1980, Jaworski 1994). This probably accounts for the rapid spread of *Alnus* and the development of alder woods around the lake and in other low lying places. In all types of moist woodland *Humulus lupulus* could grow.

Since about 9050 cal. BP the regular occurrence of *Hedera helix* and *Viscum album* has been recorded. The presence of flowering *Hedera helix* shows that the mean temperature of the coldest month was not lower than –1.7°C up to –2°C. *Viscum* pollen ensures that the mean temperature of the warmest month was above 16°C (Iversen 1944, Granoszewski 2003). The low proportion of heliophilous herbs represented by e.g. the Cyperaceae, Poaceae, Chenopodiaceae, Rubiaceae, *Filipendula*, *Urtica*, *Thalictrum*, *Lotus*, and *Lythrum* shows a paucity of open communities. In the shore zone, reed swamp stands occurred with *Phragmites*, *Sparganium*, and/or *Typha angustifolia* and *T. latifolia*. The shallow water contained *Nuphar*, *Nymphaea alba*, *Potamogeton*, and *Ceratophyllum*. Green algae frequency increased considerably, particularly of *Botryococcus*, *Coelastrum reticulatum*, and *Scenedesmus*. The contribution of *Tetraedron* was highest at the bottom and top of the zone. The picture of the vegetation cover in zone Mł10 was consistant with data obtained from the G1/87-6 *Corylus-Alnus-Quercus* zone at the Gościąż site and W8 at Woryty. The upper limits of the analogous zones in those two sites were demarcated before the period of maximum incidence of elm and lime, rise of *Fraxinus*, and when the representation of *Corylus* was least. The metachronism of successional phenomena is particularly evident at the bottom of the zones.

Zone Mł11 *Ulmus-Tilia-Alnus (Quercus)* (ca. 8600–5800 cal. BP)

Higher areas with rather fertile soils were favourable for the development of mesophilous multispecies deciduous woodland with *Tilia*, *Quercus*, *Ulmus*, and *Fraxinus*. As well as elm, lime reached its maximum spread in the catchment area of the site. *Acer* also grew sporadically and the understorey was composed of *Corylus*, *Sambucus nigra*, *Frangula alnus*, and *Rhamnus*. There may well have been a considerable density of forest. Repeated hazel peaks could have been caused by the activities of the local Mesolithic people, resulting in small gaps in the forest canopy (Wacnik 2009). Pine-birch forest was further limited, particularly on slightly moist and fertile soils. In such habitats pine and birch were outcompeted by such trees as *Tilia*, *Quercus*, and *Ulmus* which not only needed more fertile soil but were also more shade tolerant.

Around the lake stands of mixed coniferous-deciduous woodland similar to present-day pine-oak forest grew with contribution of birch, lime and aspen. *Juniperus* was a component of the understorey. Juniper pollen grains were detected at Szczepanki 8 archaeological site, while juniper wood was identified at the neighbouring archaeological site at Dudka, both located several kilometres east of Miłki (Gumiński 1995, Gumiński & Michniewicz 2003, Wacnik & Ralska-Jasiewiczowa 2008). *Vaccinium* and *Pteridium aquilinum* grew in the herb layer of coniferous woodland. Places periodically flooded were occupied by carr and woodland mainly composed of *Alnus* and *Ulmus*, but with small amounts of *Tilia*, *Quercus*, and *Fraxinus*. Stable, but not very numerous components of these communities were *Salix*, *Populus*, and *Betula*.

The presence of *Hedera helix*, *Humulus lupulus*, and *Vitis* pollen shows that these climbers formed part of the vegetation. *Vitis vinifera* subsp. *sylvestris* is a sub-oceanic species associated with warm and very warm climates (Ellenberg et al. 1991) which has been accepted as a characteristic for elm-ash carr in western Europe (Granoszewski 2003).

The pollen grains of such taxa as the Cyperaceae, *Filipendula*, *Ranumculus flammula*, *Gentiana pneumonanthe* type, *Thalictrum*, *Urtica*, *Cirsium*, and/or *Carduus*, Poaceae (part), and *Artemisia* (*A. vulgaris* grows nowadays in the herb layer of *Salix-Populus* carr) would almost certainly have originated from moist habitats.

Stands of reed swamp vegetation grew immediately adjacent to the lake shore and were composed of Cyperaceae, *Phragmites* type, *Sparganium*, and/or *Typha angustifolia* and *Thelypteris palustris*. Patches of communities similar to *Thelypteridi-Phragmitetum* would probably have existed around the lake. Shallow water close to shore contained *Nuphar*, *Nymphaea alba*, *Myriophyllum verticillatum*, and *Potamogeton*.

The zone was characterized by the highest numbers of *Coelastrum*, represented by *C. reticulatum*, and *C. polychordum*. Representatives of *Pediastrum* were rather scarce, apart from *P. boryanum var. boryanum*. The importance of *Scenedesmus* decreased considerably *Tetraedron* and *Botryococcus* numbers were high.

The age of the top of zone Mł11 was defined as a little older than 5060±45 ^{14}C BP. (ca. 5800 cal. BP).

STAGE X: THE EXPANSION OF OAK, ANTHROPOGENIC DISTURBANCE OF WOODLAND

Zone Mł12 *Quercus-Ulmus* (ca. 5800–3900 cal. BP)

In the Lake Miłkowskie catchment the multispecies deciduous woodland was particularly subject to change. *Ulmus* and *Tilia* numbers decreased alongside a rapid expansion of the less light demanding *Quercus* on moist, fertile soils.

The main elm fall which occurred both in Poland and elsewhere in Europe has been described by many authors (Huntley & Birks 1983, Peglar 1993, Ralska-Jasiewiczowa et al. 2004b, Clark & Edwards 2004). It was observed at Miłki at about 5060 cal. BP. A high incidence of oak was characteristic for this zone and it was probably present in several different types of community. In drier places stands of open, thin oak forest with *Pinus*, similar to the association *Potentillo albae-Quercetum* Libb. 1933, may have existed. Nowadays stands of this community are found in some places on the southern slopes of morainic hills. Oak could also have been the basic tree forming the mixed woodland probably similar to the *Querco roboris-Pinetum* (W. Mat. 1981) J. Mat. 1988 association (Matuszkiewicz 2001). In such forest, pine, birch, aspen and lime could have been growing alongside the oak. The slightly open woodland favoured intensive development of understorey with *Corylus avellana* and *Frangula alnus* plus a herb layer containing *Vaccinium* and *Pteridium aquilinum*. *Corylus*, together with *Quercus*, could have formed patches of shrub-forest communities similar to the *Quercion robori-petraeae* alliance (Ralska-Jasiewiczowa et al. 2003a). The systematically noted *Fagus* pollen suggests the presence of isolated beech trees in the region. The lake lies beyond the recent *Fagus* range limit, but beech did occur slightly to the west and north of Miłki (Zając & Zając 2001). In the immediate vicinity of the lake, in waterlogged places carr and alder woodland persisted. The >1% values of hornbeam pollen suggest that hornbeam could have been present in small numbers around lake, together with *Picea* (from ca. 4850 cal. BP onwards). The presence of *Viscum* and *Hedera* provides evidence of a mild, warm climate during the decline of the Holocene climatic optimum. Nowadays, the blooming individuals of *Hedera helix* do not occur in the Mazurian Lake District, its grow far to the west in the low Vistula region (Zając & Zając 2001). Simultaneously with the changes in composition of the mixed forest the indicators of human activity such as Cerealia, *Plantago lanceolata*, *P. major*, *Rumex acetosella*, *Spergula*, Chenopodiaceae, and *Artemisia* were noted. Early finds of cereal type pollen was an interesting phenomenon, suggesting the beginning of plant cultivation. This topic has been discussed in the context of local settlement history in a separate publication (Wacnik 2009). Among the green algae identified, *Tetraedron*, *Botryococcus*, and *Coelastrum* were the most numerous.

Zone Mł13 *Corylus-Quercus-Alnus* (ca. 3900–3800 cal. BP)

In the forest neighbouring, the lake a temporary reduction in the content of lime, oak and ash,, and initially also in that of birch, occurred alongside elm decline. Hazel expansion, or its more intensive pollen production, may have resulted from the selective removal of trees by man, leading to the formation of clearings. Most likely the shrub-forest communities dominated by *Corylus* and *Quercus* were still present locally. Both the second elm decline and the Subboreal maximum of hazel were possibly the results of human activity. However, the spread of *Corylus* could also have been induced by drier climate conditions (low water level in the lakes) and a dry phase in peat bogs between 4050 and 3650 cal. BP (Żurek & Pazdur 1999), and its great potential for vegetative survival (Tallantire 2002).

Carpinus and *Picea* occurred regularly in mixed deciduous forest. Woodland disturbance as a consequence of local human activity promoted their spread. Stable amounts of alder and only a minor increase of willow suggest that forest growing at lower wetland sites was changed only minimally. The local presence of spruce suggests colder winters and moister soil as well as thicker snow cover (Dahl 1998, Heikkilä & Seppä 2003).

PALAEOALGOLOGICAL ANALYSIS OF THE LAKE MIŁKOWSKIE SEDIMENTS. SUCCESSION OF GREEN ALGAE

Palaeoalgological investigations supplementing pollen analysis have been undertaken many times in Poland when assessing changes in the aquatic environment during times of sedimentation (Hjelmroos-Ericsson 1981, Bałaga 1990, Latałowa 1992, Noryśkiewicz 1993, Wasylikowa 1999–2001). In many instances they were restricted to a summarised record of the presence of representatives of *Pediastrum* and *Botryococcus*, thereby limiting possible palaeoecological interpretation. Over the last decade the accuracy and number of analyses of this group of non-pollen microfossils have increased (Ralska-Jasiewiczowa et al. 1998b, Makohonienko 2000, Wołowski et al. 2002, Latałowa & Borówka 2006, Kupryjanowicz 2004, 2007).

Changes in green algae frequency are governed by a number of different factors e.g. the trophic state of the lake, physical and chemical properties of the water, fluctuations in water level, and competition (e.g. Tyson 1995, Makohonienko 2000). The lack of physical and chemical analyses of the Lake Miłkowskie sediments means that the problems concerning interpretation of the observed changes can be discussed only to a limited degree.

Phase A in the algal succession covers a broad time range (ca. 16 600–14 250 cal. BP), corresponding to nearly four local pollen zones (Fig. 7). It was a time when sandy silts accumulated in the lake basin and unstable plant cover occupied its shores. The main distinguishing feature of phase A is by the domination of *Botryococcus* and *Pediastrum kawraiskyi* (Plate 1). The occurrence of *Botryococcus* (mostly *B. pila*), together with the sporadic representation of other green algae, may be an indicator of extreme environmental factors. These could have been cold water, oligotrophy or dystrophy (Jankovská & Komárek 2000). However, the possibility that the high values of *Botryococcus* might have been partly caused by redeposition from older sediments cannot be ruled out. Similar results were obtained from algal analyses of the pre-Allerød section of the Švarcenberk profile where depressed values of *Scenedesmus* and *Tetraedron minimum* were associated with low nutrient content (Pokorný & Jankovská 2000). *Pediastrum kawraiskyi* is an indicator of extensive oligotrophy, or mesotrophy in cold water lakes. It is more resistant to low temperatures than most other green algae. Its presence appears to be connected with the alkalinity of the water (Crisman 1978). Studies at Lake Maardu in Estonia showed a correlation of the numbers of *P. kawraiskyi* with the level of delivery of terrigenous matter to the lake. Its occurrence also indicates unstable soil cover (Veski 1998). *Pediastrum kawraiskyi* cenobia have been regularly noted in Late Glacial sediments from Denmark, Estonia, Russia, the Czech Republic and Poland. *Pediastrum kawraiskyi* and *P. integrum* are recognized as glacial relicts. The presence of *Botryococcus pila* and *Pediastrum kawraiskyi* as codominants, accompanied by sporadic *P. integrum* which occurred in Lake Miłkowskie, have been found elsewhere e.g. at a site in the Vlčí rokle gorge (Czech Republic) in mineral sediment of the oldest part of the Late Glacial (Jankovská & Komárek 2000). The phase A analyses of Lake Miłkowskie indicate an oligotrophic cold water lake around which ongoing processes of soil and plant cover formation were taking place. At that time intensive accumulation of mineral material occurred in the lake as a result of erosion.

Phase B is characterized by the almost complete disappearance of *Pediastrum kawraiskyi* and the decline of *Botryococcus*, and their replacement by *Tetraedron*, *Scenedesmus* and other *Pediastrum* species. The higher incidence of green algae (*Scenedesmus*, *Tetraedron*, *Pediastrum integrum*, *P. boryanum* var. *boryanum*, *P. duplex* var. *rugulosum*, and *P. boryanum* var. *longicorne*) coincided with local woodland development (Pl. 1,2). *Pediastrum integrum* is regarded as an indicator of oligotrophic or dystrophic lakes. It is regularly recorded in the lacustrine sediments of the Late Glacial and early Holocene. Its presence in Central European material may indicate ecological and climatic conditions that were suitable for the development of forest tundra or tundra (Komarek & Jankovská 2001). The presence of *Pediastrum boryanum* var. *longicorne* is characteristic for small lakes overgrown by peat as well as for large ones surrounded by peat bogs, often containing dystrophic water. On the other hand, *Pediastrum duplex* var. *rugulosum* is associated with shallow water in which grow plants with floating leaves. This planktonic alga is generally recorded in the Late Glacial and Holocene sediments of the Czech Republic, Russia, and Switzerland (Pokorný & Jankovská 2000, Komárek & Jankovská 2001). The other species often noted, *P. boryanum* var. *boryanum*, is a cosmopolitan taxon with a very broad ecological amplitude. Because it has been widely redorded from the Late Glacial up to recent times, it cannot be treated as a palaeoecological indicator. *Pediastrum angulosum* is a good indicator of oligotrophic lakes with neutral or slightly acid water. It is a thermophilous species (Veski 1998).

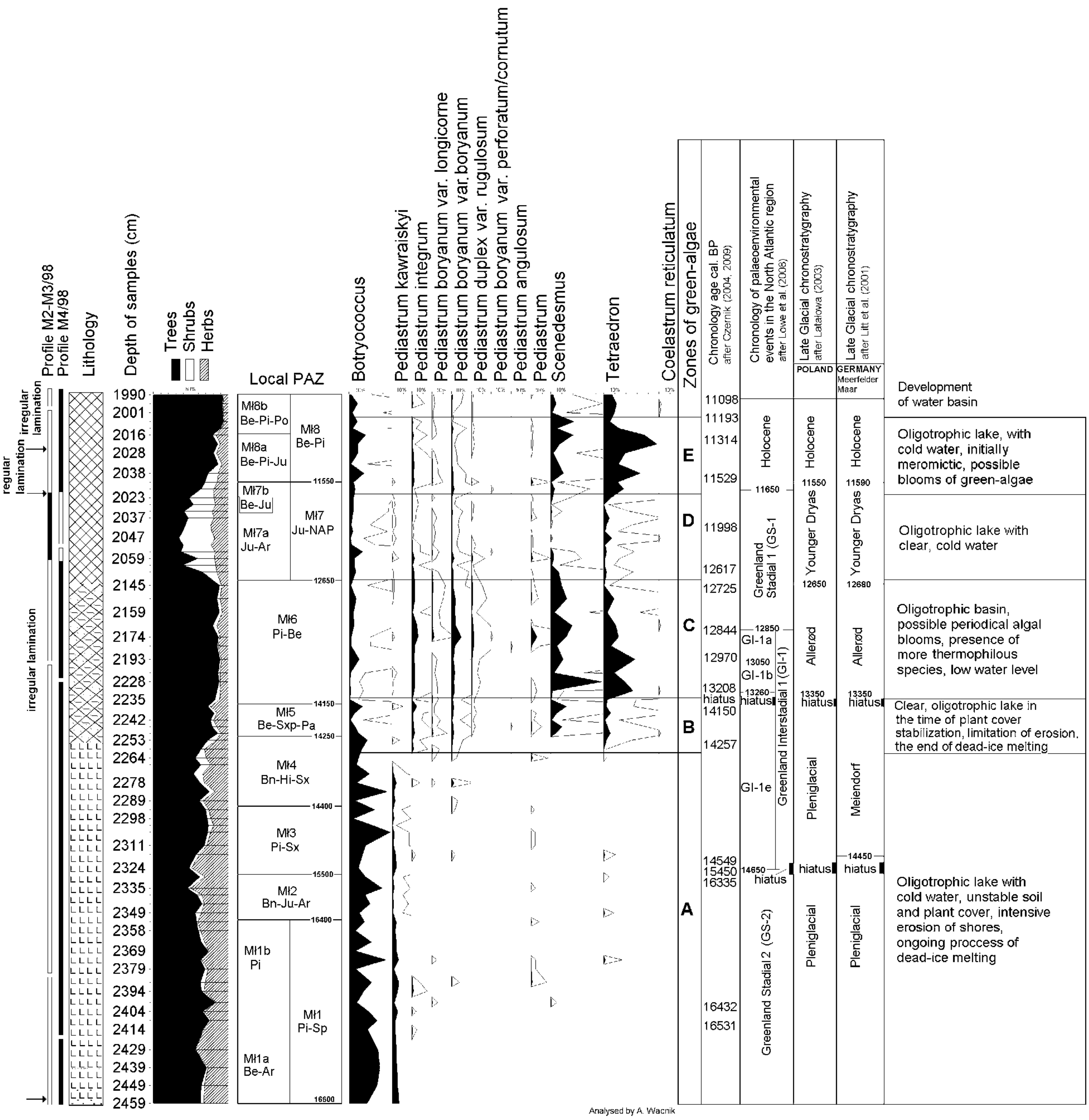

Fig. 7. The Late Glacial part of the Lake Miłkowskie profile. Percentage diagram of green algae remains, chronology, and stages in the development of the lake

The contemporaneous presence of *Pediastrum integrum*, *P. boryanum* var. *longicorne*, and *Botryococcus pila* in the sediment is an indicator of cold, quite clear water of not very extensive, dystrophic basins, particularly in the Late Glacial and early Holocene. Taking into consideration observations from several sites in the southern Czech Republic (Jankovská 1980), and north-west Russia (Jankovská & Komárek 2000, Jankovská & Panova 1998), we can infer that phase B in Lake Miłkowskie represents a stage of lake development during which the water was clear, the soil stabilised by plant cover and soil erosion around the lake minimal.

Phase C (13 200–12 650 cal. BP) corresponds to the Allerød interstadial and is characterized by particularly high frequency of *Tetraedron* and *Scenedesmus* forming periodic blooms as well as by the appearance of more thermophilous taxa such as *Pediastrum boryanum* var. *perforatum*/*cornutum*, *P. angulosum*, and *Coelastrum reticulatum* (Pl. 2,3), all indicators of an amelioration of the climate. The water level may have been quite low, as is shown by the presence of the highest number of terrestrial plant macro-remains in this section of the profile.

Phase D covers the period of maximum reduction of forest cover and development of open plant communities as a reaction to the climate cooling in the Younger Dryas (ca. 12 650–11 700 cal. BP). This phase is distinguished by a decline in representation of the majority of algae and the retreat of *Pediastrum kawraiskyi*. It is a section of the profile, where a sedimentological gap was found in addition to inserts of sandy material. The composition of green algae flora suggests a lake with cold, clear water during a period of active erosion. The climatic deterioration resulted in a decline in the number and taxonomic diversity of the phytoplankton.

Phase E corresponds to the transition between the Late Vistulian and the Holocene (ca. 11 700–11 200 cal. BP). The disappearance of *Pediastrum kawraiskyi*, reduction of *Botryococcus* (mostly *B. pila*), rapid expansion of *Tetraedron*, and later of *Pediastrum boryanum* var. *boryanum*, *P. integrum*, *P. boryanum* var. *longicorne*, *P. duplex* var. *rugulosum*, and *Scenedesmus* (see Fig. 8), were probably associated with rapid climatic amelioration which occurred at the onset of the Holocene (Brauer et al. 1999, Renssen & Isarin 2001, Ralska-Jasiewiczowa et al. 2003b, Lowe et al. 2008). Lake Miłkowskie was at that time a basin with oligotrophic cold water. The gradual rise of temperature favoured mass appearance of some algae such as *Tetraedron* and *Scenedesmus*. The decline of *Pediastrum* coenobia (incl. *P. boryanum* var. *boryanum* with broad ecological scale) was probably the result of competitive pressure from *Tetraedron* and *Scenedesmus* (Pokorný & Jankovská 2000).

Phase F covers a considerable part of the Preboreal and Boreal periods (ca. 11 200–9000 cal. BP). Alga representation remained at a stable, low level (Fig. 8). This phase represents a further stage of lake development with clear cold water. The water temperature had become more favourable, accounting for the sporadic appearances of taxa with higher thermal requirements such as *Pediastrum angulosum*, *P. boryanum* var. *perforatum*/*cornutum*, and *Coelastrum reticulatum* were observed (Pl. 2,3).

Phase G occurs at the beginning of the Atlantic period (ca. 9000–7800 cal. BP). A rise in alga numbers was again noted. The lake contained mostly *Tetraedron*, *Botryococcus*, and *Scenedesmus*. *Botryococcus* was represented by *B. pila* and *B. neglectus* which prefer smaller, mesotrophic basins. The coexistence of *Pediastrum simplex* and *Coelastrum reticulatum* is thought to indicate favourable climatic conditions, possibly higher summer temperatures, and higher nutrient levels in the lake (Jankovská & Komárek 2000). The simultaneous presence of these algae has been noted in the sediments from several sites, among others, Lake Švarcenberk in the south of the Czech Republic (Jankovská 1980). The very high and fluctuating amounts of *Tetraedron* in Lake Miłkowskie suggest the possibility of seasonal blooms. The absolute *Tetraedron* maximum at the top of phase G was accompanied by the reappearance of *Pediastrum kawraiskyi* (possibly indicating the input of mineral matter from shore erosion) and *P. simplex* (an indicator of eutrophication). The synchronous rise of herb numbers preceded by the presence of charcoal may suggest that the noted phenomena were linked to the activities of the Mesolithic people in the vicinity of the lake. Phase G covers the period of mesotrophic lake development, with warmer water submitting gradually to the process of natural eutrophication.

Phase H (ca. 7800–6800 cal. BP) represents the stage during which the natural balance was disturbed, probably as a result of water level changes. The numbers of algae decreased rapidly, although the basic taxonomic diversity was preserved. It is difficult to interpret univocally the changes noted. They show a correlation with the anthropogenic changes of woodland communities but it is rather fanciful to imagine that the activities of hunter-gatherers resulted in the disturbance of the natural balance of the lake (see 1st settlement phase, Wacnik 2009). A possible reason for the noted changes have been an increase in water level at the beginning of the phase (compare e.g. Ralska-Jasiewiczowa & Latałowa 1996), as is suggested by the disappearance of *Pediastrum duplex* var. *rugulosum* and the presence of the pelagic form of *P. duplex* var. *gracillimum*. A high lake water level was reported from the

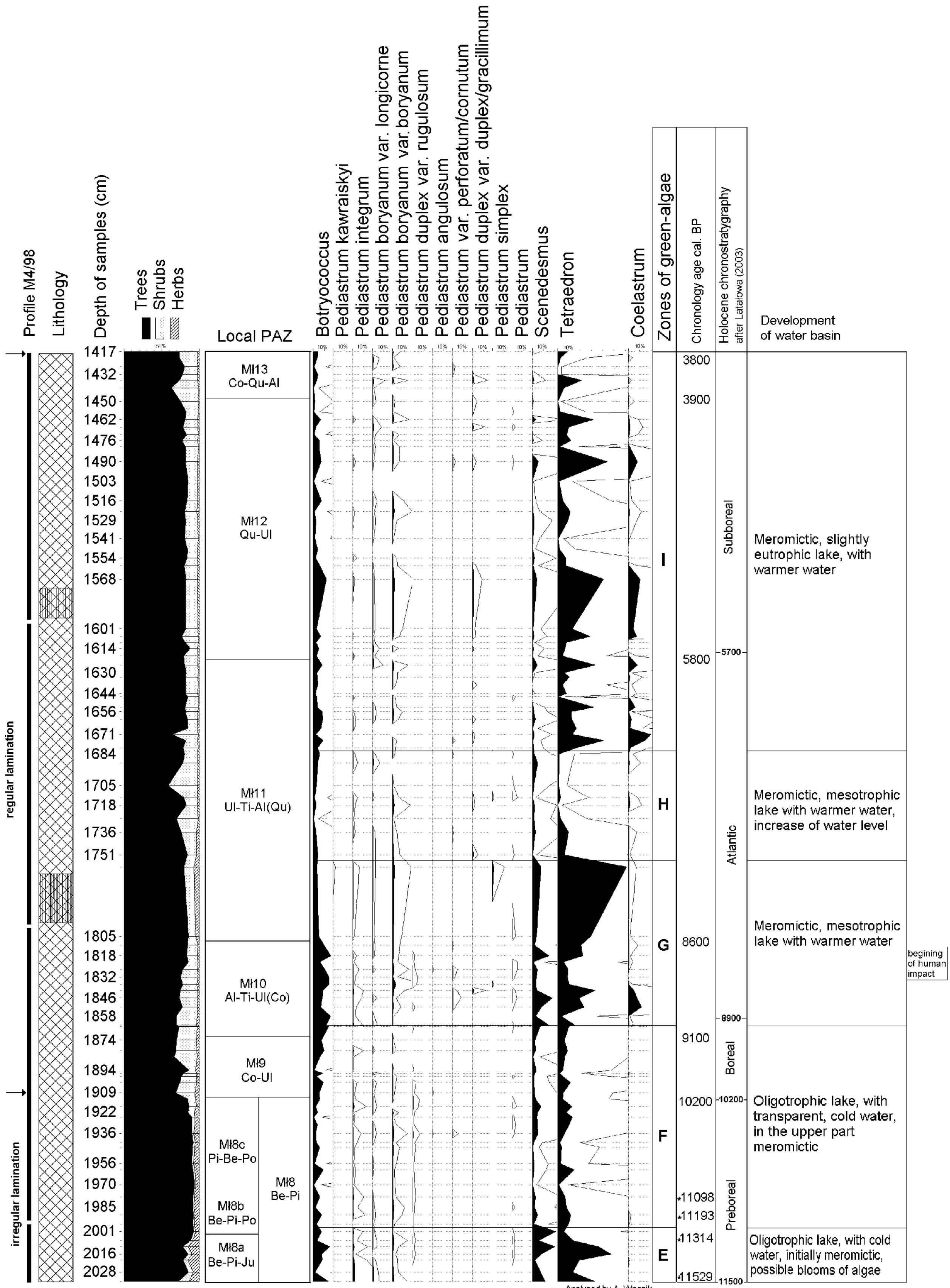

Fig. 8. The Holocene part of the Lake Miłkowskie profile. Percentage diagram of green algae remains, chronology, and stages in the development of the lake

neighbouring Lake Staświńskie (Gumiński 2008). Lake Miłkowskie was a slightly eutrophic basin with rather warm water.

Phase I covers a considerable part of the Atlantic and the beginning of the Subboreal periods (ca. 6800–3800 cal. BP) when the next rapid green algae expansion, particularly of *Tetraedron* and *Coelastrum*, was noted. The large fluctuations in *Botryococcus* numbers may have been the results of brief mass occurrences. *Botryococcus*, represented by *B. pila* and *B. neglectus*, was a stable element of the phytoplankton. The frequency of *Scenedesmus* and *Pediastrum* remained at a low level. The characteristic feature was the regular occurrence of *P. duplex* var. *gracillimum*. It was also noted sporadically in the lacustrine sediments in the Czech Republic and Russia. Its presence shows the existence of large, slightly eutrophic lakes, probably without submarged aquatic vegetation (Jankovská & Komárek 2000).

In addition to *Coelastrum reticulatum* phase I witnessed the appearance of a new species, *C. polychordum* (Pl. 3). It has been recorded several times in Holocene sediments in Poland (Makohonienko 2000). The occurrence of *Coelastrum* is considered to be an indicator of eutrophication. It has been noted most frequently in samples with totally dominated by *Tetraedron minimum*. A similar phenomenon has been recorded in Swiss lakes, e.g. in the sediments from Gerzensee and Le Loclat (Lotter et al. 1997, Jankovská & Komárek 2000). The next stage in the evolution of Lake Miłkowskie is marked by progressive eutrophication. The water level may have been slightly higher then, as is suggested by the limited representation of limnophytes rooted in the lake bottom and a decline in the importance of shore vegetation such as *Thelypteris palustris*.

GREEN ALGAE VERSUS CLIMATIC AND ANTHROPOGENIC CHANGES

Limnophytes reacted more rapidly than terrestrial plants to climatic amelioration and much more slowly to its cooling. They are thus good indicators of climatic changes (e.g. Birks et al. 2000, Ralska-Jasiewiczowa et al. 2003b). Undoubtedly the short life cycle of green algae enables them to react faster to climatic changes than aquatic angiosperms. This phenomenon can be observed in the reaction of algal frequency to climate changes shown, for example, in phases C, D and E (Fig. 7). The climatic cooling at the end of the interstadial caused a reduction in almost all green algae. *Tetraedron* declined at ca. 12 850 cal. BP, followed by *Scenedesmus*. The increase in *Tetraedron* at the end of the Younger Dryas (ca. 11 700 cal. BP) was also faster than that of *Scenedesmus*. The high resolution analysis of samples at the transition from the Late Glacial to the Holocene in the sediments of Lake Gościąż showed that the increase in *Tetraedron minimum* numbers was a good indicator of climatic amelioration (Ralska-Jasiewiczowa et al. 2003b). The results from Lake Miłkowskie support this conclusion. They generally confirm the higher sensitivity of *Tetraedron* to increases in temperature and suggest also its greater sensitivity to temperature drop than is found in the other green algae identified. The results of investigations of the youngest bottom deposits at Ponte Tresa-Becken in Switzerland also point to the quite close relationship between the changes in *Tetraedron* numbers and of temperature fluctuations (Ratschiller-Burkhalter 2002).

LAKE MIŁKOWSKIE PALYNOLOGICAL DATA IN A REGIONAL CONTEXT

For regional comparison of vegetational changes pollen profiles thought to be representative were used for the Mazurian Lake District: eastern part – Lake Mikołajskie; western part – Woryty; central Poland – Lake Gościąż; for the Suwałki Lake District – Lake Wigry (Fig. 9). Analysis of the pollen sequence from Lake Mikołajskie, about 30 km west from Miłki, suggests it is a younger age. The deposition of sediments at Woryty began in the middle of the Allerød interstadial (Fig. 10), corresponding to the Greenland Interstadial 1a (GI 1a).

The lacustrine sedimentation in most cases began in the Late Glacial part of the Vistula glaciation (Błaszkiewicz 2005). Lake Miłkowskie is an example of a lake basin in which the accumulation of deposits started in the pleniglacial.

Plenivistulian vegetation formed under periglacial climatic conditions was of open in character. Tundra-steppe-like formations, dominated by herbs with scattered larches

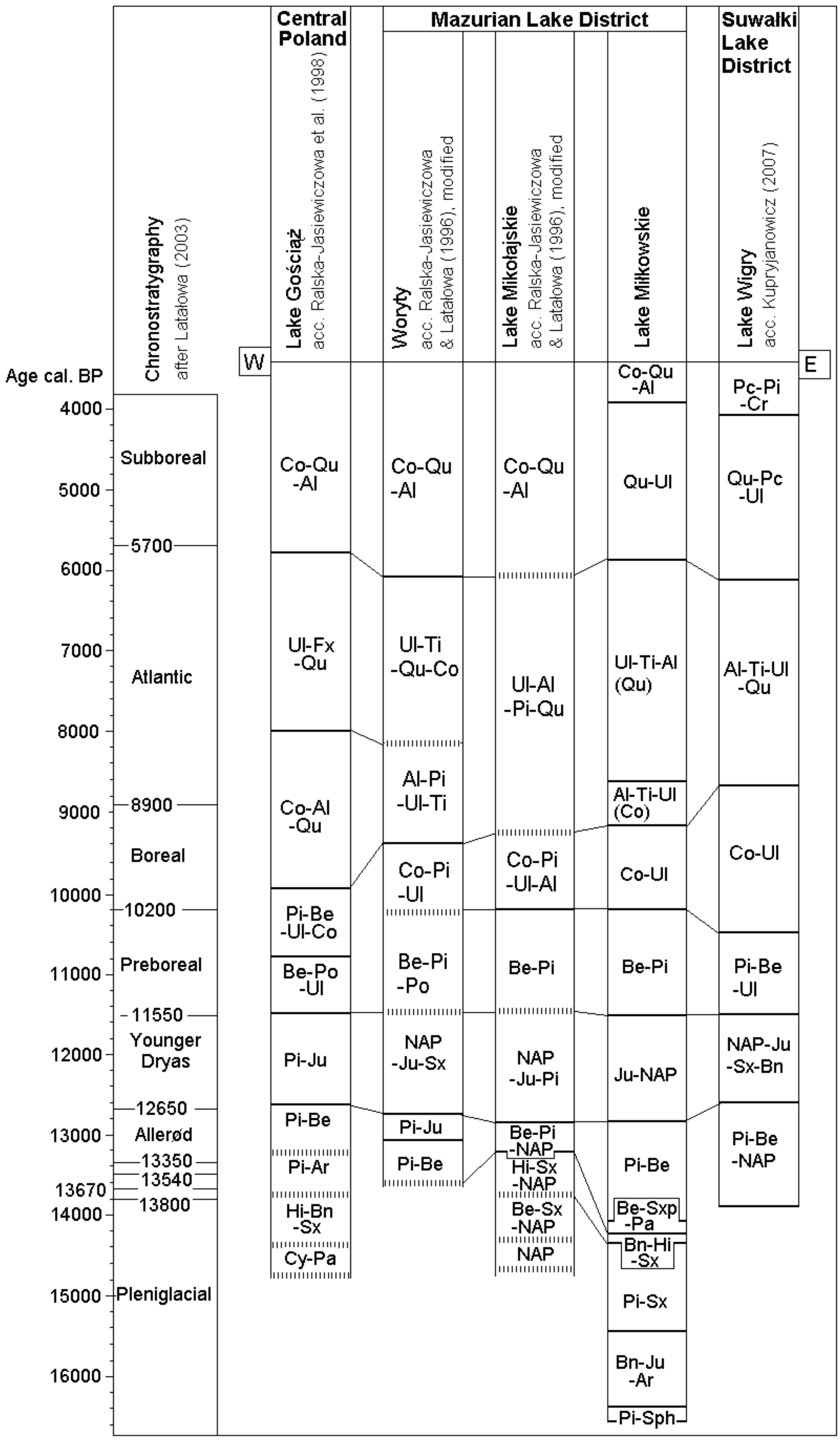

Fig. 9. Palynostratigraphy of profiles representative of the Mazurian Lake District area in relation to the profiles from central (Lake Gościąż) and eastern Poland (Lake Wigry)

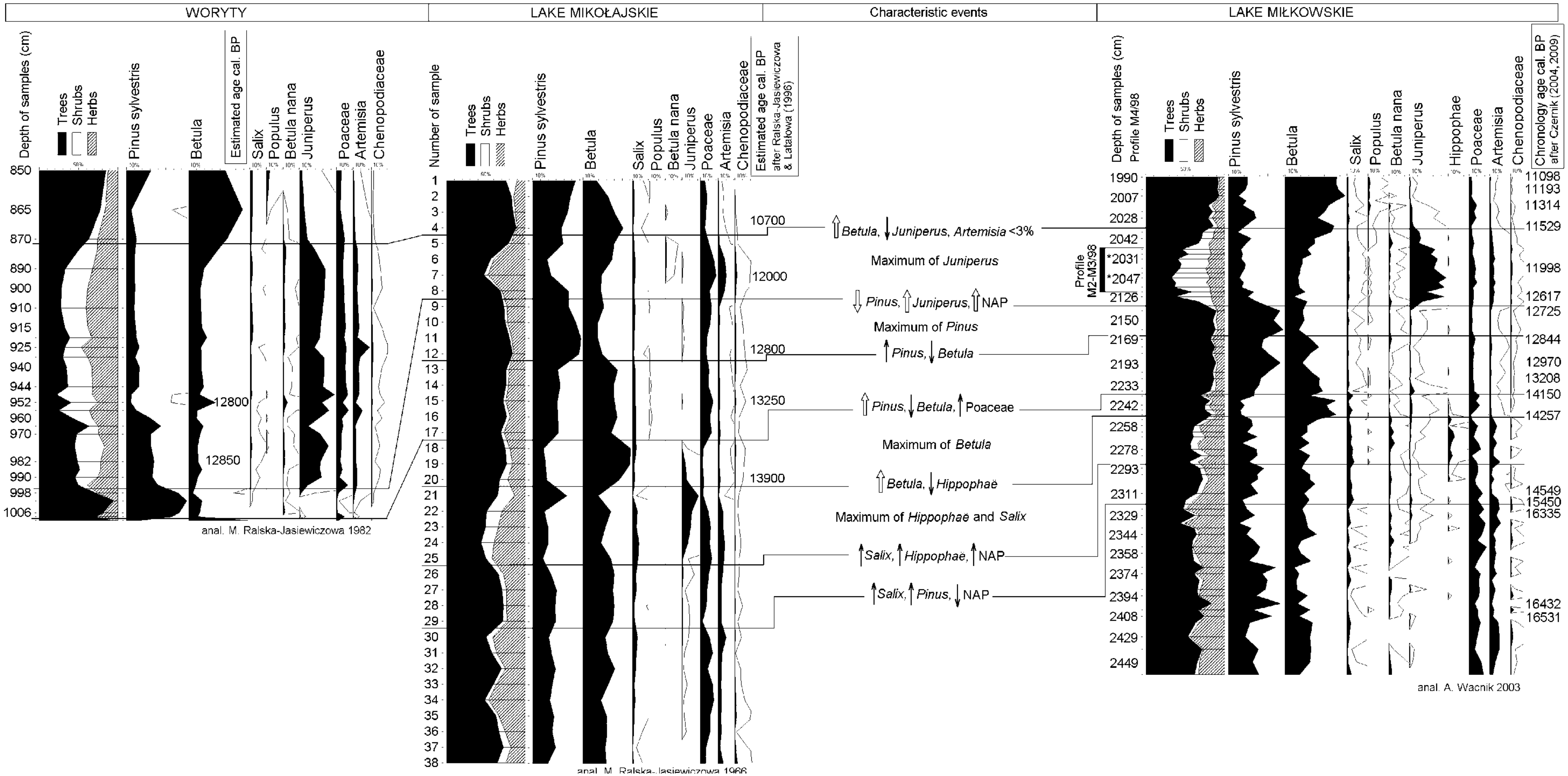

Fig. 10. Correlation of characteristic events in the Late Glacial development of the vegetation of the Mazurian Lake District. Pollen diagrams from this region

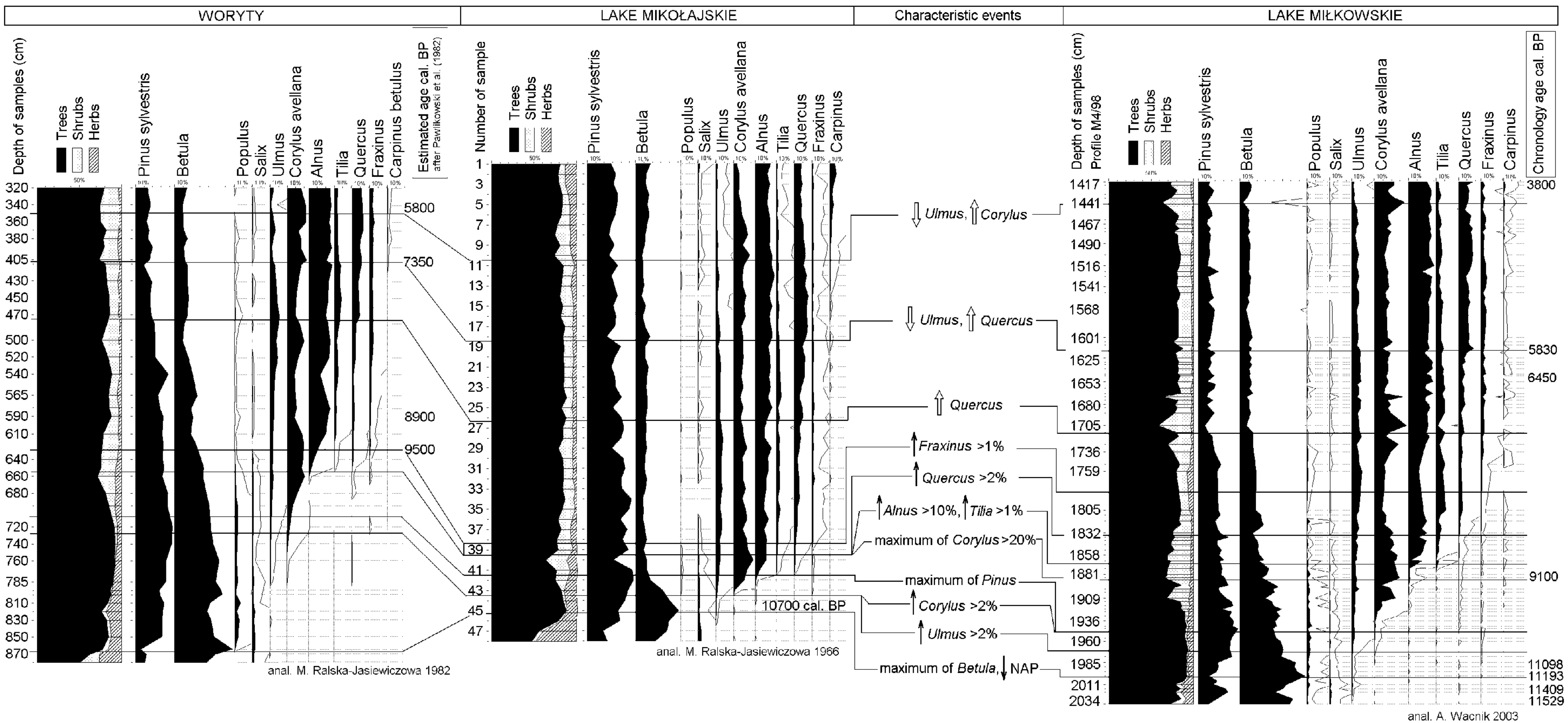

Fig. 11. Correlation of characteristic events in the Holocene development of the vegetation of the Mazurian Lake District. Pollen diagrams from this region

and shrubs, formed a patch mosaic on unstable mineral soils. Lake sediment was strongly contaminated with rebedded material inwashed from moraines surrounding the lake (PAZ Mł1 and Mł2, ca. 16 600–14 600 cal. BP). It was deposited during the Greenland (isotope) Stadial 2 (GS-2). From ca. 14 600 cal. BP shrub expansion, especially of *Salix* and *Betula nana*, started as a reaction to a more favourable climate (Lowe et. al. 2008). The whole area was steppe-tundra-like, with larches scattered here and there. Zone Mł3 corresponds to the Greenland Interstadial 1e (GI-1e). A characteristic period of *Hippophaë* dominance was noted at ca. 14 500–14 300 cal. BP, much earlier then it had been previously reported from the area (in Lake Gościąż this phase was imprecisely dated to 12 720±500 ^{14}C BP, Ralska-Jasiewiczowa et al. 1998b). It was followed by an expansion of tree birch. *Betula* culmination dated here to ca. 14 200 cal. BP, seems to have occurred earlier than in Lake Mikołajskie (ca. 12 000±130 ^{14}C BP; Ralska-Jasiewiczowa 1989) and later than (ca. 14 450 cal. BP) in e.g. Witów and Perespilno from central Poland (Czernik 2004). According to radiocarbon dating PAZ Mł4 and Mł5 are related to GI-1e (Fig. 2). The inter zonal transition in Lake Miłkowskie was accompanied by changes in sediment type. The presence of peat-like deposits is considered to mark the end of the melting out of lumps of dead ice (Błaszkiewicz 2005); the hiatus was noted above PAZ Mł5 in the studied profile. The younger deposits dated to ca. 13 200 cal. BP cover part of the Late Glacial Interstadial, comparable to GI-1b and GI-1a. Pine spread, dated in Lake Miłkowskie at ca. 13 200–12 600 cal. BP, is a widely known phenomenon following the period of birch domination (usually described as the older part of the Allerød). That phase is missing in the Lake Miłkowskie profile. The next pollen zone (Mł7) was characterized by the thinning of woodland in response to the climate cooling. Shady conifer-dominated forest was replaced by more open, well-lit communities constituting a mosaic of forest-shrub tundra and forest-steppe. Characteristic for the Miłki area was a high representation of *Juniperus* at ca. 12 600–11 500 cal. BP (Fig. 10), simillar to that found in the Woryty region but absent from Lake Mikołajskie and Lake Wigry (Ralska-Jasiewiczowa 1966, Pawlikowski et al. 1982, Kupryjanowicz 2007). Throughtout the whole region the beginning of the Holocene witnessed renewed establishment of woodland, mainly birch but with some pine, aspen and larch (PAZ Mł8). During the Holocene three main phases of tree immigration occurred: at ca. 9450 BP of *Ulmus* and *Corylus*; at ca. 8160 of *Alnus*, *Tilia*, *Quercus*, and *Fraxinus*; at ca. 3900 of *Carpinus*, *Picea*, *Acer*, and maybe also of *Fagus*. A pattern of changes in woodland composition fit the pattern accepted for that region of Poland (Ralska-Jasiewiczowa & Latałowa 1996). However, individual sites did show some variations e.g. first elm fall in the Woryty area (ca. 5150 cal. BP) was later than in Lake Miłkowskie (5830 cal. BP) while the second elm fall (ca. 3960 cal. BP) was earlier than in the Miłki area (3900 cal. BP); pine representation was higher around Lake Mikołajskie than at Miłki and Woryty; *Alnus*, *Corylus*, *Tilia*, and *Fraxinus* were more common around Lake Miłkowskie and Woryty than around Lake Mikołajskie; the presence of a triple maximum of hazel (in Preboreal, middle Atlantic and Subboreal) clearly marked in the Lake Miłkowskie and Woryty pollen record was not so evident in case of Lake Mikołajskie (Fig. 11).

The comparison of results from the Great Mazurian Lake District with well-dated profiles from neighbouring regions showed that *Picea* arrived later there than in the Suwałki Lake District where spruce appeared at ca. 5900 cal. BP (Kupryjanowicz 2007). This observation confirms that of spruce migrated from east to west.

CONCLUSIONS

Based on palynological, palaeoalgological and chronological investigations of the sediment sequence from Lake Miłkowskie, the following conclusions can be drawn:

1. The studied profile constitutes the longest pollen record so far of the pleniglacial and post-glacial evolution of terrestrial and lacustrine vegetation in north-eastern Poland, with a sedimentation process which began in the Plenivistulian at ca. 16 600 cal. BP.

2. Detailed radiocarbon dating revealed the presence of sedimentological gaps in the Late Glacial part of the profile. Despite that, a reconstruction of the Late Vistulian vegetation, poorly recognized so far, was possible.

3. Ten stages of local plant cover development

in the Lake Miłkowskie area have been described.

4. Pollen analysis of the Late Vistulian deposits confirmed: the local presence of *Larix* since the Plenivistulian; the early occurrence of *Hippophaë rhamnoides* preceded by an expansion of *Salix* and *Betula nana*; a phase of *Hippophaë* domination at ca. 14 400–14 200 cal. BP; the early immigration of tree birch confirmed by finds of macrofossil remains and the establishment of woodland (ca. 14 200–14 150 cal. BP); a rapid decline of trees and development of juniper shrub, especially in the older part of the Younger Dryas (ca. 12 600–12 000 cal. BP).

5. A change of sediment type from sandy silt to peat-like deposits with sand and gyttja making the end of the melting of dead ice was observed at ca. 14 200 cal. BP.

6. In the Preboreal period, changes observed in the pollen diagram at ca. 11 300 cal. BP seemed to reflect the reaction of vegetation to the Preboreal oscillation. The maximal spread of *Betula* was dated to ca. 11 200 cal. BP. In the remaining part of the Holocene three phases of post-glacial tree migration have been described.

7. A triple maximum of *Corylus* occurrence was noted in the Lake Miłkowskie pollen record similar to that found in other lakes from this region. A second culmination, dated to the early Atlantic, was a reaction to woodland disturbance caused by the Mesolithic people.

8. The migration of spruce from the east into the lake surroundings which began at ca. 3900 cal. BP was much delayed in comparison with the Suwałki Lake District where spruce was present at ca. 5900 cal. BP.

9. Palaeoalgological studies confirmed close correlations among climate, nature of sediment and fossil green algae taxonomic composition. Several stages of lake evolution, from oligotrophic with cold water, through a meromictic, mesotrophic basin to one with slightly eutrophic warmer water, were distinguished. Possible changes of water level were observed. The rapid response of *Tetraedron* to climate cooling as well as to its warming was noted.

It is necessary to stress that the accepted chronostratigraphy of the Late Vistulian for Poland needs to be verified. In the context of the pollen data from Lake Miłkowskie it is clear that without detailed radiocarbon chronology of the material studied, the combination of a high probability of sedimentological gaps and lack of a pollen profile representative of the Late Glacial make it impossible to reconstruct the history of local vegetation and use the data obtained for regional comparisons. Currently our knowledge of the palynostratigraphy of the Last Glacial Termination in the Mazurian Lake District is not yet adequate, but the studies of Lake Miłkowskie represent a major advance.

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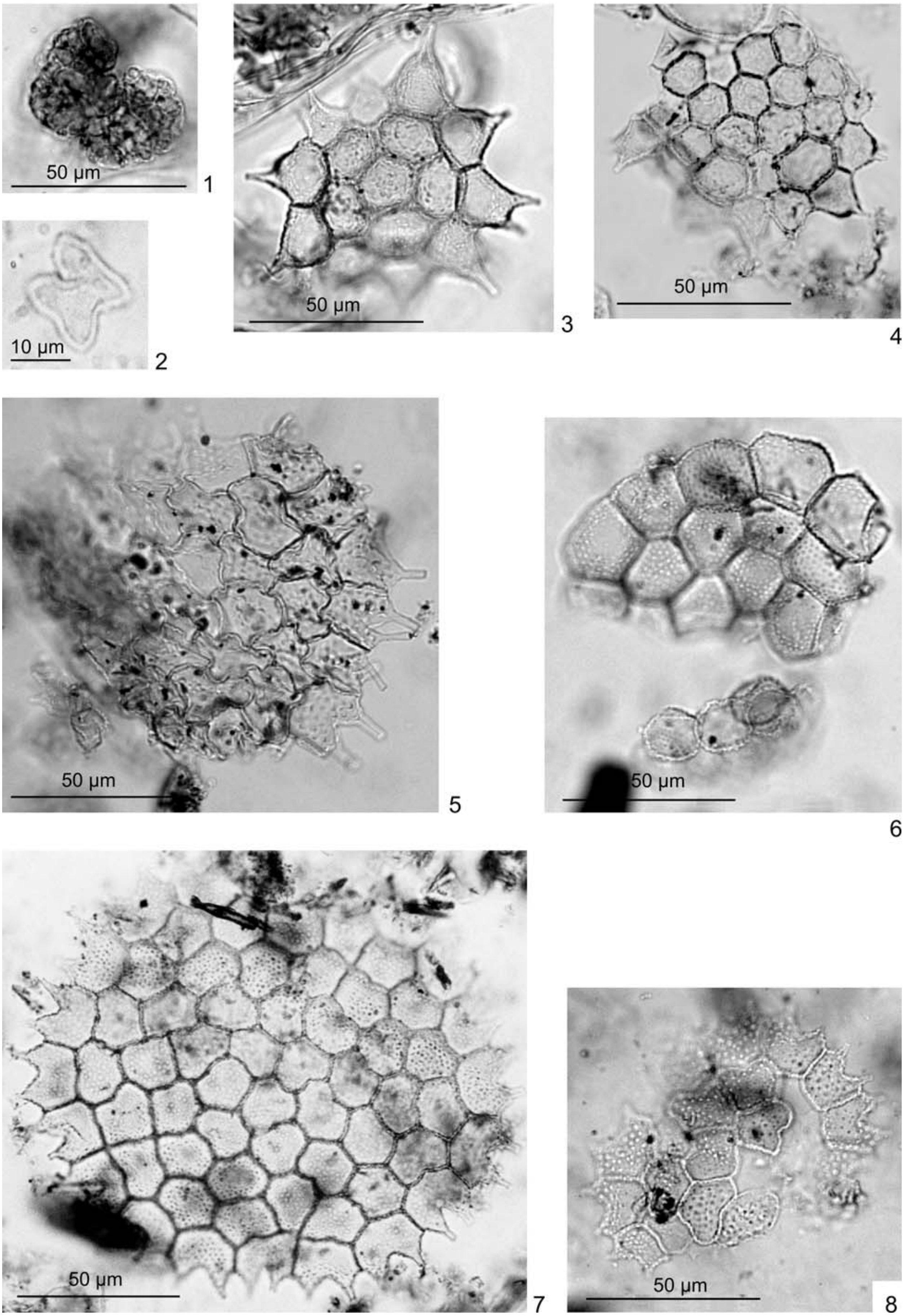
PLATES

Plate 1

Green algae remains from Lake Miłkowskie sediments

1. *Botryococcus pila*
2. *Tetraedron* sp.
3,4. *Pediastrum kawraiskyi*
5. *Pediastrum boryanum* var. *longicorne*
6. *Pediastrum integrum*
7,8. *Pediastrum boryanum* var. *boryanum*


50 µm
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8

Plate 2

Green algae remains from Lake Miłkowskie sediments

1. *Pediastrum duplex* var. *rugulosum*
2. *Pediastrum simplex*
3. *Botryococcus neglectus*
4. *Pediastrum angulosum*
5. *Pediastrum boryanum* var. *pseudoglabrum*

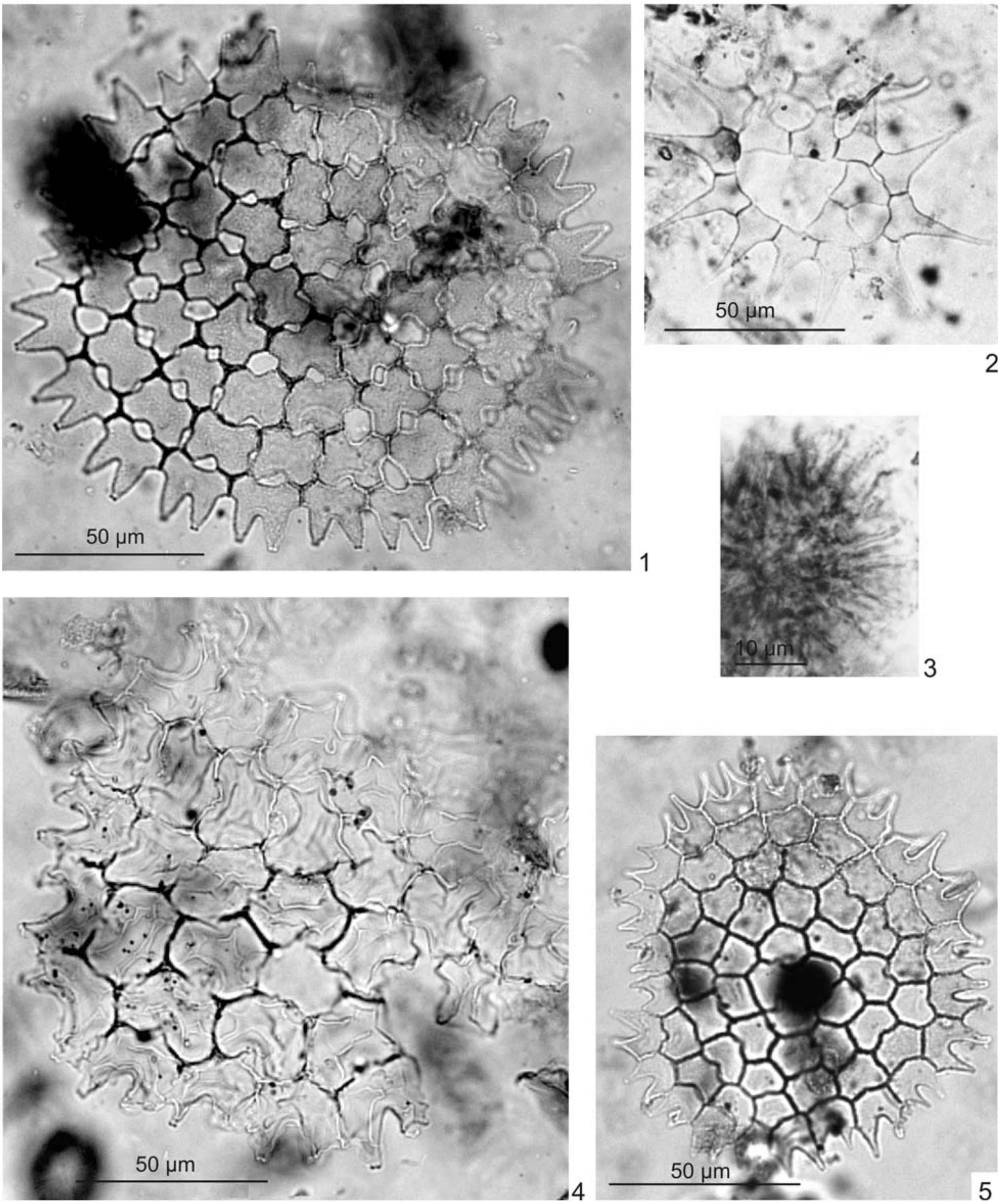
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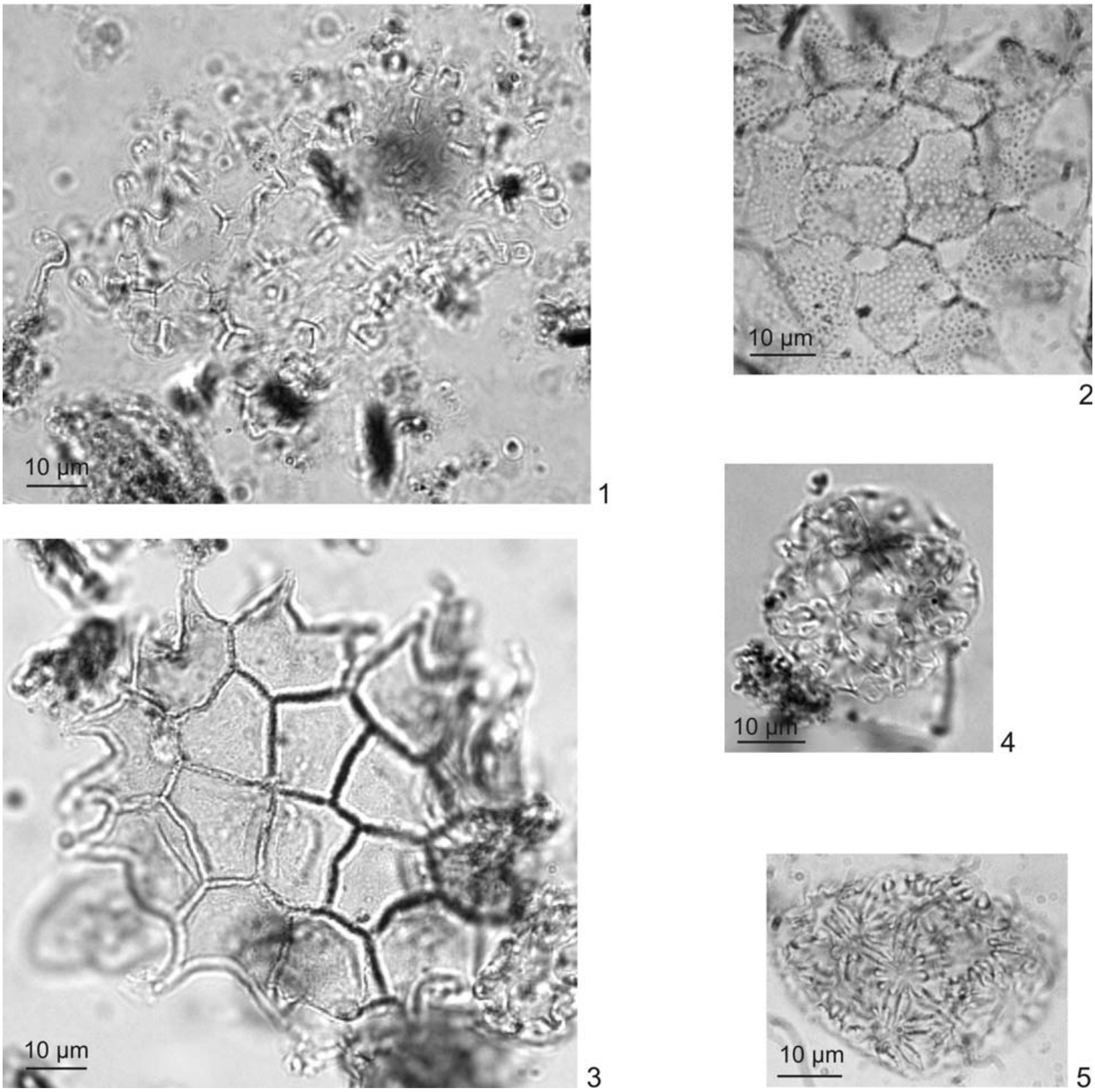
Plate 3

Green algae remains from Lake Miłkowskie sediments

1. *Pediastrum duplex* var. *duplex*
2. *Pediastrum boryanum* var. *perforatum/cornutum*
3. *Pediastrum boryanum* var. *forcipatum*
4. *Coelastrum reticulatum*
5. *Coelastrum polychordum*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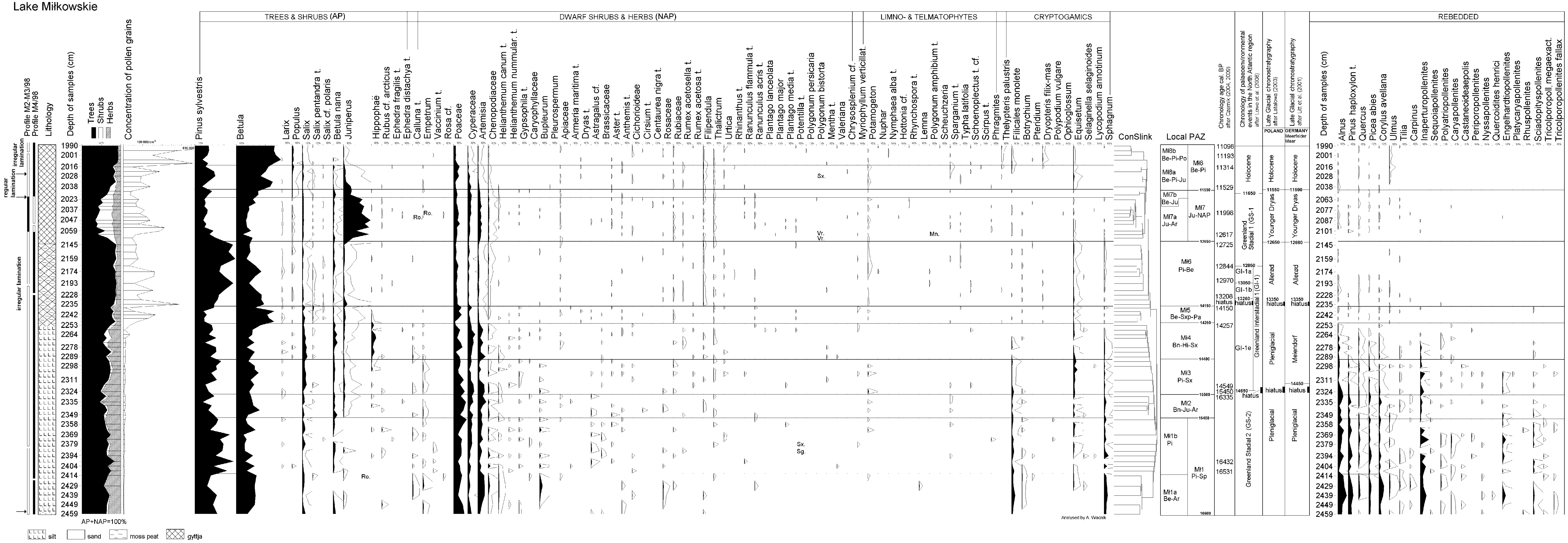

Fig. 2. Percentage pollen diagram from the Late Glacial part of the Lake Miłkowskie deposits. Abbreviations: **Pi** – *Pinus sylvestris*, **Be** – *Betula*, **Bn** – *Betula nana* type, **Sx** – *Salix*, **Sxp** – *Salix pentandra* type, **Ju** – *Juniperus*, **Hi** – *Hippophaë*, **Po** – *Populus*, **Ar** – *Artemisia*, **Pa** – Poaceae, **NAP**-herbs, **Ro.** – *Rosa* cf., **Sx.** – *Saxifraga oppositifolia*, **Vr.** – *Veronica*, **Mn.** – *Menyanthes trifoliata*

Lake Miłkowskie

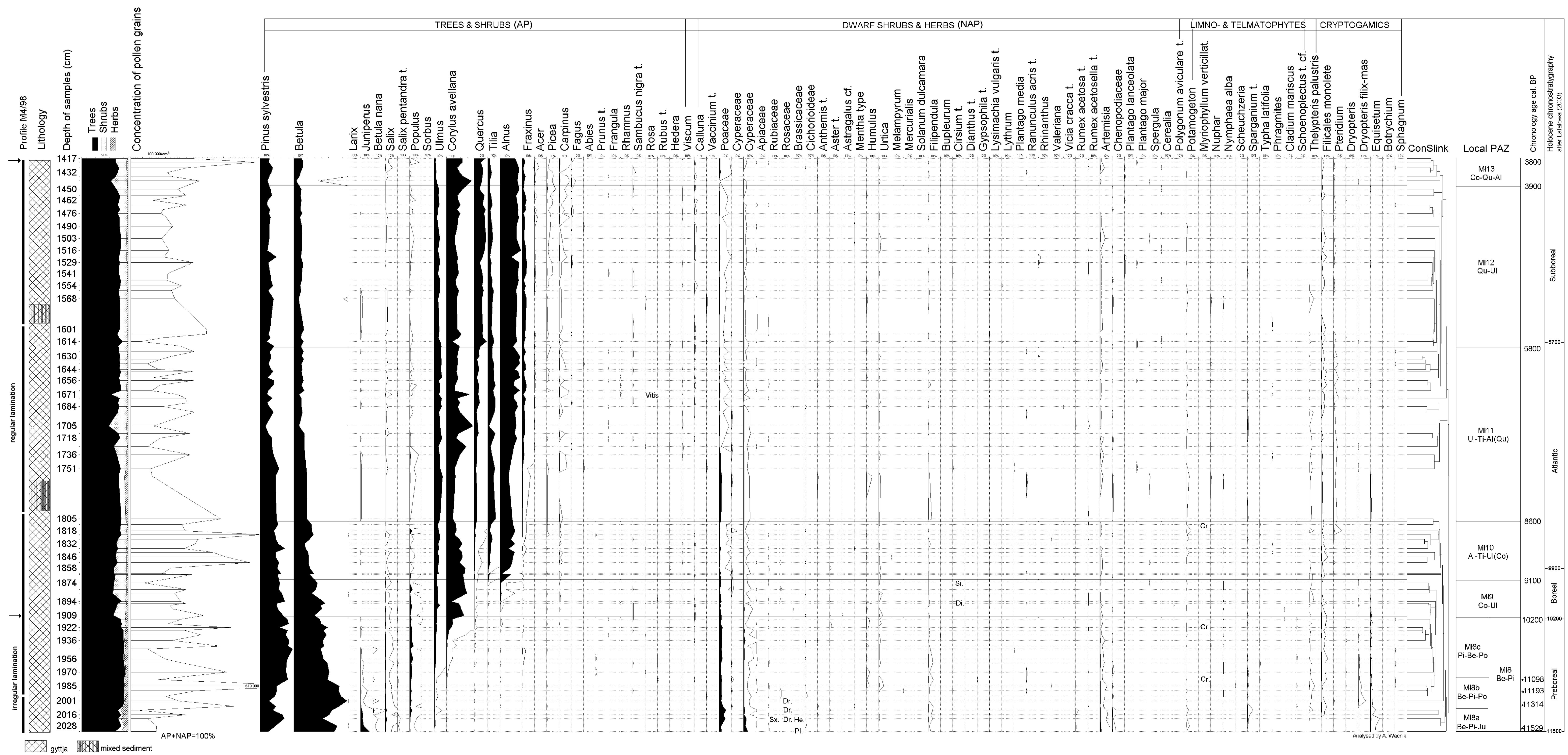

Fig. 5. Percentage pollen diagram from the Holocene part of the Lake Miłkowskie deposits. Abbreviations as follows: **Pi** – *Pinus sylvestris*, **Be** – *Betula*, **Ju** – *Juniperus*, **Po** – *Populus*, **Co** – *Corylus avellana*, **Ul** – *Ulmus*, **Qu** – *Quercus*, **Al** – *Alnus*, Ti – *Tilia*, **Dr.** – *Dryas*, **Sx.** – *Saxifraga oppositifolia*, **He.** – *Helianthemum*, **Si.** – *Silene*, **Pl.** – *Pleurospermum*, **Cr.** – *Ceratophyllum* leaf-spines