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INDICATIVE VALUE OF POLLEN ANALYSIS OF SPRING-FED FENS DEPOSITS

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Abstract

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Spring-fed fens are unique peat-forming ecosystems, interesting not only in terms of their floral composition, but geological structure and palaeo-ecological development as well. Their existence is supported by a constant supply of groundwater rich in calcium carbonate. Geological structure is characterized by the occurrence of alternating layers of biogenic and carbonate deposits which reflect changes in moisture and temperature conditions in the fen's surrounds. Despite the low frequency of sporomorphs, in many cases pollen analysis of these biogenic deposits shed light on the changes in the plant communities before the activation of spring waters. In addition, it provided new facts for palaeo-environmental interpretations, mainly concerning climate-habitat changes. Based on the composition of pollen spectra, the examined deposits were related in most cases to the Early Holocene or the Late Glacial/Preboreal transition. The one exception here was the middle Mesoholocene age determined in the northernmost site. The results permit us not only to determine the beginning of development of these forms but also to draw climatic-stratigraphic and palaeo-environmental conclusions on a regional scale.

Key words: fens, palynology, calcareous tufa, biogenic deposits, Holocene, Poland

Introduction

Spring-fed fens are unique peat-forming ecosystems, whose development is conditioned by constant supply of groundwater rich in calcium carbonate (Kovanda, 1971; Dembek, 2000; Tobolski, 2000). They are characterized by distinct differences in floristic-habitat conditions (e.g. Alexandrowicz, W.P., 2004; Hájek et al., 2002, 2006; Hájkova, Hájek, 2003; Bowles et al., 2005; Urban, Sławiński, 2008; Fránková et al., 2009), and also in their hydrologic conditions (Dembek, 2000) and morphological and lithologic features (Kovanda, 1971; Dobrowolski, 2000). For these reasons, they are objects of interest to phyto-sociologists, hydrologists, geologists and also geo-morphologists. Their geologic structure is characterized by occurrence of alternating layers of biogenic and carbonate deposits (peat-tufa rhythmite *sensu* Dobrowolski, 2011), which reflect the changes in their deposition environment. These involve changes in the moisture and temperature conditions in their vicinity. Their thickness depends on the dynamics of the deposition processes, and differs from 2 to over 10 m. With respect to stratigraphy, they represent Late Glacial or/and the whole Holocene. The continuous record of carbonate-biogenic deposition in spring-fed fens is a major reason for utilizing their deposits for detailed interdisciplinary palaeo-environmental research from multi-proxy data (Dobrowolski et al., 1996, 1999, 2002, 2005, 2011; Gedda, 2006). However, indicative values of their individual proxies deviate due to their lithogenetic differences. Tufa layers excellently record the changes in moisture and temperature conditions, which are well identified from isotopic composition of oxygen and carbon, molluscan spectra and geochemical profiles (Alexandrowicz, S.W., et al., 1994; Alexandrowicz, W.P., 2004; Dobrowolski et al., 1999; Gedda, 2006). The beds of spring-fed fens are also noteworthy because of the possibility of radiocarbon dating of both the organic and carbonate fractions. Based on these obtained results, the reservoir effect can be estimated and C14 ages corrected. However, pollen grains are poorly preserved in carbonate deposits of spring-fed fens in contrast to calcareous gyttja and lacustrine chalk (Tobolski, 2000, 2007).The destruction of pollen results mainly from oxidizing conditions in the environment of tufa deposition (Dobrowolski et al., 1996, 1999). It is difficult and often impossible to macroscopically distinguish the calcareous gyttja from the gyttja-like calcareous tufa (the silt tufa *sensu* Dobrowolski, 2011). Therefore, the state of the preservation of pollen grains and spores in deposits can be an important feature indicative of deposit origin.

Approximately a dozen profiles from spring-fed fens were examined using the pollen analysis method as part of two projects (Nos. NN 306 279 035 and NN 304396638) aimed at interdisciplinary research in different regions of Poland. Despite the widely accepted difficulties with pollen analysis of spring-fed fens, including poorly preserved sporomorphs, their selective destruction and low frequency, we obtained unambiguous results of palynological dating of the bottom portions of the profiles at many sites. These results were confirmed by radiocarbon and malacological dating (Dobrowolski et al., 1999, 2011; Dobrowolski, 2006; Pidek et al., 2010).

Results of pollen analysis of ten spring-fed fen profiles are shown herein in Figure 1. These were used for dating bottom organogenic deposits made before the activation of ascending groundwater supply and formation of the spring-fed fen itself, and also for broadening palaeo-geographical interpretation of the entire spring-fed fen series. Based on the above, it was possible to develop a method of preparation of material for pollen analysis of spring-fed fen deposits.

The selected sites of the spring-fed fens are in the following physico-geographical subprovinces of Poland (Kondracki, 2000), which differ in morphogenesis and landscape:

Southern Baltic lakelands (Bobolice, Opatówek, Ogartowo and Stara Słupia sites), Eastern Baltic coastlands (Spurgle site), Podlasie-Belarus plateaux (Kuźnica site) and Middle Polish lowlands (Radzików site).

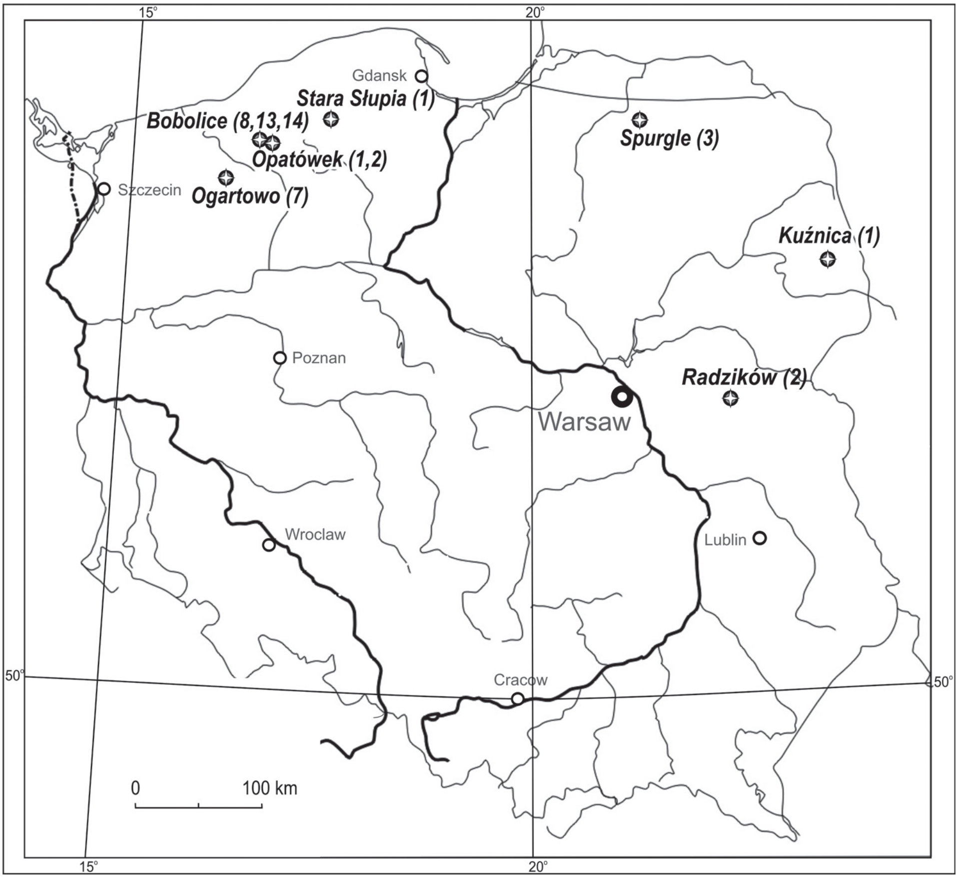

Fig. 1. Location of the studied sites – with numbers of the studied profiles in brackets.

Material and methods

Because of the different lithology of material in the examined fens, pollen analysis was applied to those deposits which macroscopically appeared promising for well-preserved sporomorphs. Palynological samples (2 cm^3) were prepared by the standard Erdman's acetolysis method (Berglund, Ralska-Jasiewiczowa, 1986) after treatment with HCl in order to remove carbonates and heating with 10% KOH. All samples needed additional treatment with HF for 24 hours because of the admixture of mineral substances.

The description of deposits in each site is presented in tabular form, and the results of pollen analysis are depicted in diagrams or histograms derived from POLPAL software (Nalepka, Walanus, 2003).

Results

The spring-fed fens are presented in regional order from Southern Baltic lakelands in the north to Middle Polish lowlands in central-eastern Poland.

Southern Baltic lakelands

The Opatówek 1 and 2 and Bobolice 8, 13 and 14 profiles are situated in the eastern part of the Drawsko lakeland, near the boundary of the Bytów lakeland, in the Chociel river valley near Bobolice village. This section of the valley is of melt-out depression nature (Karczewski, 1989) and soligenous mires occur at its base. A quite large area of the valley is occupied by spring-fed fens, conditioned by an ascending groundwater supply. Vast spring-fed fens occur on southern slopes of kame hills near Porost and Opatówek villages.

The vegetation cover in the described area is very diversified due to the occurrence of different mire habitats and to different forms of agricultural landuse practised on mires during the last century. Over 50 plant communities in the area belong to the following 6 plant classes: spring vegetation of *Montio-Cardaminetea* Br.-Bl. et R. Tx. 1943; rush communities of *Phragmitetalia* R. Tx. et. Prsg. 1942; mire vegetation of *Scheuchzerio-Caricetea nigrae* (Nordh. 1937). R. Tx. 1937; meadows of *Molinio-Arrhenatheretea* R. Tx. 1937 (1970); forest and shrub vegetation of *Alnetea glutinosae* Br.-Bl. et R. Tx. 1943 and *Querco-Fagetea* Br.-Bl. et Vlieg. 1937 (Osadowski, 2000).

The Bobolice 8 profile is situated in the area covered by rush vegetation (*Caricetum acutiformis* Sauer 1937), while the Bobolice 13 and 14 profiles are overlain by meadow vegetation (*Junco-Molinietum* Prsg. 1951 and *Polygono bistortae-Trollietum europaei* (Handt 1964) Bal.-Tul. 1981). The Opatówek 1 and 2 profiles are situated in the area covered by the sedge and herb communities of *Caricetum cespitosae* Steffen 1931 and *Filipendulo-Geranietum* Koch 1926.

Seven full profiles with thickness from 350 to 750 cm were taken in four sites selected for palaeo-ecological investigations of the spring-fed fens. The preliminary examination of several dozen samples revealed that deposits with a high proportion of calcareous tufa were poor in pollen grains, and that some even lacked sporomorphs. Microscopic examination highlighted that samples were an amorphous, shapeless mass with very rare occurrence of single pollen grains in different states of preservation. Some corroded grains were only recognizable due to their distinct characteristic features. The extremely poor pollen spectra could not be used in palaeo-ecological interpretation because it is possible that the more delicate grains may have been destroyed. Satisfactory results of pollen analysis were obtained, however, for the peat-like deposits with rare fragments of calcareous tufa. Such deposits occurred in the bottom portions of the following profiles: Opatówek 1 and 2 (Fig. 2), Bobolice 8 and 14 (Fig. 3), Stara Słupia 1 and Ogartowo 7 (Fig. 4). In Bobolice 13 (Fig. 3), samples were collected from peat-like inter-beddings in calcareous tufa, and these promised positive results.

Opatówek 1 profile

The following samples of bottom deposits were taken for pollen analysis; (1) the layer of humopeat (Table 1) with small fragments of calcareous tufa at depths of 706 and 708 cm, and (2) the layer of sand with clay and peat at the depths of 709 and 710 cm. The obtained results are presented as a pollen percentage diagram in Fig. 2.

T a b l e 1. Lithologic description of deposits in the Opatówek 1 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	**Lithology**	**T-S system**
0–20	sedge peat, strongly decomposed, with sand	Th^{4}4(Car.), nig.4, strf.0, sicc.3, elas.0, lim. sup. sup.0
20–180	sedge peat, strongly decomposed	Th^{34}4(Car.), nig.4, strf.0, sicc.3, elas.1, lim. sup. sup.0
180–705	calcareous tufa – from fine- to coarse-grained – with interbeddings of strongly decomposed sedge peat (tufa-peat rhythmite)	Cp(maj.)2, Cm(min.)1, Th$^{3-4}$1(Car.), nig.0-3, strf.3, sicc.2, elas.0, lim. sup. sup.1
705–710	strongly decomposed peat = humopeat	Sh4, nig.4, strf.0, sicc.2, elas.0, lim. sup. sup.0
710–750	sand, fine-grained, with clay	Gmin4, As++, nig.2, strf.0, sicc.3, elas.0, lim. sup. sup.0

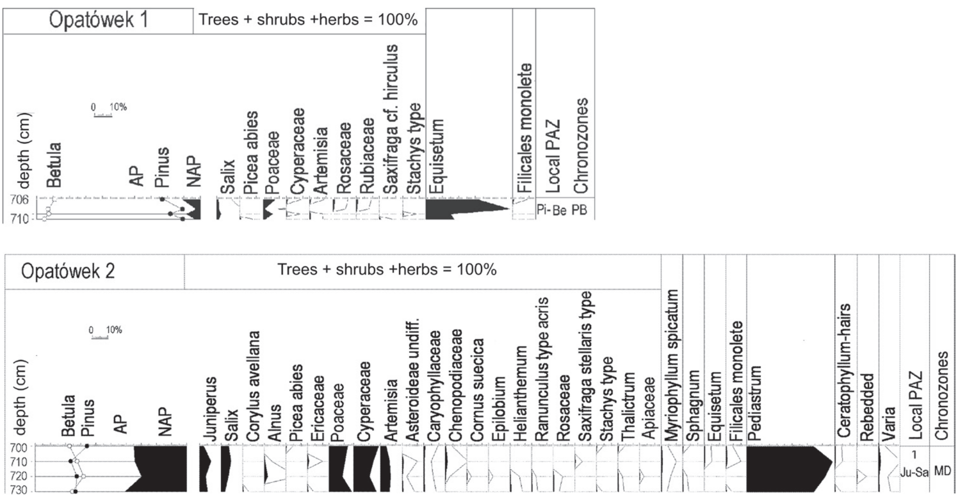

Fig. 2. Percentage pollen diagrams of the Opatówek 1 and 2 profiles.
Explanation to Figs 2–5: *Chronozones MD = Younger Drays, PB = Preboreal, AT = Atlantic, SB = Subboreal, SA = Subatlantic, LG = Late Glacial; Local pollen assemblage zones Pi-Be = Pinus-Betula, Pi-Co = Pinus – Corylus, Ju-Sa = Juniperus-Salix*

Despite selective sporomorph destruction, it can be concluded from the results of pollen analysis that deposits were formed when pine forest with birch admixture grew in the surrounds, and plant communities with horsetail (*Equisetum*) developed on this fen. Horsetail spores reached a maximum of 50% of AP+NAP+*Equisetum* total. Fragments of tracheids occurring beside sporomorphs indicate that *Equisetum* was a component of plant communities of the fen. Cyperaceae, Poaceae, Rosaceae, Rubiaceae, *Artemisia, Saxifraga* cf. *hirculus* and *Stachys* types also grew on the fen and in its immediate environs. Exotic sporomorphs sporadically found in the samples with clay admixture most likely originated from washed older deposits and entered peat in its sedentation. Based on the pollen spectra presented in the diagram, it is difficult to unambiguously determine the age of the examined deposits. However, taking into account the presence of pine and birch pollen, we can relate the bottom part of the deposits to the Preboreal period with some certitude. This interpretation is additionally supported by the close similarity between plant succession recorded in the examined fragment of the Opatówek 1 profile (Fig. 2) and those from the bottom portions of the Bobolice 14 (Fig. 3; samples from depths of 590 and 600 cm) and Ogartowo 7 (Fig. 4; samples from depths of 230 and 240 cm) profiles, which are unambiguously of Early Holocene age.

Opatówek 2 profile

Four samples of bottom deposit were taken from the Opatówek 2 profile for pollen analysis at depths of 700, 710, 720 and 730 cm. The obtained results are presented as a pollen percentage diagram in Fig. 2.

T a b l e 2. Lithologic description of deposits in the Opatówek 2 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	**Lithology**	**T-S system**
0–50	sedge peat, strongly decomposed, black, with sand at 0-15 cm	$Th^{3\text{-}4}4$(Car.), nig.4, strf.0, sicc.3, elas.1, lim. sup. sup.0
50–100	sedge peat, strongly decomposed, with capsules of sedges and fragments of twigs	$Th^{3}4$(Car.), Dl+, nig.4, strf.0, sicc.3, elas.2, lim. sup. sup.0
100–150	sedge peat, medium decomposed	$Th^{2}4$(Car.), nig.4, strf.0, sicc.3, elas.2, lim. sup. sup.0
150–168	sedge peat, strongly decomposed	$Th^{3\text{-}4}4$(Car.), nig.4, strf.0, sicc.3, elas.2, lim. sup. sup.0
168–200	sedge peat, strongly decomposed, interbedded with calcareous tufa (at 168–172, 184–185,187–191) – peat-tufa rhythmite	$Th^{3}2$(Car.), Cp(maj.)2, nig.3, strf.2, sicc.2, elas.1, lim. sup. sup.0
200–650	calcareous tufa, coarse-grained, with interbeddings of sedge peat (at 532–536) and sand (at 540–560), wood fragments in places	Cm(maj.)2, Cm(min.)1, $Th^{3\text{-}4}1$(Car.), Dl+, nig.1, strf.3, sicc.2, elas.0, lim. sup. sup.1
650–688	calcareous tufa, coarse-grained and sharp-edged (diameter of 1–2.5 cm)	Cm(maj.)4, Th^{+}, nig.1, strf.1, sicc.2, elas.0, lim. sup. sup.1
688–730	strongly decomposed peat (humopeat), compact, weakly waterlogged, plastic	Sh4, nig.4, strf.0, sicc.2, elas.1, lim. sup. sup.1
730–750	sand, fine-grained, light-grey	Gmin4, nig.2, strf.0, sicc.3, elas.0, lim. sup. sup.0

The examined deposit formed in a water environment as indicated by the sporomorphs of aquatic plants (*Myriophyllum spicatum* 1.0%), algae of *Pediastrum* genus (56.6%) and *Ceratophyllum* hairs. It was most likely a shallow eutrophic lake formed on mineral substratum. Modern communities with *Myriophyllum spicatum* are considered to be pioneer, and these developed on mineral habitats (Matuszkiewicz, 2005).

The deposits of this part of the profile were correlated with Younger Dryas cold period. At that time, the lake was surrounded by park tundra with the predominant proportion of birch and an admixture of pine, while drier places were occupied by *Juniperus* shrubs. Iso-pollen maps of Poland (Okuniewska-Nowaczyk et al., 2004) show that juniper was maximally spread in north-western Poland in the Younger Dryas (with pollen values of *Juniperus* from 3 to 15%), and was replaced by pine-birch forests at the beginning of the Holocene. High proportions of juniper enable us to distinguish the Younger Dryas based on pollen analysis. *Artemisia*, Caryophyllaceae, Chenopodiaceae, and *Epilobium* were the most strongly represented among other heliophilous plants. *Epilobium* often grows on initial habitats. The pollen grains from heliophilous *Helianthemum* genus are also indicative of the Late Glacial (Noryśkiewicz et al., 2004). These are found in all periods of the Late Glacial, when this taxon was a component of dwarf shrub tundra and occurred in open places in loose forests. Species of this genus currently grow in Poland but they are scattered. Therefore, their pollen can sporadically appear in the Holocene pollen spectra but it is no longer so important. Other herbs growing around the Late Glacial lake belonged to the Poaceae, Cyperaceae, Asterioideae, Rosaceae, Apiaceae families, *Ranunculus acris* type, *Stachys* type and *Thalictrum* genus.

Bobolice 8 profile

From a 750 cm thick core (Table 3), only the bottom 670 to 740 cm fragment was analyzed (Fig. 3). The layer from 670 to 690 cm is organic silt, and samples collected at a depth of 700–740 cm were taken from the inter-beddings of weakly decomposed moss peat contaminated with calcium carbonate.

Table 3. Lithologic description of deposits in the Bobolice 8 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	**Lithology**	**T-S system**
0–10	sedge peat, strongly decomposed, mineralized, black, single grains of sand	$Th^4$4, Dh++, Ag++, nig.4, strf.0, sicc.3
10–30	sedge peat, well decomposed, dark-brown to black, abundant sedge detritus	Th^3(Car.)3, Dh++, nig.4, strf.0, sicc.2, lim. sup.0
30–50	sedge peat, medium decomposed, dark-brown to black, abundant reed and sedge detritus, fragments of weakly decomposed wood in the bottom	Th^3(Car.)3, Th^3 (Phra.)1, Dh++, trunci, nig.4, strf.0, sicc.2, lim. sup. 0

T a b l e 3. (Continued)

Depth (cm)	Lithology	T-S system
50–57	moss peat, medium decomposed, dark-brown, abundant sedge and moss detritus, wood fragments in the bottom	$Tb^3$3, $Th^3$1(Car.), Dh++, trunci, nig.3, strf.0, sicc.2, lim. sup.1
57–142	sedge peat, medium decomposed, dark-brown, accessory wood and reed, gyttja traces	Th^3(Car.)3, Th^3(Phra.)1, Dh++, Ld+, trunci, nig.3, strf.0, sicc.2, lim. sup. 1
142–200	sedge peat, medium decomposed, strongly decomposed in places, dark-brown, accessory reed detritus, abundant wood detritus, numerous fragments of not decomposed wood	$Th^{3\text{-}4}$(Car.)3, $Tl^{3\text{-}4}$1, Ld+, trunci, nig.3, strf.0, sicc.2, lim. sup.1
200–300	sedge peat, medium decomposed, strongly decomposed in places, accessory weakly decomposed wood fragments (220) and reed detritus (260–270)	$Th^{3\text{-}4}$(Car.)4, Dh++, trunci, nig.4, strf.0, sicc.2, lim. sup.0
300–326	sedge peat, well decomposed, dark-brown to black	Th^3(Car.)4, nig.4, strf.0, sicc.2, lim. sup.0
326–340	calcareous tufa, fine-grained, with well decomposed sedge peat	Cp(maj.)2. $Th^3$2(Car.), nig.3, strf.1, sicc.2, lim. sup. 1
340–345	calcareous tufa, fine-grained, medium-grained in places, with traces of organic matter streaks	Cp(maj.)3, Cm(min.)1, Th^4(Car.)++, nig.0-1, strf.2, sicc.2, lim. sup. 1
345–367	sedge peat, well decomposed, contaminated with amorphous calcium carbonate, not abundant malacofauna	$Th^4$4, Cp(maj.)++, nig.3, strf.1, sicc.2, lim. sup.2, test. moll.
367–390	calcareous tufa, fine- and medium-grained, interbedded with well decomposed sedge peat, abundant malacofauna	Cp(maj.)2, Cm(min.)1, $Th^4$1, nig.2, strf.2, sicc.2, lim. sup.1, test. moll.
390–422	calcareous tufa, medium-grained, with interbeddings of well decomposed sedge peat, abundant malacofauna	Cm(min.) 4, Th^4++, nig.1, strf.2, sicc.2, lim. sup. 1, test. moll.
422–426	sedge peat, well decomposed, contaminated with amorphous calcium carbonate	$Th^4$4, Cp(maj.)++, nig.3, strf.1, sicc.2, lim. sup.2
426–495	calcareous tufa, medium-grained, with interbeddings of well developed sedge peat, abundant malacofauna	Cm(min.)4, Th^4+, nig.0-1, strf.2, sicc.2, lim. sup.2, test. moll.
495–500	sedge peat, well decomposed, contaminated with amorphous calcium carbonate	$Th^4$3, Cp(maj.)1, nig.3, strf.0, sicc.2, lim. sup.1
500–512	calcareous tufa, fine- and medium-grained, with interbeddings of well decomposed sedge peat, abundant malacofauna	Cp(maj.)2, Cm(min.)2, Th^4+, nig.1-2, strf.2, sicc.2, test moll., lim. sup. 1.
512–550	calcareous tufa, coarse-grained, thin inter-beddings of well decomposed sedge peat, abundant malacofauna	Cm(maj.)4, Th^4+, nig.0, strf.2, sicc.2, test. moll., lim. sup.1
550–570	calcareous tufa, fine-grained, with inter-beddings of well decomposed sedge peat – distinct streaking	Cp(maj.)3, $Th^4$1, nig.1, strf.3, sicc.2, lim. sup.1

T a b l e 3. (Continued)

Depth (cm)	Lithology	T-S system
570–578	calcareous tufa, medium- and coarse grained, thin interbeddings of well decomposed sedge peat in places	Cm(min.)2, Cm(maj.)1,, $Th^4$1, nig.0-1, strf.2, sicc.2, lim. sup.1
578–590	calcareous tufa, coarse-grained, with layers of well decomposed sedge peat, insert of weakly decomposed moss peat in the bottom part	Cm(maj.)3, $Th^4$1, Tb^0+, nig.1, strf.2, sicc.2, lim. sup.1
590–630	calcareous tufa, coarse-grained	Cm(maj.)4, Th^4+, nig.0, strf.1, sicc.2, lim. sup.1
630–660	calcareous tufa, fine- and medium-grained, interbedded with well decomposed sedge peat	Cp(maj.)2, Cm(min.)1, $Th^4$1, nig.2, strf.3, sicc.2, lim. sup.0
660–675	moss peat, well decomposed, contaminated with amorphous calcium carbonate	$Tb^4$4, Cp(min.)+, nig.4, strf.1, sicc.2, lim. sup.1
675–693	silt, organic-carbonate	As3, Lc1, nig.2, strf.2, sicc.2, lim. sup. 1
693–695	sandy carbonate silt, single gravels of Scandinavian rocks	As2, Ag2, Lc+, nig.2, strf.0, sicc.2, lim. sup. 1
695–700	sedge peat, strongly decomposed, dark-brown to black	$Th^4$4, Lc+, Ag+, nig.4, strf.0, sicc.2, lim. sup.1
700–740	silty sand, with interbeddings of weakly decomposed moss peat contaminated with calcium carbonate	Ag2, As1, $Tb^2$1, nig.3, strf.2, sicc.2, lim. sup.1
740–750	sedge peat, medium decomposed, with a small admixture of sand	$Th^2$4, Ag+, nig.4, strf.0, sicc.2, trunci et rami, lim. sup.0
750–800	sand, coarse-grained, with gravels of Scandinavian rocks	Gmin2, Gma2, nig.0, strf.0, sicc.2, lim. sup.2

The bottommost sandy sample with a small amount of organic matter was very poor in pollen – only 13 pollen grains of pine and 3 of birch were calculated on 4 cm^2 of microscopic slide. Since frequency was high enough in other samples, approximately 200 grains of AP+NAP were counted and presented in a pollen diagram, in which two local pollen assemblage zones (LPAZs) were distinguished. The older zone (1 LPAZ 680–750 cm) is characterized by the occurrence of juniper,and maximum amounts of herbs. Pine and birch were predominant among tree pollen while Poaceae, Cyperaceae, *Artemisia* and *Filipendula* dominated the herb pollen. These taxa belong to heliophilous plants and described spectra depict the occurrence of loose communities of park tundra with juniper shrubs typical of the Younger Dryas. The overlying pollen zone (2 LPAZ 670–680 cm) indicates that pine forests, typical of the early Preboreal, grew on the fen surface and its surrounds. Cyperaceae, Poaceae and *Salix* species occurred in places with a high level of groundwater.

Bobolice 13 profile

Four samples were collected for pollen analysis from sedge and *Sphagnum*-sedge peat at depths of 45, 70, 150 and 160 cm (Table 4).

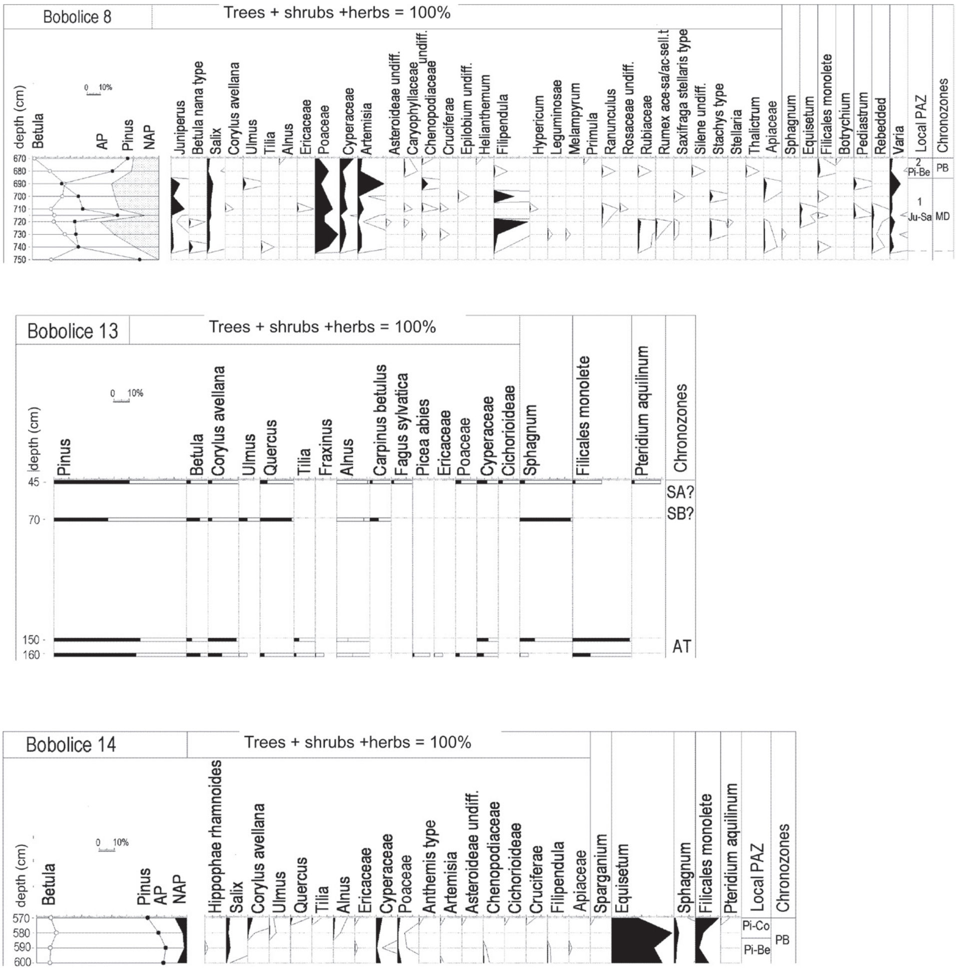

Fig. 3. Percentage pollen diagrams of the Bobolice 8, 13 and 14 profiles.

Pollen grains were selectively destroyed, in all analyzed samples, and some grains had exine with very well preserved sculpture elements, while some had such thin exine that they could not be classified to any taxon. Despite the low frequency of sporomorphs, at least 100 grains were counted and a pollen histogram was drawn (Fig. 3). Based on the occurrence of mesocratic tree pollen, it can be deduced that deposit from a depth of 150–160 cm was formed in the period not older than the Atlantic, and perhaps in the younger part of the Subatlantic. *Sphagnum*, Cyperaceae and Filicales monolete grew on the fen surface.

The occurrence of hornbeam pollen in samples from depths of 45 and 70 cm indicates that this deposit was formed not earlier than in the younger Subboreal or perhaps only in

T a b l e 4. Lithologic description of deposits in the Bobolice 13 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	Lithology	T-S system
0–15	sedge peat, strongly decomposed, with sand	Th$^{3-4}$4(Car.), Gmin+, nig.4, strf.0, sicc.2, elas.2, lim. sup.0
15–110	*Sphagnum*-sedge peat, weakly decomposed	Tb^{1}(Sphag.), Th^{1}(Car)1, nig.3, strf.0, sicc.2, elas.3, lim. sup.0
110–320	sedge peat, medium decomposed, in the bottom stronger decomposed, dark-brown to black, accessory wood fragments	Th$^{3-4}$4(Car), Dl++, nig.3-4, strf.0, sicc.2, elas.1, trunci et rami, lim. sup.0
320–650	calcareous tufa – from medium- to coarse-grained (up to 2 cm) – with interbeddings of strongly decomposed sedge peat (tufa-peat rhythmite), accessory wood	Cm(min.)2, Cm(maj.)1, Th^{4}1(Car), Dl++, nig.0-3, strf.0, sicc.1, elas.1, trunci et rami, lim. sup.1
650–670	organic-mineral deposit (silty sand and sandy silt)	Gmin.2, Ag2, Sh++, nig.2-3, strf.0, sicc.1, elas.0, lim. sup.1

the Subatlantic, because hornbeam has spread in north-western Poland since about 4000 years BP (Ralska-Jasiewiczowa et al., 2004). Numerous spores of *Sphagnum* found at a depth of 70 cm indicate that this mire may have been a high peat bog. The hydrologic situation was changed later, and this is visible in the pollen diagram as a decrease in the *Sphagnum* values, together with increased Filicales monolete, Poaceae and Cyperaceae frequencies in the sample from 45 cm depth.

Bobolice 14 profile

Ten samples, macroscopically promising for the occurrence of sporomorphs, were taken from the bottom sand and sedge peat and from peat inter-beddings of the bottom part of the tufa-peat rhytmite (Table 5). These samples were taken at the following depths: 550, 560, 570, 580, 590, 600, 610, 620, 630 and 640 cm.

From these ten samples, only the four from 570, 580, 590 and 600 cm contained any sporomorphs, so these were subjected to pollen analysis. The results are presented as a pollen percentage diagram in Fig. 3.

Pollen spectra indicate that the surrounds of the fen were first covered by pine forests with a birch admixture, and then *Corylus* and *Ulmus* appeared, followed by *Tilia* and *Quercus*. Willows most likely grew in the immediate vicinity, and on the fen itself; with grasses, sedges, Chenopodiaceae, horsetails, ferns and *Sphagnum*. Macroscopic analysis revealed the occurrence of *Equisetum limosum* remains in this fragment of the profile (Drzymulska, 2009). This species currently occurs in quiet, shallow parts of lakes on an organic substratum; most often peat (Matuszkiewicz, 2005). The diagram represents the Preboreal period with pollen spectra of two samples from the bottom. These are similar to those from the Opatówek 1 diagram

T a b l e 5. Lithologic description of deposits in the Bobolice 14 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	Lithology	T-S system
0–25	sedge peat, strongly decomposed, with sand	Th$^{3-4}$4(Car.), Gmin+, nig.4, strf.0, sicc.2, elas.2, lim. sup.0
25–90	sedge-reed peat, weakly decomposed, with wood fragments	Th^{1}3(Car.), Th^{1}(Pra)1, Dl+, nig.3, strf.0, sicc.2, elas.3, lim. sup.0
90–95	*Sphagnum*-sedge peat, weakly decomposed	Tb^{1}(Sphag.), Th^{1}(Car)1, nig.3, strf.0, sicc.2, elas.3, lim. sup.0
95–190	sedge peat, strongly decomposed, dark-brown to black, with wood fragments	Th$^{3-4}$4(Car.), Dl++, nig.3-4, strf.0, sicc.2, elas.1, lim. sup.0
190–324	sedge peat, strongly decomposed and water-logged, with wood fragments	Th^{4}4(Car.), Dl++, nig.3, strf.0, sicc.1, elas.1, lim. sup.0
324–565	calcareous tufa – from fine- to coarse-grained (up to 3 cm) – with thin interbeddings of strongly decomposed and water-logged sedge peat (tufa-peat rhythmite), wood fragments in places	Cp(maj.)2, Cm(maj.)1, Th$^{3-4}$1(Car.), Dl++, nig.0-3, strf.0-2, sicc.0-2, elas.0-1, lim. sup.1
565–604	sedge peat, strongly decomposed, with wood fragments, contaminated with amorphous calcium carbonate at a depth of 580-584 cm	Th^{4}4(Car.), Dl++, Cp(min.)++, nig.4, strf.0, sicc.2, elas.0, lim. sup.
604–650	sand, fine-grained, light-grey	Gmin4, nig.2, strf.0, sicc.3, elas.0, lim. sup.0

(Fig. 2, 706, 710 cm), and most likely represent the older part of this period. Pollen grain of *Hippophaë rhamnoides* indicates that this heliophilous shrub, which formed thickets before the Late Glacial expansion of trees in favourable conditions, survived until the Preboreal period. Samples from depths of 570 and 580 cm represent the younger part of the Preboreal period, as highlighted by the occurrence of pollen of mesocratic trees, including elm, lime and oak.

Ogartowo 7 profile

The Ogartowo 7 profile is in the Łobez plateau mesoregion, in the Dębnica river valley (tributary of the Parsęta river), in the inner zone of hummocky moraine plateau, which is composed of glaciogenic deposits consisting mainly of tills and vari-grained sands.

It is situated in eutrophic reed rush *Urtico-Phragmitetum* S u c c. 1970. This association, physionomically resembles aquatic reed rush, including nitrophilous and heliophilous species, and this testifies to the drainage and mineralization of the fen surface layer (Wołejko, 2000; Osadowski, 2000).

From the core of a shallow (240 cm) profile, five samples were taken for pollen analysis from the bottom sedge peat (Table 6).

T a b l e 6. Lithologic description of deposits in the Ogartowo 7 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	**Lithology**	**T-S system**
0–10	sedge peat, strongly mineralized, with single grains of sand, with not decomposed plant roots	$Th^4 3$, Gmin1, nig.4, strf.0, sicc.3
10–45	sedge peat, well decomposed, with single grains of sand	$Th^4 3$, Gmin1, nig.4, strf.0, sicc.2, lim. sup.0
45–65	calcareous tufa, fine-grained, with interbeddings of plant detritus (sedge and reed)	Cm(min.)2, Cp(maj.)1, Dh^+, nig.1, strf.1, sicc.2, lim. sup.3
65–70	calcareous tufa, fine-grained, with interbeddings of medium decomposed sedge peat, abundant malacofauna	Cm(min.)3, $Th^1 1$, nig.2, strf.2, sicc.2, lim. sup.3, test. moll.
70–75	sedge peat, well decomposed, contaminated with amorphous calcium carbonate, abundant malacofauna	$Th^3 3$, Cp(maj.)1, nig.3, strf.1, sicc.2, lim. sup.3, test. moll.
75–78	calcareous tufa, fine-grained, with scattered plant detritus	Cp(maj.)4, Dh^+, nig.2, strf.1, sicc.2, lim. sup.3
78–80	sedge peat, well decomposed, contaminated with amorphous calcium carbonate	$Th^3 3$, Cp(maj.)1, nig.3, strf.1, sicc.2, lim. sup.3
80–95	calcareous tufa, fine-grained, with abundant malacofauna	Cp(maj.)4, nig.1, strf.1, sicc.2, lim. sup.3
95–100	calcareous tufa, fine-grained, very rich in amorphous organic matter	Cp(maj.)3, Sh1, nig.2, strf.0, sicc.2, lim. sup.3
100–110	calcareous tufa, medium-grained	Cm(min.)4, Sh^{++}, nig.2, strf.0, sicc.2, lim. sup.3
110–125	sedge peat, well decomposed, contaminated with amorphous calcium carbonate, visible traces of streaking	$Th^3 3$, Cp(maj.)1, Dh^+, nig.3, strf.2, sicc.2, lim. sup.2
125–170	calcareous tufa, medium- and fine-grained, with interbeddings of plant detritus and amorphous humus	Cp(maj.)2, Cm(min.)2, Dh^+, Sh^+, nig.2, strf.1, sicc.2, lim. sup.2
170–215	sedge peat, well decomposed, with abundant malacofauna	$Th^3 4$, nig.4, strf.0, sicc.2, lim. sup.2
215–218	sedge peat, very rich in amorphous calcium carbonate	$Th^3 2$, Cp(maj.)2, nig.3, strf.1, sicc.2, lim. sup.3
218–232	sedge peat, well decomposed, with abundant malacofauna	$Th^3 4$, nig.4, strf.0, sicc.2, lim. sup.3, test. moll., lim. sup.0.
232–380	sandy silt, with single gravels of Scandinavian rocks	Ag4, As^+, Dh^+, $Gmin^+$, nig.3, strf.0, sicc.2, lim. sup.0

The best pollen frequency was found in the bottom-most 40 cm of well decomposed sedge peat. Pine is the predominant taxon in pollen spectra of this part of the profile but it has a distinct minimum at a depth of 210 cm (Fig. 4). This most likely was not caused by an actual decrease in pine trees proportion around the site, but by expansion of herbs.

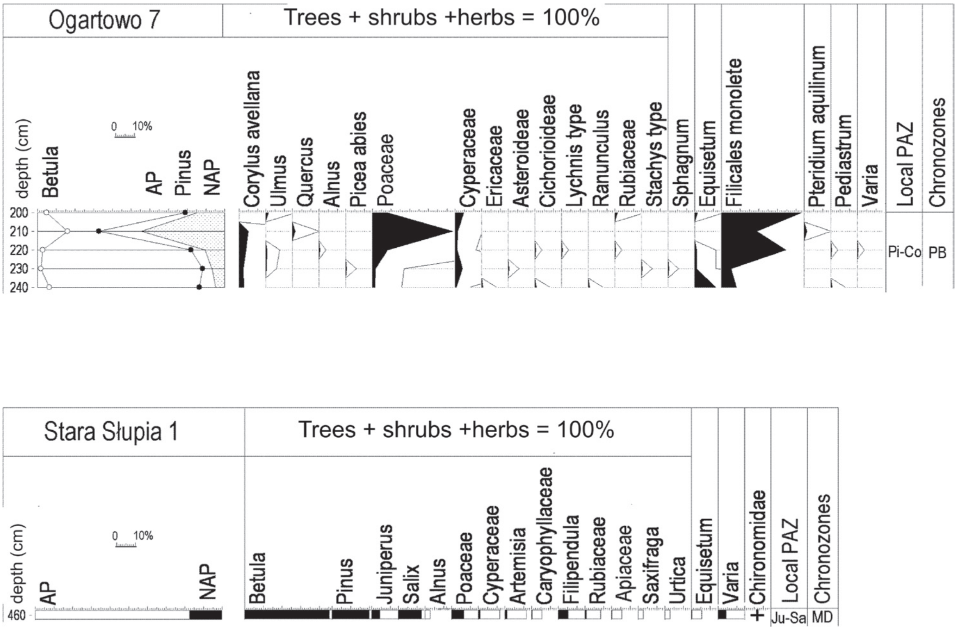

Fig. 4. Percentage pollen diagrams of the Ogartowo 7 and Stara Słupia 1 profiles.

The herb pollen is dominated by Poaceae. Birch pollen also occurs in the profile with the predominant pine, together with single pollen grains of elm, oak, alder and spruce. They are accompanied by hazel, and this pollen composition indicates that the examined deposit was formed in the Preboreal period. The abundant occurrence of spores of local plants is a very distinctive feature of this profile. Spores of *Equisetum* predominate in its bottom part, and these are gradually replaced vertically by spores of Filicales monolete. The presented pollen spectra of this regional and local vegetation are quite similar to those from the Bobolice 14 (Fig. 3) and Opatówek 1 (Fig. 2) profiles. Sedentation of the deposits examined in the three profiles commenced in the Pre-boreal period when pine forests predominated. Succession of local vegetation, such as Cyperaceae, Poaceae, *Equisetum* and Filicales monolete was also similar in these sites.

Stara Słupia 1 profile

The Stara Słupia 1 profile is situated in the Stara Słupia river valley, in the Polanów plateau mesoregion. Spring-fed fens occur at the foot of this valley's left slope. These are small peat-tufa cupolas, used as hay-growing meadows until recently. The fens are dominated by phytocenoses of wet meadows, with low sedge rushes and alder carrs *Cardamino-Alnetum glutinosae* (M e i j e r-D r e e s 1936) P a s s. 1968. There is also a large population of *Equi-*

setum maximum, and the site is overgrown with rushes of *Caricetum acutiformis* S a u e r 1937 and *Caricetum paniculatae* Wa n g e r i n 1916.

Six samples for pollen analysis were taken from the 470 cm thick peat profile overlying the vari-grained sand (Table 7).

T a b l e 7. Lithologic description of deposits in the Stara Słupia 1 profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	Lithology	T-S system
0–20	sedge peat, strongly decomposed, with living sedge rootlets	Sh4, nig.4, strf.0, sicc.3, elas.0, lim. sup.0
20–115	sedge peat, strongly decomposed, with wood fragments	Th^{3-4}4(Car.), Dl++, nig.4, strf.0, sicc.3, elas.0, lim. sup.0
115–470	sedge peat, strongly decomposed, interbedded with fine-grained calcareous tufa (tufa-peat rhythmite), with silt in the bottom, light-grey to black, with wood fragments (wood detritus at a depth of 460–470 cm), not abundant malacofauna	Th^{3-4}3(Car.), Cp(maj.)1, Dl++, nig.2-4, strf.1, sicc.3, elas.0, test moll, lim. sup.0
470–550	sand, varigrained, light-grey	Gmin4, nig.2, strf.0, sicc.3, elas.0, lim. sup.0

Only the sample from 460 cm contained well preserved sporomorphs, and the sum of tree, shrub, dwarf shrub and herb pollen was 324. The pollen spectrum of this sample is presented as a histogram in Fig. 4, and description of all pollen spectra is presented in tabular form in Table 8.

Pollen spectrum of the sample from the 460 cm depth indicates that park tundra, with predominant birch, with an admixture of pine, dominated this landscape. Based on the remains of Chironomidae, it can be deduced that the examined material was deposited in a water environment, as they provide a good indication of lacustrine accumulation (Hofmann, 1986). The dry habitats were overgrown by juniper shrubs and heliophilous *Artemisia*. *Filipendula* species, plants of Cyperaceae, Poaceae, Apiaceae, Rubiaceae families and others grew in the lake's surrounds. *Filipendula* was a common component of plant communities, which occurred at the end of Late Glacial and at the beginning of the Holocene (Miotk-Szpiganowicz et al., 2004). The presence of juniper provides a good indication of the Younger Dryas period, and therefore formation of this examined deposit is correlated with the Younger Dryas.

Eastern Baltic coastlands

Spurgle 3 profile

The Spurgle site is situated in the Sępopol lowland mesoregion, in the water-head basin of the small unnamed stream carrying water to the Łyna river.

T a b l e 8. Description of pollen spectra in the Stara Słupia 1 profile.

Depth (cm)	**Description of pollen spectrum**
90	sedge peat with wood fragments, besides the fragments of broken air sacs of pine pollen, microscope image reveals macerated, hardly recognizable pollen grains of pine, and macerated pollen grains of *Alnus* with thin exine
140	sedge peat interbedded with calcareous tufa (number of pollen grains determined on 4 cm^2 of microscopic slide: *Alnus* – 29, *Pinus* – 23, *Betula* – 11, *Quercus* – 5, *Tila* – 2, *Corylus* – 5). This pollen spectrum indicates that peat occurring at a depth of 140 cm was formed no earlier than in the Atlantic period
245	sample without pollen
329	AP sum = 28, in it few pollen grains of *Pinus, Betula* and *Alnus*
410	sample with selectively destructed but recognizable pollen grains of: *Alnus* – 8, *Betula* – 2, *Pinus* – 21, *Salix* – 1, *Tilia* – 4, *Corylus* – 2, *Artemisia* – 1, Chenopodiaceae – 1, Cyperaceae – 1, Poaceae – 3. Selective destruction of sporomorphs suggests that some less resistant pollen grains could have been eliminated. However, based on the occurrence of lime pollen, we can conclude that the deposit was formed no earlier than in the Atlantic period.
460	sample with low frequency of sporomorphs but some of them are well preserved. *Betula* is dominant (45.6%), *Pinus* reaches 19.9%, *Salix* 12.6%, *Juniperus* 4.4%, *Filipendula* 5.6%, Poaceae 6.7%, *Galium* t. 0.9%. Additionally, there are found two spores of *Equisetum* and 1–2 pollen grains of the following taxa: *Alnus*, Caryophyllaceae, Apiaceae, *Saxifraga*, *Urtica*. Fragments of mouth apparatuses of *Chironomidae* larvae and fungal spores are present. The percentage of unrecognizable sporomorphs is 4.3%.

The profile Spurgle 3 (SPU-3) for detailed palaeo-ecological analysis was taken from the cupola culmination of this spring-fed fen, where the peat-tufa bed had its maximum thickness. Lithologic description of the core is presented in Table 9. Preliminary pollen analysis was made for 11 samples from the following depths: 460, 515, 525, 620, 685, 695, 705, 710, 720, 730 and 745 cm.

The best frequency of sporomorphs was found in the 7 bottom samples at 685–745 cm, where the counted AP+NAP totals approximated 200 pollen grains. The results obtained for these samples are presented as a pollen percentage diagram in Figure 5. Pollen was absent in other samples, except for the 525 cm sample, which contained a dozen or so pollen grains belonging to the following taxa: *Pinus*, *Alnus*, *Tilia*, *Ulmus*, *Corylus* and Cyperaceae. However, this sample was not included in the diagram, as sporomorph frequency was too low.

Although the very similar composition of pollen spectra from depths of 685–745 cm and the low totals do not permit us to distinguish several pollen zones, these following results are notable; (1) relatively high pollen values for *Ulmus*, *Tilia*, *Quercus*, *Corylus*, *Fraxinus* and

T a b l e 9. Lithologic description of deposits in the Spurgle 3 (SPU-3) profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	Lithology	T-S system
0–10	reed peat, well decomposed, dark-brown to black, abundant detritus	$Th^{3-4}4$, Cp(min.)++, nig.3-4, strf.0, sicc.3, elas.1
10–45	reed peat, weakly decomposed, very rich in amorphous calcium carbonate, light-grey to light-brown	$Th^{1}3$(Phragm.), Ld++, Cp(min.)1, nig.3, strf.0, sicc.3, elas.1, lim. sup. 1
45–50	calcareous tufa, medium-grained, light-grey to white	Cm(min.)4, Th^{4}++, nig.0-1, strf.1, elas.0., sicc.3, lim. sup. 1
50–58	sedge peat, medium decomposed, strongly contaminated with amorphous calcium carbonate	$Th^{2}4$, Cp(maj.)++, nig.3, elas.2., sicc.3, strf.0, lim. sup. 1
58–70	calcareous tufa, medium-grained, with traces of streaking, downwards with interbeddings of sedge peat, medium decomposed, sharp top and bottom boundaries	Cm(min.)3, $Th^{4}1$, nig.1-2, strf.2, sicc.3, elas.0., lim. sup. 1
70–72	silt, massive, grey, sharp, non-erosional top boundary	Ag4, nig. 2, strf. 1, sicc.2, elas.0, lim. sup.3
72–125	sedge-reed peat, medium decomposed, dark-brown to black, sharp, non-erosional top boundary	Th^{2}(Carex.)2, Th^{2}(Phragm.)2, Cp(min.)+, nig.4, strf.0, sicc.3, elas.2., lim. sup. 2
125–178	calcareous tufa, medium- and coarse-grained, light-grey to white, olive-grey in the bottom, traces of stratification, one fragment of not decomposed wood (145–150 cm)	Cm(min.)2, Cm(maj.)1, $Th^{3}1$, nig.0-2, strf.3, sicc.3, elas.0, lim. sup.0
178–182	sedge-reed peat, medium decomposed, dark-brown, with a small admixture of silt	$Th^{2}4$, Cp(min.)++, Ag+, nig.4, elas.2., sicc.3, strf.0, lim. sup. 2
182–192	silt, organic-carbonate, grey to olive-grey	Ag2, Cp(min.)++, nig.1-2, strf.3, sicc.2, elas.0, lim. sup. 2
192–205	sedge-reed peat, well decomposed, dark-brown to black, with amorphous calcium carbonate, silty in the bottom, one fragment of not decomposed wood (195–203 cm)	$Th^{3-4}2$, $Tl^{2-3}2$, Cp(min.)++, nig.2-3, strf.1, sicc.3, elas.1, lim. sup.1
205–250	sedge-wood peat, numerous fragments of weakly decomposed wood, abundant malacofauna, fragments of not decomposed wood (245–250 cm)	$Th^{3}3$, $Tl^{2}1$, Dl++, Cp(min.)++, nig.4, sicc.3, elas.2, strf.0, test moll, lim. sup.2
250–280	sedge-reed peat, medium decomposed, with malacofauna in the bottom	$Th^{2-3}4$, Cp(min.)++, nig.3-4, sicc.3, strf.0, part test moll., elas.1, lim. sup.0
280–286	calcareous tufa, fine-grained, silty in the bottom, very light-grey to white	Cp(min.)2, Cp(maj.)1, $Th^{4}1$, nig.1, strf.1,elas.1, sicc.3, lim. sup.1
286–300	sedge peat, well decomposed, silty, with traces of stratification	$Th^{4}3$, Ag1, As+, nig.3, strf.2,elas.1, lim. sup.1
300–345	carbonate silt, with organic matter streaks, interbeddings of well decomposed sedge-reed peat, fragments of not decomposed wood (325–335 cm)	Ag3, $Th^{4}1$,As++, Dl.++, nig.2-3, strf.2, elas.0-2, lim. sup. 1

T a b l e 9. (Continued)

Depth (cm)	Lithology	T-S system
345–350	sand, fine-grained, light-grey	Gmin3, Ag1, nig.2, sicc.3, strf.0, elas.0, lim. sup. 1
350–360	sandy silt, light-grey, with organic matter streaks	Ag3, As1, Th^{4}+, nig.1-2, sicc.3, elas.0, strf.2, lim 2
360–400	calcareous tufa, medium- and coarse-grained, light-grey to white, stratified, with numerous interbeddings of sedge-wood peat, well decomposed sedge-reed peat, and carbonate silt (up to 2 cm thick), with malacofauna (tufa-peat rhythmite)	Cm(maj.)2, Cm(min.)1, Th^{3-4}1, nig.2-3, strf.2, sicc.3, elas.1, lim. sup.2
400–445	sand, fine-grained, interbedded with silt, light-grey (silt-sand rhythmite)	Gmin3, Ag1, nig.2, sicc.3, strf.2, elas.0, lim. sup. 1
445–460	sedge-wood peat, brown, well decomposed, strongly contaminated with amorphous calcium carbonate in the bottom	Th^{3-4}3, Tl^{3}1, Cp(min.)++, nig.3-4, sicc.3, elas.1, strf.0, lim. sup.0
460–500	calcareous tufa, medium- and coarse-grained, white to dark-grey, interbedded with sedge-wood peat (tufa-peat rhythmite)	Cm(maj.)2, Cm(min.)1, Th^{2}1, Tl^{1}++, nig.0-1, strf.2, elas.0, sicc.3, lim. sup.0
500–535	sedge-wood peat, well decomposed, very dark-brown to black, with wood detritus, not abundant malacofauna	Th^{3-4}3, Tl^{2}1, nig.4, strf.0, sicc.3, elas.2, trunci et rami, test. moll., lim. sup.1
535–545	organic silt, with interbeddings of sedge-wood peat	Ag3, Th^{3}1, nig.1, sicc.3, elas.0, strf.2, lim. sup.1
545–570	sedge-wood peat, well and medium decomposed, silty in places, dark-brown to black, with wood detritus, not abundant malacofauna	Th^{3-4}3, Tl^{2}1, As+, Ag+ nig.4, sicc.3, strf.0, elas.2, lim. sup.1
570–595	sandy silt and fine-grained silty sand, light-grey	Ag3, Gmin1, nig.2, strf.2, elas.0, sicc.3, lim. sup.0
595–610	sand, fine-grained, steel-grey (silt-sand rhythmite)	Gmin3, Ag1, nig.3, strf.2, sicc.3, elas.0, lim. sup.0
610–630	sedge-reed peat, medium decomposed, średniorozłożone, interbedded with sandy silt, abundant malacofauna	Th^{3-4}3, Ag1, Gmin.++, strf.1, nig.3, strf.2, sicc.3, elas.1, test. moll., lim. sup.1.
630–680	silt-fine-grained sand rhythmite	Gmin2, Ag2, nig.2, strf.2, elas.0, sicc.3, lim. sup.1
680–715	sedge-moss peat, well decomposed, with features typical of humopeat, rich in amorphous calcium carbonate	Th^{4}2, Tb^{4}2, Cp(min.)++, nig.3, sicc.3, strf.0, elas.0, lim. sup.0
715–730	silty-sandy rhythmite, with organic matter in places	Gmin2, Ag2, Sh++, nig.2, strf.2, elas.0, sicc.3, lim. sup.1
730–747	silt, massive, steel-grey	Ag4, nig.2, strf.0, elas.0, sicc.3, lim. sup.0
747–750	sand, fine-grained, steel-grey	Gmin3, Ag1, nig.3, strf.0, sicc.3, elas.0, lim. sup.0

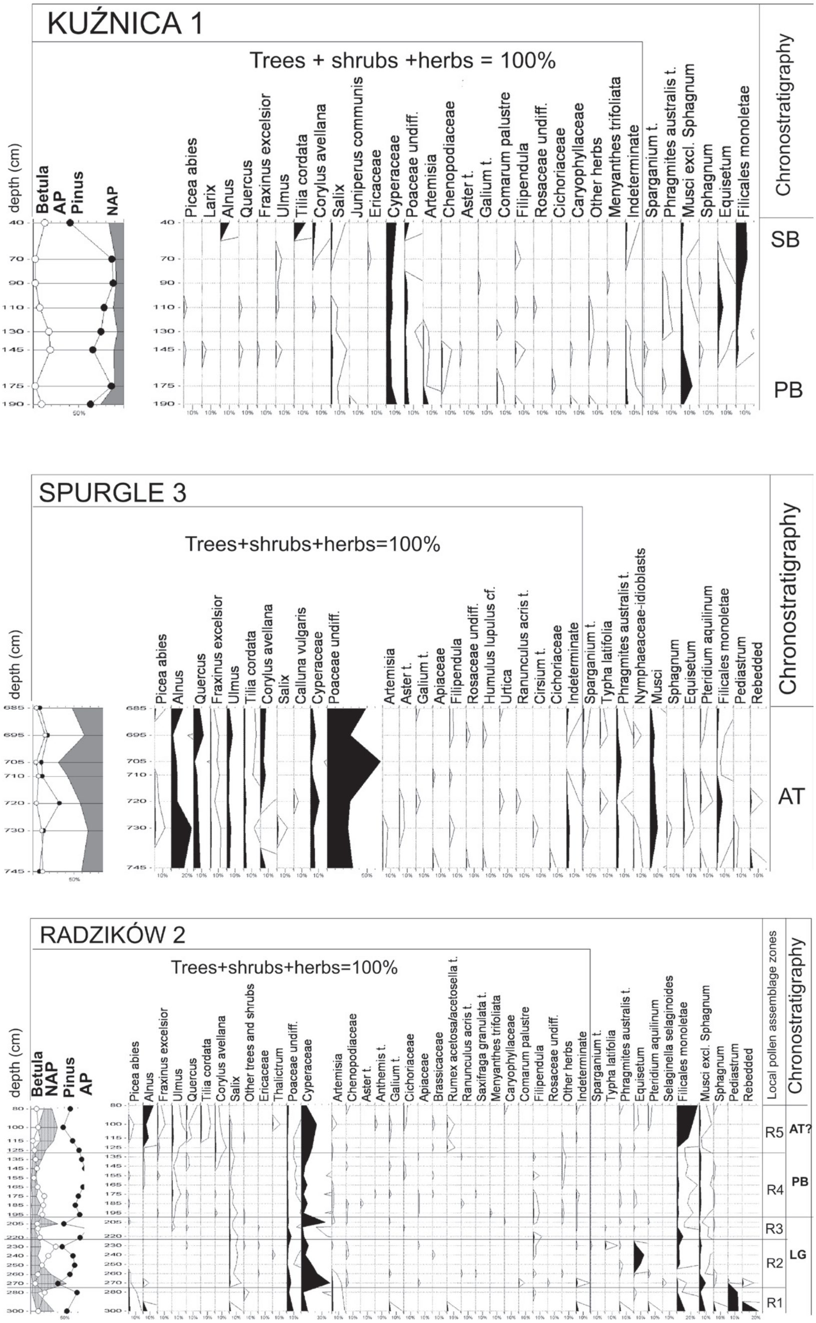

Fig. 5. Percentage pollen diagrams of Spurgle 3, Kuźnica 1 and Radzików 2 profiles.

Alnus; (2) *Pinus*, *Betula* and *Picea* pollen occurs in different frequencies; (3) the Poaceae pollen is rather abundant, with its maximum in samples from 705–710 cm; (4) Cyperaceae pollen is also abundant, with its maximum in a sample at 720 cm; (5) the pollen of rush vegetation *Phragmites australis* t., *Typha latifolia*, *Sparganium* t. is present with taxa of riverine and wet meadow habitats, *Humulus*, *Filipendula*, *Urtica*, *Cirsium*, *Ranunculus acris* t. and *Galium* t; (6) spores of *Musci*, Filicales monolete and also *Pteridium aquilinum* are quite frequent, and (7) Neogene re-bedded sporomorphs are apparent in samples at 745 and 720 cm. As also evident in other samples, these are Dinoflagellata cysts which indicate washing of Tertiary marine deposits.

Based on the composition of pollen spectra, in which the values of pine and birch are not high, and both Late Glacial elements and anthropogenic indicators are absent, we can relate the examined deposit to the middle Mesoholocene. High pollen frequencies of *Ulmus*, *Tilia*, *Quercus* and complete absence of *Carpinus* and *Fagus* indicate that the deposit was formed in the Atlantic period. This conclusion is confirmed by radiocarbon dating (7205 ± 85 yr. BP). We consider that different riverine communities with elm, ash and alder occurred in the landscape surrounding this spring-fed fen, and this was confirmed by agglutinated pollen grains of *Fraxinus* and *Ulmus*. These communities were a likely source of *Humulus*, *Filipendula* and *Urtica* pollen, and also the majority of Filicales spores. Wet meadows and mires also occurred in the site environs, and these provided pollen from grasses, sedges and other species.

The subject of this research almost certainly began as a small lake, and this supposition is supported by the occurrence of *Pediastrum genus* algae. Some Quarternary material was washed from the substratum into the lake, which then became overgrown and a fen developed.

Podlasie-Belarus plateaux

Kuźnica 1 profile

The Kuźnica site is in the Sokółka hills mesoregion. With respect of geo-morphology, it is situated in a vast melt-out depression formed in the younger part of the Saalian. This depression is drained by an unnamed stream into the Łosośna river (Szwarczewski et al., 2008).

The profile for detailed palaeo-ecological analysis came from the cupola culmination of a spring-fed fen. Lithologic description of the core is presented in Table 10 and samples for pollen analysis were taken from the following depths: 40, 70, 90,110, 130, 145, 175 and 190 cm.

The initial stage of fen development is represented by the sample from a depth of 175 cm, in which pine pollen predominates, birch pollen values are low and pollen of other trees is absent. Pollen of Cyperaceae and Poaceae reaches relatively high frequencies, and that of *Artemisia*, Chenopodiaceae and *Comarum* t. is also present. Based on pollen spectra, we can conclude that the deposits were most likely formed at the beginning of the Preboreal period

T a b l e 10. Lithologic description of deposits in the Kuźnica profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	Lithology	T-S system
0–10	herb peat, well decomposed, weakly mineralized	$Th^3$3, Dh1, Ag+, nig.4, strf.0, elas.1, sicc.1
10–44	herb peat, well decomposed, dark-brown to black, carbonate in the bottom, with single shells of molluscs	$Th^4$4, Dh++, nig. 4, strf 0, elas.2, sicc.2, part. test.moll, lim. sup.0
44–65	calcareous tufa, fine-grained, silty in places, light-grey to white	Cp(maj.)3, Cp(min.)1, Sh+, part.test.moll., nig.0, strf.1, elas.0, sicc.2, lim. sup.2
65–70	sedge peat, well decomposed, interbedded with fine- and medium-grained calcareous tufa (peat-tufa rhythmite)	$Th^3$2, Cp(maj.)1, Cm(min.)1, nig. 1-4, strf.3, elas.2, sicc.2, lim. sup.1
90–100	calcareous tufa, medium-grained, light-grey to white	Cm(min.)4, Sh+, nig.0-1,strf.1,elas.0, sicc. 2, lim. sup.2
100–118	sedge peat, interbedded with fine- and medium-grained calcareous tufa (peat-tufa rhythmite with a single rhythm from 1 to 10 mm thick)	$Th^3$2, Cp(maj.)1, Cm(min.)1, nig.0-3, strf.4, elas.1, sicc.2, lim. sup.1
118–160	calcareous tufa, medium- and coarse-grained, interbedded with herb peat (tufa-peat rhythmite)	Cm(min.)2, Cm(maj.)1, $Th^4$1, nig. 0-2, strf.4, elas.0, sicc.2, lim. sup.2
160–167	sedge peat, well decomposed, interbedded with fine-grained calcareous tufa	$Th^3$3, Cp(min.)1, nig.2-3, strf.2, elas.0, sicc.2, lim. sup.1
167–179	calcareous tufa, fine- and medium-grained, with traces of organic matter streaks	Cp(maj.)2, Cm(min.)2, Sh+, nig.0-1, strf.2, elas.0, sicc.2, lim. sup.1
179–191	sedge peat, well decomposed, dark-brown, with gyttja	$Th^4$3, Ld1, nig.4, strf.1, elas.2, sicc.2, lim. sup.1

when pine-birch forests spread and open communities of *Artemisia* and Chenopodiaceae thrived in this landscape. The obtained results correspond to the radiocarbon date, 9890 ± 160 years BP of the bottom peat deposits (Urban et al., 2011).

The frequency of sporomorphs and the number of taxa are higher in the sample from 145 cm depth. *Pinus* and *Betula* pollen still predominate, but *Ulmus, Quercus, Picea, Larix* and *Fraxinus* pollen appears among AP. The presence of elm and ash indicates the formation of riverine communities near the site. Increased frequency of *Salix* pollen most likely indicates the occurrence of willow shrubs. *Quercus* and *Picea* could have been components of both riverine communities and pine forests. Riverine communities were most likely a source of *Humulus* pollen. In addition to the NAP taxa recorded in the previous zone, these are also noteworthy; (1) the presence of *Aster* t., *Dianthus* and *Menuanthes trifoliata* pollen; (2) the pollen values of *Filipendula* and Chenopodiaceae are higher, and (3) Filicales monolete and *Equisetum* appear among spores. Non-pollen microfossils were also recorded, especially hyphopodia of *Gaeumannomyces* cf. *caricis*. Their presence indicates development of sedge communities (van Geel, 1986; Tobolski, 2000), while the spores of *Equisetum* most likely also originated in the mires.

A further lower frequency of sporomorphs in the sample from 130 cm depth, a higher degree of their destruction and the disappearance of tree pollen in the pollen spectrum (except for *Pinus* and *Betula*) suggest a change in the water supply. This comprised the activation of the ascending spring in the cupola culmination and the resulting change in redox conditions from a reducing to an oxidizing environment. This is manifested in the lithologic profile by the occurrence of calcareous tufa between peat layers (= peat-tufa rhythmite). The frequency of sporomorphs is higher in the sample from a depth of 110 cm., with higher values of Filicales monolete and *Equisetum* spores. The latter species is most likely *Equisetum fluviatile*, since their macro-remnants had previously been found in the examined site (Urban et al., 2011). Pollen spectra of the samples from depths of 145 and 130 cm also most likely represent the Preboreal period.

The first pollen grain of *Corylus* appeared in the sample from a depth of 70 cm and the values of fern spores increased. However, the pollen spectrum for the sample at a depth of 40 cm is different, and the high pollen values noted for *Tilia* and *Alnus* indicate its considerably younger age, which is estimated as Atlantic or younger. This conclusion corresponds with the radiocarbon dating results revealing the Subboreal age of deposits collected from the bottom herb peat at 3105 ± 45 years BP (Urban et al., 2011).

Middle Polish lowlands

Radzików 2 profile

The Radzików site is situated in a vast depression of glacial-melt out (Mojski, 1972) or of glacitectonic origin (Albrycht, 2004), and this is drained by the Liwiec river in its riverheads. The modern vegetation cover is of meadow communities of *Arrhenatherion* alliance. These are mostly species typical of the *Molinio-Arrhenatheretea* class, and the floral composition testifies to over-fertilization of this habitat. Species typical of cupola spring mires, such as the *Carex paniculata* and *Parnasia palustris* occur only on the summit of the cupola.

The profile Radzików 2 (RAD-2) for pollen analysis was from the cupola culmination of the spring-fed fen, and the lithologic description of the core is presented in Table 11. There were 21 samples taken from the bottom-most sandy layers and sedge peat as well as from the thickest sedge-moss inter-beddings in the tufa-peat rhytmite. Sample depths are listed in Table 12.

The frequency of sporomorphs and their state of preservation are very different, even in neighbouring samples, which indicates the high dynamics in these habitat conditions. The percentages of individual taxa in the pollen spectra are presented in Table 12.

Bottom samples from depths of 280–300 cm (R1 LPAZ-,-Fig. 5) most likely represent the Alleröd interstadial period within the Late Glacial when the lake was formed. Pinus dominates the pollen spectra, and *Betula* and *Salix* pollen is frequent, while Poaceae and Cyperaceae are common among the NAP. This age interpretation is confirmed by the occurrence of algae of the *Pediastrum* genus, which occupy stagnant, relatively shallow water

T a b l e 11. Lithologic description of deposits in the Radzików profile including the T-S system after Troels-Smith (1955), Tobolski (2000) and Dobrowolski (2011).

Depth (cm)	**Lithology**	**Troels-Smith system**
0–20	sedge peat, well decomposed, dark-brown	Th ^{4}4, Sh ++, sicc. 2, nig. 4, elas. 2, strf. 0
20–25	sedge peat, medium decomposed, dark-brown	Th ^{2}4, sicc. 2, nig. 3-4, elas. 2, strf. 0, lim. sup. 1
25–55	sedge peat, medium decomposed, dark-brown	Th ^{3}4, sicc. 2, nig. 3-4, elas. 2, strf. 0
55–80	sedge peat, medium decomposed, dark-brown, with a small admixture of gyttja	Th ^{3}3, Ld1, sicc. 2, nig. 3, elas. 2, strf. 0
80–115	sedge peat, medium decomposed, dark-brown to black	Th ^{4}4, sicc. 2, nig. 3-4, elas. 1, strf. 0, elas.1, lim. sup.0
115–124	sedge peat, medium decomposed, beige-brown, with gyttja	Th^{3}3, Ld1, Lc+, sicc. 2, strf. 0, lim. sup. 0
124–187	calcareous tufa, silty, light-grey to white, with interbedding of weakly decomposed sedge-moss peat, abundant malacofauna, streaking (tufa-peat rhythmite with a single rhythm from 1 to 2 mm)	Cp(maj.) 2, Th^{2}1, Ld +, sicc. 2, nig. 1, elas. 1, strf. 3, test moll., lim. sup. 0
187–195	sedge-moss peat, weakly decomposed, with interbeddings of amorphous calcium carbonate	Th^{1}2, Tb^{1}2, Cp(maj.)++, sicc. 2, nig. 3, elas. 3, strf. 1, lim. sup. 1
195–200	moss-sedge peat, weakly decomposed	Tb^{1}3, Th^{1}1, sicc. 2, nig. 3, elas. 4, strf. 1, lim. sup.1
200–223	sedge-moss peat, light-brown, with a large admixture of gyttja, streaked with amorphous calcium carbonate	Th^{2}2, Cp(maj.) 2, sicc. 2, nig. 2, elas. 1, strf. 4 (?), lim. sup. 1
223–226	wood – not decomposed fragment of branch (?)	*trunci et rami IV*
226–230	sedge peat, medium decomposed, with wood fragments	Th^{3}4, sicc. 2, nig. 4, elas. 2, strf. 0, lim. sup. 0, Dl-*detritus lignosus?*
230–236	wood – not decomposed fragment of branch (?)	*trunci et rami IV*
236–245	sedge peat, medium decomposed, dark-brown	Th^{3}4, sicc. 2, nig. 4, elas. 3, strf. 0, lim. sup. 0
245–268	sedge peat, well decomposed, with a small admixture of gyttja, in the bottom with a small admixture of sand	Th^{4}4, Ld+, G.min.+, sicc. 2, nig. 4, elas. 1, strf. 0, lim. sup. 0,
268–290	sand, varigrained, light-grey, with humus in the top, with single gravels of Scandinavian rocks	Gmin. 3, Gmaj. 1, Sh+, nig. 0, elas. 0, strf. 0, lim 4
290–300	sandy silt, light-grey	Ag3, Gmin. 1, nig. 0, elas. 0, strf. 0, lim. sup. 1

T a b l e 12. Description of pollen spectra in the Radzików profile.

Local pollen zone	Depth (cm)	Description of pollen spectrum
R 1 – LPAZ 300–280 cm	300 280	very low frequency of sporomorphs, rebedded pre-Quaternary sporomorphs at a depth of 300 cm (20%), *Pinus* dominant (54–69%), quite numerous pollen grains of *Betula* (up to 20%), in it *B. nana* type, sporadic pollen grains of *Alnus* (in it 4-pored forms), *Picea* about 1–2%, single grains of *Larix*, Poaceae and Cyperaceae several % each, frequent *Artemisia*, numerous colonies of *Pediastrum*
R2 LPAZ 270–220 cm	270 260 250 240 230 220	high frequency (except the sample from a depth of 220 cm), *Pinus* definitely dominant (up to 73%), numerous pollen grains of *Betula* and *Salix*, high percentage of NAP, in it high values of Cyperaceae (in the sample from a depth of 260 cm – up to 24%) and *Filipendula* pollen as well as *Equisetum* (in the sample from a depth of 240 cm) and Filicales monolete spores (up to 10% in the sample from a depth of 220 cm), notable occurrence of *P. cembra*, *B. nana* and *Saxifraga granulata* t.
R3 LPAZ 205 cm	205	Cyperaceae dominant (up to 34.5%), *Pinus* – 50%, *Betula* – 10%, quite frequent pollen of *Artemisia*, Chenopodiaceae, *Filipendula*, lower values of Filicales monolete and *Equisetum* spores
R4 LPAZ 195–145 cm	195 185 175 165 155 145	*Pinus* dominant again (up to 83%), high value of *Betula* (up to 19%), continuous curve of *Ulmus*, sporadic pollen grains of *Quercus*, and in the uppermost sample of the zone also *Corylus* and *Alnus*; Cyperaceae (up to 8.5%) dominates among NAP, rather frequent Poaceae, hyphopodia of *Gaeumannomyces* cf. *caricis* are present
R5 LPAZ 135–80 cm	135 125 115 100 80	frequency, high in the lower samples, decreases upwards, *Pinus* dominant, lower values of *Betula*, increase of *Ulmus*, *Corylus*, *Alnus* and *Quercus* frequencies, *Tilia* and *Fraxinus* appear, numerous pollen grains of Cyperaceae and taxa of wet meadows, and very numerous spores of Filicales monolete

bodies. Sporomorphs of pre-Quaternary taxa attained high values in the sample from 300 cm depth. These taxa included older Coniferales, Gleicheniaceae and cysts of Dinoflagellata originating from the washed and re-bedded Tertiary marine deposits. A few pollen grains from thermophilous trees, including *Tilia*, also most likely originated from older deposits. The lake was surrounded by pine forests with an admixture of birch and spruce, and possibly larch. Forest communities were relatively open as indicated by high percentages of Poaceae and *Artemisia*, while the sedge-moss communities with *Equisetum* and *Sphagnum* dominated wet habitats.

We can presume that the R2 pollen zone, with rising values of, among others, *Pinus*, *Salix* and *Filipendula*, and higher frequency of sporomorphs, represents the pine phase of Alleröd. Among other taxa, Cyperaceae was initially dominant, and then successively – *Equisetum* and Filicales monolete. This succession most likely indicates development of fen with abundant *Equisetum*, *Filipendula*, *Thalictrum* and species of the Rubiaceae family, followed by subsequent encroachment of ferns and the development of willow shrubs in the fen's surrounds. At that time, the regional vegetation was represented by widespread pine and pine-birch communities. The pathogenic fungi *Gaeumannomyces* cf. *caricis* (*vide*

Tobolski, 2000) in this portion of the profile enable the identification of sedge peat based on results of mycological research.

The R3 pollen zone with predominant Cyperaceae most likely represents the Younger Dryas. It is possible that the sample from 220 cm is also of the Younger Dryas age but the very low frequency of sporomorphs in this sample makes it impossible to define the boundary between Alleröd and Younger Dryas based on pollen analysis. In the sample from 205 cm, the actual percentages of *Artemisia* and Chenopodiaceae are likely higher than the results obtained from our calculations due to error resulting from the over-representation of Cyperaceae in the pollen spectrum. In such an interpretation, the Younger Dryas period in the examined site would be characterized by spread of sedge fens and additional types of heliophilous herb communities with high proportions of *Artemisia* and Chenopodiaceae. At that time, the area occupied by the communities of boreal forests decreased.

Very high frequency of sporomorphs, again high values of *Pinus*, permanent occurrence of *Ulmus*, sporadic pollen grains of *Quercus*, a decrease in the values of *Artemisia* and increase in *Filipendula* in the R4 LPAZ unambiguously indicate the examined deposit formed in the Preboreal period. Communities of boreal pine forests were widespread at that time, and elm riverine forests started to develop on wet and fertile habitats. The occurrence of the fen in the examined area is highlighted not only by the presence of abundant Cyperaceae, *Filipendula*, and several other taxa of wet habitats, including the *Menyanthes*, *Ranunculus*, Apiaceae, *Galium* t., *and Sonchus* t., but also of hyphopodia of fungi *Gaeumannomyces* cf. *caricis*.

In the R5 LPAZ higher pollen percentages of thermophilous trees (*Ulmus* and *Quercus*) and *Corylus*, increasing values of *Alnus* and the occurrence of sporadic pollen grains of *Tilia* and *Fraxinus* in the upper samples indicate that the examined deposit was formed after the Preboreal period and is of Boreal age or even younger. At that time, the pine forests were replaced by rich and multi-component communities of deciduous forests. The initially abundant sedges were replaced by ferns, and together with the decreased frequency of sporomorphs and the signs of their destruction, this indicates that the sedge fens were likely overgrown.

Discussion

Lithologic analyses of spring-fed fen deposits are very difficult due to the occurrence of gyttja-like deposits suggesting their lacustrine origin. Pollen analysis is also difficult (Tobolski, 2000; Pidek et al., 2010; Dobrowolski, 2011). In contrast to the lacustrine deposits and peat which contain numerous sporomorphs, deposits of spring-fed fens are characterized by their low frequency or even absence. Therefore, the samples from these deposits require time-consuming maceration and the results are not always satisfying. Statistically correct results of palynological analyses are usually obtained only for the bottom portions of profiles, which *de facto* represent biogenic deposition before the activation of ascending groundwater supply. These are usually Late Vistulian lacustrine deposits (Dobrowolski et al., 1999; Dobrowolski, 2006) or strongly decomposed peats (humopeats) from the Preboreal era (Wołejko, 2001; Osadowski, 2000, 2010). In many cases pollen analysis of these biogenic deposits can shed light on the changes in plant communities before activation of aggressive, strongly oxygenated spring waters. The age of the examined forms is usually confirmed by radiocarbon dating (Dobrowolski et al., 1996, 1999; Pazdur et al., 2002). Only basic palynological analysis was possible because of the low frequency and badly preserved state of the sporomorphs, so here, the results do not permit us to reconstruct plant succession in the whole profile. It was also impossible to calculate the thickness of layers representing the individual periods of the Holocene. However, as proven by the results obtained for the Polish profiles of spring-fed fens described herein, pollen analysis contributes considerably to determination of the age of these forms and/or confirms results of radiocarbon dating of these profiles. It also enables reconstruction of climate-habitat changes, and thus provides several new facts for palaeo-environmental interpretation. These changes are recorded both in the deposit sequence and in the succession of plant communities. Interdisciplinary research in spring-fed fens concentrating especially on pollen analysis of the bottom portions of examined profiles, permits us to determine the initiation of development of these forms and to draw climatic-stratigraphic and palaeo-environmental conclusions on a regional scale.

Conclusion

1. Spring-fed fens are unique, not only in their special method of water supply and diversity of modern vegetation cover, but also in the bio-lithofacial record (peat-tufa rhythmite) of cyclic changes in environmental conditions, especially temperature and moisture.
2. Pollen analysis of these deposits is an extremely valuable proxy for reconstruction of climate-habitat changes, and provides several new facts for palaeo-environmental interpretations. However, the main methodological problem with using this proxy is the low frequency of sporomorphs and time-consuming maceration.
3. Different frequency and states of preservation of sporomorphs are a result of the change in redox conditions during the fen's functioning. However, reconstruction of plant succession is not possible in every case, and therefore a multi-proxy approach in palaeo-ecological studies of these objects is required.
4. Valuable results of palynological analyses are usually obtained for the bottom parts of profiles representing biogenic accumulation before activation of the ascending groundwater supply. These are usually Late Vistulian lacustrine deposits or strongly decomposed peats from the Preboreal period. Palynological results are usually confirmed by radiocarbon dating. In such cases, pollen analysis of these biogenic deposits indicates the starting point of ascending supply and activation of aggressive, strongly oxygenated spring waters.

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