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INTERDISCIPLINARY STUDIES OF SPRING MIRE DEPOSITS FROM RADZIKÓW (SOUTH PODLASIE LOWLAND, EAST POLAND) AND THEIR SIGNIFICANCE FOR PALAEOENVIRONMENTAL RECONSTRUCTIONS

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Abstract: The paper presents the results of interdisciplinary (multi-proxy) palaeoenvironmental studies of peat – calcareous tufa depositional sequences of spring mire from Radzików site (east Poland). Analyses of three biotic proxies (plant macrofossils, pollen, molluscs) were supplemented with sedimentological, geochemical, oxygen and carbon stable isotopes analyses and radiocarbon dating and used for reconstruction of environmental changes in Late Glacial and Holocene. The obtained results enable us to (1) reconstruct main phases of mire development and (2) determine environmental factors influencing changes of water supply.

The object started to develop in Allerød. The Late Glacial and Early Holocene deposit sequence is relatively thick (about 1.0 m), with good palaeoecological record. The boundary between Younger Dryas and Preboreal is especially well confirmed by palynological and malacological analyses as well as radiocarbon dating. The Mesoholocene deposits are considerably worse preserved. Mire development was evaluated in terms of general mire ecology.

Keywords: spring mire, peat, calcareous tufa, palaeoenvironmental reconstructions, Holocene, South Podlasie Lowland.

1. INTRODUCTION

Spring mires belong to the rare group of alkaline fens supplied by groundwater of concentrated flow. Their biogenic-carbonate sequences are excellent analytical material for the Late Glacial-Holocene palaeoenvironmental reconstructions (Dobrowolski *et al.*, 1999, 2005; Pazdur *et al.*, 2002). Despite their morphological similarity and small size (usually < 1 ha), spring mires are found in very different conditions. In Central Europe they occur in different landscape types, geological-morphological and climate conditions. They are known from mountains (Hajek *et al.*, 2002, 2006; Hajkova and Hajek, 2003), carbonate karst uplands (Kovanda, 1971; Dobrowolski,

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1998, 2000, Dobrowolski *et al*., 2005), and young glacial moraine plateaux (Wołłejko *et al*., 1994; Grootjans *et al*., 2006; Osadowski *et al*., 2009). Alkaline spring mires are much rarer in old glacial landscapes. Interdisciplinary investigations of such objects, which occur in old glacial landscapes predominating in Central Europe, seem to be especially important.

The Radzików site, representing cupola spring mire type (*sensu* Dobrowolski 1994 and Dobrowolski *et al.*, 1996, 2005), is situated in the eastern part of the Central Polish Lowlands. The site was described earlier, mostly as a peat bed, by Żurek (1990). In this paper we present the results of palaeoenvironmental studies of the Radzików site sedimentary sequence. The investigations undertaken in the Radzików site included: (1) land survey with the use of GPS (*Global Positioning System*) receivers, (2) detailed geological-sedimentological investigations of the bed, and specialist analyses, i.e. (3) geochemical, (4) palynological, (5) malacological, (6) of plant macrofossil remains, (7) of carbon and oxygen stable isotopes, (8) radiocarbon dating.

2. INVESTIGATED SITE

The object under study is cupola spring mire (γ52°09’50”N - 52°09’56”N; λ22°30’06”E - 22°30’20”E; area *ca.* 2 ha), which forms distinct, 300 m long and maximum 100 m wide, peat-tufa ridge rising 2.5-3 m over a peat plain (151-156 m a.s.l.). This plain fills a vast depression of glacial-melt out (Mojski, 1972) or glacitectonic origin (Albrycht, 2004), which is drained by the Liwiec River in its riverheads (**Fig. 1**). In physico-geographical respect the object is situated in the central part of the South Podlasie Lowland macroregion, in the inner zone of end moraine hills from the post-maximum phase of the Warta glaciation (Brzezina, 2000). In the immediate vicinity of the studied site there are exposed Vistulian fluvial deposits (sands and silts of the higher

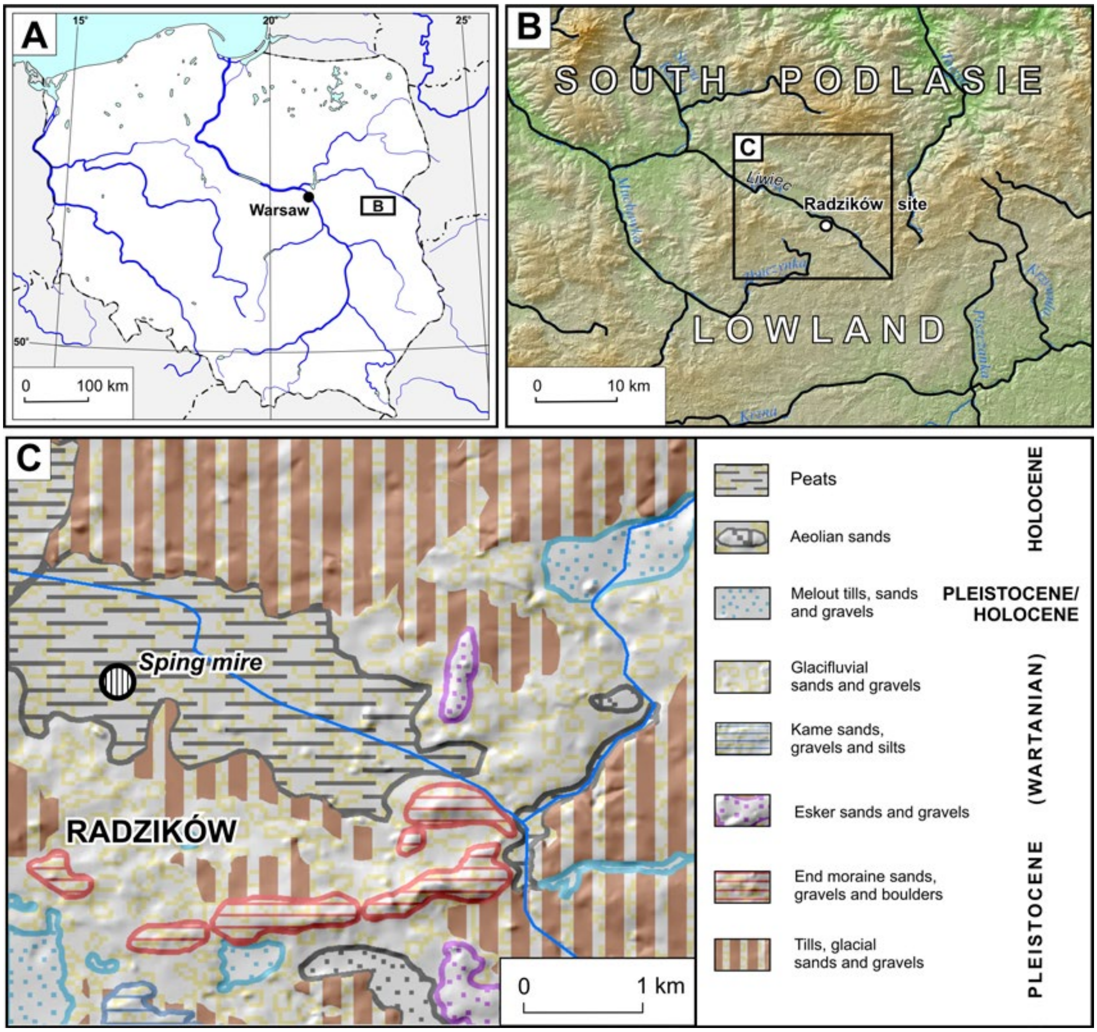

Fig. 1. *Location of Radzików site in relation to: A – Poland, B – South Podlasie Lowland, C – geological situation in the surroundings of the upper Liwiec River valley (after Brzezina, 2000).*

river terrace) and Holocene alluvial soils, organic-mineral alluvia and peats (filling the bottom of the Liwiec River valley) (**Fig. 1**). Deposits occurring in higher hypsometric positions – in the vicinity of the river valley – are mostly the Wartanian glacial and fluvioglacial sands with gravels and tills as well as the Late Vistulian dune sands (Albrycht and Pruś 1998; Albrycht, 2000; Brzezina, 2000; Małek, 2002).

The modern vegetation cover of the examined cupola spring mire is composed of meadow communities of *Arrhenatherion* alliance. These are fresh meadows with predominant grasses and a small proportion of dicotyledonous perennial plants typical of the *Molinio-Arrhenatheretea* class. Floral composition of patches is evidence of strong overfertilization of the habitat. Mire species, such as *Carex paniculata* and *Parnasia palustris* – typical of cupola spring mires – occur in a small proportion only on the summit of the cupola.

3. MATERIAL AND METHODS

Sedimentological analysis

Lithology of the deposits occurring in the cupola spring mire and its immediate vicinity was examined in detail. Cores of undisturbed structure were taken from drillings made every 10-25 m along the geodetically outlined profiles perpendicular to the cupola axis (**Fig. 2A**). Core drillings were made, using Eijkelkamp percussion drilling set 04.19.SC with two types of peat samplers: (1) open sampler 1 m long with 10 cm in diameter (only for top parts of deposits), and (2) closed sampler with transparent liner (1 m long with 5 cm in diameter). In total, 22 drillings were made. Macroscopic lithofacial analysis of biogenic and mineral-biogenic sediments was made, using the non-genetic Troels-Smith method for the description of deposits (Troels-Smith, 1955; Tobolski,

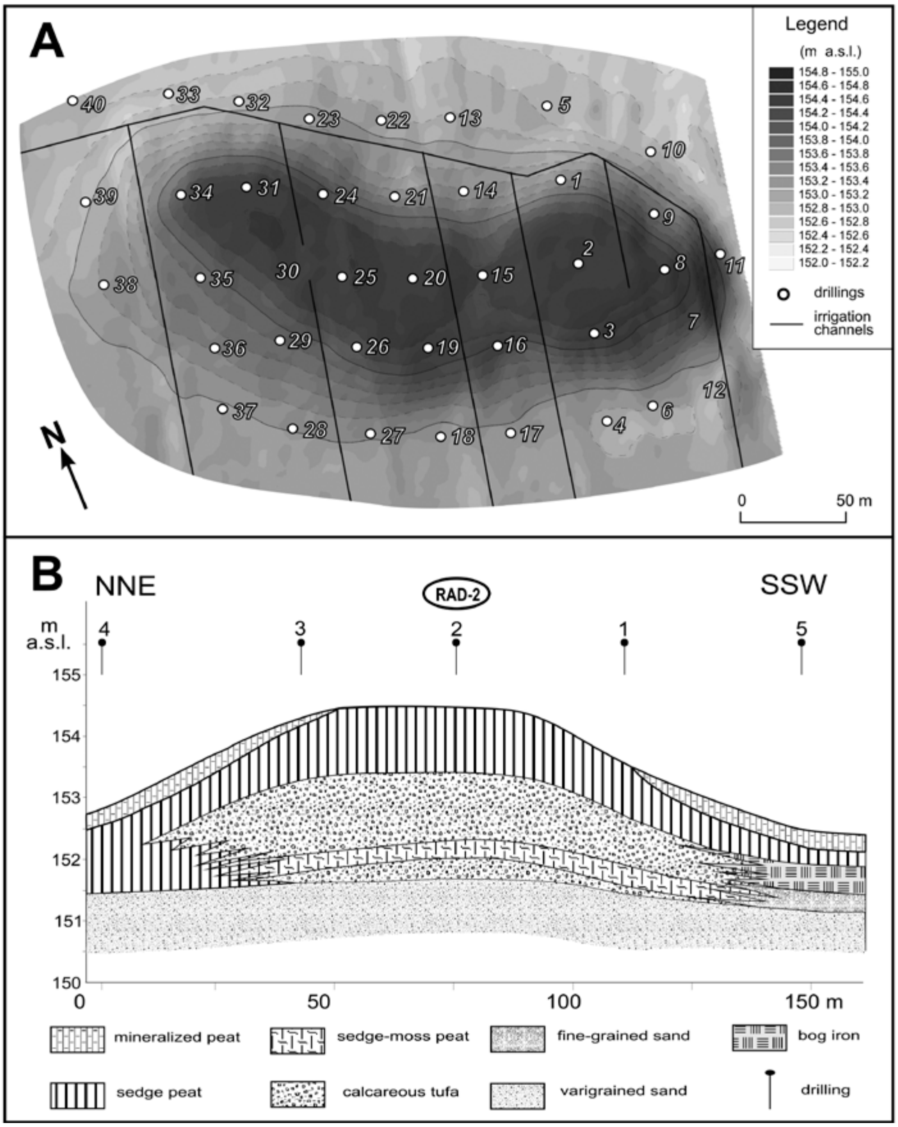

Fig. 2. *A – Digital model of cupola spring mire relief (based on GPS survey) together with location of geological drillings; B – geological section through spring mire cupola, RAD-2 – place from which core was taken for multi-proxy studies.*

2000). One core (RAD-2), 10 cm in diameter and 3 m long, was taken from the south-eastern part of the cupola (γ52°09'52"N; λ22°30'17"E) for detailed laboratory analyses of the deposits.

Pollen analysis

Samples for pollen analysis were taken from the deposits (RAD-2 core) representing all lithologic units of the profile. Samples (2 cm^3 in volume) were taken from these layers which were macroscopically promising as for the possibility of obtaining well preserved sporomorphs. In total, 21 samples were palynologically analysed. They were prepared according to standard Erdtman's acetolysis after removing of carbonates in HCl and boiling in 10% KOH (Berglund and Ralska-Jasiewiczowa, 1986). All samples needed the additional treatment with cold HF for 24 hours.

Malacological analysis

Detailed malacological analysis was carried out for 19 samples. The samples, representing the 5 cm thick sections of the profile, were subjected to standard laboratory treatment (washing, drying and picking shell material out). All undamaged specimens were analyzed, as well as young forms and shell fragments possible to identification. Shell material was examined according to standard malacological analysis (Ložek, 1964; Alexandrowicz, 1987) using determination keys and standard comparative collections. Individual taxa were classified into the following ecological groups: 5 – open-country species, 7 and 8 – species of wide ecological tolerance (mesophilous), 9 – hygrophilous species, 10 – water species, which occupy periodically disappearing water bodies and also periodically flooded land environments, 11– water species typical of perennial water bodies.

Plant macrofossil analysis

Material for plant macrofossil analysis (samples 30-50 cm^3 in volume) was taken from the RAD-2 core every 5 cm (altogether 51 samples). Separation of plant macrofossils was carried out according to the method developed by Tobolski (2000). Available keys and atlases (Dombrovskaya *et al*., 1959; Grosse-Brauckmann, 1972, 1974; Grosse-Brauckmann and Streitz, 1992; Tobolski, 2000) were used to identify plant marocfossils. Names of vascular plants were given after Mirek *et al*. (2002) and names of Bryophyta after Ochyra *et al*. (2003). As far as possible, plant macrofossils were identified to species, and their percentage contents in a sample were calculated.

Geochemical analysis

Geochemical analysis was carried out for 51 samples taken from the RAD-2 core every 5 cm. Dry mass, ash content, organic matter (OM), pH_{H_2O} and $pH_{1M\ KCl}$ were determined by standard methods used in chemical analysis of organogenic deposits (Sapek and Sapek, 1997). The amount of carbonates reacting with HCl, expressed in $CaCO_3$, was determined by volumetric method modified by Lityński *et al*. (1976), using Scheibler apparatus. Total contents of macroelements (Na, K, Ca, Mg, Fe) and microelements (Mn, Sr, Cu, Zn, Pb, Ni, Co) were determined. Samples of constant weight (about 1 g) were digested in concentrated acids (hydrofluoric and perchloric). Residue was dissolved in hot 6M HCl. Acid solutions were analyzed by the AAS (*Atomic Absorption Spectrophotometry*) method using the Perkin-Elmer 3300 apparatus. The obtained results were calculated as the percentages of dry mass. Precision of geochemical analyses did not exceed 10% in all cases.

Stable isotopes ^{18}O and ^{13}C

Isotopic analysis was carried out using a dual inlet and triple collector mass spectrometer (modified and modernized MI1305 model). Carbonate samples were analyzed for CO_2 produced by reaction with 100% H_3PO_4 in a glass vacuum line connected to the inlet system of the mass spectrometer. The reaction proceeded at electronically controlled temperature of 25°C ±0.2°C to achieve $\delta^{18}O$ in the PDB scale. For normalization of both $\delta^{13}C$ and $\delta^{18}O$ values the international standard NBS-19 was analyzed in each series of samples. The analytical uncertainty of both delta values in terms of standard deviation was better than 0.06‰. There were analysed 35 samples of carbonates from the RAD-2 core.

Radiocarbon dating

Radiocarbon dating was performed for bulk samples of organic matter or peat layers from the RAD-2 core. The samples were treated with 2% HCl to remove carbonates and transferred to benzene for Liquid Scintillation Counting or combusted to CO_2 for Gas Proportional Counting. The measurement results are expressed as radiocarbon ages BP with associated uncertainty.

TL dating

Thermoluminescence method was applied to determine the age of 4 samples of fluvial sands underlying the series of biogenic-carbonate deposits of the cupola spring mire in the Liwiec River valley.[1]

4. RESULTS

Sedimentological analysis

Biogenic-carbonate deposits composing the spring mire bed are 2.5-2.7 m thick. They are genetically much differentiated in vertical profile, and their lateral diversity is little (**Fig. 2B**). The deposit sequence includes 4 main

[1] TL dating was carried out by Dr Jarosław Kusiak in the Department of Physical Geography and Palaeogeography, Institute of Earth Sciences, Maria Curie-Skłodowska University, Lublin.

lithostratigraphic units labelled chronologically from 1 to 4. The bottom unit 1 consists of massive sedge peats, strongly and medium-decomposed, with gyttja traces (45-50 cm). Upwards they are progressively replaced by slightly decomposed moss-sedge peats (35-40 cm) with traces of horizontal streaks of amorphous calcium carbonate (unit 2). Peats are overlain by 60-65 cm thick series of fine-grained calcareous tufa (unit 3), in places with the inserts of slightly decomposed sedge-moss peat. The unit 4 is composed of massive, strongly decomposed sedge peats with the thickness reaching 125 cm (**Table 1**).

Pollen analysis

The frequency and preservation of sporomorphs were various, often much different in adjoining samples. This is evidence of great dynamics of habitat conditions. The analysis results are illustrated with pollen diagram (**Fig. 3**) drawn up basing on the POLPAL software (Walanus and Nalepka, 1999; Nalepka and Walanus, 2003). The diagram was divided into five local pollen assemblage zones (LPAZ), numbered from bottom to top of the profile. The percentages of individual taxa were calculated on the basis of the sum of AP +NAP = 100%, excluding pollen of aquatic plants and spores. The percentages of individual taxa in pollen spectra are presented in **Table 2**.

Malacological analysis

Molluscan assemblages occurred only in two parts of the RAD-2 core: at a depth of 0.00-0.05 m and 1.20-2.10 m. The whole analyzed material comprises 1274 specimens belonging to 20 species (13 taxa of land snails, 4 species of waters snails, and 3 species of bivalves) (**Table 3**). The number of species varies from 4 to 13 per sample, while the number of specimens from 27 to 127, respectively (**Fig. 4N**).

The total molluscan assemblage examined in the Radzików site is quite poor. Open country molluscs (ecological group O) are represented by 3 taxa (*Vertigo pygmaea* (Drap.), *Pupilla muscorum* (L.) and *Vallonia pulchella* (Müll.)). They occur mostly in the top part of the profile where they predominate in the assemblage (**Figs. 4Mf, 5MSI, Table 3**). In the lower section they are rarer and represented mostly by *Vallonia pulchella* (Müll.) (**Fig. 4Mf**). Five taxa belong to mesophilous molluscs (ecological group M). They occur in almost all samples but only *Euconulus fulvus* (Müll.) is of greater

Table 1. *Description of the deposits from the RAD-2 core according to Troels-Smith (1955) and Tobolski (2000).*

Depth (m)	Lithological description	Units	Troels-Smiths Formula	Remarks
0.00-0.20	Sedge peat, medium-decomposed, dark brown		Th^{4}4, Sh ++, sicc. 2, nig. 4, elas. 2, strf. 0	
0.20-0.25	Sedge peat, medium-decomposed, dark brown		Th^{2}4, sicc. 2, nig. 3-4, elas. 2, strf. 0, lim. 1	
0.25-0.55	Sedge peat, medium-decomposed, dark brown		Th^{3}4, sicc. 2, nig. 3-4, elas. 2, strf. 0	**C14 (RAD-2/28)**
0.55-0.80	Sedge peat, medium-decomposed, dark brown, with gyttja admixture	4	Th^{3}3, Ld1, sicc. 2, nig. 3, elas. 2, strf. 0	**C14 (RAD-2/73)**
0.80-1.15	Sedge peat, medium-decomposed, dark brown		Th^{4}4, sicc. 2, nig. 3-4, elas. 1, strf. 0, elas.1, lim.0	
1.15-1.24	Sedge peat, medium-decomposed, brown, with gyttja admixture		Th^{3}3, Ld1, Lc +, sicc. 2, strf. 0, lim. 0	**C14 (RAD-2/123)**
1.24-1.87	Fine-grained tufa, light-grey to white, with insert of slightly decomposed sedge-moss peat	3	Lc3, Th^{2}1, Ld +, sicc. 2, nig. 1, elas. 1, str. 3, test moll., lim. 0	**C14 (RAD-2/133)** – peat insert **C14 (RAD-2/153)** abundant malacofauna, traces of streaking (1-2 mm rhythms)
1.87-1.95	Sedge-moss peat, slightly decomposed, light-brown, with insert of amorphous calcium carbonate		Th^{1}2, Tb^{1}2, Lc ++, sicc. 2, nig. 3, elas. 3, strf. 1, lim. 1	
1.95-2.00	Moss-sedge peat, slightly decomposed, light-brown	2	Tb^{1}3, Th^{1}1, sicc. 2, nig. 3, elas. 4, strf. 1, lim. 1	**C14 (RAD-2/198)**
2.00-2.23	Sedge-moss peat, with abundant gyttja, light-brown, with streaks of amorphous calcium carbonate		Th^{2}2, Lc2, sicc. 2, nig. 2, elas.1, strf. 4 (?), lim. 1	**C14 (RAD-2/222)**
2.23-2.36	Sedge peat, medium-decomposed, with pieces of wood		Th^{3}4, sicc.2, nig.4, elas.2, strf. 0, lim.0, *trunci et rami IV*	**C14 (RAD-2/236)**
2.36-2.45	Sedge peat, medium-decomposed, dark brown	1	Th^{3}4, sicc. 2, nig. 4, elas. 3, strf. 0, lim. 0	
2.45-2.68	Sedge peat, strongly decomposed, with gyttja admixture, slightly sandy		Th^{4}4, Ld+, Gmin. +, sicc. 2, nig. 4, elas. 1, strf. 0, lim. 0	**C14 (RAD-2/268)**
2.68-2.90	Varigrained sand, with humus in the top part, light-grey, with single Scandinavian gravels	Bedrock	Gmin. 3, Gmaj. 1, Sh +, nig. 0, elas. 0, strf. 0, lim. 4	
2.90-3.00	Sandy silt, light-grey		Ag3, Gmin. 1, nig. 0, elas. 0, strf. 0, lim. 1	

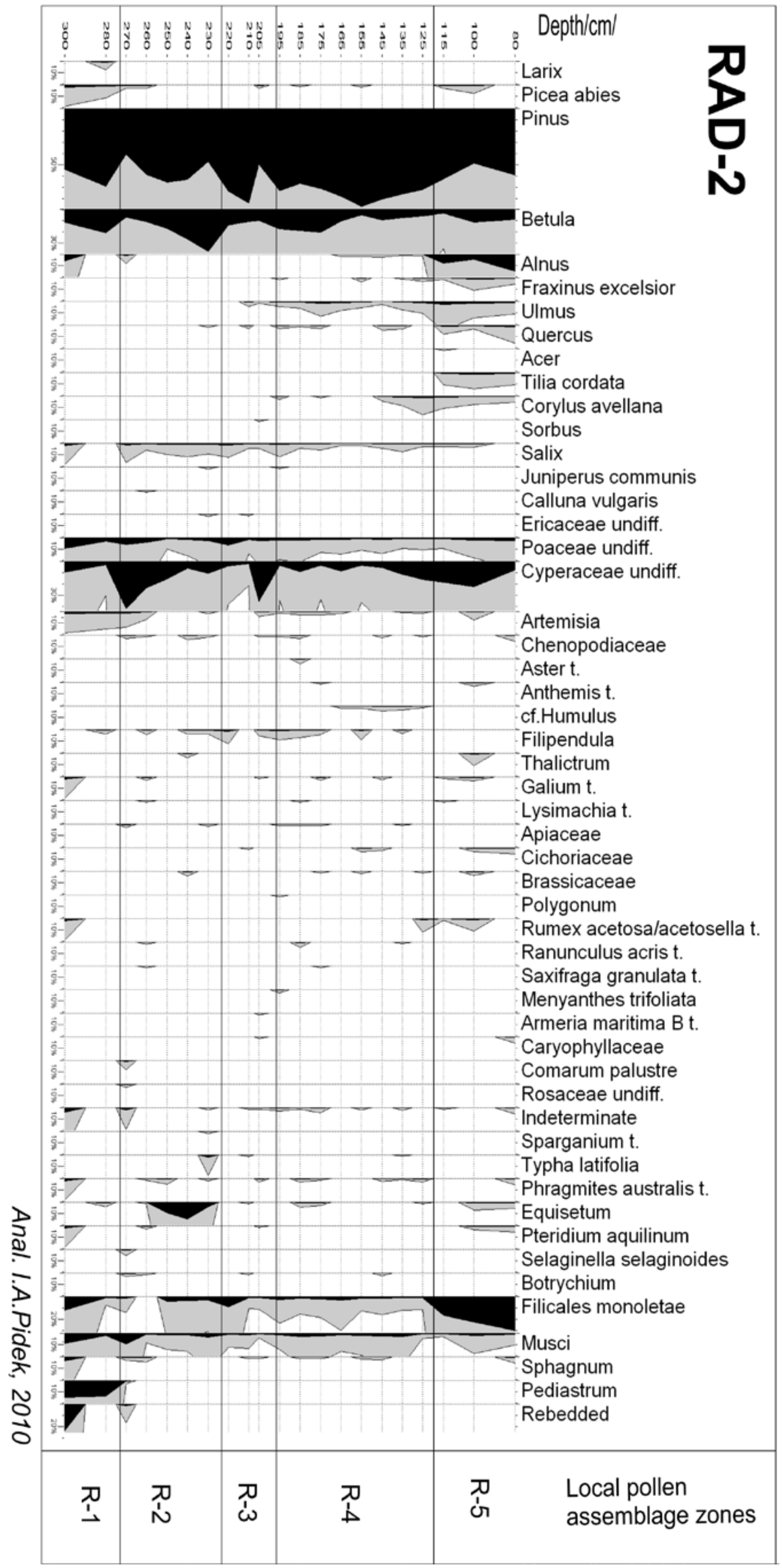

Fig. 3. *Pollen diagram from the Radzików spring mire (RAD-2 core).*

importance. It constitutes even up to 20% of the assemblage (depth 1.35-1.40 m) (**Figs. 4Mf**, **5MSI**, **Table 3**). Hygrophilous molluscs (ecological group H) are very important. They are represented by 5 species. *Carychium minimum* (Müll.) and *Succinea putris* (L.) appear almost in the whole profile (except the top part) and their proportion in the assemblage often exceeds 10% (**Fig. 4Mf**, **Table 3**). The most important hygrophilous taxon is *Vertigo genesii* (Gredl.). It is typical of very wet habitats of tundra type, which prefers cold, polar climate (Pokrysz-

Table 2. *Description of the pollen assemblage zones of the RAD-2 core.*

Local Pollen Assemblage Zone (LPAZ)	Features of pollen spectra
R1 – LPAZ 3.00-2.80 m	Frequency of sporomorphs very low, redeposited pre-Quaternary sporomorphs (20%) at a depth of 3.00 m; *Pinus* dominates (54-69%), quite numerous pollen grains of *Betula* (up to 20%), in it of *B. nana* type, sporadic *Alnus* (in it 4-porous pollen grains), *Picea* about 1-2%, *Larix* as single grains, Poaceae and Cyperaceae – each several per cent, frequent *Artemisia*, numerous colonies of *Pediastrum*
R2 – LPAZ 2.70-2.30 m	High frequency of sporomorphs; pine definitely dominates (up to 73%), numerous pollen grains of birch and willow, high percentage of NAP, in it high values of Cyperaceae (in sample 2.60 m – up to 24%), *Filipendula*, as well as spores of *Equisetum* (in sample 2.40 m) and Filicales monolete, notable presence of *Pinus cembra, Betula nana, Saxifraga granulata* t.
R3 –LPAZ 2.20-2.05 m	Samples of a very low frequency of sporomorphs, the lowest at a depth of 2.20-2.10m where *Pinus* dominates and *Quercus*, *Ulmus*, cf. *Sorbus*, *Salix* appear as single pollen grains together with some herbaceous taxa; numerous sporomorphs show increased degree of sculpture damage; Cyperaceae dominate in pollen spectrum (up to 34.5%), *Pinus* – 50%, *Betula* – 10%; pollen grains of *Artemisia*, Chenopodiaceae, *Filipendula* are quite numerous, spores of Filicales monolete and *Equisetum* are less frequent
R4 – LPAZ 1.95-1.35 m	Frequency of sporomorphs is the highest in the whole profile, *Pinus* dominates again (up to 83%), high values of *Betula* (up to 19%), continuous curve of *Ulmus*, sporadic pollen grains of *Quercus* and in the top part of the zone also of *Corylus* and *Alnus*; Cyperaceae predominate among NAP (up to 8.5%), Poaceae are quite numerous
R5 – LPAZ 1.25-0.8 m	Frequency of sporomorphs is high in the lower part of the zone and decreases upwards; *Pinus* dominates, lower percentage of *Betula*, rising values of *Ulmus*, *Corylus*, *Alnus* and *Quercus*, appearance of *Tilia* and *Fraxinus*; high pollen values of Cyperaceae and taxa of wet meadows, and very numerous spores of Filicales monolete

Table 3. *Snails and bivalves from the Radzików site.*

E	TAXON	0-5	120-125	125-130	130-135	135-140	140-145	145-150	150-155	155-160	160-165	165-170	170-175	175-180	180-185	185-190	190-195	195-200	200-205	205-210
O	Vertigo pygmaea	2																		
O	Pupilla muscorum	10		1				1	3	3	1	1	3							1
O	Vallonia pulchella	18	1		8	4	3	3	13	4		4	5		3	4	2	4	1	
M	Cochlicopa lubrica		2																	
M	Vertigo angustior	4																		
M	Nesovitrea hammonis		1																	4
M	Limacidae		1	1	1										1	1				
M	Euconulus fulvus		7	7	8	12	3	6	4		1	1	6			4		4	1	1
H	Carychium minimum		5	14	10	3	1	2	10	2	1	1	3				1	6	1	
H	Succinea putris			7	9	6	1	11	13	8	14	7	6	2	7	7	3	3	4	
H	Vertigo genesii		14	16	22	15	17	14	11	7	1		4	2	9	12	6	9	5	4
H	Vertigo geyeri								2										1	
H	Zonitioides nitidus		1															1		
T	Valvata cristata		1					1												8
T	Galba truncatula		1	3	3	7	14	10	26	97	86	101	34	87	43	25	17	13	14	
T	Pisidium obtusale		8	16																
T	Pisidium obtusale lap.		15	27	4	4	14	6		1	3		1	9			2	2		9
W	Stagnicola palustris								8				3							
W	Anisus contortus				1		4			5										
W	Pisidium casertanum		1	7	1	4		1				2								
	SPECIES	**4**	**13**	**10**	**10**	**8**	**8**	**10**	**9**	**8**	**7**	**7**	**9**	**4**	**5**	**6**	**6**	**8**	**7**	**6**
	SPECIMENS	**34**	**58**	**99**	**67**	**55**	**57**	**55**	**90**	**127**	**107**	**117**	**65**	**100**	**63**	**53**	**31**	**42**	**27**	**27**

E *– ecological groups of molluscs:* ***O*** *– open-country species,* ***M*** *– mesophilous species,* ***H*** *– hygrophilous species,* ***T*** *– water species of intermittent water bodies,* ***W*** *– water species of perennial water bodies.*

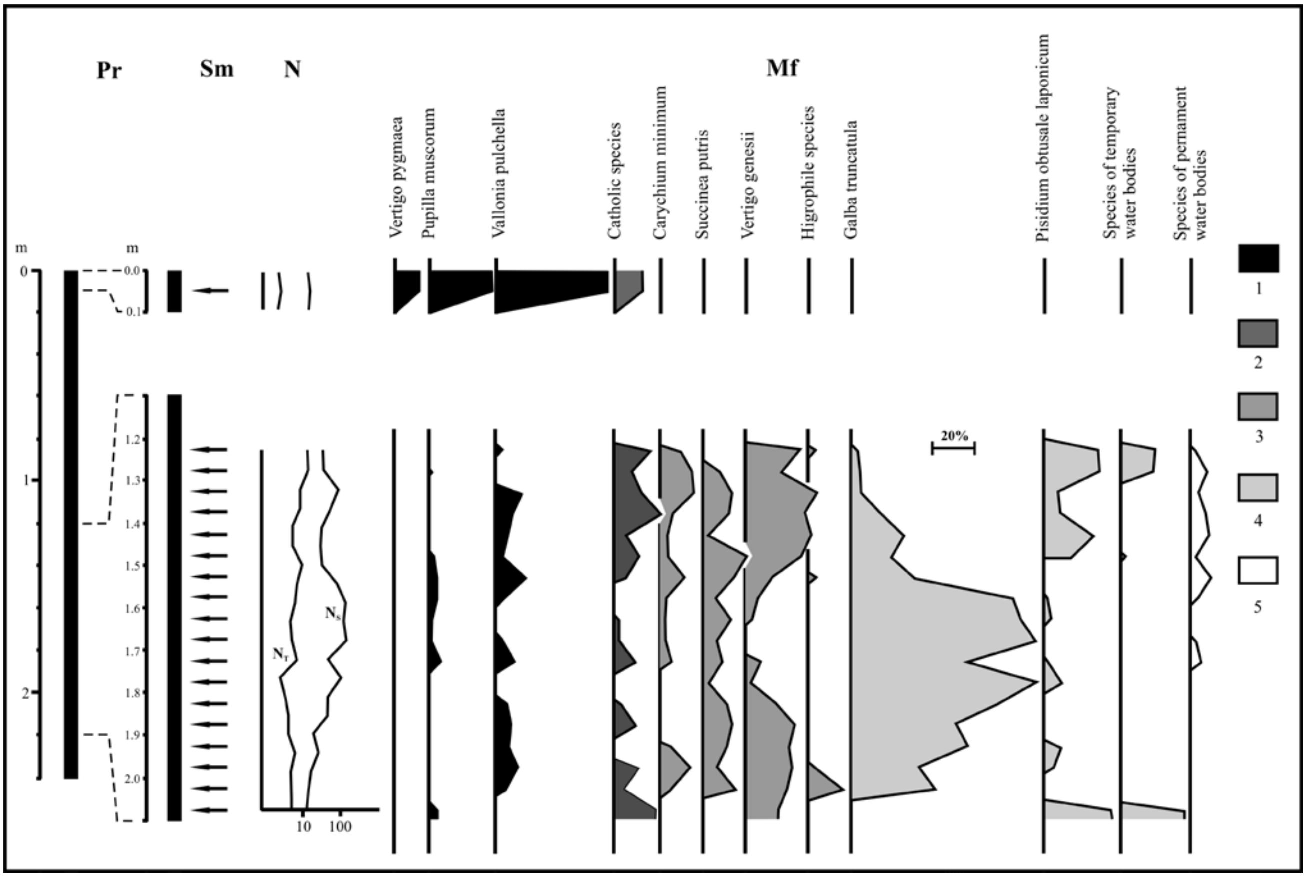

Fig. 4. *Molluscan fauna of the Radzików site; Pr – profile, Sm – samples, N – number of taxa (N_T) and specimens (N_S), Mf – molluscan fauna: 1 – open-country species, 2 – mesophilous species, 3 – hygrophilous species, 4 - water species of intermittent water bodies, 5 – water species of perennial water bodies.*

ko, 1990). It is numerous almost in the whole lower part of the profile, and its proportion in the assemblage can exceed 30%. Two other hygrophilous taxa, i.e. *Zonitioides nitidus* (Müll.) and *Vertigo geyeri* Lind., occur rarely. The latter one is more numerous in the lower part of the profile constituting 15% of the assemblage (**Fig. 4Mf**, **Table 3**). The total percentage of hygrophilous taxa varies from several to even 60% of the assemblage (**Figs. 4Mf**, **5MSI**, **Table 3**). Molluscs occupying intermittent water bodies (ecological group T) are the second (besides hygrophilous forms) predominant component of the described fauna. Two from among four taxa belonging to this group are important. The first one is *Galba truncatula* (Müll.) – water species of very wide ecological and climatic tolerance. It can occupy different types of water bodies, and is also frequently found in very wet meadow habitats (e.g. periodically flooded meadows) (Piechocki, 1979). This form is very numerous, especially at a depth of 1.55-1.95 m where it is definitely predominant constituting even up to 90% of the assemblage (**Fig. 4Mf**, **Table 3**). The second important species belonging to the discussed ecological group is bivalve *Pisidium obtusale laponicum* Cless. This form is typical of small, drying lakes and cold, polar climate (Piechocki and Dyduch-Falniowska, 1993). This species is numerous at a depth of 1.20-1.60 m and 2.05-2.10 m (**Fig. 4Mf**, **Table 3**). It is accompanied by two taxa, which appear more rarely: *Valvata cristata* (Müll.) and *Pisidium obtusale* (Lam.). Total percentage of forms occupying intermittent water bodies can constitute over 90% of the assemblage (**Figs. 4Mf**, **5MSI**, **Table 3**). Water taxa typical of perennial water bodies, i.e. *Stagnicola palustris* (Müll.), *Anisus contortus* (L.) and *Pisidium casertanum* (Poli) are rare and their proportion in the assemblage never exceeds 10% (**Figs. 4Mf**, **5MSI**, **Table 3**). Two former are typical of small and strongly overgrown water bodies, while *Pisidium casertanum* (Poli) is characterized by very wide ecological tolerance (Piechocki, 1979; Piechocki and Dyduch-Falniowska, 1993).

Plant macrofossil analysis

The obtained results of plant palaeoremains analysis permit us to distinguish four distinct macrofossil assemblage zones, which represent the successive phases of spring mire development (**Fig. 6**).

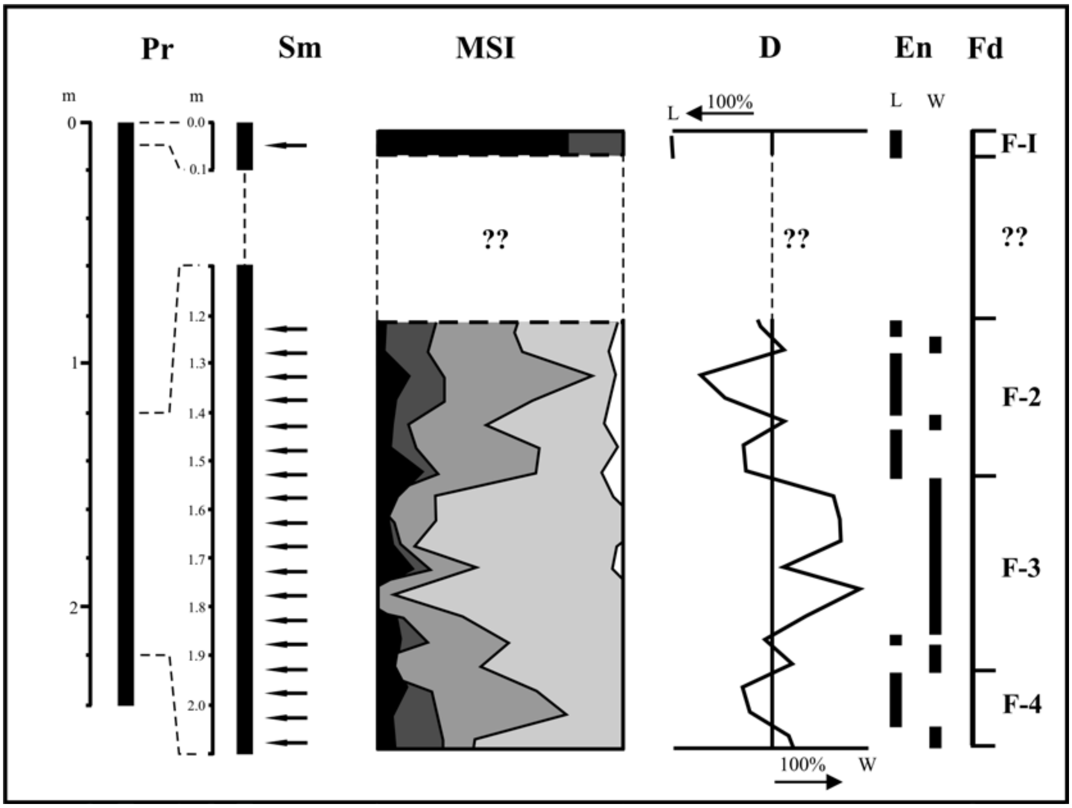

Fig. 5. *Changes of molluscan assemblage in Radzików site; Pr – profile, Sm – samples, MSI – molluscan spectrum, D – two-component diagram, En – environmental changes, L – land species, W - water species, Fd – phases of mire development – F-1 – F-4 – detailed description in the text.*

Zone I (2.75-2.30 m) is characterized by medium frequency of *Carex* sp. (up to 25%), with the admixture of *Phragmites australis* (up to 15%), *Equisetum fluviatile* (up to 5%), and a low percentage of mosses. A considerable proportion of *Betula pubescens* bark (up to 25%) occurs at a depth of 2.40-2.45 m.

Zone II (2.30-1.30 m) is dominated by Bryophyta, and peat-forming phytocenoses from this period are determined as *Drepanocladus* communities. The species prevailing among Bryophyta belong to three genera: *Drepanocladus, Warnstorfia,* and *Limprichtia*. Cryptogams (*Magnoliophyta = Angiospermae*) constitute a small admixture. The percentages of *Drepanocladus sendtneri* and *Warnstorfia fluitans* are almost stable. *Warnstorfia exannulata, Limprichtia cossoni, Hamatocaulis vernicosus*, *Tomentypnum nitens* and *Calliergon* sp. (in it *Calliergon giganteum*) occur in slightly less stable proportions. Other moss species, i.e. *Calliergonella cuspidata*, *Meesia triquetra*, *Helodium blandowii* and *Thuidium* sp., occur sporadically in single samples. High frequency of the mentioned species indicates that communities from this zone belong to the *Caricetalia davallianae* order from the *Scheuchzerio-Caricetea nigrae* class.

Three subzones can be distinguished in this zone. The subzone 1 (2.30-2.05 m) and 3 (1.70-1.35 m) are characterized by high content of *Menyanthes trifoliata*. In the subzone 1 it constitutes up to 15% of macrofossils, and in the subzone 3 – up to 5%. In the subzone 2 (2.05-1.70 m) *Limprichtia cossoni* occurs and *Menyanthes trifoliate* is absent.

Zone III (1.30-0.80 m) is characterized by a considerable proportion of species from the *Carex* genus, and low content of mosses with the sporadically occurring species of the zone II. In the samples from this phase of mire development there is found the occurrence of *Typha* sp., *Thelypteris palustris, Equisetum fluviatile*, and constant though low content (up to 5%) of *Phragmites australis*.

Zone IV (0.80-0.05 cm). Macrofossil analysis of the upper part of the profile indicates a stable predominance of sedge communities from the *Magnocaricion* alliance. In eight samples they are determined to species (*Carex rostrata*). Single individuals *Carex acutiformis* and *Carex lasiocarpa* occur.

Sedges are always accompanied by *Phragmites australis*, the content of which does not exceed 5% but in one sample it reaches 10%.

Based on macrofossil analysis and floral composition of modern plant cover, we can reconstruct the probable stages of plant succession of spring mire in the Radzików site. The succession of plant communities could have been as follows: rush phytocenoses from the *Magnocari-*

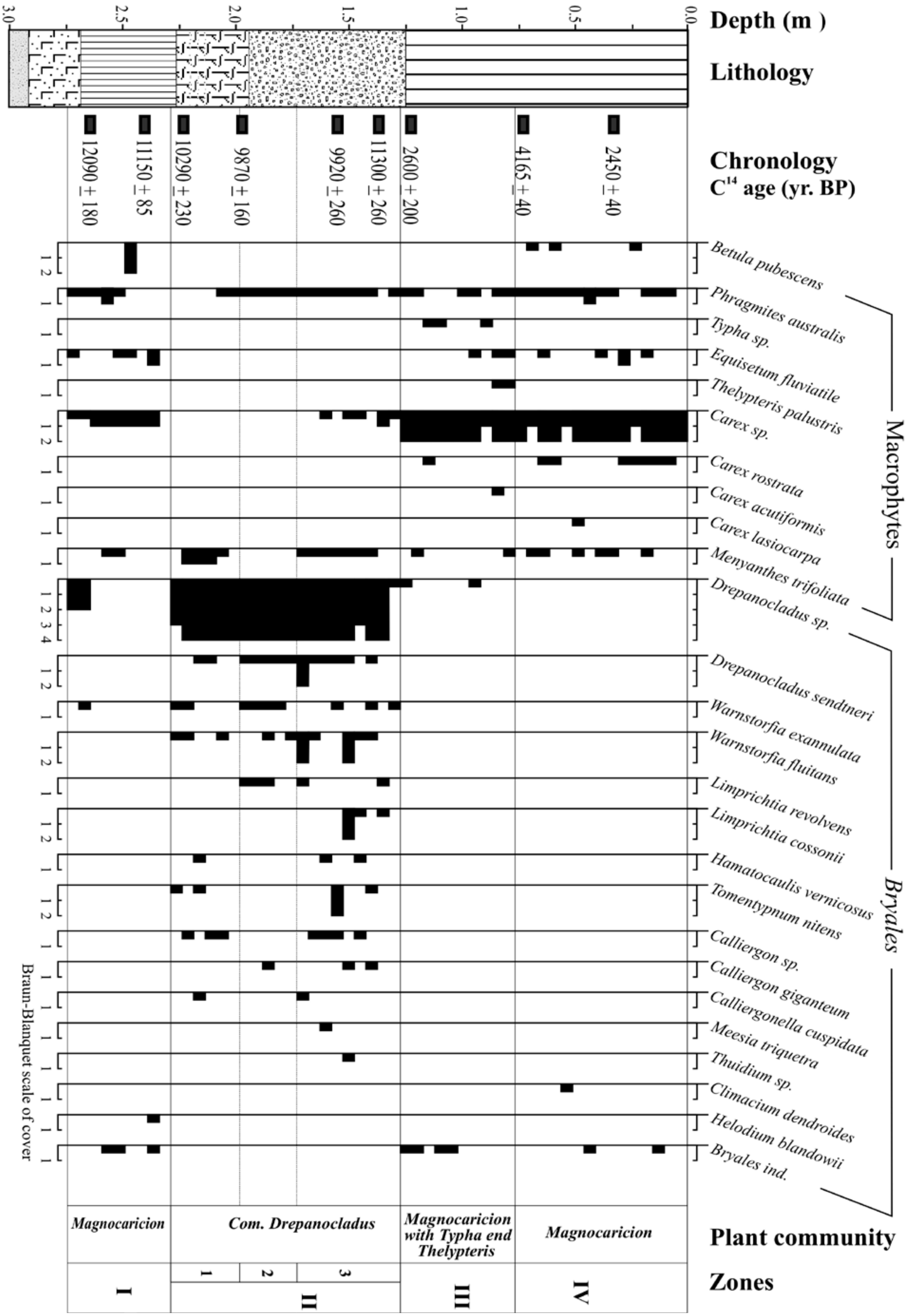

Fig. 6. *Plant macrofossil diagram from the Radzików spring mire (RAD-2 core); explanation of lithological units as in* Fig. 2B.

cion alliance → shrub phytocenosis with *Betula pubescens* → forest community with *Betula pubescens* → rush phytocenoses from the *Magnocaricion* alliance → phytocenoses from the *Caricetalia davallianae* order → sedge rushes from the *Magnocaricion* alliance (probably *Caricetum rostratae* or *Caricetum acutiformis*, *Caricetum lasiocarpe* and *Caricetum paniculatae*) → meadow phytocenosis (modern) with *Carex paniculata*.

Geochemical analysis

Distinct correlation between the concentrations of particular geochemical components (OM/ash, pH, micro- and macroelements) and lithological changes of deposits composing spring mire (core RAD-2) is clearly visible. We can distinguish four distinct geochemical zones in vertical deposit succession (except for bedrock), which represent different conditions of deposition environment.

Zone I – corresponds to the first stage of mire development (high content of OM, pH <6.5). In this zone two levels of increased concentrations of Mg (up to 5.33g/kg), Na (up to 3.08 g/kg), K (up to 4.45 g/kg) and Fe (up to 16.40 g/kg) are found. In the level 2.68-2.65 m it can be related with sorption of these elements (originating from silicate minerals of bedrock) by organic matter of developing mire. The maximum concentrations in the level 2.50-2.45 m, correlated with higher ash content, were probably the result of flood episode in the Liwiec River valley and silting-up of the bottom peat layers.

Zone II – represents the phase of tufa deposition ($CaCO_3$ – 45-85%) in spring mire, as is also indicated by abrupt increase of Ca and Sr concentrations. The increased concentrations of Co, Ni, Mn and Pb resulted from sorption of these metals from water by the surface of fresh deposit during $CaCO_3$ precipitation. It is accompanied by the decrease of Fe, Na and K concentrations. The Fe/Mn ratio indicates the change of reduced into oxidized conditions. This fact indirectly suggests the change of mire feeding associated with the supply of deeper confined water (probable development of paralimnic basin). At the same time, high $CaCO_3$/OM ratio indicates considerably higher temperature and humidity of environment.

Zone III – is the record of paralimnic basin paludization (higher content of OM) and associated change of redox conditions (increase of Fe/Mn ratio, decrease of pH). Relatively high concentrations of Fe (absorbed mostly by organic matter) and K are accompanied by the decrease of Ca, Sr, Mn, Co and Ni concentrations resulting from the increased solubility of these elements in water in reduced conditions.

Zone IV – represents the phase of anthropogenic transformation of spring mire. The abrupt increase of some macroelements (K and Fe) and microelements (Zn and Pb) concentrations, as well as Fe/Mn ratio are the evidence of higher rate of peat mineralization resulting from the modern, extensive agricultural drainage works.

Stable isotopes ^{18}O and ^{13}C

Results of $\delta^{18}O$ and $\delta^{13}C$ analysis are presented in **Fig. 8**. For carbonates from the bottom sediments consisting of sandy silt (depth 280-300 cm) the mean $\delta^{13}C$ and $\delta^{18}O$ values vary considerably from the rest of the record, what was expected given the lithological changes (see **Figs. 2B**, **7**). The values of $\delta^{13}C$ are close to the zero, observed for bedrock carbonates, which would suggest detrital provenience of the latter. However, $\delta^{18}O$ quite lower than zero (ca. -5‰) counteract this hypothesis. The $\delta^{13}C$ are likely to be modified by soil and vegetation cover development, which is doubtful for the considered period of time (ca. 15 000 cal BP), which would give explanation of these relatively high values.

The isotopic composition of carbon and oxygen for the Late Glacial and early Holocene indicates dramatic changes in the sedimentation environment. The beginning of Younger Dryas (12 500 cal BP) is marked by the decline of ca. 2.5‰ for $\delta^{13}C$ and ca. 1‰ for $\delta^{18}O$. These values are similar to that known for lake sediments (Piotrowska and Hałas, 2009).

Radiocarbon dating

The results of radiocarbon dating are presented in **Table 4**. They were subjected to calibration with the use of IntCal09 calibration curve and OxCal v.4 software. The probability distributions of calendar ages for all samples are presented in **Fig. 9A**, plotted on the depth scale. The results demonstrate that the recovered core reaches ca. 14500 years cal BP.

Two of the dates are probable outliers, and the possible reasons of that fact will be investigated and discussed in the separate publication. The remaining dates indicate almost constant accumulation rate. As almost surely a hiatus is present in the core around depth 120-125 cm, the dates are divided into the upper and lower part, and the relevant accumulation rates are *ca*. 0.2 mm/yr for the period 2000-5000 cal BP and 0.4 mm/yr for 11000-14500 cal BP.

For the five samples from the bottom part of the core (depth 130-300cm) an attempt to construct continuous calendar age-depth model was undertaken, similar to the previously reported by De Vleeschouwer *et al*. (2009) for peat deposit or Piotrowska *et al*. (2007) for lake sediments. For this purpose the calibration of radiocarbon dates was performed including information of stratigraphic position of samples with the use of *P_Sequence* function in OxCal programme (Bronk Ramsey, 2008). The results of these calculations are presented in **Figs. 9B**, **10**. For building depth-age model a non-linear approach called mixed-effect regression, realized with the use of generalized additive model (GAM) was used, as described by Heegaard *et al*. (2005). The calculations were performed within each period on the middle-point of the 68.2% range of calibrated age, while the uncertainty equal to half of this range was assumed. The resulting

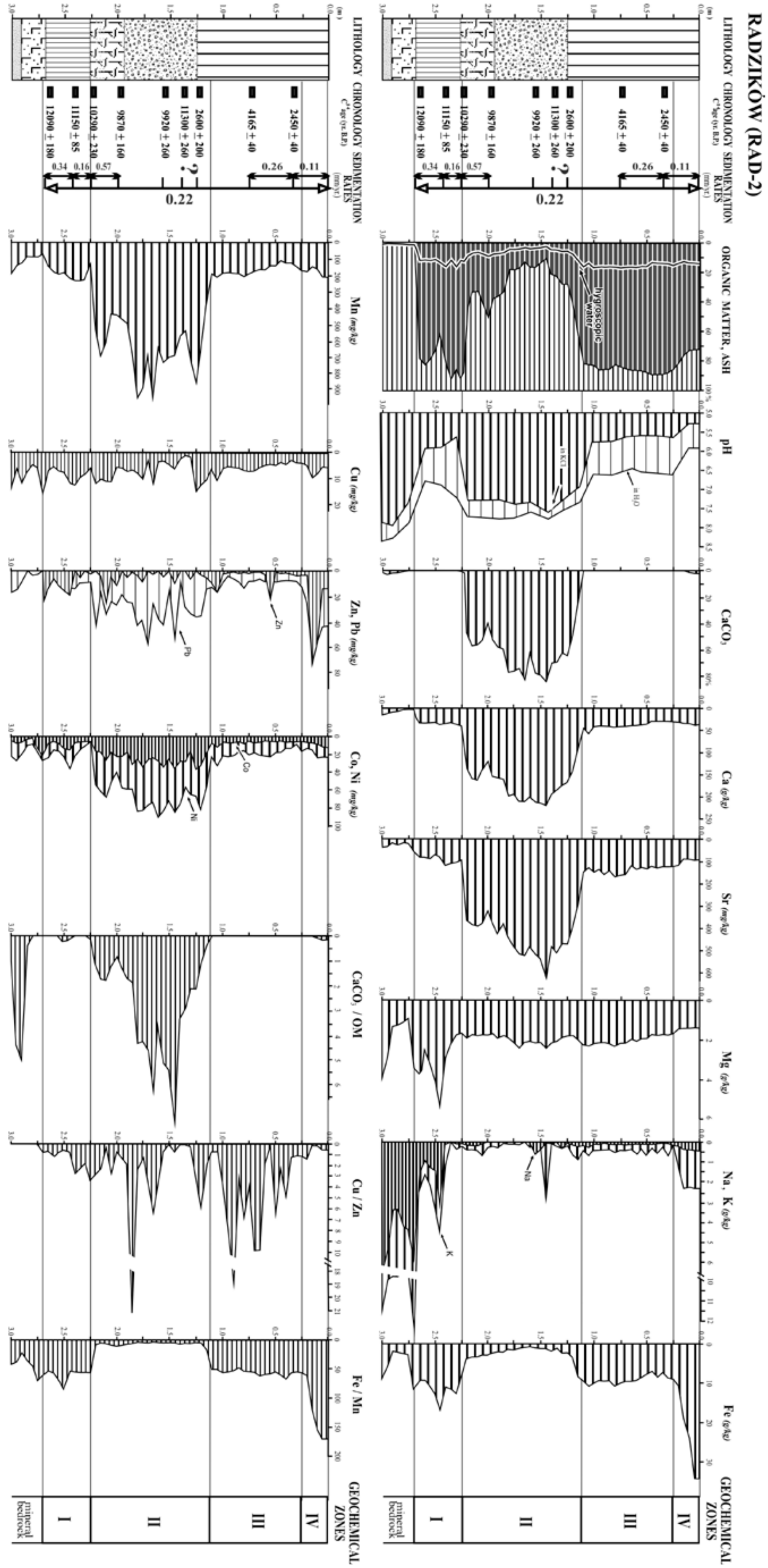

Fig. 7. *Lithology and geochemistry of the biogenic-tufa deposits of Radzików spring mire (RAD-2 core); explanation of lithological units as in* Fig. 2B.

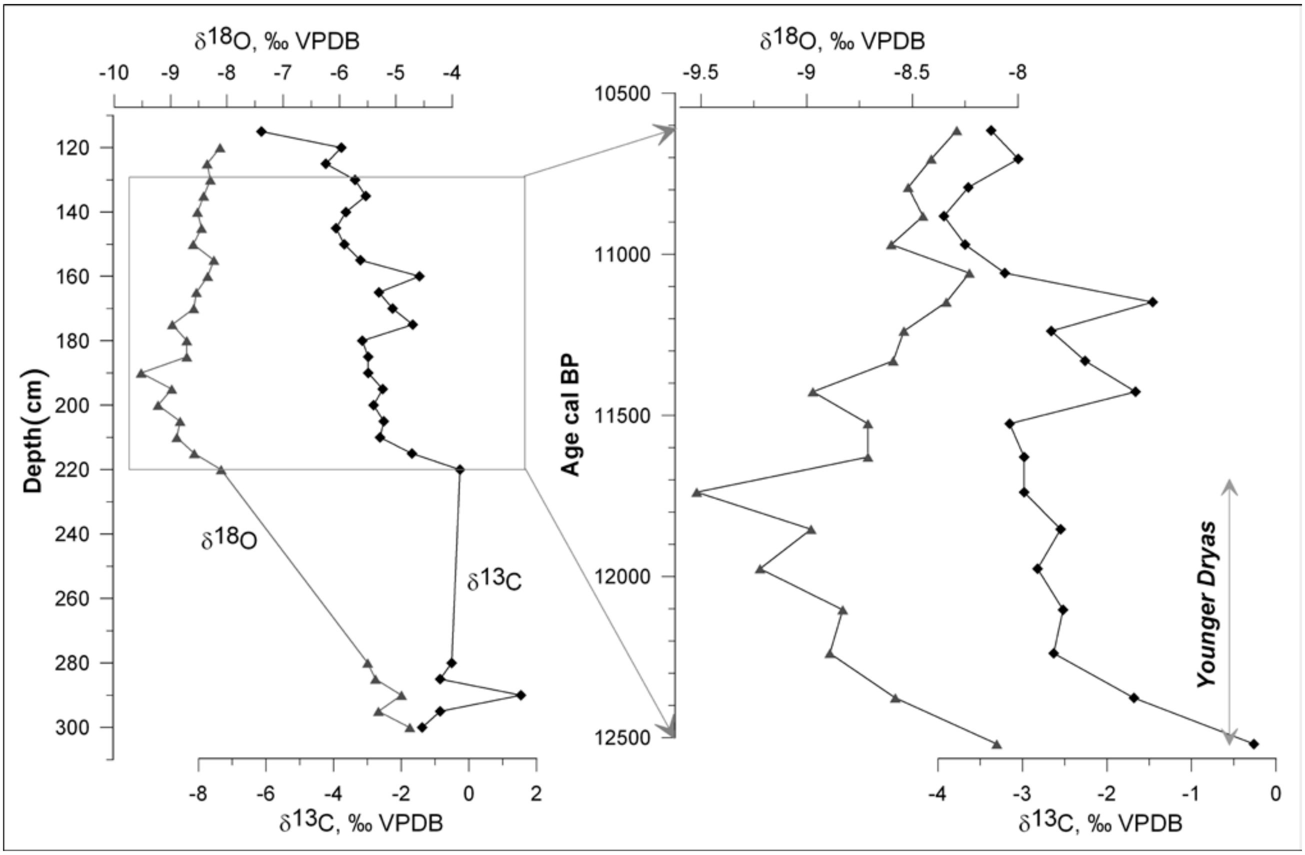

Fig. 8. *Stable isotope composition of carbonate from Radzików profile. Left: all results versus the depth, right: results plotted versus modeled age, for the interval covered by the age-model (see Fig. 10). The approximate position of Younger Dryas is marked, however, note the uncertainties of the age model are ca. 150-200 years.*

Table 4. *Results of radiocarbon dating of peat and tufa deposits from the RAD-2 core.*

No	Sample name	Lab. No	Age ^{14}C (BP)	Calibrated age (cal BC) range 68.2%	Calibrated age (cal BC) range 95.4%
1	RAD-2/28	GdS-916	2450±40	750 - 685 (20.6%) 665 - 645 (6.2%) 555 - 480 (24.3%) 470 - 410 (17.1%)	760 - 680 (23.1%) 670 - 405 (72.3%)
2	RAD-2/73	GdS-917	4165±40	2875 - 2840 (12.8%) 2815 - 2675 (55.5%)	2890 - 2620 (95.4%)
3	RAD-2/123	GdS-969	2600±200	930 - 410 (68.2%)	1290 - 1280 (0.2%) 1270 - 350 (92.8%) 310 - 200 (2.4%)
4	RAD-2/133	Gd-30250	11 300±260	11450 - 10990 (68.2%)	11770 - 10880 (95.4%)
5	RAD-2/153	Gd-248	9920±220	10010 - 9930 (4.2%) 9880 - 9210 (64.0%)	10400 - 10370 (0.3%) 10290 - 10250 (0.6%) 10240 - 8760 (94.5%)
6	RAD-2/198	GdS-976	9740±240	9650 - 9600 (2.8%) 9530 - 9480 (2.3%) 9460 - 8750 (63.1%)	10090 - 8540 (95.2%) 8510 - 8490 (0.2%)
7	RAD-2/222	GdS-975	10160±290	10400 - 10360 (1.8%) 10350 - 10330 (0.7%) 10290 - 9360 (65.6%)	10860 - 9140 (95.4%)
8	RAD-2/236	GdS-924	11150±120	11210 - 10990 (68.2%)	11300 - 10930 (95.4%)
9	RAD-2/268	GdS-974	11960±250	12170 - 11540 (68.2%)	12750 - 11340 (95.4%)

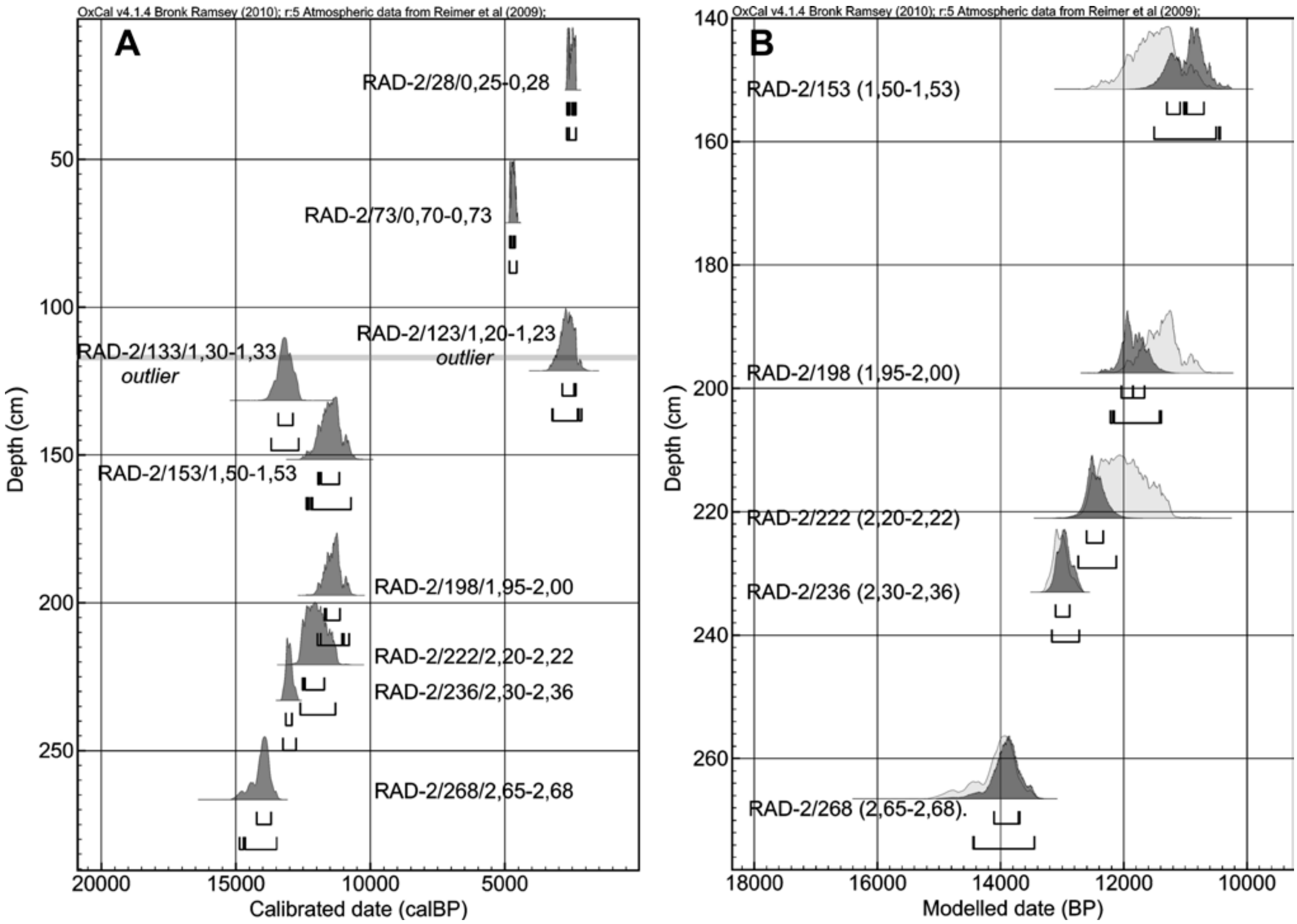

Fig. 9. *Probability distributions of calendar ages of dated samples vs. depth of the core. A – All samples presented, thick horizontal grey line shows possible position of a hiatus, note two outliers around this depth; B – Results of calibration with information about stratigraphical order for the samples below depth 150 cm. Light grey shades represent original probability distribution (the same as at "A" figure), while results of modeling are in dark grey.*

age-depth relationship provides a mean age and an age range for samples in 1-cm intervals (**Fig. 10**). From 130 to 170 cm the uncertainty of model is the highest, reaching ca. 300 years, while it decreases to ca. 150 years for the depth range 220-240 cm and increases downwards the core to ca. 250 years.

The further work will be carried out on the construction of the continuous age-depth model for a complete core, however, it would require better recognised thickness and depth of a hiatus.

TL dating

The results of TL dating of fluvial sands and silty sands are presented in **Table 5**.

5. PALAEOENVIRONMENTAL RECONSTRUCTION

Based on the collected research material, we can find that different data from multi-proxy studies are compatible as for the palaeoenvironmental events recorded during the main development stages of the Radzików cupola spring mire, especially the Late Glacial-Early Holocene ones.

Main development stages

Plenivistulian – bedrock age and origin

Fluvial (fluvio-periglacial) sands of different grain-size, thermoluminescence dated to Plenivistulian, are mineral bedrock of cupola spring mire. Fining-up sequence indicates decreasing energy of flow. The occurrence of Neogene Coniferales and Gleicheniaceae pollen and Dinoflagellateae cysts in the top part of the series indirectly suggests the redeposition of older deposits, originating probably from washed end moraines of the Wartanian ice-sheet maximum phase, which included Neogene deposits during glaciotectonic processes.

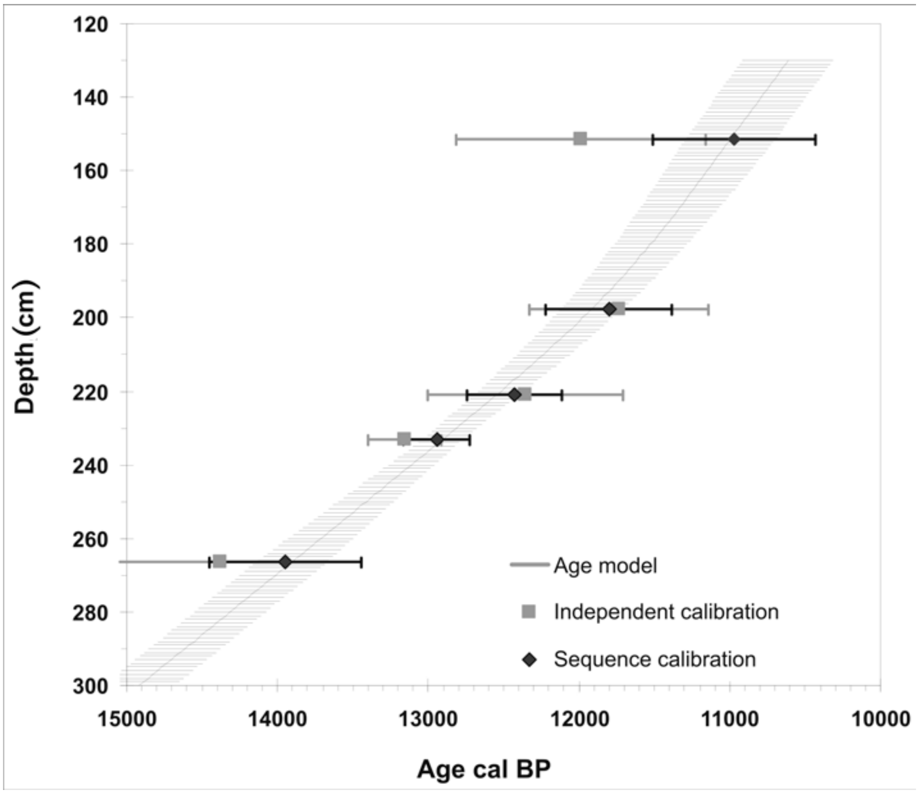

Fig. 10. *Results of calibration and age modeling for the bottom part of the core (depth 130-300 cm). Diamonds and squares represent mid-points of 95.4% probability range of calibrated age, while error bars correspond to half of this range. Thick grey line represents mixed-effect regression age model with 1-sigma uncertainties.*

Table 5. *Results of thermoluminescence dating of the bedrock of cupola spring mire in the Radzików site (RAD-2 core).*

Sample No	Lithology	Depth (m)	Lab. No Lub-	Dose rate (Gy/ka)	Equivalent dose (Gy)	TL age (ka)
RAD-12/1	fine-grained sand, silty in the top	1.0-1.3	4730	2.02±0.16	44±5	22±3
RAD-12/2	medium-grained sand	1.3-1.5	4731	1.93±0.15	36±2	19±2
RAD-12/3	medium-grained sand	1.3-1.7	4732	0.98±0.08	34±3	35±4

Late Glacial – Allerød

The beginning of biogenic sedimentation in the examined site is radiocarbon and palynologically dated to Allerød. Shallow, consistently shallowing and swamping floodings in the Liwiec River valley (evidenced by the occurrence of algae of *Pediastrum* genus) were replaced by the succession of fens, in which Cyperaceae predominated, and then also *Equisetum fluviatile*. Based on the occurrence of Gaeumannomyces hyphae in peat (*vide* Tobolski 2000) we can mycologically identify sedge peat. Sporadically increasing flood flows of the Liwiec River are recorded in the site profile as thin silt interbeddings (higher ash content and occurrence of allogenic silicate minerals) in sedge peat. Remnants of *Betula pubescens* bark and wood in peat (depth 2.23-2.45 m) indicate that birch forest community could have periodically developed in the site. Constant presence of willow pollen indicates development of shrub communities around the site. Pine forests with birch and probable admixture of single larch trees (Wacnik *et al*., 2004) grew in the surroundings. Forest communities were relatively loose as indicated by the considerable proportions of Poaceae and *Artemisia*. Sedge-moss communities with accessory admixture of *Equisetum* prevailed on moist habitats.

Late Glacial – Younger Dryas

This period was distinctly colder (marked in oxygen isotope composition by the decline of ca. 1‰ for $\delta^{18}O$). Sedge-moss fens expanded in the examined site (Cyperaceae prevail in pollen spectrum and *Drepanocladus* in macrofossils) and formed a small elliptic cupola parallel to valley axis. In spite of the low frequency of sporomorphs we can suppose that communities of boreal forests were reduced and high values of *Pinus* in pollen spectra resulted at least partially from long-distance transport of pine pollen. Willow shrubs still existed in the cupola vicinity and also different types of heliophilous herb and dwarf-shrub communities (with Ericaceae, *Artemisia, Filipendula* among other things) developed. In molluscan assemblage this period is characterized by predominance of taxa preferring wet habitats and cold, polar climate (*vide* Ložek, 1964; Alexandrowicz, 1987; Limondin-Lozouet and Rousseau, 1991; Limondin-Lozouet, 1992; Krolopp and Sümegi, 1993; Preece and Day, 1994; Alexandrowicz and Alexandrowicz, 1995a, b; Alexandrowicz, 1997, 1999, 2004; Gedda, 2001; Meyrick, 2001, 2002). High proportion of land taxa (almost or over 50%) is notable. Hygrophilous cold-loving taxa typical of Late Glacial (*Vertigo genesii* (Gredl.) and *Vertigo geyeri* Lind.) are the most important in the stage. They are accompanied by hygrophilous and mesophilous snails of wide temperature tolerance: *Succinea putris* (L.), *Nesovitrea hammonis* (Ström) and *Euconulus fulvus* (Müll.). Taxa of intermittent water bodies (euryecological *Galba truncatula* (Müll.) and very cold-loving *Pisidium obtusale laponicum* Cless.) are also found in the assemblage.

Eoholocene – Preboreal

The end of Late Glacial and the beginning of Holocene is characterized by a considerable increase of humidity (evidenced by pollen and molluscan assemblages) and temperature (recorded in oxygen and carbon stable isotopes). This fact resulted in the change of mire supply with water (activation of confined groundwater supply), development of paralimnic reservoir of limnokren type on top of peat cupola, and complete change of sedimentation conditions (deposition of silty calcareous tufa). Molluscs prevailing in limnokren reservoir are typical of intermittent water bodies, especially *Galba truncatula* (Müll.), which can constitute over 80% of assemblage. It is accompanied by hygrophilous taxa, mostly *Vertigo genesii* (Gredl.) and *Succinea putris* (L.). Increasing air temperature of the Preboreal beginning is recorded in pollen succession as increasing values of *Ulmus*, appearance of other thermophilous trees (*Fraxinus* and *Quercus*) and constant presence of *Filipendula.* Frequency of sporomorphs is higher and their state of preservation considerably better. Considerably wetter habitat with higher content of calcium ions is recorded in macrofossils by occurrence of many species of calciphilous mosses, especially of *Drepanocladus* genus.

Middle and upper Preboreal is characterized by very high pollen values of *Pinus*, permanent occurrence of *Ulmus* and *Humulus*, sporadically appearing *Quercus* and decrease of *Artemisia.* Gradually decreasing humidity resulted probably in weaker supply of peat cupola with ascending water. Land snails developed again more abundantly in gradually shallowing limnokren. Hygrophilous taxa with higher temperature requirements prevailed: *Vertigo genesii* (Gredl.), *Succinea putris* (L.), *Carychium minimum* Müll. Mesophilous snails (*Euconulus fulvus* (Müll.)), and even snails preferring more dry open-country habitats (*Vallonia pulchella* (Müll.)), became slightly more numerous. Communities of boreal pine forests were spread in the vicinity of spring mire, and riverside forests with elm started to develop on wet and fertile habitats.

Mesoholocene

The end of Eoholocene and the whole Mesoholocene are recorded in the examined profile very ambiguously. Based on insufficient paleobotanic data, we can suppose that temperature increased from the end of Preboreal and pine forests were gradually replaced by rich multi-component deciduous communities. It is recorded in pollen succession as higher pollen values of thermophilous trees (*Ulmus* and *Quercus*), *Corylus*, increasing percentage of *Alnus* and sporadic occurrence of *Tilia* and *Fraxinus* pollen. Gradual swamping of spring mire cupola is recorded in macrofossils as high contents of *Typha latifolia*, *Thelypteris palustris, Equisetum fluviatile*, which are considered to be indicators of wet habitats (Wójciak, 2003; Kłosowski and Kłosowski, 2006). The occurrence of *Equisetum* is also recorded among spores. The main part of the Atlantic period seems to be a hiatus in the examined profile (depth 120-125 cm). It should be related to an erosion phase in the Liwiec River valley, which resulted from a considerable increase in humidity. Such interpretation is indirectly confirmed by the results of radiocarbon dating (two dates are outliers), malacological analysis (lack of molluscan shells in the overlying peat series), geochemical and sedimentological analyses (sharp lithological boundaries and sharp changes in concentrations of elements). Intensified erosion was probably associated with complete change of drainage system in the upper section of the Liwiec River valley. The Wartanian melt-out depressions without outflow were included into this system.

Neoholocene

Peat-forming processes on top of peat cupola became active again in Subboreal period. Limnokren was transformed into helokren. New paludic succession in the examined object is evidenced by the permanent occurrence of *Menyanthes trifoliata* in plant macrofossils. Its presence also indicates that habitat was more humid. It is recorded in lithological profile as the succession of sedge peats (consisted mostly of *Carex rostrata*, *Carex acutiformis* and *Carex lasiocarpa*). Typical feature of this part of the profile is almost complete absence of molluscan shells except of open-country species prevailing in the uppermost part of the profile (depth 0-10 cm), which represents modern stage of mire transformation. Taxa of rather dry and open terrestrial habitats prevail (**Fig. 5MSI**): *Vertigo pygmaea* (Drap.), *Pupilla muscorum* (L.), *Vallonia pulchella* (Müll.). Water and hygrophilous taxa, common in earlier phases, are absent. This situation can be interpreted as a result of rapid drying of mire during agricultural drainage works, which were carried out with different intensity in the last century.

6. DISCUSSION AND CONCLUSIONS

The research material, despite rather small thickness of the deposit series (3.0 m), indicates a high dynamics of habitat conditions and their great variability in the profile. The results obtained to date are generally consistent from an interpretation aspect. They allow us to distinguish the main evolution phases of mire (paralimnic phase and paludic phases), which were connected with the changes of moisture, temperature and hydrological conditions in Late Glacial and Holocene. Interdisciplinary (multi-proxy) approach to the problem of palaeoenvironmental reconstructions allows us to determine many-sided factors (regional and local) influencing the direction of changes of the examined site and its surroundings. We also obtained the material of new quality for comparison with other sites of cupola spring mires in Poland (*vide* Dobrowolski *et al*., 1996, 2002, 2005; Pazdur *et al*., 2002; Osadowski *et al*., 2009).

Late Glacial and Early Holocene deposit sequence is relatively thick (about 1.0 m), with good palaeoecological record. The object started to develop in Allerød as valley sedge fen. Its development was conditioned by higher air temperature and precipitation and associated raise of groundwater table in river valley (with sporadically active flood flow). A considerable change of climatic conditions and then hydrological conditions in this period is widely evidenced by sedimentological and palaeobotanical record in lakes and mires of Central Europe (Ralska-Jasiewiczowa and Starkel, 1988; Ralska-Jasiewiczowa *et al*., 1998; Bałaga *et al*., 2002; Litt *et al*., 2003; Latałowa, 2004).

Younger Dryas was distinctly cold period (as indicated by stable isotope analysis) though still relatively humid, especially in its end part. Similar trends of temperature and humidity are recorded in many sites of fossil limnic deposits accumulated in this period in Poland (Pazdur *et al*., 1994, 1995; Wojciechowski, 2000; Alexandrowicz, 2007) and Europe (Magny and Ruffaldi, 1995; Starkel *et al*., 1996; Schwander *et al*., 2000). The Younger Dryas – Preboreal transition in Radzików site is especially well confirmed by palynological and malacological analyses as well as radiocarbon dating and sedimentological succession. It was also the main phase of cupola spring mire development, connected with activation of ascending groundwater supply and development of paralimnic reservoir on top of cupola. Both processes should be related to complete degradation of permafrost and activation of groundwater circulation (so-called under-till groundwater – according to terminology proposed by Żurek 1990). Similar regularities connected with the development of this type of mires were also found in other sites in Poland (Dobrowolski *et al*., 1999, 2005; Osadowski *et al*., 2009; Osadowski, 2010). The Late-Glacial – Early Holocene development of the Radzików spring mire is the best recorded and preserved in the whole deposit sequence under study. The Mesoholocene deposits are worse preserved. It was probably caused by erosion episode(s) associated with a considerably higher precipitation and complete change of drainage system in the upper section of the Liwiec River valley. Intensified erosion occurred in many river valleys of Central Europe at that time (Starkel, 2005, 2006; Kalicki, 2006, 2007; Starkel *et al*., 2006). Especially intensive flood episodes in Radzików site should be related to two European periods of major flooding (dated to 7590 cal BP and 6790-6820 cal BP after Macklin *et al*., 2006). They correspond with distinctly higher water-level of lakes in mid-Europe (Magny *et al*., 2003). Moreover, the lack of deposits from Atlantic period in deposit profiles of cupola spring mires occurring in river valleys is quite commonly found in Poland (Urban *et al*., in press) and neighbouring countries (Brande, 1996, 2007; Wolters, 2002 after Brande, 2007).

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