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Origin and Neoholocene evolution of spring-fed fens in Wardzyń, Łódź Upland, central Poland

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Spring-fed fens in Wardzyń represent the rare group of alkaline mires supplied by artesian groundwater. Using multidisciplinary methods (including sedimentological, hydrometric and hydrochemical, pollen, macrofossil, malacological, geochemical, radiocarbon dating, and stable oxygen and carbon isotope analyses) we have been able to (1) reconstruct the main phases of spring-fed fen development, and to (2) determine the cause of Neoholocene groundwater ascension responsible for the mire inception. These phases are characterized by cyclic organic (peat) and carbonate (tufa) sedimentation associated with the Holocene fluctuations in humidity and temperature. The beginning of the activation of hydrological systems (involving the flow of confined groundwater of the Cretaceous aquifer) at Wardzyń occurred in the Subboreal period of the Holocene, after a long episode of decreased humidity initiated ca. 4.2 ka cal BP.

Key words: spring-fed fen, calcareous tufa, peatland, Neoholocene, Łódź Upland, central Poland.

INTRODUCTION

Spring-fed fens belong to the group of soligenous alkaline mires fed by confined groundwater. These unique and remarkably rare mires assume the form of small or elongated ridges elevated visibly above the level of peatbog plains, which are usually characterized by different ecological conditions and types of water supply. In such ecosystems, the presence of highly oxygenated water contributes to faster decomposition of organic matter or to the secondary precipitation of calcium carbonate (= carbonate encrustations of plants in the spring niche), depending on the presence of autogenic or climatically controlled conditions (Kovanda, 1971; Dobrowolski, 1994; Grootjans et. al., 2012). Consequently, the major part of a spring-fed fen is built of peat-tufa rhythmite (*sensu* Dobrowolski, 2011) which consists of alternating layers of carbonate and biogenic sediments. Since the deposition of calcareous tufa is closely connected with the surrounding environment, these sediments are successfully employed as the basis of detailed palaeoenvironmental reconstructions and are treated as an important indicator of humidity-temperature changes in the Holocene (Dobrowolski et al., 2002, 2005, 2012, 2016; Pazdur et al., 2002; Mazurek et al., 2014). Their palaeogeographic significance is further strengthened by wide geographic distribution in the Northern Hemisphere, as well as their appearance throughout hypsometrically, climatically and morphogenetically diverse regions. They are known from mountains (Hajek et al., 2002; Hájkova and Hájek, 2003; Grootjans et. al., 2012), carbonate uplands (Kovanda, 1971; Pazdur et al., 1988; Dobrowolski, 1994, 1998, 2000; Dobrowolski et al., 2002, 2005, 2016; Alexandrowicz, 2004), and moraine plateaus (Jasnowski, 1975; Alexandrowicz and Żurek, 1996; Wołejko, 2002; Osadowski et al., 2009; Dobrowolski et al., 2010, 2012; Szwarczewski et al., 2011; Mazurek et al., 2014).

Because of the ascending character of the water supply to spring-fed fens, their beginning has always been explicitly associated with the unlocking of vertical circulation of groundwater

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due to the degradation of the Weichselian permafrost (Dobrowolski, 2006). Hence, the bottom spring-fed series has been dated, depending on the geographical location of the site, as belonging to either the end of the Late Glacial or the beginning of the Early Holocene (Dobrowolski et al., 2002, 2005, 2010, 2012; Pazdur et al., 2002; Mazurek et al., 2014).

The Wardzyń spring-fed fens should be recognized as a unique site, different from all previously researched, while the cause of the ascension as one of the most palaeogeographically and hydrogeologically significant research objectives. Even though the Wardzyń site was already described earlier, mostly as a peat bed and in the context of hydrological conditions of spring-fed fen functioning (Ziułkiewicz et al., 2012), it is the first time we have attempted to describe the genesis and palaeoenvironmental evolution of this object with the use of multi-proxy data. Consequently, the aim of this study was (1) to define the geological and hydrological basis for the formation of the spring-fed fen in the middle of the Subboreal period of the Holocene, and (2) to reconstruct the main evolution phases of the mire in relation to the Neoholocene humidity-temperature changes and/or human impacts based on multidisciplinary studies of peat-tufa deposits.

STUDY SITE

The study site is located in the central part of the Polish Lowlands, within the Łódź Hills mesoregion (Fig. 1). It is situated in the southern part of this regional unit, within a glacially elevated area, the so-called Romanowskie Hills (*sensu* Wieczorkowska, 1975). It is a watershed between the catchments of the Vistula and Odra rivers. This region is characterized by a relatively greater number of mires than other parts of central Poland (Okupny et al., 2014). The research area is surrounded by a glacifluvial depression associated with the marginal water flows during the recession of the Wartanian ice sheet.

The alkaline spring mires in Wardzyń consist of two separate spring-fed cupolas (see Figs. 1 and 2), named Wardzyń-1 (51°38’13”N; 19°38’17”E; 191.5 m a.s.l.) and Wardzyń-2 (51°38’20”N; 19°38’21”E; 193.5 m a.s.l.). They are located within a vast complex of valley fens (ca. 20.8 ha, *vide* Turkowska and Wieczorkowska, 1999) at the foot of the slopes of a kame plateau, in the contact zone with the Wolbórka drainage basin (Fig. 1). The lithology and present hydrological conditions of both cupolas were earlier identified by Ziułkiewicz et al. (2012) and Okupny (2013). They protrude 1.0–1.2 m above the surface of the peat plain, and cover the area of ca. 1.5 ha (Fig. 2). We analysed in detail the larger cupola that is a distinct landform of 314 m in length and a maximum of 75.5 m in width. The spring-fed fens in Wardzyń represent the eutrophic-calcareous type of soligenous mires *sensu* Wołejko (2000).

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The study area (Romanowskie Hills) is built mainly of Wartanian glacigenic deposits that consist of: (1) discontinuous series of tills covered partially by (2) sands with gravels of dead-ice moraines and (3) sands of kames (Wieczorkowska, 1975; Turkowska and Wieczorkowska, 1994). The area is drained by the riverheads of the Wolbórka River. The valley floor is composed of Holocene deluvial silt, organic silt and peat (Fig. 3). Beneath them, there are Weichselian sands and fluvial silts with patches of organic matter, and deposits of a Wartanian ice-marginal lake (Turkowska and Wieczorkowska, 1994). Hydrogeologically, the Wardzyń site is located within the Mesozoic Łódź Basin, upon one of its elevated tectonic blocks separated from the adjacent horsts by sub-latitudinal faults. They act as a barrier for groundwater flow. One of these faults may possibly contribute to an ascending spring that supplies the studied objects. The Upper Cretaceous limestone, marl and opoka are the aquifer in the top part of the Mesozoic complex in this part of the Łódź Basin (Ziułkiewicz, 2003). In the study area, the water flows within these rocks from north to south. The Upper Cretaceous deposits are covered by low-permeable Paleogene residual clays or by ice-marginal lake deposits.

Their thickness attains 40 m on average, although this seal is only 7–25 m thick in the environs of Wardzyń (Olczak, 1994). It is lower and less lithologically diverse in the southwestern part of the area, near Tuszyn. It consists of several metres thick layers of Paleogene marl and loam or Wartanian till. The sealing series disappears in the upper segment of the Ner River valley, where the Upper Cretaceous and Quaternary deposits constitute a unified aquifer. The springs, which contributed to the development of the cupolas in Wardzyń, correspond with the conditions of the functioning of groundwater outflows in the Łódź Hills in terms of the hypsometric and morphological location, discharge, and water mineralization. The water-bearing Quaternary deposits are the main usable aquifer in the study area (Fig. 4A). The Romanowskie Hills are the area of local recharge of the water-bearing Quaternary beds, located directly close to the drainage zone of the springs in Wardzyń. The lack of continuity within the moraine tills in this area explains the occurrence of a single aquifer in the Quaternary deposits (Moszczyńska, 1986; Ziułkiewicz et al., 2012). In Wardzyń, the Quaternary groundwater table occurs slightly above the level of the Upper Cretaceous groundwater table (Fig. 4B).

The outflow of water from the spring niches in Wardzyń is of ascending character and occurs in multiple spots. The peat-tufa cupolas rise above the spring niches and the pattern of the groundwater outflow in this region is dispersed. The elevations of the outflow points range between 191.5 m a.s.l. (Wardzyń-1 cupola) and 193.5 m a.s.l. (Wardzyń-2 cupola). The total discharge rate of the spring complex in Wardzyń is 10.6–16.5 dm^3/s (Ziułkiewicz et al., 2012).

MATERIAL AND METHODS

HYDROMETRIC AND HYDROCHEMICAL ANALYSES

The basic hydrochemical analyses were carried out for: (1) spring water flowing from the mineral substratum in the spring niches, and from the surface of the fen cupolas, and for (2) unconfined and confined groundwater – in piezometers reaching water from the Quaternary and Upper Cretaceous aquifers, installed approximately 0.25–0.85 km away from the studied object.

The hydrochemical and hydrometric studies were conducted in the period of 2009–2012, in quarterly intervals. The measurements of SEC, pH (H_2O), Eh and DO were performed *in situ*. Each repeated sampling involved the collection of water for laboratory analysis. The scope of the analysis covered: dry residue, TH, main ions, ammonium ions, nitrite ions, nitrate ions and ferrous ions. SI (saturation index) was calculated using the *PHREEQC* software with the *wateq4f* database. The chemical analyses were carried out according to Witczak and Adamczyk (1995). The Database of the Polish Hydrological Survey, which is an archive of local groundwater analyses, was used to identify the local hydrochemical background.

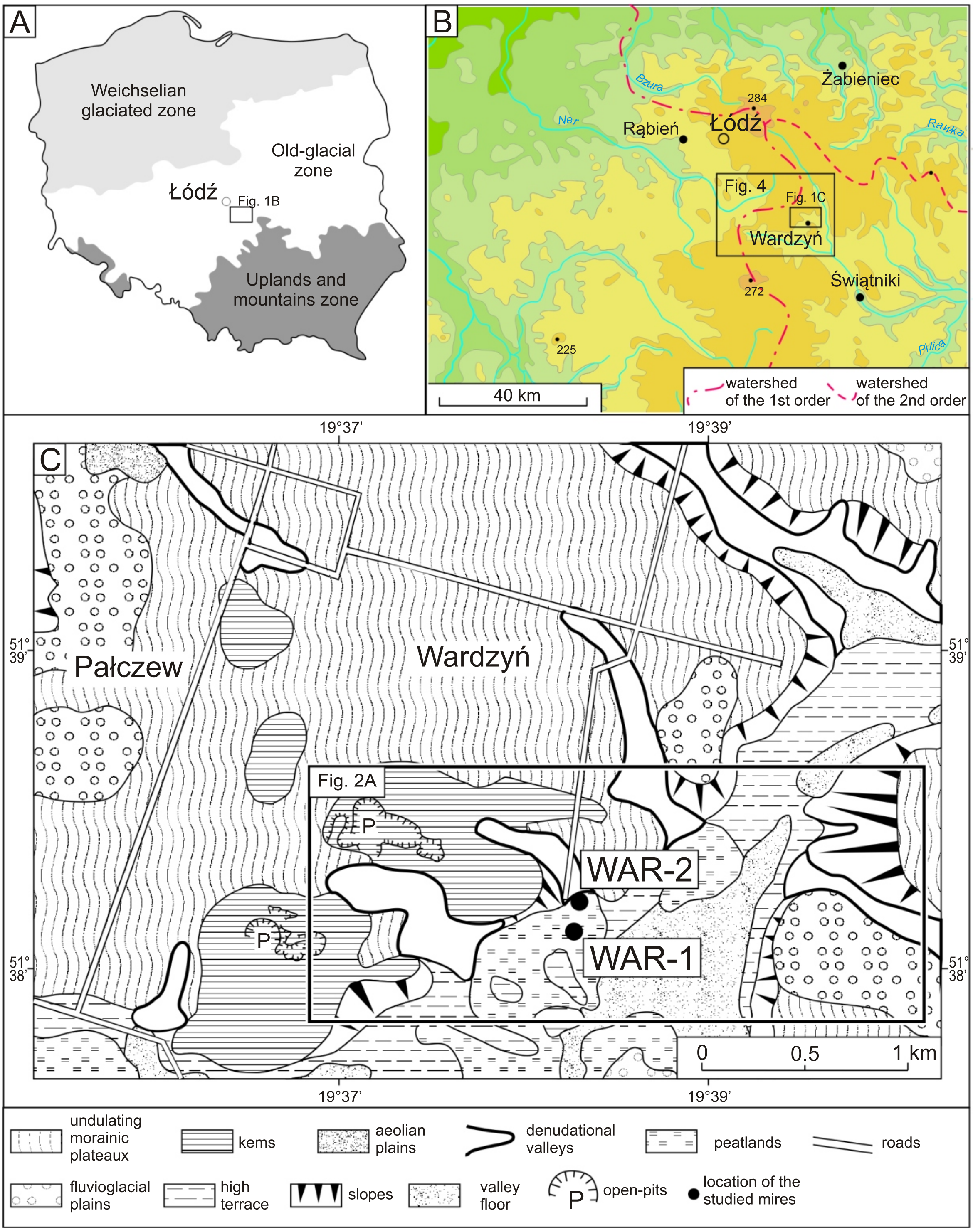

Fig. 1. Location of the Wardzyń site: A – in Poland, B – in the southern part of the Łódź Hills, C – geomorphological situation in the study area region

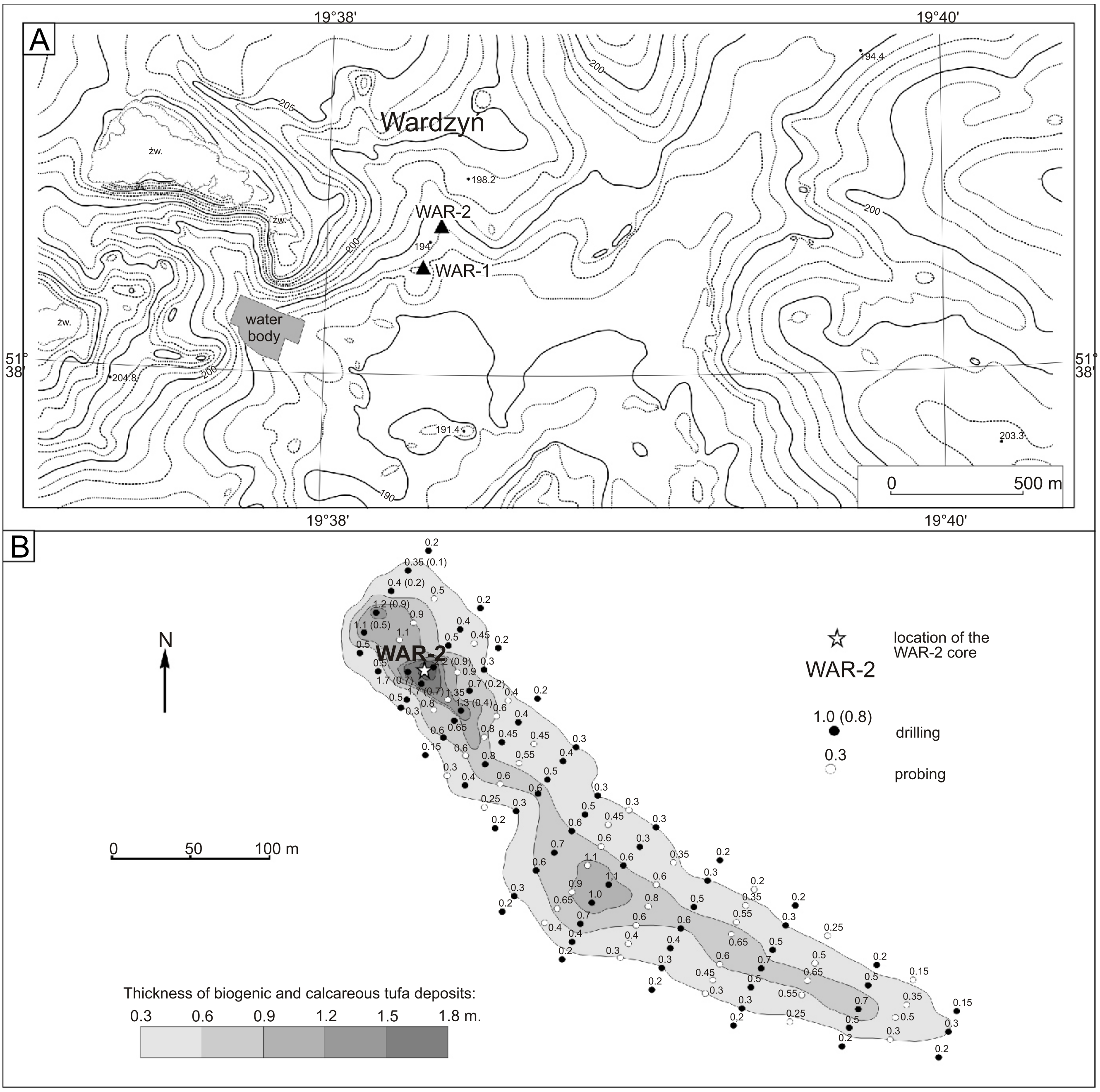

Fig. 2A – hypsometric map of the study area (based on a topographic map at a scale of 1:10,000) with the location of spring-fed cupolas (WAR-1, WAR-2); B – thickness of peat-tufa deposits in the Wardzyń-2 cupola (based on a tachymetric survey) paired with the location of drillings and probing

SAMPLING AND SEDIMENTOLOGICAL ANALYSIS

Geological and palaeomorphological situation of the whole bedrock of the alkaline spring-fed fens (both cupolas) was recognized on the basis of 112 geological borings, situated along 20 sections perpendicular to the axis of each cupola (Fig. 2B). The core drillings were performed every 7–15 m, using *Eijkelkamp*, a standard Russian peatborer (length 50 cm; diameter 5.0 cm). The survey data collection was conducted using a self-reducing laser tachometer (*TOPCON GST-105N*). The macroscopic lithofacies analysis of organic-carbonate sequences of the deposits was made using the non-genetic Troels-Smith method for the description of deposits (Troels-Smith, 1955) with Dobrowolski's (2011) modification. One core (coded WAR-2; 51°38'18"N; 19°38'23"E), 2.5 m long, was taken from the western part of the cupola Wardzyń-2 (Fig. 2B) for detailed laboratory analyses of the deposits.

PALAEOBOTANICAL ANALYSIS – POLLEN AND MACROFOSSILS

Pollen. Samples for pollen analysis were taken from the WAR-2 core at 5 cm or 20 cm intervals. Detailed pollen analyses were carried out for 14 samples (2 cm^3 in volume). They were prepared according to standard Erdtman's acetolysis after removal of carbonate in HCl and boiling in 10% KOH (Berglund

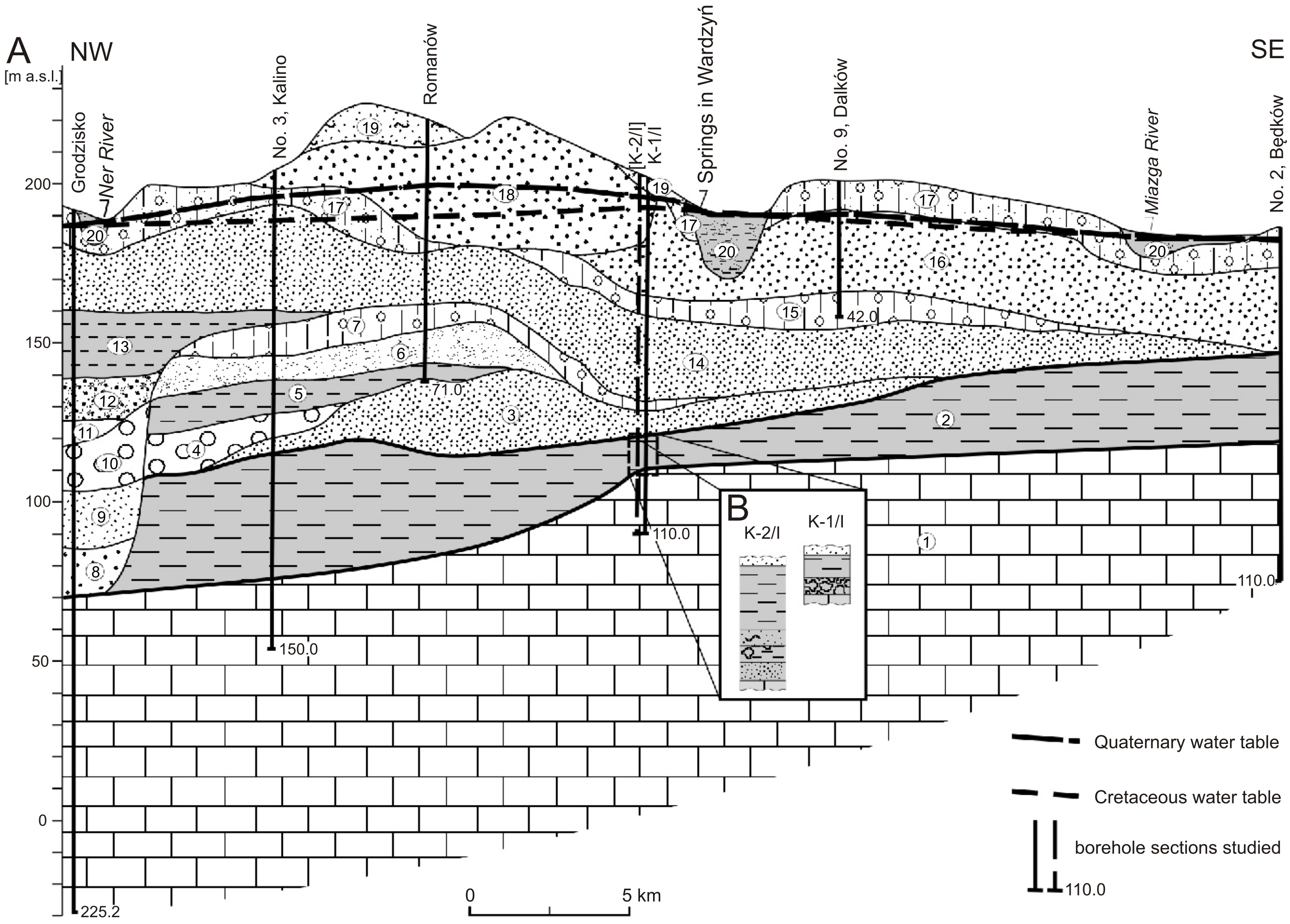

Fig. 3. Geological cross-section through the study area (location as in Figure 4)

A: 1 – limestone (Upper Cretaceous), 2 – clay and silt (Neogene), 3 – fine sand, 4 – sand with gravel, 5 – silt and clay, 6 – medium-grained sand, 7 – till, 8 – gravel, 9 – fine sand, 10 – gravel, 11 – clay, 12 – gravel with sand, 13 – clay, 14 – silt and sand, 15 – till, 16 – fine sand, 17 – till, 18 – sand with gravel and silt, 19 – sandy till, 20 – sandy silt, organic mud and peat; **B** – full picture of the bottom part of the sections (Upper Cretaceous–Neogene) near the spring in Wardzyń

and Ralska-Jasiewiczowa, 1986). The percentage of individual taxa was calculated in the ratio of the sum of the pollen of trees and herbaceous (AP+NAP), excluding telmatic plants, aquatic plants, and spores. Pollen diagrams were made using the POLPAL software; selected curves of trees, shrubs and herbs are presented (Nalepka and Walanus, 2003).

Macrofossils. For the macrofossil analysis, 30–50 cm^3 sediment sampleswere taken at 5 cm intervals from the WAR-2 core. Plant macrofossils were separated from 48 samples according to the method developed by Tobolski (2000), and identified using the keys of Dombrovskaya et al., (1959), Grosse-Brauckmann, (1972, 1974), Grosse-Brauckmann and Streitz (1992), Tobolski (2000) and Hedenäs (2003). The names of vascular plants were given after Mirek et al. (2002) and the names of Bryophyta after Ochyra et al. (2003). Plant macrofossils were identified to the level of species or, in some cases, of genus, and their percentage contents were calculated in a given sample.

MALACOLOGICAL ANALYSIS

A total of 9 samples were collected at 10 cm thick intervals from the WAR-2 core. Molluscan assemblages occurred only in the bottom parts of the profile at a depth of 1.4–2.3 m. The samples were wet-sieved using a 0.5 mm mesh sieve. After drying, all the specimens and identifiable fragments of shells were collected for unanimous classification. The standard methods of malacological analysis were used, as described by Ložek (1964) and Alexandrowicz and Alexandrowicz (2011). Individual taxa were classified into the following ecological groups: shadow-loving species (F ecological group), open-country species (O ecological group), mesophilous molluscs (M ecological group), hygrophilous molluscs (H ecological group) and freshwater species (W ecological group).

GEOCHEMICAL ANALYSIS

The geochemical analysis was carried out on 112 samples taken every 1 cm (at high lithofacies differentiation of sediments) or 2.5 cm (in the case of homogeneous sediment) from the WAR-2 core. Ash and organic matter (OM) contents, as well as pH in H_2O were determined by standard methods used in chemical analysis of organogenic deposits (Myślińska, 2001). The ash was used to estimate the content of biotic and terrigenous silica in the deposits by removing the components soluble in HCl and KOH. The amount of carbonates (expressed

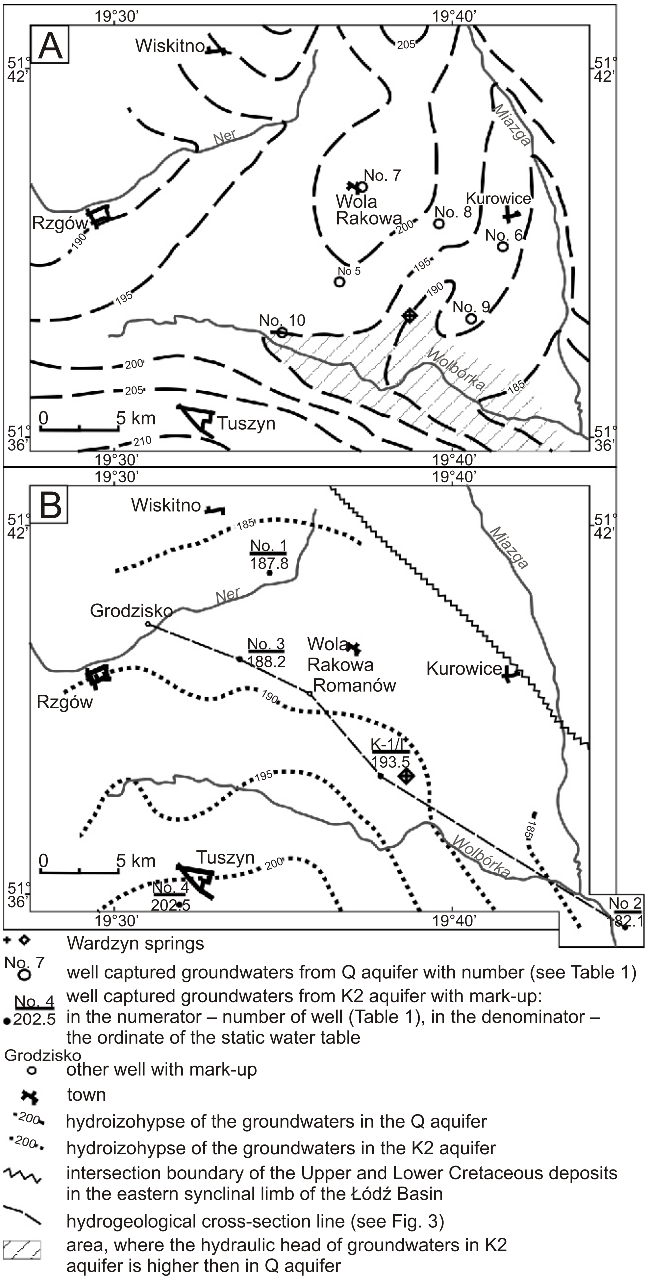

Fig. 4. Groundwater table contour of the Quaternary (Q) aquifer (A) and Upper Cretaceous (K_2) aquifer (B) in the Wardzyn area

in $CaCO_3$) was determined by the volumetric method using the Scheibler apparatus (*vide* Turski, 1986). The total contents of macroelements (Na, K, Ca, Mg, Fe) and microelements (Mn, Cu, Zn, Pb, Ni, Cr) were determined. Samples of constant weight were digested in concentrated (nitric, hydrochloric and perchlorate) acids. The acid solutions were analysed by the Atomic Absorption Spectrophotometry (AAS) method, using the *Solaar 969* apparatus. The proportions of these compounds can be used to reconstruct changes in water level, biological productivity, and type of denudation in the peatland catchment in accordance with the conclusions of Ławacz et al. (1978) and Borówka (1992, 2007).

RADIOCARBON DATING

The chronology of accumulation of biogenic-carbonate deposits is based on the radiocarbon dating of deposits containing a high amount of organic matter. The radiocarbon analysis was carried out at the Gliwice Radiocarbon Laboratory, by the Liquid Scintillation Counting (LSC) method. The age was calculatedfor four samples.

STABLE ISOTOPES

The isotopic analysis was carried out using a dual inlet and triple collector mass spectrometer (modified and modernized MI1305 model). Carbonate samples were analysed on CO_2 produced by the reaction with 100% H_3PO_4 in a glass vacuum line connected to the inlet system of the mass spectrometer. The reaction proceeded at an electronically controlled temperature of 25 ± 0.2°C to achieve ^{18}O in the VPDB scale. For the normalization of both the ^{13}C and ^{18}O values, the international standard NBS-19 was analysed in each series of the samples. The analytical uncertainty of both delta values in terms of standard deviation was better than ±0.08‰.

RESULTS

HYDROMETRIC AND HYDROCHEMICAL ANALYSES

The calcareous tufa of both the spring cupolas precipitated from the groundwater flowing out of the springs. The solution had to reach supersaturation with calcium carbonate, which can be described as $SI_{CaCO3} > 5\%logK$. The speciation-solubility model of the groundwater in the Wardzyń area indicates that precipitation of carbonates is not possible at the present time. The saturation index (SI) for calcite is 0–0.5, i.e. $SI < +5\%logK$ in the vast majority of cases (Table 1). The model state of the studied solutions indicates that the partial CO_2 pressure corresponds with the conditions of the top part of the vadose zone.

The sets of hydrochemical data from the years 1959–2012 (CBDH) were tested (Mann-Whitney U tests) to verify the statistical significance of the differences between the Quaternary and Upper Cretaceous aquifers (Table 2). The *p* values indicate a significant hydrochemical similarity between the two water-bearing environments.

The relationship between the products of the dissociation of calcium bicarbonate suggests the presence of subtle differences between the groundwater present in various water-bearing strata and the spring water of Wardzyń (Fig. 5).

The results presented in Figure 5 document a significant dependence of the drop in the disproportion between the concentration of $Ca^{2+}$and HCO_3 ions with increasing depth to the aquifer. The Upper Cretaceous waters are practically balanced, while the concentration of Ca^{2+} in the unconfined groundwater displays a marked difference from the concentration of HCO_3 which is caused by the presence of other calcium compounds (Ziułkiewicz et al., 2012). The same is true for the water in the spring niches in Wardzyń. However, the water penetrating the cupolas and the ascending water flowing out onto their surface have a different ratio of the concentration of the ions. The relation between the lines of regression allows interpreting this state as a result of the chemical composition of waters in both the Quaternary and Upper Cretaceous aquifers, that is, of the effect of mixing of waters from both aquifers.

Table 1

Saturation index (SI) for carbonate minerals, calculated for the groundwater from the Quaternary and Upper Cretaceous aquifers in the Wardzyń area

Minerals (±5%logK)	Wells										Piezometer
	Upper Cretaceous aquifer (K2)				Quaternary aquifer (Q)						**Aquifer K2**
	No. 1*, Stefanów	No. 2, Będków	No. 3, Kalino	No. 4, Tuszyn	No. 5, Pałczew	No. 6, Kurowice	No. 7, Wola Rakowa	No. 8, Brójce	No. 9, Dalków	No. 10, Modlica	K-1/I
Calcite (±0.4)	0.006	0.318	**0.559**	0.171	0.002	0.016	0.182	0.114	0.004	–0.065	0.157
Dolomite (±0.8)	–1.145	–0.368	0.088	–0.602	–1.190	–1.038	–0.585	–0.848	–1.108	–1.245	–0.970
Siderite (±0.5)	0.052	0.366	0.275	0.191	–1.196	–0.094	0.085	0.057	–0.679	–0.573	0.213

* – number and name of well, location as in Figure 4; note: the SI values in bold indicate a state of supersaturation of solution in relation to a given solid phase: SI > 5%logK, the grey-shaded SI values indicate an equilibrium between the solution and a given solid phase: –5%logK < SI < +5%logK, non-highlighted fields indicate under-saturation of water in relation to a given mineral: SI < –5%logK

Table 2

Results of the U test for a series of analyses of Ca^{2+} and HCO_3 ions, dry residue, and the pH of groundwater from the Quaternary and Upper Cretaceous aquifers in the Wardzyń area; $p = 0.05$

Parameter	Ca^{2+}	HCO_3	Dry residue	pH reaction
p	0.810	0.676	0.733	0.887

Note: calculations conducted with *STATISTICA v.7.1* software

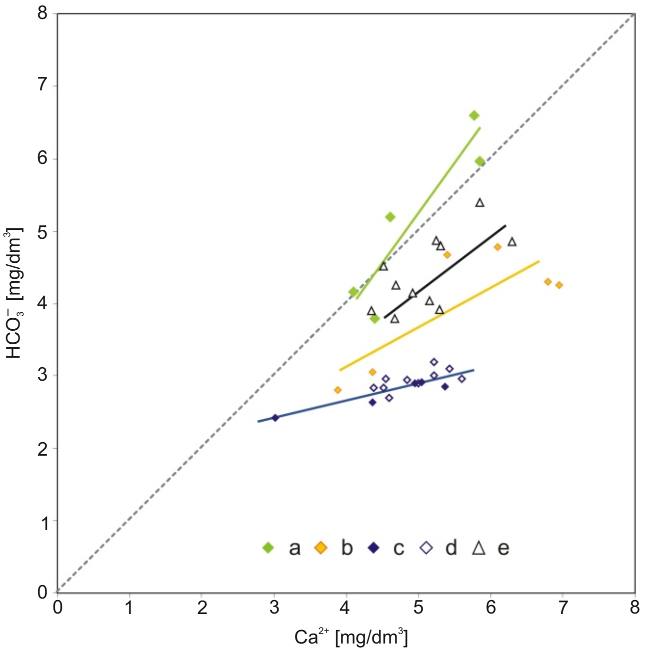

Fig. 5. The ratio of equivalent concentrations of calcium and bicarbonate ions in groundwater and spring waters of Wardzyń, analysed in the years 2009–2013

a – Upper Cretaceous confined groundwater, b – Quaternary confined groundwater, c – unconfined groundwater, d – spring waters flowing from mineral substratum, e – spring waters flowing from the surface of the Wardzyń-1 cupola

SEDIMENTOLOGICAL ANALYSIS

The biogenic-carbonate deposits of the spring-fed fen are 2.2 m in thickness. Fine-grained sands with massive structure, bored into a depth of 2.5 m, constitute their mineral substratum. The sequenceof peat and tufa deposits includes four main lithostratigraphic units, coded chronologically 1–4 (Table 3). Unit 1 is composed of mineral-organic deposits progressively passing into strongly decomposed sedge-wood peat with dispersed carbonate matter. It is covered by a thin layer of sand with inserts of slightly decomposed plant detritus and calcareous tufa. At lower depths, it passes into a peat-tufa rhythmite composed of thin packets of coarse- and medium-grained calcareous tufa, separated by layers of strongly decomposed sedge-wood peat (unit 2). The total thickness of the deposits of unit 2 exceeds 80 cm. It is covered by a packet (ca. 20 cm thick) of silty calcareous tufa with dispersed organic matter, which represents unit 3. The top lithostratigraphic unit (unit 4) is composed of reed-wood and sedge-wood peat without carbonates, with inserts of slightly decomposed wood.

PALAEOBOTANICAL ANALYSIS – POLLEN AND MACROFOSSILS

Pollen. The results of pollen analysis are illustrated in the pollen diagram (Fig. 6). The frequency and preservation of sporomorphs in deposits that represent spring-fed fen were relatively good (Dobrowolski, 2011; Pidek et al., 2012). The peat of the topmost layer (20–100 cm) exhibited a quite high frequency and taxonomical diversity of pollen. The sum of AP+NAP was about 100–465 grains in the tested samples. Based on the obtained pollen diagram, four local pollen zones (LPAZ) have been distinguished.

1. *Alnus–Corylus* LPAZ (210–180 cm)

This zone displays increased values of *Alnus* and *Pinus* pollen with a significant percentage of *Corylus* pollen. The curves of *Betula*, *Tilia* and *Picea* pollen are continuous. Intermittently, there are also *Quercus*, *Ulmus* and *Salix* pollen. As far as herbaceous plants are concerned, only single *Artemisia* pollen grains have been recorded. The spores of Polypodiaceae display quite high values, especially in the upper part of the zone.

2. *Quercus–Picea* LPAZ (179–125 cm)

This zone is characterized by the occurrence of *Quercus* and *Picea* pollen, as well as by high pollen values of *Pinus* and *Betula*. The frequency of *Corylus* pollen is lower. The bottom

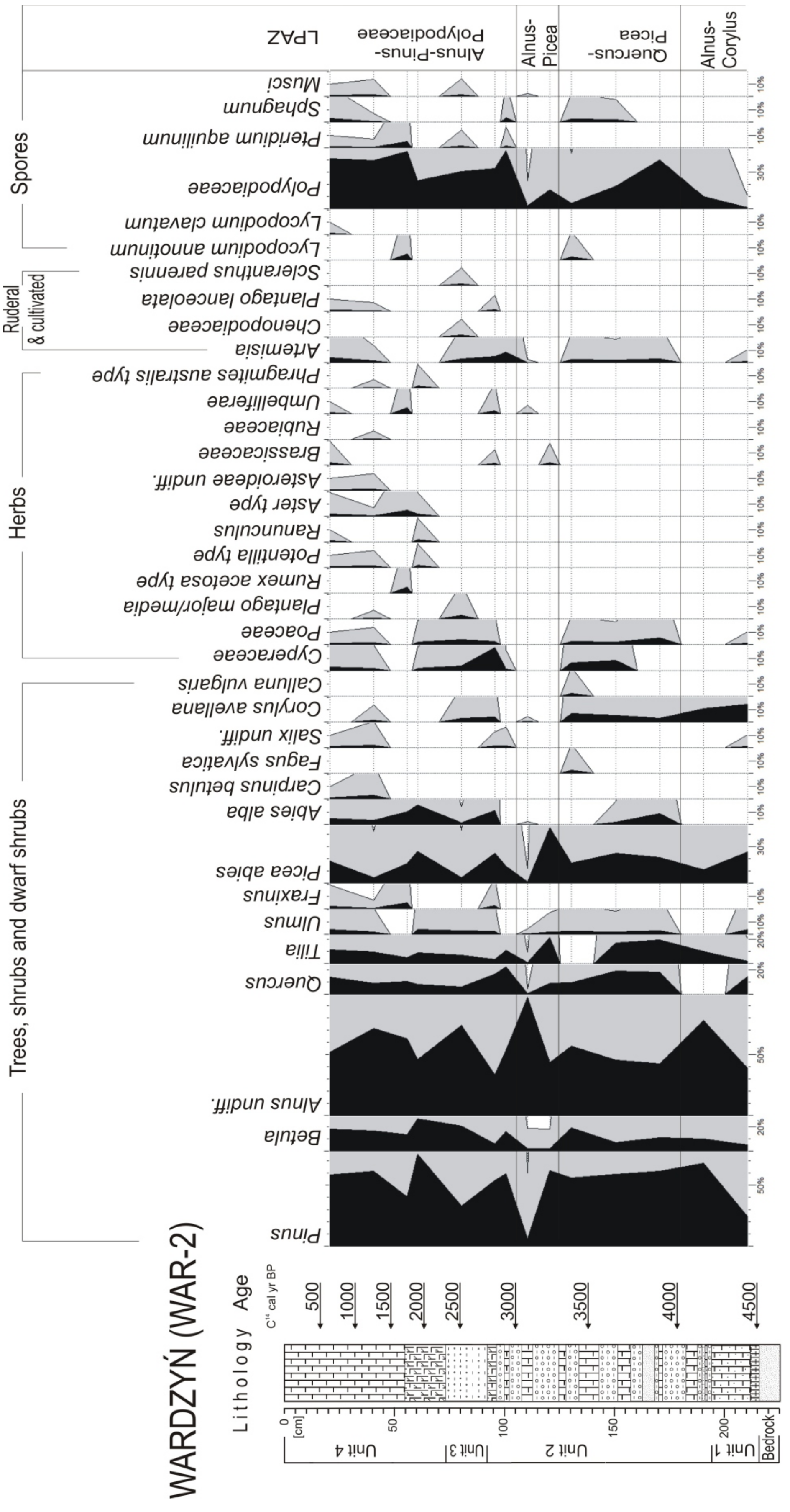

Fig. 6. Pollen diagram for the WAR-2 core

For lithology see Table 3

Table 3

Description of deposits from the WAR-2 core according to the Troels-Smith method (Troels-Smith, 1955) with Dobrowolski's (2011) modification

Depth [cm]	Units	Lithology	T-S Formula
0–55	4	Wood-sedge peat, highly decomposed, with inserts of slightly decomposed wood, dark brown	Tl^{3}3, Th ^{4}1,nig.3, strf.0, sicc.3, elas.2, trunki et rami. I-II
55–74		Reed-wood peat, moderately decomposed, in places with inserts of slightly decomposed wood, dark brown	Tl^{3}3,Th^{3}1 , nig.3, strf.0, sicc.3, elas.2, lim 0, trunki et rami. I-II
74–92	3	Silty calcareous tufa, grey, with dispersed organic matter	Cp(min.)4, Sh++, nig.2, strf.0, elas. 0, sicc.3, lim 2
92–113	2	Peat-tufa rhythmite, with rhythm size of 0.5 mm – 5 cm	Cl(maj.)1-3, Th^{3}1-2, Tl^{3}1-2, Cp(min.)++, nig.1-2, strf.1-3, sicc.3, elas.0-1, sicc.3, lim 2-3
113–175		Peat-tufa rhythmite, with rhythm size of 1 mm – 5 cm, with malacofauna	Cl(maj.)1-3, Th^{3}1-2, Tl^{3}1-2, Cp(min.)+, nig.1-2, strf.1-3, sicc.3, elas.0-1., sicc.3, lim 2-3, test moll
175–185	1	Fine-grained sand, with inserts of wood peat and calcareous tufa	Gmin3, Ag1, Sh+, Cp(min.)+, nig.1, sicc.2, elas.0, strf.0, lim 0
185–210		Sedge-wood peat, highly decomposed, dark brown, with a small admixture of sand in the bottom, with scarce malacofauna	Th^{4}4, Cp(min.)+, Gmin +, nig.4, elas.2., sicc.2, strf.0, lim 1, test moll
210–220		Mineral-organic matter, dark brown, with scarce malacofauna	Th^{4}2, Gmin1, Ag1, nig.3, strf.0, elas.0, sicc.2, lim.0, test moll
220–240	Bedrock	Fine-grained sand, light grey, with inserts of organic matter	Gmin3, Sh1, nig.2, strf.0, sicc.2, elas.0, lim.1
240–250		Fine-grained sand, light grey	Gmin4, nig.1, strf.0, sicc.3, elas.0, lim.1

part of the zone is marked by a significant presence of *Tilia* and a noticeable presence of *Abies* pollen. The pollen curves of *Poaceae* and *Artemisia* are low and continuous. The pollen of *Cyperaceae* appears in the top part of the zone along with *Calluna vulgaris* and spores of *Lycopodium annotinum* and *Sphagnum*. The frequency of Polypodiaceae spores is highest in the bottom part of the zone.

3. *Alnus*–*Picea* LPAZ (124–100 cm)

Zone 3 is characterized by the maximum pollen values of *Picea* in its lower part, and of *Alnus* in the upper part, as well as by the scarcity of other pollen. Only pollen of *Tilia* and spores of Polypodiaceae exhibit a higher frequency in the bottom part.

4. *Alnus*–*Pinus*–Polypodiaceae LPAZ (99–20 cm)

This zone is rich in *Pinus* and *Alnus* pollen. The pollen curve of *Picea* exhibits considerable variability, similarly to the curve of *Abies*. Quite high frequencies of *Quercus* and *Tilia* pollen are found in the bottom part of the zone. The pollen curves of *Ulmus, Fraxinus, Salix* and *Corylus* are discontinuous. The pollen values of herbaceous plants are relatively high. Pollen of *Plantago lancelata, Artemisia* and other meadow species such as *Rumex acetosa, Aster* type and *Umbeliferae* is present. Polypodiaceae are clearly dominant among Cryptogamae.

Since the formation of the studied water body, the dominant forest communities were populated mainly by *Alnus glutinosa* with an admixture of *Picea abies*. The significant frequencies of *Pinus* and *Quercus* pollen indicate that large areas around the mire were also covered by pine and mixed forests. The pollen curves of *Ulmus, Fraxinus* and *Tilia* also confirm the presence of riparian communities. The pollen values show that such communities might have been dominated by lime. However, it cannot be excluded that the frequency of *Ulmus* and *Fraxinus* is underestimated, since their pollen is more fragile and susceptible to corrosion. Similarly, corrosion could have also affected the pollen grains of hornbeam, which appear only in the topmost layer (see Balwierz, 2010). Fir was also present in forest communities and its maximum proportion should be related to the period from 2800 cal BP, although single pollen grains of *Abies* appear as early as ca. 3900 cal BP.

The fundamental changes in the development of forest communities should be ascribed to: (a) a decrease in the presence of hazel and the spreading of the Polypodiaceae family ferns (ca. 4000 cal BP), (b) the maximum pollen values of *Alnus* and *Picea* (ca. 3100 cal BP), and (c) the advancement of herbal communities with the ruderal and cultivated indicators, as well as ferns (*ca.* 1800 cal BP). The high frequency of Polypodiaceae spores and the presence of photophilous meadow species point to the occurrence of open areas. The human farming activity can be substantiated by the presence of anthropogenic indicators such as *Plantago lanceolata* or *Pteridium aquilinum*.

Macrofossils. Based on the analysis of 45 samples of macrofossils, taken from a depth of 5–235 cm, four zones (coded Mac 1–4) are distinguished. They correspond to the main phases of the mire development (Fig. 7).

Mac-1 zone (235–190 cm). This zone is recognized as the most diverse in terms of species, with the simultaneous dominance of *Alnus*, helophytes and hydrophilous species (*Equisetum fluviatile*, *Typha angustifolia* and *Schoenoplectus lacustris)* as well as hydrophytes (*Chara* sp. and *Ceratophyllum demersum).* There is also a modest proportion of brown moss, including species such as: *Tomentypnum nitens, Limprichtia cossoni, Philonotis fontana*, *Hamatocaulis vernicosus, Caliergonella cuspidata, Campylium stellatum* and *Bryum pseudotriquerum*. The occurrence of the former four species is limited solely to this zone. *Corylus avellana* (fragment of a pericarp) was also found in the bottom part.

Mac-2 zone (189–145 cm). The second zone is still rich in *Alnus, Carex* sp. and *Phragmites*, as well as *Bryales* showing the highest frequency, while the diversity of species is lower (compared with Mac-1). *Menyanthes trifoliata* is permanently present and so are other rush species such as *Equisetum fluviatile* and *Thelypteris palustris.* The species composition of macrophytes indicates very wet and inhospitable humidity conditions.

Mac-3 zone (144–100 cm). This zone is marked by the highest content of *Alnus glutinosa* with a small amount of *Carex*

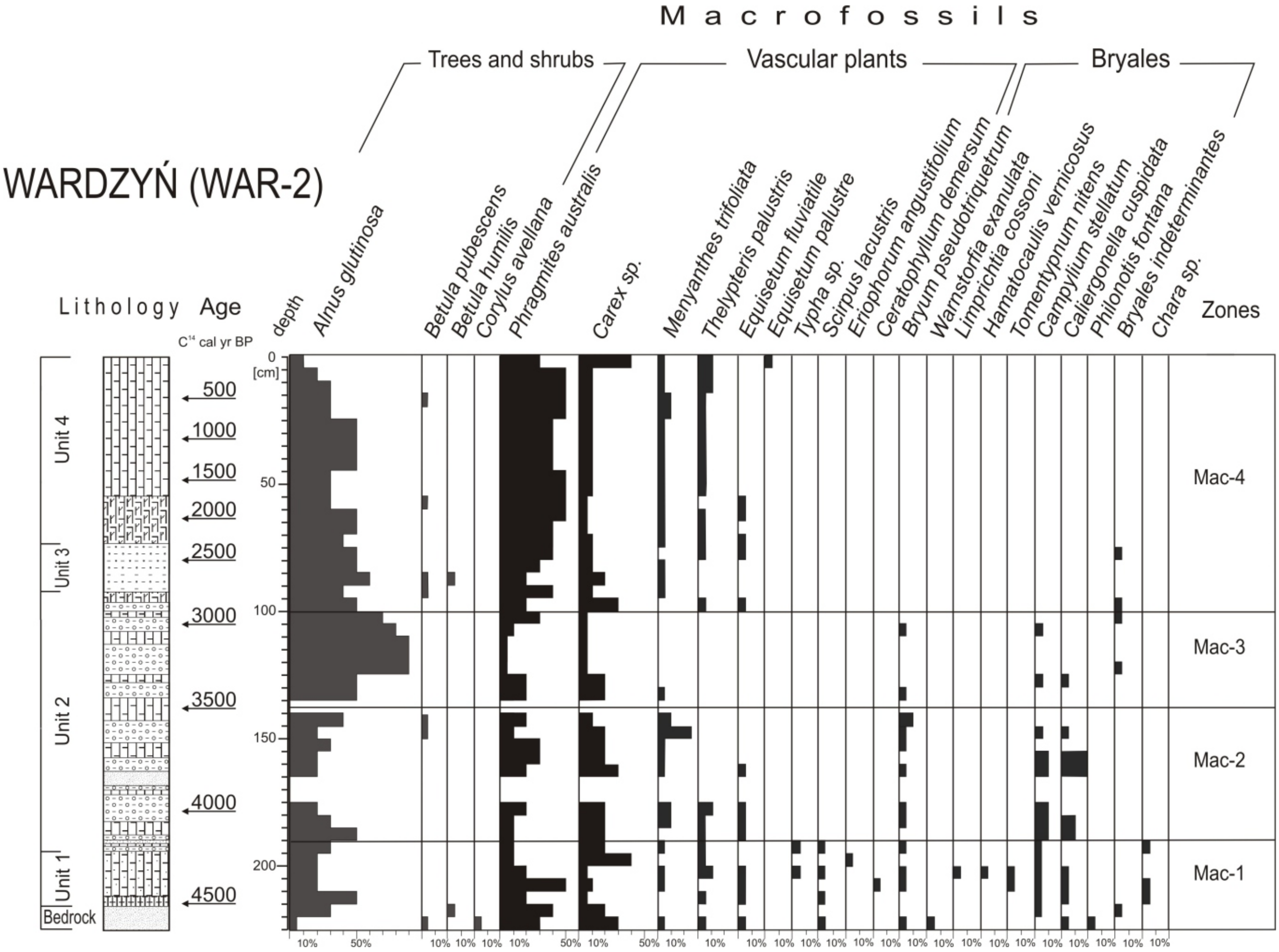

Fig. 7. Diagram of plant macrofossils for the WAR-2 core

For lithology see Table 3

and *Phragmites* macrofossils, and with a simultaneous trace presence of brown moss. In the top part of the zone, the contents of *Carex* and *Phragmites* significantly increase. In addition, *Thelypteris* and *Equisetum fluviatile* appear intermittently.

Mac-4 zone (99–5 cm). It is characterized by the marked co-dominance of alder and reed (*Phragmites*) macrofossils with the simultaneous presence of rush species of *Magnocaricion* alliance. Brown moss is almost absent in this zone. The humidity conditions are still relatively inhospitable, which can be observed from the continuous but limited presence of *Thelypteris palustris* and *Menyanthes trifoliata.*

The analysis of the macrofossils indicates that the area has been covered by a forest community favouring peat sedentation since the beginning of the spring-fed fen. In composition, it was close to the present-day *Ribeso nigri–Alnetum.* However, the species composition of its undergrowth had undergone significant transformations in response to the change of the humidity conditions in the Neoholocene (Fig. 7).

MALACOLOGICAL ANALYSIS

In total, 21 mollusc species, represented by over 1000 specimens and over 400 unclassifiable shell fragments, have been identified within the entirety of the study material. The number of taxa in individual samples varied from 6 to 18, and the number of specimens from 102 to 145 (Fig. 8 and Table 4).

The malacological sequence in the Wardzyń site is clearly bipartite.

Mal-1 zone (230–200 cm) is characterized by the dominance of aquatic species (*Pisidium casertanum, Radix balthica*). The composition of this assemblage is typical of small, highly overgrown water bodies. All the species present here are resistant to drying and can live in distinctly humid terrestrial habitats for relatively extended periods of time (Piechocki, 1979; Piechocki and Dyduch-Falniowska, 1993). The faunal assemblage is complemented by terrestrial species typical of wetland habitats. Sporadic shells of mesophilous snails appear here as well.

Mal-2 zone (199–140 cm) contains a fundamentally different assemblage of molluscs. Aquatic species are represented almost solely by *Pisidium casertanum* and constitute a secondary component of the fauna. The main role is assumed by terrestrial taxa, especially those of wetland habitats (*Carychium minimum*, *Zonitoides nitidus* and *Perforatella bidentata*). The topmost part of the sequence contains quite numerous shells of species typical of open-area habitats.

GEOCHEMICAL ANALYSIS

We can distinguish six discrete geochemical zones (coded Chem 1–6) in the vertical deposit succession (Fig. 9), using the *PAST* software (Hammer et al., 2001).

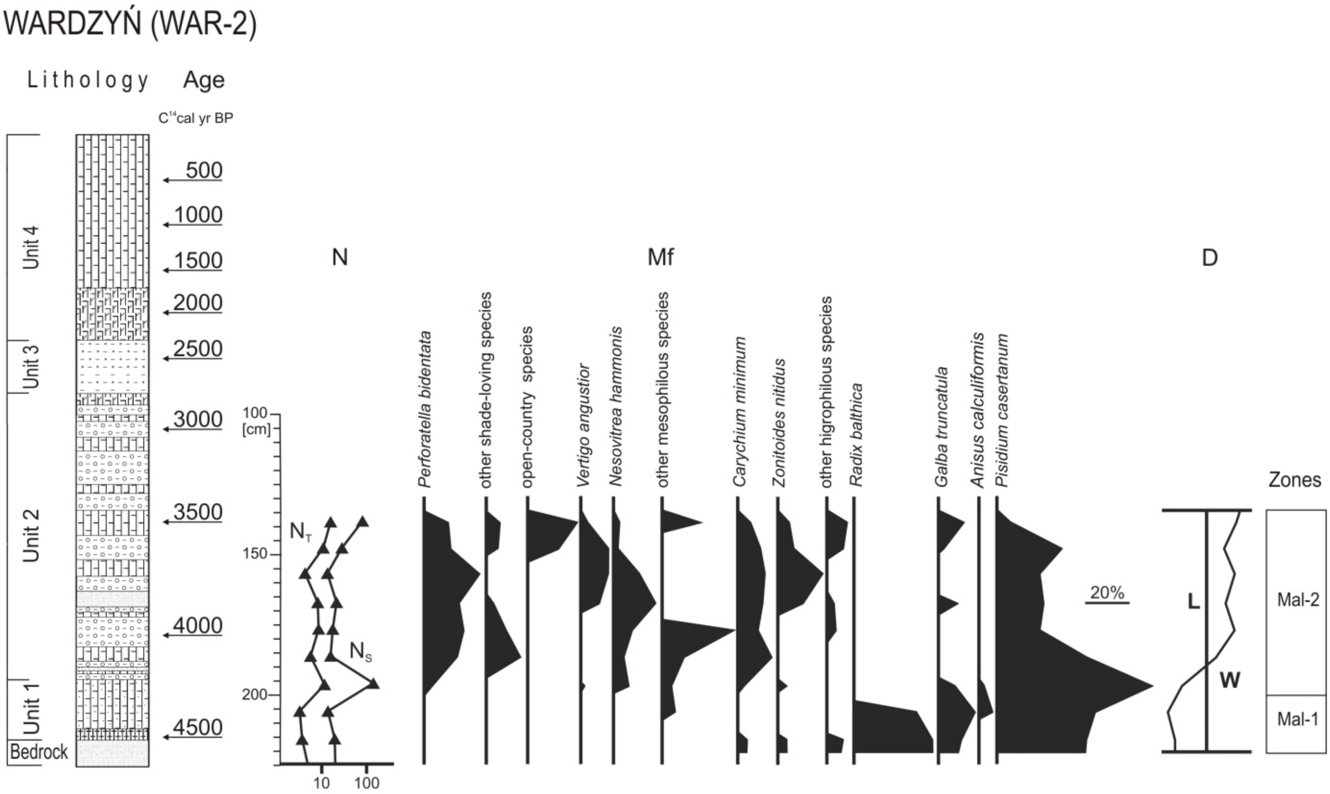

Fig. 8. Malacofauna in the WAR-2 core

N – number of taxa (N_T) and specimens (N_S), Mf – molluscan fauna, D – two-component diagrams showing the ratios of selected molluscan groups, which indicate the changes in environmental conditions of deposition: L – terrestrial species, W – aquatic species; for lithology see Table 3

Chem-1 zone (210–194 cm) – represents the phase of mineral-organic deposition (OM – 0.74–31.1%) in reducing conditions (Fe/Mn ratio >1000) and in the environment characterized by increased mechanical denudation (Na+K+Mg/Ca ratio – 0.2–0.8). This zone contains one level with increased concentrations of Na (up to 0.11 mg/g), K (up to 0.97 mg/g), Mg (up to 1.08 mg/g), Fe (up to 72.1 mg/g), Cu (up to 20.8 mg/g), Cr (up to 2.6 mg/g) and Ni (up to 160.2 mg/g). The maximum concentrations of these elements at the level of 2.07–2.09 m, correlated with mineral matter (Pearson correlation indicator r – 0.42–0.58), were probably the result of silting-up of the bottom organic layers.

With respect to bulk geochemical composition, the Chem-2 zone (194–68 cm) can be divided into three subzones:

Chem-2a subzone (193–186 cm) is the record of sedentation of autochthonous rock-forming matter of autogenic origin (increase of the OM content to 67%) and an associated change of mechanical denudation and redox conditions (decrease of lithogenic elements, Fe/Mn ratio and pH). An almost unrecognisable plant structure in the peat indicates sedentation of organic matter in the conditions of well-oxygenated water outflow.

Chem-2b subzone (185–125 cm) represents the phase of calcareous tufa deposition ($CaCO_3$ – up to 93%) in the spring mire. In this layer, the Ca content increases from 7 mg/g to 264 mg/g (the coefficient of variation of this element is 28%). The Fe/Mn ratio (mean value 339) indicates a change from reducing to oxidized conditions. A simultaneous increase in the $CaCO_3$/OM (to 15.8) and Ca/Mg (to 383) ratios indicates a considerably higher temperature and humidity of the environment and an increase in chemical denudation (Fig. 9).

Chem-2c subzone (124–68 cm) is the record of a dynamic change in the type of sedimentation – from tufa deposition to peat sedentation – which is also indicated by an abrupt increase of the OM (from 26 to 51%) and Fe concentrations (from 7 to 44 mg/g). This zone includes one level of decreased concentrations of Na (up to 0.02 mg/g), K (up to 0.01 mg/g), Mn (up to 0.03 mg/g) and Cu (up to 0.9 mg/g. On the other hand, the calcareous-rich layer ($CaCO_3$ – 24–83%) was deposited in oxidizing conditions (mean Fe/Mn ratio is 320) and in the environment characterized by decreased mechanical denudation (Na+K+Mg/Ca ratio < 0.1).

Chem-3 zone (67–0 cm) is the record of the sedentation of autochthonous rock-forming matter (increase of the OM content to 90%) and the associated change from chemical denudation to mechanical denudation (decrease of Na/K and Ca/Mg ratios) as well as the change in redox conditions (decrease of Fe/Mn ratio from 2980 to 35). The abrupt increase in the concentrations of some elements (Zn and Pb) and their negative correlation with mineral matter is evidence of the atmospheric supply of heavy metals.

RADIOCARBON DATING

The results of radiocarbon dating are presented in Table 5. They were calibrated using the *IntCal09* calibration curve and *OxCal v.4* software. The age-depth model has been con-

Table 4

Snails and bivalves in the WAR-2 core

E	TAXON	Samples								
		1.4–1.5 m	1.5–1.6 m	1.6–1.7 m	1.7–1.8 m	1.8–1.9 m	1.9–2.0 m	2.0–2.1 m	2.1–2.2 m	2.2–2.3 m
F	*Cochlodina orthostoma* (Menke)						3			
F	*Alinda biplicata (Mont.)*	4			1	2				
F	*Bradybaena fruticum* (Müll.)	2	2							
F	*Perforatella bidentata* (Gmel.)	10	5	4	6	4	3	5		
O	*Vertigo pygmaea* (Drap.)	12	3							
O	*Vallonia pulchella* (Müll.)	8	3							
M	*Cochlicopa lubrica* (Müll.)	7					1	1		
M	*Vertigo angustior* (Jeff.)	3	5	2	3			1		
M	*Punctum pygmaeum* (Drap.)	5					1	3		
M	*Vitrina pellucida* (Müll.)	1				1				
M	*Perpolita hammonis* (Ström.)	3	1	2	7	2	1	9		
M	*Limacidae*					1				
M	*Euconulus fulvus* (Müll.)	4				5		2	1	
H	*Carychium minimum* (Müll.)	5	4	2	4	2	3	4		1
H	*Succinea putris* (L.)	7	3		1					2
H	*Vertigo antivertigo* (Drap.)	1				1				
H	*Zonitoides nitidus* (Müll.)	5	3	3	4			5		1
T	*Radix balthica* (L.)								5	10
T	*Galba truncatula* (Müll.)	10	1		3			9	3	3
T	*Anisus calculiformis* (Standb.)							1	1	
W	*Pisidium casertanum* (Poli.)	5	11	3	8	4	8	84	8	12
Species	17	11	6	9	9	7	11	5	6	
Specimens	92	41	16	37	22	20	124	18	29	

E – ecological groups of molluscs: F – shade-loving species, O – open-country species, M – mesophilous species, H – hygrophilous species, T – aquatic species of intermittent water bodies, W – aquatic species of perennial water bodies

structed using a *P_Sequence* function (Bronk Ramsey, 2008; Fig. 10). The remaining dates indicate a varying accumulation rate. The age model is semi-linear and suggests minor changes in the environmental conditions throughout this time span. The mean rate of sedimentation, as determined by radiocarbon dates, is. 0.78 mm/year^{-1}. It fluctuates from low values of 0.38 mm/year^{-1} in the Subatlantic period (= peat sedentation) to quite high values of 1.6 mm/year^{-1} during the calcareous tufa deposition in the Subboreal period (Figs. 9 and 10).

STABLE ISOTOPES

Stable isotope measurement in carbonate deposits is a sophisticated technique, yet it remains difficult because of the complex nature of sedimentation being influenced by a number of physicochemical and biological processes (Valley and Cole, 2001). Generally, inorganic calcites precipitated in small continental basins are expected to be less varying in ^{18}O with water temperature in comparison with marine sedimentation because both the water of precipitation and the magnitude of the isotope fractionation between calcite and water should partly compensate for each other. We notice lower delta values in the water, but larger calcite-water isotope fractionation with the lowering of the environmental temperature. The compensation is not ideal and calcite ^{18}O is dominated by the variation of ^{18}O in environmental water. The study by Dansgaard (1964) estimates the effect for the water of precipitation is approximately –0.7‰ per one degree of temperature lowering, whilst the calcite-water fractionation grows by 0.3‰ per one degree (Epstein et al., 1953; Craig, 1965). Therefore, the net shift of ^{18}O in calcite deposited in continental water is about –0.4‰ per one degree.

The variability of ^{18}O along the WAR-2 depth profile (Fig. 11) was low, about 7‰. This points to relatively constant temperature conditions of calcareous tufa deposition in the Neoholocene. The only exception is the sample from the 150 cm level (ca. 3.5 ky cal BP), which provides evidence for a decrease of the environmental water temperature by about 2°C. During this event, we also recorded a peak in the production of biomass, as seen in Figure 11, and a lower rate of calcite deposition. In this period, the spring water temperature could have been as low as +4°C, assuming an average value of +6°C for the remaining interval.

^{13}C is difficult for interpretation, but it significantly correlates with ^{18}O in this level. On the similar basis we can try to asses a cold event 2.8 ky cal BP, where the temperature could have decreased by 1°C (Fig. 11).

DISCUSSION

The tufa-peat series are of substantial importance for the palaeogeographical analyses that seek to document the climate-habitat transformations. These changes are inscribed into the sequence and chemical composition of deposit series and

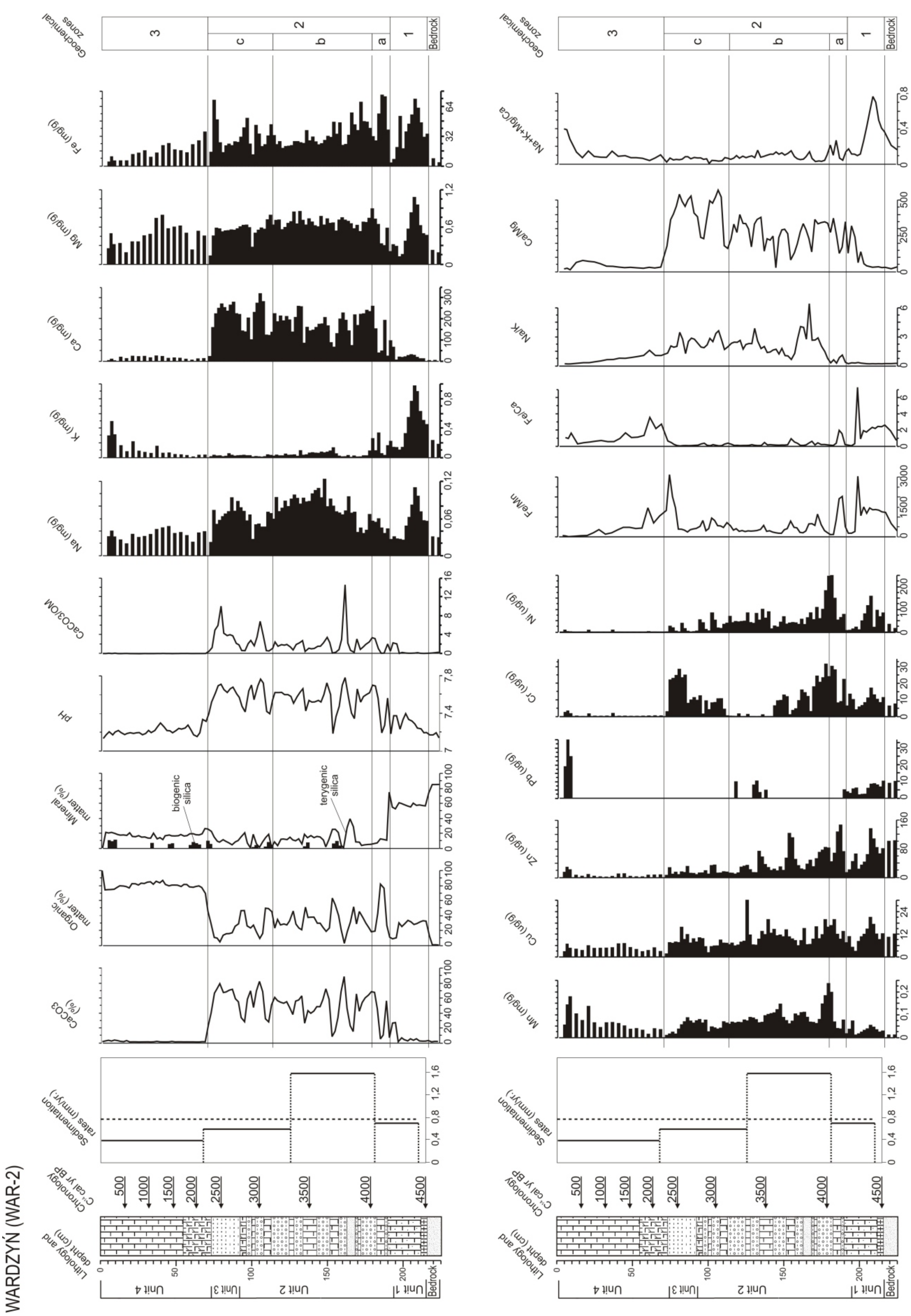

Fig. 9. Geochemistry of biogenic-carbonate deposits in the WAR-2 core

For lithology see Table 3

Table 5

Results of radiocarbon dating of peats from the War-2 core

No.	Sample name material	Lab. no.	T (^{14}C BP)	Calibrated Age (range 68%)	Calibrated Age (range 95%)
1	WAR-2/85	GdC-600	2480 ± 50	760 (23.1%) 680 cal BC 670 (45.1%) 520 cal BC	775 (84.9%) 475 cal BC 470 (10.5%) 410 cal BC
2	WAR-2/130	GdC-602	3265 ± 40	1610 (24.9%) 1570 cal BC 1565 (43.3%) 1495 cal BC	1635 (95.4%) 1440 cal BC
3	WAR-2/190	GdS-1260	3680 ± 75	2195 (4.7%) 2175 cal BC 2145 (63.5%) 1950 cal BC	2295 (95.4%) 1880 cal BC
4	WAR-2/210	GdS-1261	3950 ± 85	2575 (16.3%) 2510 cal BC 2505 (47.3%) 2330 cal BC 2325 (4.6%) 2300 cal BC	2850 (2.1%) 2810 cal BC 2745 (0.4%) 2725 cal BC 2695 (0.3%) 2685 cal BC 2680 (92.3%) 2195 cal BC 2165 (0.3%) 2150 cal BC

The dating was performed at the Gliwice Radiocarbon Laboratory

the succession of plant communities. A multidisciplinary approach to the study of spring-fed fens allows a closer look at the moment of the beginning of this ecosystem, and to draw deeper climatostratigraphic and palaeoenvironmental conclusions on a regional scale (Dobrowolski et al., 2002, 2016; Urban et al., 2011).

SPRING-FED FEN EVOLUTION

Phase 1 – middle part of the Subboreal (ca. 4400–4100 cal BP). The beginning of the formation of the fen dates back to the transition between SB 1 and SB 2 (*sensu* Starkel et al., 2013) and is related to the activation of an ascending water supply following a period of low groundwater levels. The seepage zone, which later became an area of springs with concentrated but relatively low discharge, formed a moderate limnocrenous water body with rich vegetation and a tendency to transform quickly into a helocrene, in which biogenic sediments of organic silt and sedge peat were accumulated. Geochemically, it is defined by a progressive increase of the concentration of major and trace elements. The limnocrenous, and subsequently helocrenous stages are confirmed by palaeobotanical (the occurrence of hydrophytes and telmatophytes – *Ceratophyllum demersum*, *Chara* sp., *Typha* sp, *Scirpus lacustris* and *Eriophorum angustifolium*) and malacological data (marked dominance of water species – *Radix balthica*, *Galba truncatulata* and *Pisidium casertanum).* The beginning of this phase is tied to the warm period of frequent rainfall and extreme geodynamic phenomena (Starkel et al., 2013), which occurred after an extended dry period related to the 4.2 ka event (Bond et al., 2001; Booth et al., 2005; Wanner et al., 2011). In the mire of Żabieniec, which, like the studied formation, is located in the Łódź Hills mesoregion, the extended dry period that ended the limnic phase of its development was followed by initiation of paludal processes (Forysiak et al., 2010). In Central Europe it resulted in an increase of water level in lakes (Ralska-Jasiewiczowa and Starkel, 1988; Magny, 2004; Kowalewski, 2014), and in enhanced dynamics of groundwater and improved discharge of springs, which created favourable conditions for mire development (Żurek, 1993; Żurek and Pazdur, 1999).

Phase 2 – crenous – (ca. 4100–2750 cal BP). The initial, relatively humid and warm stage of this phase was marked by an increase in the discharge of the springs providing water supply to the mire, and by the deposition of coarse- and medium-grained calcareous tufa. In the WAR-2 core this stage is evidenced by the occurrence of the peat-tufa rhythmite with the predominance of calcareous layers. The percentage of calcium carbonate increased to 93% in the profile, which was accompanied by a decrease in Fe values. The high Na/K (ca. 1.3) and Ca/Mg (ca. 350) ratio values indicate a supply of allogenic products of weathering of carbonate rocks to the mire by groundwater (Fig. 11). The sediments of the period contain the highest concentrations of trace elements as zinc, chromium and nickel within coarse- and medium-grained tufa. Very low values of the Fe/Mn and Cu/Zn ratios point to oxidizing conditions during the carbonate deposition, and the lithological properties of the sediments indicate a crenous sedimentary environment (Dobrowolski, 2011). The change in species composition of the malacological assemblages is the key quality in this regard. Aquatic species are represented almost entirely by *Pisidium casertanum* and constitute a secondary component of the fauna. The main role is assumed by terrestrial taxa, especially those related to highly humid environments (*Carychium minimum*, *Zonitoides nitidus* and *Perforatella bidentata*). Such a composition of the assemblage indicates a dominance of humid or even paludal terrestrial habitats. The copious presence of the latter species is a distinctive feature of shaded environments, most likely alder thickets, which is confirmed by the results of analyses of plant macrofossils. These communities were rich in reed (*Phragmites*), sedge (*Carex* sp) and brown moss. A poor species composition of herb pollen does not allow unambiguous determination of the presence of agricultural activity, nevertheless the increase in the values of *Artemisia* pollen and Polypodiaceae spores since ca. 3900 cal BP may indicate the presence of ruderal habitats and deforested zones in close proximity to the study site. This can be related to the expressions of the activity of the Trzciniec culture people in the Early Bronze Age (Twardy, 2008). In the sedimentological record of the remaining mires of the Łódź region, this phase is marked by a significant increase of the content of mineral matter in peat, which is interpreted as an effect of intentional deforestation and, in consequence, an increase in the intensity of erosion-denudation processes (Forysiak et al., 2011). The pollen diagrams of the cores from the Żabieniec site (Balwierz, 2010; Forysiak et al., 2010) and the Kopanicha and Polesie sites (Forysiak et al., 2011) display an unprecedented appearance of cereal pollen and pollen of species related to farmland activity and pasturing. In eastern Poland, this warm and humid period was manifested in many spring-fed fens by intense deposition of calcareous tufa (Dobrowolski et al., 2005, 2016).

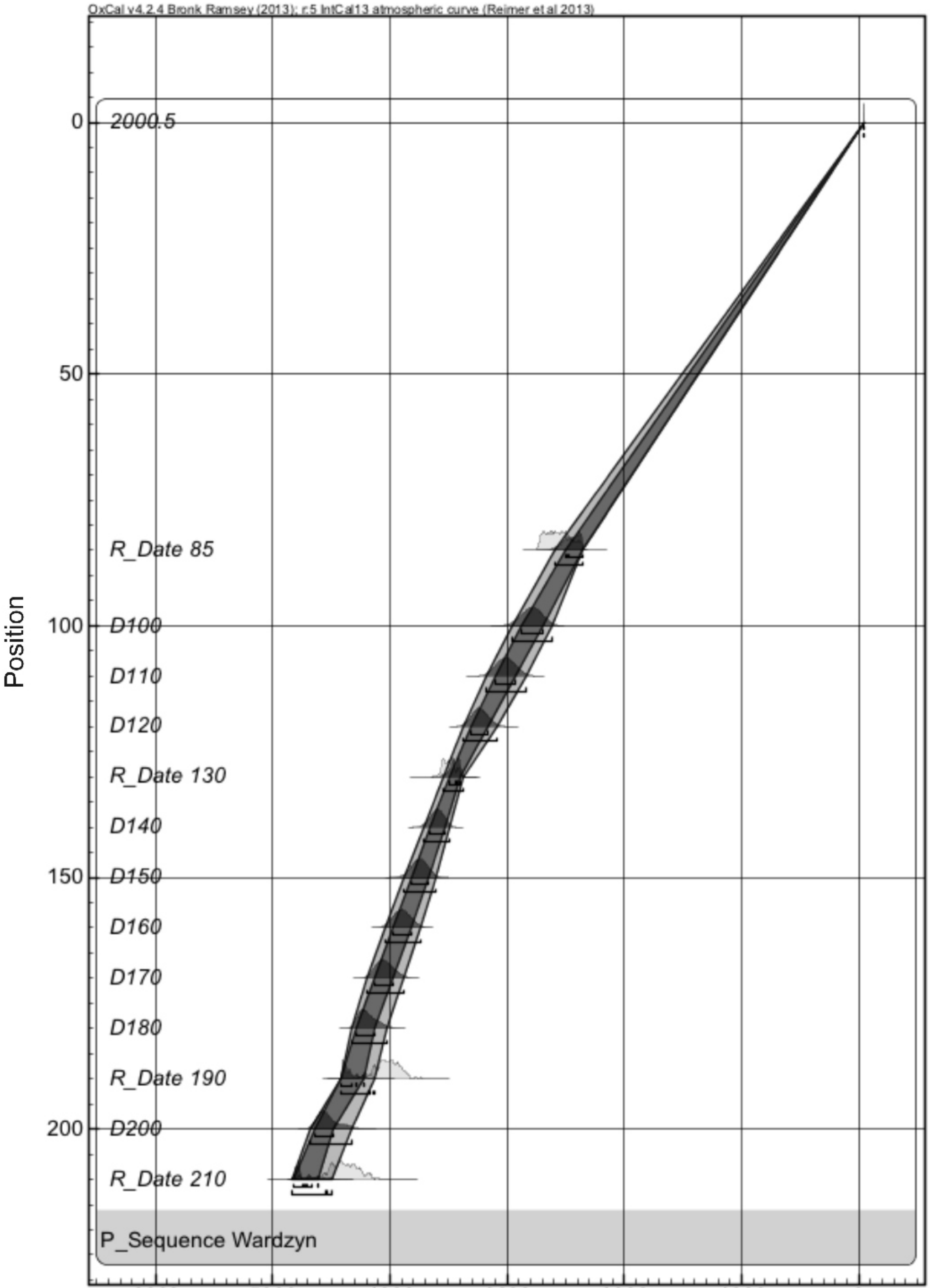

Fig. 10. The age-depth model for the WAR-2 core

Grey-shaded zones represent calibrated radiocarbon ages;
darker areas – 68.4% probability, brighter colours – 95.4% probability

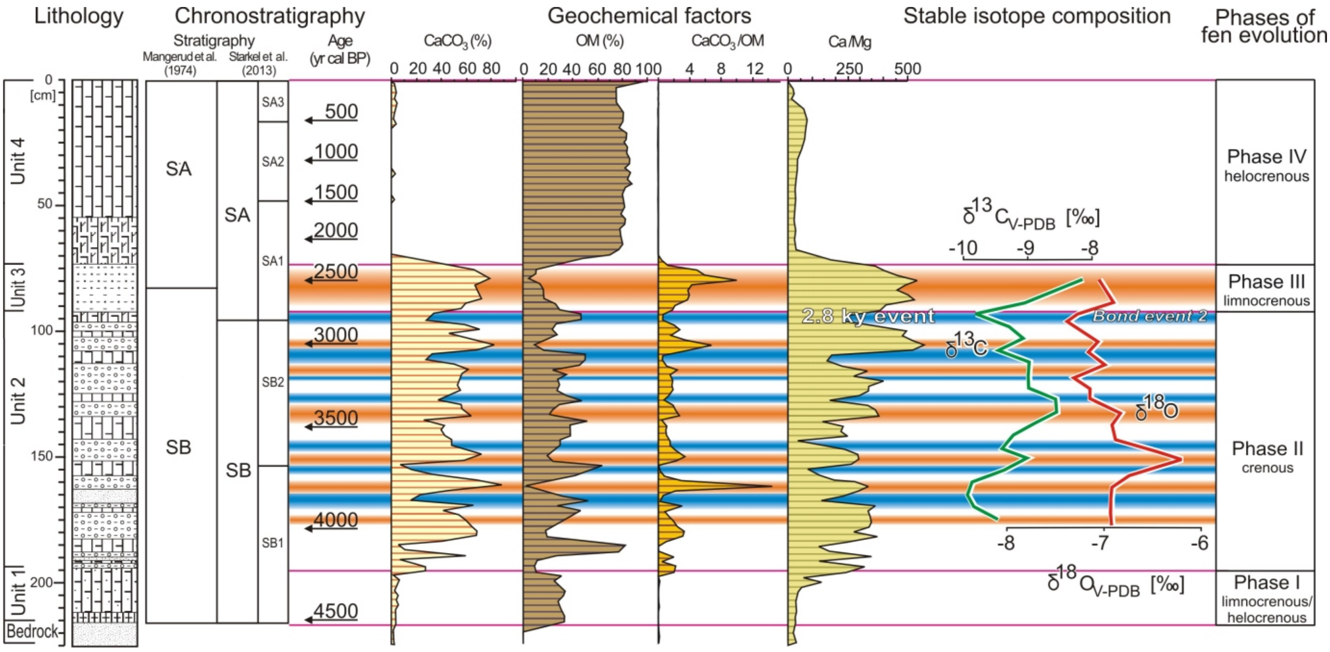

Fig. 11. Isotope composition of calcareous tufa from the WAR-2 core, in comparison with the lithology, chronology and selected chemical compositions

Blue-shaded areas mark the "cold phases" during the Neoholocene; orange-shaded areas mark the "warm phases" of the period; for lithology see Table 3

The period of 3150–3000 cal BP marks a clear drop in the humidity-temperature conditions and carries a resulting decrease of the discharge of springs. Lead appears again in the geochemical circulation (slightly above 0.01 mg/g), with a simultaneous lack of chromium in the sediments. Moreover, the high variability of the content of terrigenous silica (0.5–22%), the increase of the content of biogenic silica (up to 10%), and the increased concentration of copper (up to 0.36 mg/g) in the sediments can be caused by human impact. The palynological and macrofossil record of that time reflects the peak development of alder communities (initially with spruce) which, at certain intervals, eliminated the telmatic plants, such as reeds, sedges and bogbeans. The climate condition deterioration at that time was recorded in central Poland (Ralska-Jasiewiczowa et al., 1998; Forysiak et al., 2010; Pawłowski, 2010; Starkel et al., 2013) and, on a broader regional scale, encompassed Central and Northeastern Europe (Magny, 2004; Väliranta et al., 2007).

This relatively dry and cool period was followed by an improvement of humidity-temperature conditions, expressed by an increase in the discharge of springs. In the WAR-2 region, it is documented by the presence of inserts of coarse-grained tufa in highly decomposed sedge peat. The appearance of tufa layers in the peat is a presumptive record of relatively more humid episodes within the overall regional trend of decreasing humidity. The variability of the groundwater outflow is considered the most important cause behind the changes in the ecological conditions in the spring niches, which reacted rapidly to the changing humidity-temperature conditions of the surrounding ecosystem (Mazurek, 2010). The chemical composition of the sediments is dominated by calcium carbonate with a mean content of over 50%. The iron, calcium, chromium and nickel contents show the highest variability. This points to intense leaching of the rocks in the infiltration area. Chromium and nickel are elements that are most difficult to activate. Moreover, the activation occurs at the latest time as compared with other trace elements (Kabata-Pendias and Pendias, 1979).

A relatively cool and dry episode in the history of the spring-fed fen, present in the records of all proxies, appears in the period of 2800–2750 cal BP (Fig. 11). It documents a considerable decrease in the intensity of land-forming processes in the vicinity of the ecosystem. It is most likely related to the Bond event 2, which is widely renowned as one of the most frequently reported events correlated with specific proxy time series. It was probably influenced by a Grand Solar Minimum (Wanner et al., 2011). The 2.8 ka event is also the formal boundary between the Subboreal and Subatlantic chronozones of the Holocene (Starkel et al., 2013). In the WAR-2 core (Fig. 11) it is recorded as a sudden decrease in the intensity of carbonate deposition (the content of $CaCO_3$ drops below 30% with the simultaneous considerably higher content of autochthonous organic matter of ca. 45%) and the minimum of the ^{18}O curve (dependent on the mean annual temperature and humidity) and of the ^{13}C curve (related to the water temperature and the escape rate of CO_2 released by vegetation to the atmosphere). Both the ^{13}C and ^{18}O values changed simultaneously during the period. This dry and cool phase has been widely noted in the Polish mires to have occurred between 2900 and 2500 cal BP (Żurek et al., 2002). In a more constricted period (2910–2750 ca BP) it was also present in spring-fed fens of eastern Poland (Dobrowolski et al., 2016).

Phase 3 – limnocrenous – ca. 2750–2200 cal BP. The beginning of this phase, which corresponds to the transition between the Subboreal and Subatlantic periods, marks a significant improvement of temperature-humidity conditions, recorded in the WAR-2 core as a considerable increase in the ^{13}C and ^{18}O values (Fig. 11).

The evolution of the Wardzyń fen in the years 2750–2200 cal BP brought about the reactivation of springs (of relatively low discharge) and consequently caused its transformation into a moderate limnocrenous water body, in which silty calcareous tufa was deposited. The limited discharge of springs and the resulting rapid warming-up of water are accepted by many authors as a set of optimal conditions for the deposition of calcareous sediments (Prusinkiewicz and Noryśkiewicz, 1975; Beczała et al., 2010). It is most likely that the changing climate conditions at that time were supplemented by an increasing pressure due to human agricultural activity in the recharge area of the spring-fed fen in Wardzyń. It appears within the palynological record as an increased frequency and diversity of photophilous taxa. The hygrophytic species such as *Menyanthes trifoliata*, *Thelyptris palustris* and *Equisetum fluviatile* once more appear among the macrofossils; the proportion of *Phragmites* increases as well. The geochemical record of the human impact at the transition between the Bronze Age and the Iron Age is displayed as a twofold increase in the concentration of nickel, zinc and potassium with a simultaneous relatively high level of chromium and copper.

The beginning of the Subatlantic manifested itself in many mires of Central Europe as a change in the water balance (Ralska-Jasiewiczowa and Starkel, 1999; Forysiak, 2012). An increased supply of rainwater in that period results in the appearance of peat-forming communities adapted to an increasingly poor trophic state (Kloss and Żurek, 2010). This phenomenon applies to the region of Łódź as well, including the close vicinity of the study site. In the Świątniki mire, situated ca. 20 km south-east of Wardzyń (see Fig. 1 for location), an extended stagnant period is followed by reactivation of peat accumulation (Turkowska, 2006). At the same time, a vast improvement of humidity conditions is recorded in the Żabieniec mire (see Fig. 1 for location; Forysiak et al., 2010).

Phase 4 – helocrenous – from 2200 cal BP to Present. The final stage of the evolution of the spring-fed fen is related to the dwindling of spring activity in the cupola of the mire, its paludification and further development as a helocrene. The deposition of tufa came to a halt in ca. 2250–2200 cal BP, which had been caused by a relatively cool and dry climate and, in consequence, a smaller supply of the products of chemical denudation. The sedimentary environment underwent a full transformation. The process of chemogenic deposition of carbonates was converted into autochthonous sedentation of organic matter. In the geochemical record, it is documented by an increase in the Fe/Mn ratio with a concurrent drop in the Ca/Mg ratio (Figs. 9 and 11). The sedentation of organic matter occurred in conditions of high biological productivity (increase in the content of biogenic silica to 10%), with a simultaneous lack of deposition of calcium carbonate and an increase in the Fe/Ca ratio and heightened supply of lithophile elements towards calcium in the early phase. The reason behind this situation was not only the increase in anoxic conditions, but also the increased solubility of manganese, nickel and calcium in a more acidic environment. A similar change in the depositional conditions at that time was documented in the Radzików spring-fed fen in eastern Poland (Dobrowolski et al., 2012).

This final phase of the fen evolution is distinctly marked by signs of anthropogenic pressure inflicted upon its ecosystem. Its initial phase is connected to the activity of the Przeworsk culture people in the Roman period (Błaszczyk, 2000; Twardy, 2013). This fact is displayed in the pollen diagram as a higher frequency of pollen of herbaceous taxa, including ruderal and cultivated ones, as well as spores of *Pteridium aquilinum* and Polypodiaceae. The record of macrofossils is highly dominated by *Alnus* and *Phragmites* with an admixture of *Carex* sp., *Thelypteris palustris* and *Menyanthes trifoliata*, without brown mosses.

The increase in the potassium, sodium and magnesium contents, dated ca. 1200 cal BP, may have probably resulted from slight deforestation of the area adjacent to the fen in the Early Middle Ages, as suggested by archaeological data. There are several settlement sites discovered in the upper Wolbórka River catchment, which date to this period (Błaszczyk, 2000). Another increase in the potassium content, pointing to increased erosion in the catchment area, took place ca. 700 cal BP. It presents a record of repeated intense deforestation of the upper part of the catchment area, which serves as an infiltration area that feeds the fen with groundwater. Historical sources connect this period to the establishment of the neighbouring villages, including Wardzyń and Pałczew (see Fig. 1). Archaeological (Błaszczyk, 2000) and other historical data (Baruch, 1992) suggest that in the Late Middle Ages was the period of most intensive settlement activity in this area.

Generally, the WAR-2 core data shows the last two millennia were characterized by relatively lower humidity, accompanied by relatively stable temperature conditions. Similarly, very stable climate conditions of the last two millennia are indicated by multiple data sources in the adjacent Żabieniec mire (Lamentowicz et al., 2009), as well as in the lakes of central (Ralska-Jasiewiczowa and Starkel, 1999) and northern Poland (Gałka and Apolinarska, 2014).

ORIGIN OF ALKALINE MIRES –
A REASON FOR NEOHOLOCENE ASCENSION

Climate changes vs. human impact. The spring-fed fens in Wardzyń are relatively young in comparison with other such formations in the Polish Lowlands (Dobrowolski et. al., 2002, 2005, 2012, 2016; Osadowski et al., 2009; Urban et al., 2011; Mazurek et al., 2014). Thus, their originis dissimilar from previously described ones, in which the spring-fed fens were related to the permafrost degradation during the Late Glacial/Holocene transition. Even though the mechanism of unlocking the vertical, forced circulation of water appears to be similar, both its time constraints and the initiating factor for artesian waters are fundamentally different. The beginning of the activation of ascension that enabled the development of the spring-fed fens in Wardzyń is dated to have occurred at the beginning of the fourth millennium, so immediately after a well-documented period of decreased humidity (drier climate) in the Northern Hemisphere, referred to as the 4.2 ka event (Magny, 2004; Wanner et al., 2011) or Bond event 3 (see Bond et al., 2001). It is quite unanimously accepted that it was one of the most severe climatic events of the Holocene period in terms of the impact on cultural upheaval on a global scale (Booth et al., 2005; Roland, 2012; Roland et al., 2014). It is recorded much more visibly in areas of continental climate (e.g., Northern and Eastern Europe), than it is in more oceanic ones (e.g., Western Europe), where its palaeoclimatic interpretation could often be dubious (Hughes et al., 2000; Swindles et al., 2013; Dobrowolski et al., 2016).

The record of the cores from the biogenic sediments of the mires neighbouring the Wardzyń site contains evidence of permanent transition from the lacustrine to the paludal phase in this period (Pawłowski, 2010; Forysiak et al., 2010), or the appearance of clearly marked strata of highly decomposed peat often with increased content of mineral matter (Forysiak, 2012; Pawłowski et al., 2016). In both cases, a significant and relatively permanent drop in the groundwater level, resulting from the gradual climate drying, is quoted as the cause. Hence, it would be advisable to acknowledge consistently that the climatically induced lowering of the groundwater table in Wardzyń was responsible for the decreased water supply from the shallow aquifers to springs and the increased contribution of water from the deeper, Mesozoic aquifer. In theory, however, an identical hydrological effect could be explained by anthropopressure resulting in a decrease of forest cover, limited retention, and intensified water circulation. For example, in the Western Carpathians, there are open spring fens of age similar to the alkaline fens described in this article. Their formation is unanimously ascribed to the human impacts on the landscape, as an effect of tree cutting and/or burning (Hájková et al., 2012). Former archaeological studies of the region, however, display a lack of explicit correlation between the genetic and temporal factors, that influenced the formation of the spring-fed fens in Wardzyń, and the anthropogenic factor. The point of activation of the artesian springs occurred in the Late Neolithic, an age very poorly documented throughout the Łódź region. Even the Early Bronze Age is represented only by a few sites of the Trzciniec culture dated ca. 3900–3500 cal BP (Gąsior, 1975; Papińska, 2002), located mainly in valleys and adjacent areas of the largest rivers in the region (Twardy, 2013). As for the relatively close proximity to the Wardzyń site, the only cases of anthropogenic activity at the time have been recorded in the Pilica River valley and the mouth section of the Wolbórka River (Błaszczyk, 2000), about 5 km to the south-east of the study area, that is, downstream of the recharge zone of the fen. The upper Wolbórka River catchment most likely was not heavily utilised by man, which probably excludes deforestation as a factor that could influence the reorganization of the water circulation in the upper part of the catchment. The first traces of settlement activity in the study area are related to the Middle Bronze Age (multiple sites of the Lusatian culture) dated at ca. 3300–2400 cal BP. Therefore, it was the presence of active springs that initiated the settlement rather than the settlement was the cause of significant transformation in the water supply of the upper aquifers.

Mechanism of Neoholocene ascension and calcareous tufa deposition. Despite the fact that several separate springs of varying discharge and hydrochemical characteristics have been identified in the Łódź Hills (Burchard and Maksymiuk, 1997; Burchard and Ziułkiewicz, 1999; Ziułkiewicz, 2000, 2005, 2010), only the Wardzyń site allows to documenting tufa sediments that can be connected to currently active outflows (Ziułkiewicz et al., 2012).

Contemporary ascension zones of the waters from Upper Cretaceous deposits shield the Łódź Hills from the north (Bzura River valley), west (Ner River valley) and south-east (Wolbórka River valley). The recharge zone of the Upper Cretaceous aquifer stretches from the NNW to SSE along the intersection border of the Łódź Basin. However, the properties of carbonate rocks do not always permit the water supply from their Cenozoic cover. The effective recharge zones are then visibly spatially limited, even more so if taking into consideration the fact that the Wartanian tills and Paleogene clays (the common Cenozoic deposits) impede the infiltration of the Upper Cretaceous massif by water. These conditions have led to a situation in which the top parts of the Cretaceous deposits contain waters that was infiltrated at the beginning of the Holocene (Ziułkiewicz, 2003). Demonstrably better conditions for infiltration occur in the outcrops of Lower Cretaceous deposits. Therefore, the groundwater of those aquifers is significantly younger (Ziułkiewicz, 2003).

The origin of the springs in the Łódź Hills, one of the most spring-rich regions of central Poland (Maksymiuk and Mela, 1995), is often ascribed to the improvement of climate conditions in the Eoholocene and the consequent full degradation of extraglacial permafrost. At that time, the rising groundwater level reached the bottom parts of denudation valleys and led to the activation of descending outflows of spring water (Krzemiński, 1989). The western borders of the former proglacial valley with an outlet into the Wolbórka ice-marginal valley in the Wardzyń region also became an area of spring activity. Contrary to the other spring areas of the Łódź Hills, these springs appeared in close proximity to the regional drainage area of the Upper Cretaceous aquifer.

The Wardzyń springs are recharged by water from the intermoraine Quaternary aquifer (Moszczyńska, 1986; Ziułkiewicz et al., 2012) that currently displays in this area a large hydrochemical similarity to the Upper Cretaceous aquifer despite its different lithology of the water-bearing rocks (Tables 1 and 2). Therefore, the sealing layer of Paleogene deposits that occur between the two aquifers cannot be impermeable despite their widespread occurrence accompanied by a high lithofacies and thickness diversity (Olczak, 1994; Fig. 3). It is also necessary to take into account the occurrence of faults at the top of the Mesozoic complex, which are genetically related to the Alpine orogenic cycle (Marek, 1977) and Cenozoic halokinesis of the Tuszyn salt dome (Dadlez, 1998; Fig. 3). Moreover, the Quaternary cover contains discontinuity deformations resulting from the compression stress in the marginal zone of the Wartanian glaciation (Turkowska, 2006; Jaskulski, 2015) and tension stretching after its recession. The proof of this activity is the graben of the upper Ner River near Wardzyń (Trzmiel and Nowacki, 1987).

The pressure distribution in the hydraulic head of both aquifers in relation to the ground level makes the water table of the Wolbórka River valley stabilize at a level above the surface. The groundwater level in the Quaternary aquifer, on the other hand, relates to the contemporary drainage system. The Wardzyń springs are located adjacent to a zone where the Upper Cretaceous groundwater assumes artesian properties. Thus, it can be surmised that it constitutes an area where water from both aquifers mixes above the discontinuity of the sealing layer in the immediate vicinity of the regional drainage zone.

Hydrodynamically and lithogenetically, it is vital to attempt to determine the reasons behind the activation of the Neoholocene ascension that initiated the development of the spring-fed fens in Wardzyń. There is no doubt that total degradation of permafrost at the LG/H transition brought about conditions hypothetically advantageous for the unlocking of vertical circulation in groundwater. With favourable hydrogeological conditions, the initiation of the ascending water supply may have occurred and involved the Cretaceous aquifer waters. Unfortunately, there is little unambiguous evidence to support the theory of the Early Holocene ascension in the study area. It occurs only at the turn of SB 1 and SB 2 (*sensu* Starkel et al., 2013) following an extended dry episode – the 4.2 ka event. The origin of this event has been linked to ocean-atmospheric circulation changes in the North Atlantic (Bond et al., 2001; Booth et al., 2005). In the unique hydrogeological situation of the Łódź Hills, i.e. a considerable age difference between the waters of the two aquifers, it appears that the duration of the water deficiency determined the increase in the intensity of mixing of the waters of the Quaternary and Upper Cretaceous aquifers. Because of the presence of hydrogeological windows, the supply of water in the ascension zones was supplemented by waters from carbonate deposits, which, in turn, propagated the change in the structure of the mixture of the waters of the Mesozoic and Cenozoic aquifers. The mixing of waters with a common ion may have resulted in the state of supersaturation with calcium carbonate (Janiec, 1989/90). The prolonged dry period, along with an extreme restriction of the frequency of episodes of intense infiltration supply, may have caused a situation that, according to Kresic and Bonacci (2010), increased the importance of “old” waters acquired by a spring from deeper parts of the aquifer. The decrease of pressure in the recharging aquifer led to the water stagnation at the outflows, and paludization of the spring zones. The retention period for the water within the spring niches was increased, which could have been another destabilizing factor for the carbonate balance of the supersaturated solution by introducing the biochemical activity of phytoplankton and submerged macrophytes.

CONCLUSIONS

The results of interdisciplinary studies have allowed determining the broad geological and hydrogeological context of the beginning and functioning of soligenous alkaline fens of the Wardzyń site. The main morphogenetic and palaeogeographical conclusions resulting from the multi-proxy studies of the spring-fed fens in Wardzyń are as follows:

1. The Wardzyń spring-fed fens are unique among lowland springs because of their relatively young initiation of Neoholocene development. Their origin is different from previously described spring-fed fens, being an effect of the permafrost degradation during the Late Glacial/Holocene transition.
2. The beginning of the activation of ascension at the Wardzyń site occurred immediately after the well-documented episode of decreased humidity (climate drying) in the Northern Hemisphere, referred to as the 4.2 ka event (Bond et al., 2001; Booth et al., 2005). The duration of the water deficiency presumably determined the intensity of mixing of the waters of the Quaternary and Cretaceous aquifers, and, following the improvement of humidity conditions, served as the initiating and sustaining factor of ascending water supply.
3. Archaeological records (lack of traces of intensive human activity in the Neolithic Age) exclude the anthropogenic, intentional cause of activation of the Neoholocene ascension in this area. The first evidence of settlement activity at the study site is related to the Middle Bronze Age, a period almost a thousand years after the activation of the artesian springs.
4. Four main phases can be distinguished in the evolutionary history of the fen. These include two limnocrenous phases, separated with a crenous one, and the contemporary helocrenous phase that ends the spring phase of the fen functioning. The variability of environmental conditions accompanying the development of the fen, recorded by the variation in the lithofacies and other proxies, was related to a change of the artesian supply resulting from the Neoholocene humidity-temperature fluctuations, as well as the human impact of the last three millennia.

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