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Mazovian Interglacial sites in the Sosnowica Depression and the Parczew-Kodeń Heights (Western Polesie, SE Poland), and their stratigraphic, palaeogeographic and palaeoenvironmental significance

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We describe the geological context of the Pleistocene strata in the Sosnowica Depression and the Parczew-Kodeń Heights, as well as the main geological processes taking place in that area during the Middle Pleistocene. The stratigraphy of the Pleistocene succession is based on the analysis of new sites with Mazovian Interglacial deposits (MIS 11c) with age determinations obtained from palaeobotanical and palaeofaunal proxies, at Zahajki, Wygnanka, and Sytyta in the Sosnowica Depression, and Podedwórze and Gęś 3 in the Parczew-Kodeń Heights. The interglacial deposits documented occur in the direct subsurface and are not overlain by glacial deposits, which indicates that the study area was not covered by the ice-sheet of the Middle Polish Glaciations (Saalian, MIS 6). They are overlain by Early Liviecian (Fuhne, MIS 11b) lacustrine and bog deposits, or upper Vistulian (MIS 2) clastic and bog deposits. Holocene strata lie above. Therefore, the glacial deposits building the Parczew-Kodeń Heights are considered to derive from the Sanian 2 (Elsterian, MIS 12) Glaciation and not from the Saalian (MIS 6) Glaciation as previously thought. Palaeolakes formed in the late part of the Sanian 2 (Elsterian, MIS 12) Glaciation and remained open during the Mazovian Interglacial (Holsteinian, MIS 11c), with some still existing until the Early Liviecian (Fuhne, MIS 11b) Glaciation. The palaeolakes described were part of an extensive palaeolakeland of the Mazovian Interglacial, stretching from the southern part of Podlasie to the northern part of Western Polesie. The last ice-sheet in Western Polesie represented the Sanian 2 Glaciation.

Key words: Mazovian (Holsteinian) Interglacial (11c), palaeogeography, stratigraphy, palaeoenvironment, western Polesie, SE Poland.

INTRODUCTION

Geological and palaeobotanical studies documenting the Mazovian Interglacial succession in the Sosnowica Depression and the Parczew-Kodeń Heights (Hrynowiecka et al., 2014; Żarski and Morawski, 2019; Pochocka-Szwarc et al., 2021; Pochocka-Szwarc, 2023; Pochocka-Szwarc and Żarski, 2023; Żarski et al., 2023a, b) conducted in the last decade have sup-

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plied new data for the reconstruction of the geological setting and constraining the range of ice-sheets during the last advance of the Middle Polish Glaciations (Saalian, MIS 6). The results of these studies allow reconstruction of the palaeogeographic and palaeoenvironmental evolution of Western Polesie from the late Middle Pleistocene.

This is the first thorough revision of the age of the deposits building the subsurface in the northern part of Western Polesie based on new geological and palaeobotanical data since the studies of Zaborski (1927), whose concept of the Pleistocene geological history of the area has remained unchanged for nearly a century.

The Sosnowica Depression (Richling et al., 2021) is a flat, parallel depression, 50 km long and 24 km wide, located between the Middle Bug Valley and the Tyśmienica Valley in the west (Fig. 1). The surface of the depression lies at an elevation of 152–155 m a.s.l., which is several tens of metres lower than the surface of the Włodawa Heights bounding the depression to the south.

The Parczew-Kodeń Heights are several to over ten metres higher than the surface of the Sosnowica Depression. They represent a denudated post-glacial plateau, incised by wide depressions used at present by rivers and a channel system (Figs. 1 and 2). Both physiographic units are situated in the northern part of Western Polesie. Polesie is a vast geographic area which continues farther into Ukraine and Belarus along the Pripyat Valley for ~700 km to reach the Dnieper River.

We describe a new geological model for the Sosnowica Depression and the Parczew-Kodeń Heights, and reconstruct the palaeogeography and palaeoenvironment in the later part of the Middle Pleistocene, based on sites with Mazovian Interglacial deposits subjected to palaeobotanical and palaeontological analyses. It includes the detailed geology and results of palaeoecological analyses for 5 new sites with Mazovian deposits in

Digital Terrain Model developed by M. Pielach

sites of Mazovian Interglacial deposits with palaeobotanic documentation

Gęś 3 study sites of Mazovian Interglacial deposits with palaeobotanic documentation

Fig. 1. Location of the study area with sites of documented Mazovian Interglacial deposits in Western Polesie

Maciejowice (Albrycht et al., 1997; Brzezina, 2000); Zakrze (Albrycht et al., 1997); Celiny, Czerśl, Świderki, Świdry, Kolonia Świdry, Sarnów, Gołąbki, Kolonia Sarnów, Domaszki (Małek and Pidek, 2007); Adamów, Hermanów, Kolonia Bystrzycka, Wólka Domaszewska (Żarski, 2008, 2009; Żarski et al., 2009; Hrynowiecka et al., 2019); Przytulin (Żarski et al., 2009); Skrzynka (Żarski, 2008; Górecki et al., 2022); Zalesie, Lachówka Mała, Lipnica (Nitychoruk, 2000); Woskrzenice, Grabanów, Kaliłów (Bińka and Nitychoruk, 1995; Nitychoruk, 2000); Hrud (Lindner et al., 1991a; Nitychoruk, 2000; Szymanek, 2012); Ossówka (Nitychoruk et al., 2005, 2018); Biała Podlaska (Krupiński, 2000); Ortel Królewski (Albrycht et al., 1995; Szymanek et al., 2005, Czajkowska, 2022); Szymanowo (Szymanek, 2014); Rossosz (Albrycht et al., 1995; Krupiński, 2000); Kępa, Przymiarki, Kolonia Charlejów (Żarski et al., 2009); Poznań (Winter, 1991); Krępa (Jesionkiewicz, 1982); Annopol (Żarski, 2008); Kasyldów, Wola Okrzejska (Żarski et al., 2005); Serniki (Łozińska-Stępień et al., 1985); Korolówka, Wyryki (Żarski et al., 2023b); Ignaców (Hrynowiecka et al., 2014); Włodawa (Żarski et al., 2023b); Suszno (Stachurska, 1957, 1961; Żarski et al., 2023a); Dobropol (Hrynowiecka et al., 2014); Brus (Pidek, 2003; Hrynowiecka and Pidek, 2017)

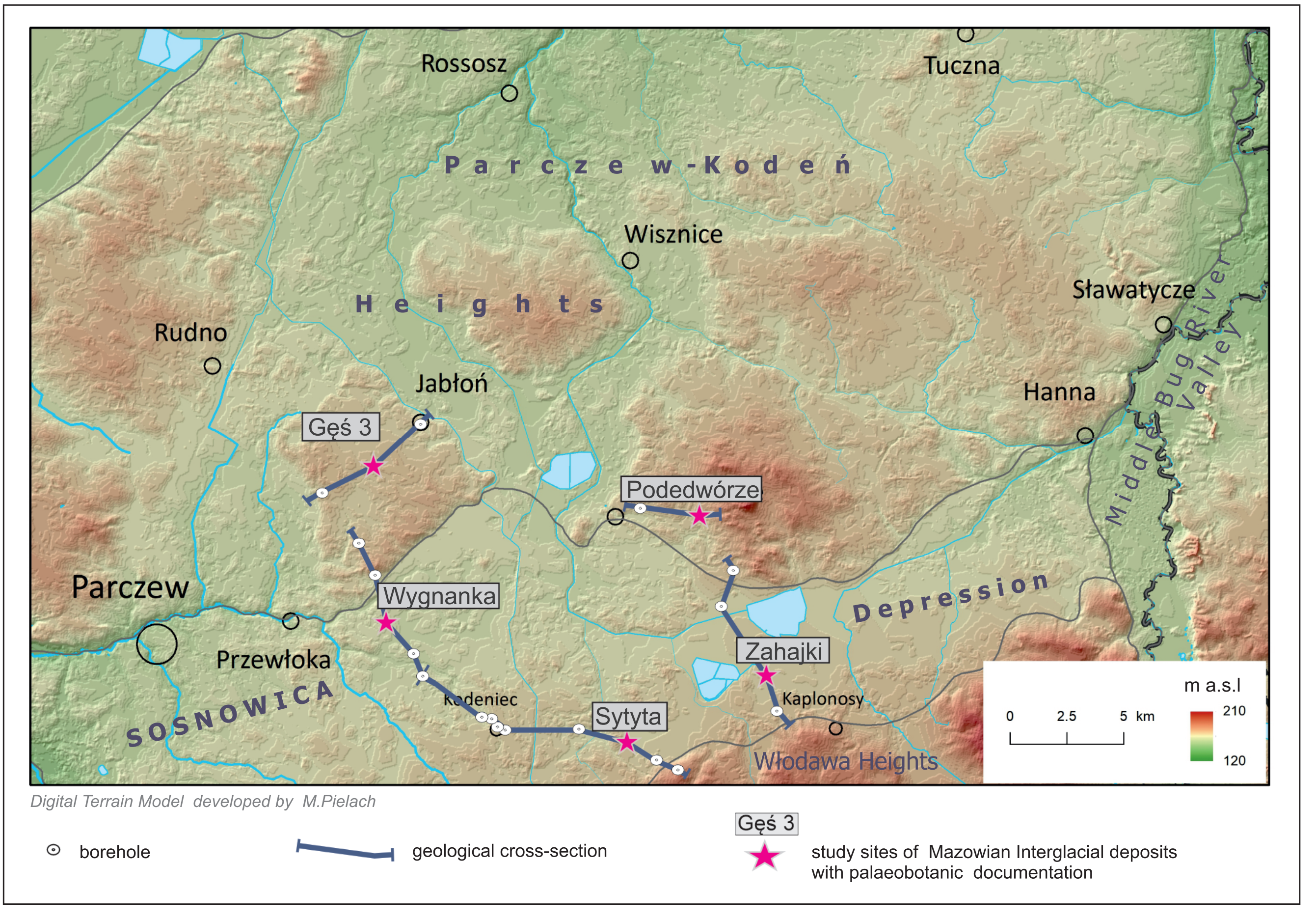

Fig. 2. Location of the sites studied (with location of geological cross-sections)

the Sosnowica Depression (Wygnanka, Zahajki, and Sytyta) and the Parczew-Kodeń Heights (Podedwórze and Gęś 3; Fig. 2), in the context of other documented sites of the interglacial (Fig. 1). Palaeobotanical studies have allowed reconstruction of the history of climate change from the end of the Sanian 2 (Elsterian, MIS 12) Glaciation, through the Mazovian (Holsteinian, MIS 11c) Interglacial, to the early part of the Liviecian (Fuhne, MIS 11b) Glaciation in Western Polesie.

REVIEW OF EARLIER STUDIES

Studies of post-glacial deposits and forms in Western Polesie go back to the early 1900s (e.g., Tutkovskiy, 1902, 1904, 1911; Gagel, 1922; Wołłosowicz, 1922, 1924), when they were documented to reconstruct the ice-sheet coverage of the area.

The first relatively detailed geological setting and palaeogeographic evolution of Polesie and Podlasie, including the study area, during the Middle Pleistocene was developed by Zaborski (1927). According to him, Western Polesie was covered for the last time by the ice-sheet of a Middle Polish Glaciation, precisely the "Middle Polish moraine" (Sawicki, 1922), which is presently correlated with the Odranian Glaciation by Lindner et al. (2013) and the Warthe/Drenthe in the western European stratigraphic scheme (Cohen and Gibbard, 2019; Table 1). Both approaches refer the glaciations to Marine Isotope Stage 6 (Saalian, MIS 6) after Lisiecki and Raymo (2005).

Zaborski (1927) distinguished the Maximum Stadial of the Middle Polish Glaciation, the range of which was depicted ~50 km to the south of the study area near Chełm. A recessive stadial (Podlasian) recorded by terminal moraines was distinguished by Zaborski (1927) along the Siedlce-Łosice-Kornica line, i.e. ~120 km to the north of the maximum range. Later, the Maximum Stadial of the Middle Polish Glaciation was elevated to the rank of an individual Odranian Glaciation (MIS 8), while the Podlasian Stadial was correlated with the Wartanian Glaciation (MIS 6) (Jersak, 1973; Różycki, 1980; Harasimiuk et al., 2004; Terpiłowski, 2001; Terpiłowski et al., 2021).

In the most recent stratigraphic scheme (Marks, 2023a, b), the upper part of the Middle Pleistocene as the Middle Polish Complex (MIS 6) corresponds to the Odranian Glaciation correlating with the Saalian in the Western European scheme (Table 1).

The concept that Western Polesie was covered by the ice-sheet of the Middle Polish (Odranian) Glaciation continues until the present and is repeated in numerous publications (Jahn, 1956; Trembaczowski, 1957, 1968; Mojski and Trembaczowski, 1961, 1973; Lindner et al., 1985; Buraczyński, 1986; Dolecki et al., 1987, 1991, 1994; Dolecki and Wojtanowicz, 1992, Buraczyński and Wojtanowicz, 1980/1981; Lindner and Marks, 1995,1999; Lindner, 2005; Ber et al., 2007). A similar view that Polesie was covered by the ice-sheet of the Dnieperian 2 (Saalian, MIS 6) Glaciation in Belarus and Ukraine has been stated e.g., by Lindner et al. (1991b, 2004, 2007), Lindner and Marks (2007) and Gozhik et al. (2012). Marks et al. (2018)

Table 1

Chronostratigraphic correlation of the Middle and Upper Pleistocene between: NW Europe (Litt et al., 2007; Head and Gibbard, 2015); Alps (Penck and Bruckner, 1901/1909); SE Poland (Lindner et al., 2006, modified; Marks et al., 2016, modified); Belarus (Velichkevich et al., 2001), and Ukraine (Lindner et al., 2004, 2006, 2007)

Age [ka BP]	Stratigraphy		NW Europe	Alps	SE Poland	Belarus	Ukraine	MIS
11.7	Holocene		Holocene	Holocene	Holocene	Holocene	Holocene	1
130	Upper Pleistocene		Weichselian	Würm	Vistulian	Poozierian	Valday	2-5d
			Eemian	Riss/Würm	Eemian	Muravian	Pryluky	5e
	Middle Pleistocene	Saalian Comlex	Warthe + Drenthe	Riss II	Odranian (Odranian+Wartanian)	Pripyatian (Dnieperian+Sozhian)	Dnieperian 2	6
			Schöningen	R I/R II	Lublinan	Shklovian	Kaydakay	7
			?	Riss I	Krznanian*	?	Dnieperian 1	8
			Dömitz-Wacken	Pre-R/R I	Zbójnian	Smolenskian	Potagylivka	9
			Fuhne	Pre-Riss	Liviecian*	?	Orelian	10
					Early Liviecian*	?		11a-11b
		Holst.	Holsteinian	Mindel/Riss	Mazovian	Alexandrian	Likhvinian	11c
		Cromerian Complex	Elsterian	Mindel	Sanian 2	Berezinian	Okaan	12
			Cromerian IV	Günz/Mindel	Ferdynandovian	Belovezhian	Lubenian	13
			Glacial C					14
			Cromerian III					15
			Glacial B	Günz	Sanian 1	Narevian	Sulian	16
			Cromerian II		Podlasian	Różan	Martonoshian	17
			Glacial A					18
780			Cromerian I					19

* – area not covered by ice-sheets

depicted the maximum range of the Wartanian Stadial of the Odranian Glaciation in Poland and Belarus, which according to us conforms with the maximum range of the Odranian (Saalian, MIS 6) Glaciation. In Poland, this limit is located along the Siedlce-Łosice-Kornica line and was also shown as such on the Detailed Geological Map of Poland at the scale of 1:200,000, Siedlce sheet (Kucharska et al., 2020; Żarski and Kucharska, 2020). In Hrynowiecka et al. (2019), Górecki et al. (2022) and on the general map at the scale of 1:250,000 of the Polish-Ukrainian-Belarus borderland (Pochocka-Szwarc and Żarski, 2023; Żarski et al., 2023b), the eastern boundary of the Middle Polish (Odranian, MIS 6) ice-sheet range overlaps the Żelechów Heights but not the Łuków Plain (Fig. 1).

The Sosnowica Depression was described by Zaborski (1927) as an extensive valley along which flowed waters from the melting ice-sheet of the Middle Polish Glaciation (presently correlated with the Odranian Glaciation, MIS 6) during its recession and subsequent glacial phases. This concept was sustained by Buraczyński and Wojtanowicz (1980/1981; Buraczyński et al., 1984). Harasimiuk et al. (2004) connected the formation of the Sosnowica Depression with the runoff of glacifluvial waters from the ice-sheet front of the Wartanian Glaciation and inferred the separation of the Wartanian Glaciation from the Odranian Glaciation. In turn, Żarski and Morawski (2019) linked the strata of the Sosnowica Depression with the Sanian 2 (Elsterian, MIS 12) Glaciation.

The Parczew-Kodeń Heights were classified by Zaborski (1927) as post-glacial plateaus of the Middle Polish Glaciation, presently correlated with the Odranian (Saalian, MIS 6) Glaciation (Table 1). The authors of later geological map sheets sustained this concept, assuming that the Parczew-Kodeń Heights and the Sosnowica Depression were covered by the ice-sheet of the Middle Polish Glaciation (Odranian) (Trembaczowski, 1968; Stochlak, 1979; Dolecki et al., 1987, 1995; Wodyk, 1999, 2000). Accordingly, these authors distinguished glacial deposits (glacial tills) and glacial forms, i.e. eskers, kames, and dead-ice moraines, from the Odranian Glaciation in the subsurface of the Parczew-Kodeń Heights.

MAZOVIAN INTERGLACIAL

The Mazovian Interglacial corresponds to MIS 11 (Lisiecki et al., 2005; Nitychoruk et al., 2005, 2006; Rohling et al., 2010; Cohen and Gibbard, 2011, 2019); in the chronostratigraphic scheme it belongs to the Middle Pleistocene and correlates with the Holsteinian Interglacial in Western Europe, particularly in Germany (Litt et al., 2007), the Aleksandrian in Belarus (Velichkevich et al., 2001), the Likhvinian in Ukraine (Lindner et al., 2007), and the Mindel/Riss in the Alps (Penck and Bruckner, 1901/1909; Table 1).

According to recent studies, the Holsteinian encompasses MIS 11c (Koutsodendris et al., 2010; Head and Gibbard, 2015; Bińka and Marks, 2018). In the Polish chronostratigraphic scheme (Lindner and Marks, 2012; Marks et al., 2016), the

Mazovian Interglacial separates the Sanian 2 (Elsterian, MIS 12) Glaciation from the Liviecian (Fuhne, MIS 11a–11b) Glaciation.

The Holsteinian/Mazovian pollen succession has characteristic feautures that allow reliable age determination of the organogenic deposits of this interglacial (Krupiński, 1995, 2000; Janczyk-Kopikowa, 1996; Mamakowa, 2003; Pidek, 2003). Recent high-resolution pollen analyses have allowed distinction of characteristic intra-interglacial climate oscillations within the Holsteinian succession. They include the Older Holsteinian Oscillation (OHO) occurring after the *Taxus* maximum and reflected in the increased pollen content of boreal trees (*Pinus* or/and *Betula*) and herbaceous plants (Hrynowiecka-Czmielewska, 2010; Hrynowiecka and Szymczyk, 2011; Koutsodendris et al., 2012; Hrynowiecka and Pidek, 2017; Hrynowiecka et al., 2019; Górecki et al., 2022). In the younger part of the climate optimum there occurs the Younger Holsteinian Oscillation (YHO) recorded as a fall in the pollen values of hornbeam (*Carpinus*) and a rise in fir (*Abies*) pollen (Hrynowiecka-Czmielewska, 2010; Hrynowiecka and Szymczyk, 2011; Hrynowiecka and Pidek, 2017; Nitychoruk et al., 2018; Hrynowiecka et al., 2019; Górecki et al., 2022). Most recent reports point to the existence of a third oscillation in the youngest phase of the interglacial, dominated by pine (*Pinus*) and reflected in the significant increase of birch (*Betula*) and herbaceous plants, and tentatively referred to as the Birch Holsteinian Oscillation (BHO), noted in Nowiny Żukowskie (Hrynowiecka-Czmielewska, 2010; Hrynowiecka and Szymczyk, 2011), and Skrzynka (Górecki et al., 2022).

The vegetation succession observed in the deposits directly overlying MIS 11c (following the *Pinus* phase of the interglacial) was commonly associated with the Early Liviecian Glaciation (MIS 10), which corresponds to the Odranian Glaciation *s.l.* (Marks et al., 2018) and the Fuhne Glaciation in Germany (*s.l.* Saalian Glaciation; Börner, 2007). Imbrie et al. (1984) previously proposed that MIS 11 comprises three substages, encompassing the relatively warm MIS 11c and MIS 11a, and the relatively cold MIS 11b. Hrynowiecka et al. (2019) adopted this subdivision, suggesting that while the Mazovian Interglacial corresponds to the entirety of MIS 11c (Koutsodendris et al., 2012; Marks et al., 2019), the palynologically documented deposits of the Early Liviecian Glaciation should correspond to MIS 11b and MIS 11a rather than MIS 10. Drawing from evidence from Hermanów (Hrynowiecka et al., 2019), Ossówka (Krupiński, 1995; Nitychoruk et al., 2005), and Brus (Pidek, 2003), it was suggested that the two cold substages should be designated as MIS 11b, with the subsequent three substages labeled as MIS 11a. In this study, we have opted to adhere to this framework when characterizing deposits associated with the Odranian Glaciation s.l. (Fuhne) based on their palynological record.

LACUSTRINE DEPOSITS OF THE MAZOVIAN INTERGLACIAL – STATE OF RECOGNITION

Western Polesie. Presently there are 19 sites in Western Polesie with lacustrine deposits of the Mazovian Interglacial documented by palaeobotanical and palaeofaunal analyses (Fig. 1), 6 in the Sosnowica Depression (Hrynowiecka et al., 2014; Żarski and Morawski, 2019; Pochocka-Szwarc et al., 2021; Żarski et al., 2023b) and 6 in the Parczew-Kodeń Heights (Żarski et al., 2023a, b; Figs. 1 and 2). The remaining sites can be found in the Łomazy Depression, the Włodawa Heights, and the Łęczna-Włodawa Lakeland (Żarski et al., 2023a, b).

Lacustrine interglacial deposits correlated with the Mazovian Interglacial were discovered for the first time in the Bug Valley escarpment in Włodawa (Lilpop, 1925), the report being one of the first palynological analyses in Poland. Lacustrine and bog deposits of the Mazovian Interglacial were discovered and described farther to the north, also in the Bug Valley escarpment in Suszno, Włodawa and Dobropol (Fig. 1; Trembaczowski, 1957; Mojski and Trembaczowski, 1961). Palaeobotanical studies in Suszno and Włodawa were conducted by Stachurska (1957, 1961), and in Dobropol by Hrynowiecka et al. (2014). One of the sites in Western Polesie with the most detailed palaeobotanical analysis of the Mazovian Interglacial is in Brus, which is located to the south of the Włodawa Heights in the Łęczna-Włodawa Lakeland (Pidek, 2003; Hrynowiecka and Pidek, 2017). The sites of Rossosz, Ortel Królewski and Szymanowo, well-known for their mollusc and ostracod remains, are located in the Parczew-Kodeń Heights and the Łomazy Depression (Albrycht et al., 1995; Szymanek et al., 2005; Szymanek, 2011, 2014). In all sites noted, the Mazovian Interglacial succession is not overlain by glacial deposits.

Southern Podlasie. Near Biała Podlaska and Łomazy there are over a dozen sites with lacustrine deposits from the Mazovian Interglacial (Lindner et al., 1990; Bińka and Nitychoruk, 1995; Lindner and Marciniak, 1997, 1998; Nitychoruk, 2000; Krupiński, 2000; Nitychoruk et al., 2005, 2006, 2018; Szymanek et al., 2005; Szymanek, 2011, 2012, 2013; Fig. 1). As in Western Polesie, the Mazovian Interglacial strata are not overlain by glacial deposits.

Near Łuków, Miedzyrzec Podlaski, Kock and Adamów (Fig. 1), over 20 sites of the Mazovian Interglacial were documented by palaeobotanical analyses (Żarski, 2007a, b, 2008, 2009; Małek and Pidek, 2007; Żarski et al., 2009, 2024; Pidek et al., 2011; Terpiłowski et al., 2014; Czubla et al., 2019; Hrynowiecka et al., 2019; Górecki et al., 2022). In sites located on the Łuków Plain, the lacustrine succession of the Mazovian Interglacial is not overlain by glacial deposits.

Sites located in the Żelechów Heights have a thin glacial till cover correlated with the Odranian Glaciation (Żarski, 2008, 2009; Żarski et al., 2009, 2024).

GEOLOGICAL SETTING

Sosnowica Depression. In the Sosnowica Depression there are three new sites with biogenic deposits from the Mazovian Interglacial, i.e. Zahajki, Wygnanka, and Sytyta. A detailed description of the lithology and stratigraphy can be found in Table 2. Exploratory and hydrogeological boreholes have documented the geological setting of the Pleistocene strata and their substrate at each site.

Zahajki (157 m a.s.l.) – the site occurs in the eastern part of the Sosnowica Depression, to the north of Kaplonosy, in a small, drainless depression. It is 230 m long and 180 m wide. A pond occurs in its central part (Fig. 3A, B); an exploratory borehole was sited on the western part of the pond (Fig. 3C). Lacustrine and biogenic interglacial deposits are 9.1 m thick, and include gyttja, peat and silts (not completely penetrated). Their age was documented by palynological analysis. Above the interglacial deposits occur 2.25 m of gyttja and lake silts of the Early Liviecian (MIS 11b) Glaciation (Table 1), above which occur 0.64 m of peat and gyttja correlated with the Late Vistulian (Weichselian MIS 2). Vistulian strata are covered by 1.29 m of Holocene peat.

Lacustrine and bog deposits in Zahajki infill a fossil melt-out depression rooted in glacifluvial sands and gravels of the Sanian 2 (Elsterian, MIS 12) Glaciation (Fig. 3D). Below these deposits occurs a second series of glacifluvial sands and gravels, from several to over ten metres thick, which may be corre-

Table 2

Lithological-stratigraphic characteristics of the sites studied

Site	Depth [m]	Deposits	Origin	Stratigraphy	MIS
Zahajki 51°36'53.2"N 23°16'59.8"E 157 m a.s.l.	0.0–2.20	strongly-decomposed peats, brown	bio	Holocene	1
	2.20–2.96	weakly decomposed peats, brown	bio		
	2.96–3.10	gyttja with plant detritus, olive-grey, -HCL	li	Vistulian (Weichselian)	2
	3.10–3.60	very weakly decomposed peats, brown, -HCL	bio		
	3.60–4.04	peaty gyttja, brown, -HCL	li		
	4.04–4.20	clay silts, grey, -HCL	li		
	4.20–4.25	sandy silts, grey, -HCL	li		
	4.25–5.40	sandy gyttja with plant detritus, olive, -HCL	li	EarlyLiviecian (Fuhne)	11b
	5.40–6.10	fine sands, grey, -HCL	d		
	6.10–6.50	gyttja, grey-olive, laminated, +HCL	li		
	6.50–7.40	gyttja, grey-olive, +++HCL	li	Mazovian (Holsteinian)	11c
	7.40–9.0	gyttja, slightly clayey, dark grey, -HCL	li		
	9.0–9.30	gyttja, dark grey-brown, with mollusc remains, +++HCL	li		
	9.30–9.40	strongly-decomposed peats, black, -HCL	bio		
	9.40–10.20	gyttja, olive, with large amounts of crushed mollusc remains, +++HCL	li		
	10.20–10.50	gyttja, clayey, olive, with crushed mollusc remains, ++HCL	li		
	10.50–13.40	clay silts, grey, ++HCL	li		
	13.40–13.60	silts, dark grey, with abundant molluscs, +++HCL	li		
	13.60–14.90	sands, grey	d		
	14.90–15.0	gyttja, dark grey, +++HCL	li		
	15.0–15.60	gyttja, grey (grey silts), crushed mollusc remains in the base, plant macroremains, +++HCL	li		
Wygnanka 51°39'05.7"N 23°03'28.9"E 153 m a.s.l.	0.0–0.4	fine sands with humus, dark grey	h	Holocene	1
	0.4–0.8	fine sands with silty sands, grey-beige	n-li	Vistulian (Weichselian)	2
	0.8–1.05	fine sands with silty sands and humus smears, dark grey	n-li		
	1.05–1.25	silts with humus smears, dark grey	li		
	1.25–1.35	silts with rare gravels, light grey	li		
	1.35–1.90	strongly-decomposed peats, brown-black	bio	Mazovian (Holsteinian)	11c
	1.90–2.55	strongly-decomposed peats, brown-black	bio		
	2.55–5.65	carbonaceous gyttja, olive, with crushed mollusc remains, +++HCL	li		
	5.65–6.25	carbonaceous gyttja, dark brown, with crushed mollusc remains, +++HCL	li		
	6.25–8.0	gyttja, olive-dark grey, slightly carbonaceous, ++HCL	li		
	8.0–8.80	fine sands with rare gravels, grey	fg	Sanian 2 (Elsterian)	12
	8.80–9.0	sandy silts, grey-greenish	li-g		
Sytyta 51°36'32.3"N 23°12'7.2"E 157 m a.s.l.	0.0–0.20	silts with humus, grey-black	h	Holocene	1
	0.20–1.0	sandy silts, yellow-grey	n-li	Vistulian (Wiechselian)	2
	1.0–1.3	fine sands, grey	n-li		
	1.3–2.5	silts, grey	n-li		
	2.5–3.4	peats, brown-black	bio	Mazovian (Holsteinian)	11c
	3.4–5.0	fine sands, grey	fg	Sanian 2 (Elsterian)	12
Gęś 3 51°42'36.9"N 23°1'45.0"E 158 m a.s.l.	0.0–0.3	peats, brown-black	bio	Holocene	1
	0.3–1.9	silts, grey-brown, compact	li	Vistulian (Weichselian)	2
	1.9–2.4	fine sands with rare gravels, grey	d		
	2.4–2.5	silts, grey, compact	li	Mazovian (Holsteinian)	11c
	2.5–2.9	silts, brown	li		
	2.9–3.37	gyttja, brown, diluted, +HCL	li		
	3.37–4.7	well-decomposed peats, brown-black	bio		
	4.7–5.3	peaty gyttja, brown	li		
	5.3–5.4	peaty gyttja, brown, with shales, +++HCL	li		
	5.4–5.5	olive gyttja, compact, +HCL	li		
	5.5–5.75	silts, grey	li		
	5.75–5.95	silts, grey	li	Sanian 2 (Elsterian)	12
	5.95–6.0	glacial tills, grey-blue	g		

Tab. 2 cont.

Site	Depth [m]	Deposits	Origin	Stratigraphy	MIS
Podedwórze 51°41'27.1"N 23°14'31.0"E 159 m a.s.l.	0.0–0.6	silts, dark grey	li-h	Holocene	1
	0.6–2.7	clay silts, grey	n-li	Vistulian (Weichselian)	2
	2.7–2.9	clay silts, brown	li	Early Liviecian	11b
	2.9–3.40	strongly-decomposed peats, brown-black	bio	Mazovian (Holsteinian)	11c
	3.40–4.0	strongly-decomposed peats, brown-black, with mollusc fragments, ++HCL	bio		
	4.0–4.5	peaty gyttja, brown, with mollusc fragments, +++HCL	li		
	4.5–5.41	strongly-decomposed peats, brown-black	bio		
	5.41–5.43	fine sands, grey	d		
	5.43–6.3	strongly-decomposed peats, brown-black	bio		

li – limnic, bio – biogenic, d – deluvial, fg – fluvioglacial, g – glacial, n-li – niveolimnic, h – humic

lated with the Sanian 1 (MIS 16) Glaciation (Fig. 3D). The substrate of Pleistocene strata comprises Middle Miocene terrestrial deposits (sands and silts with intercalations of lignite), underlain by Upper Maastrichtian chalk and marls (Fig. 3D) (Pochocka-Szwarc and Żarski, 2023). The surface in this part of the Sosnowica Depression is covered by Holocene peat, as well as niveolimnic silts and sands, probably representing the Late Vistulian and forming extensive flat surfaces with poor surface runoff (Pochocka-Szwarc and Żarski, 2023).

Wygnanka (153 m a.s.l.) – this site is located ~10 km to the east of Parczew. It is a depression ~300 m long and up to 90 m wide (Fig. 4A, B). A borehole was drilled in the central part of the depression (Fig. 4A, B). The thickness of lacustrine and bog deposits (gyttia and peat) of the Mazovian (Holsteinian, MIS 11c) Interglacial is 6.65 m (Table 2). Above, there is 0.95 m of fine sands and silts of the Vistulian (MIS 2), and Holocene sands (Fig. 4C).

In Wygnanka, the deposits fill a palaeobasin carved in the glacifluvial surface. This is probably a fossil post-glacial trough which, after the recession of the Sanian 2 Glaciation and after being preserved by dead ice, was transformed into a lake in warm interglacial climate conditions. The surface is covered by Vistulian niveolimnic and Holocene deposits.

In the northern part of the Sosnowica Depression and in the neighbouring part of the Parczew-Kodeń Heights, the Pleistocene deposits below the Vistulian are represented by a glacifluvial succession of various ages, reaching 25–30 m in thickness. These strata accumulated during the Nidanian (MIS 22), Sanian 1 (MIS 16) and Sanian 2 (MIS 12) glaciations (Table 1 and Fig. 4D). Upper Maastrichtian marls occur below (Pochocka-Szwarc, 2023; Pochocka-Szwarc and Żarski, 2023).

Sytyta (157 m a.s.l.) – this site lies in the central part of the Sosnowica Depression, between Zahajki and Wygnanka near the drainage channel (Fig. 5A, B). The terrain morphology does not indicate the presence of a palaeobasin below the surface, so its boundaries and size are difficult to determine (Fig. 5A, B). Peats of the Mazovian Interglacial reach a thickness of 0.90 m (Fig. 5C). Below there are glacifluvial sands (Table 2), correlated with the Sanian 2 (Elsterian, MIS 12) Glaciation. Interglacial peats infill a palaeobasin incised into Sanian 2 glacifluvial sands and gravels. In the part of the Sosnowica Depression analysed, the thickness of Pleistocene strata (glacifluvial sands and gravels) is ~25 m (Fig. 5D), overlying Upper Cretaceous carbonate rocks (Pochocka-Szwarc, 2023; Pochocka-Szwarc and Żarski, 2023).

The biogenic interglacial deposits are overlain by 2.3 m of niveolimnic sandy silts and fine sands (Fig. 5D and Table 2). OSL determinations indicate an age of 31 ±7 ky (Palczewski, 2019). These deposits represent accumulation in extensive, shallow floodplains which functioned in periglacial conditions that prevailed in the area during the Vistulian.

The geological setting of Pleistocene strata in this part of the Sosnowica Depression is similar to that in the vicinity of Zahajki and Wygnanka. Glacifluvial deposits of various age (Sanian 2, MIS 12) occur in the subsurface, mostly overlain by Vistulian niveolimnic deposits. A characteristic feature is the presence of an 80 m-deep post-glacial trough infilled with glacifluvial deposits, located in Sosnowica Depression (Fig. 5D). Upper Maastrichtian marls lie beneath the Pleistocene deposits. In the eastern part of the study area, the Sosnowica Depression lies adjacent to the Włodawa Heights (Fig. 5D) built mostly of glacial tills from the Sanian 2 Glaciation (MIS 12).

Parczew-Kodeń Heights. A characteristic feature of this mesoregion is the occurrence of isolated outliers comprising post-glacial plateaus built of glacial tills. They occur mostly in the central and southern parts of the area. The outlier surfaces generally occur at 150–152 m a.s.l. to the east of Podedwórze, the area rising to 160 m a.s.l. to the top of Góra Grabowska (190 m a.s.l.), which is a frontal moraine of the recessive phase of the Sanian 2 (MIS 12) ice-sheet (Pochocka-Szwarc and Żarski, 2023). However, the plateaus do not form a uniform surface but are incised by depressions which are from several hundred metres to several kilometres across, infilled with Vistulian washout (niveolimnic) and Holocene deposits (Pochocka-Szwarc and Żarski, 2023). The geological structure of these depressions indicates that they are fossil routes of glacifluvial flow, which functioned during the retreat of the Sanian 2 ice-sheet. Glacifluvial sands and gravels are overlain by fine niveolimnic deposits from the Vistulian Glaciation as well as from the Odranian Glaciation (Pochocka-Szwarc and Żarski, 2023).

Podedwórze (158 m a.s.l.) – this site is located in the southern part of the Parczew-Kodeń Heights. It is a small, narrow, 160 m long, E–W oriented depression. In its eastern part, the depression widens to give an oval shape with a width of ~60 m (Fig. 6A, B); a borehole was drilled here (Fig. 6C). The depression in Podedwórze was in historical times part of a system of surface runoff from the nearby "Warzewo" flood plain.

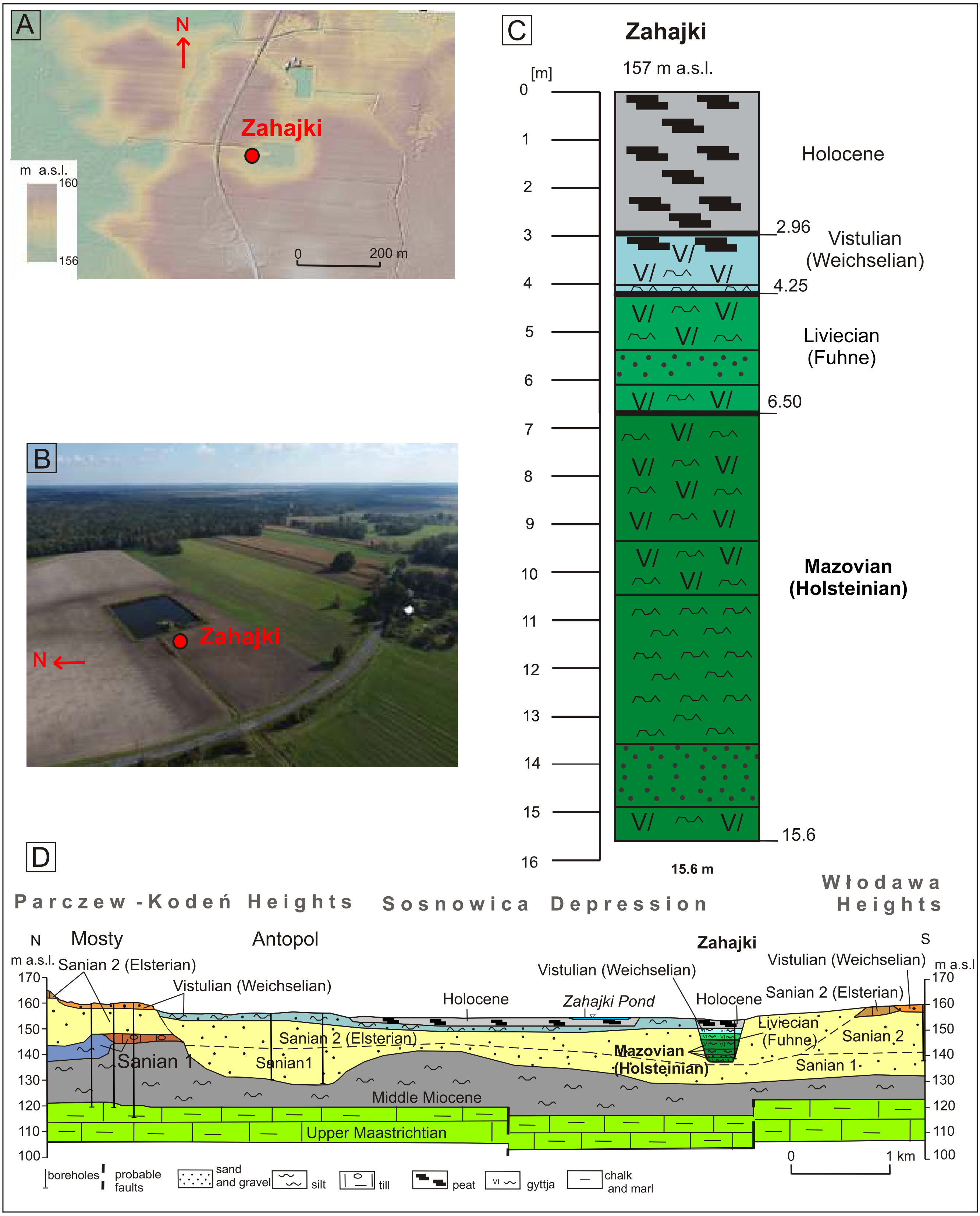

Fig. 3. Zahajki site: A – location on a Digital Terrain Model (DTM), B – location on an aerial photograph, C – lithological log, D – geological cross-section showing the geological structure of the Sosnowica Depression

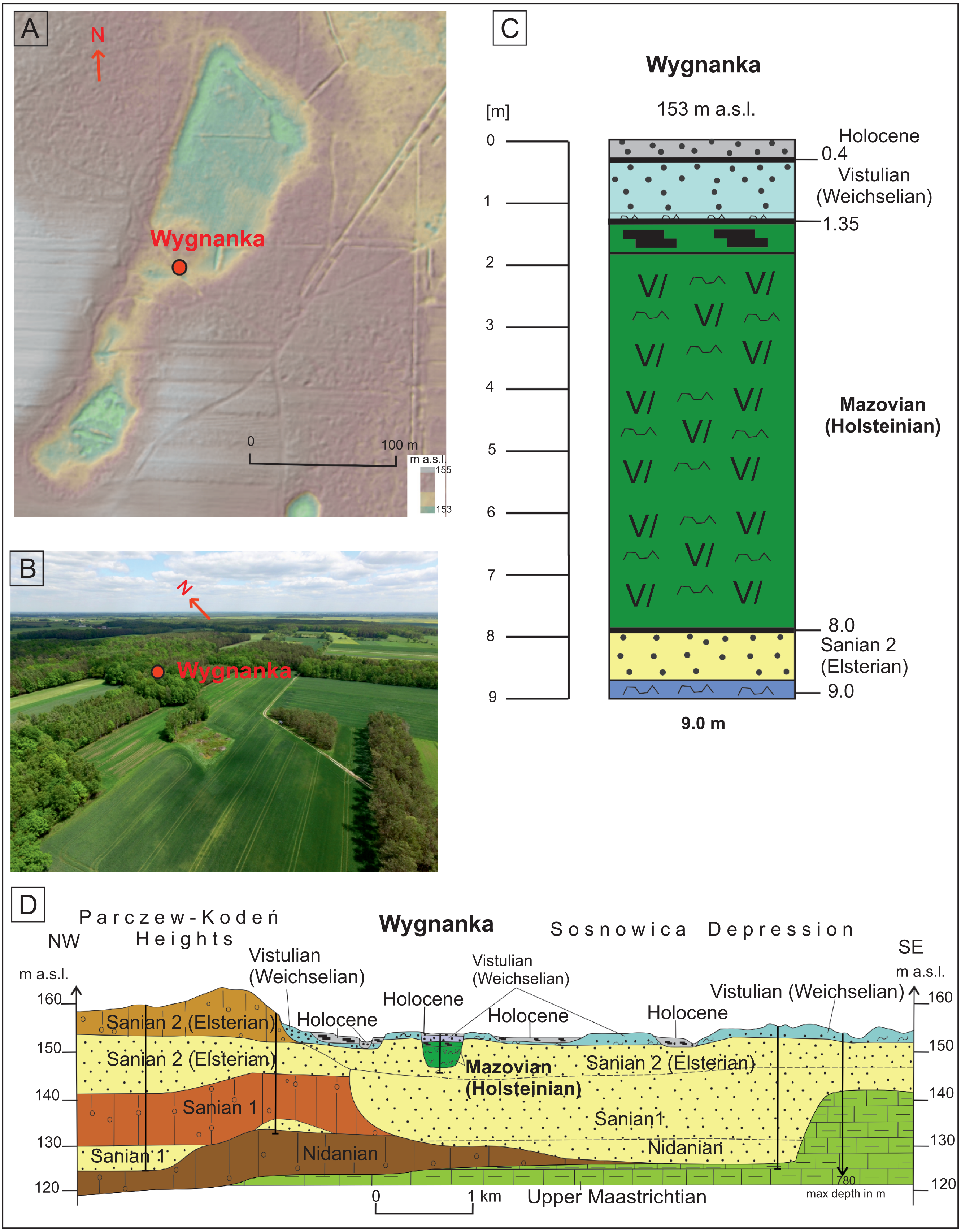

Fig. 4. Wygnanka site: A – location on a Digital Terrain Model, B – location on an aerial photograph, C – lithological log, D – geological cross-section showing the geological structure of the western Sosnowica Depression and Parczew-Kodeń Heights (see Fig. 2)

For other explanations see Figure 3

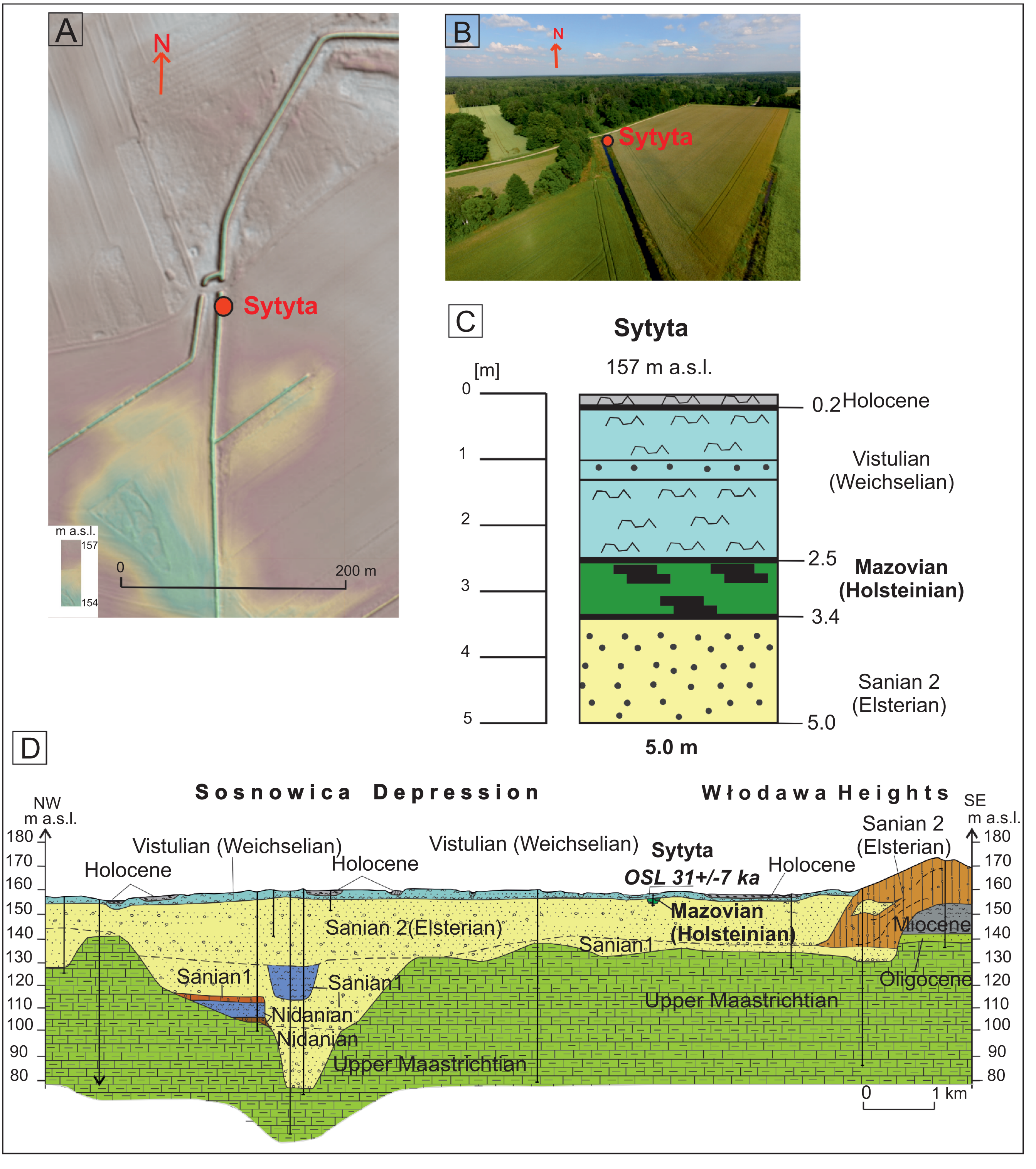

Fig. 5. Sytyta site: A – location on a Digital Terrain Model, B – location on an aerial photograph, C – lithological log, D – geological cross-section showing the geological structure of the Sosnowica Depression and the northwestern part of the Włodawa Heights (see Fig. 2)

For other explanations see Figure 3

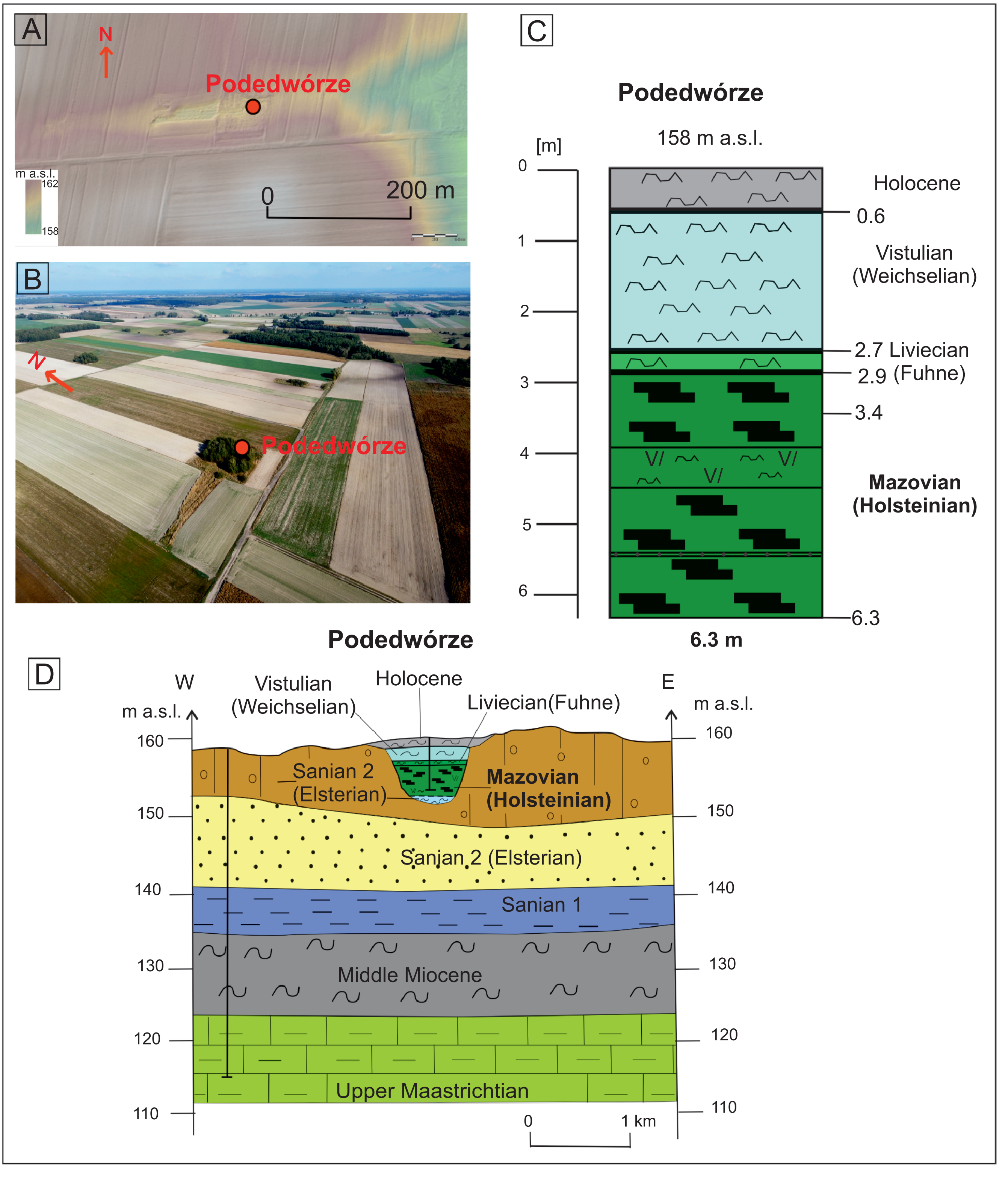

Fig. 6. Podedwórze site: A – location on a Digital Terrain Model, B – location on an aerial photograph, C – lithological log, D – geological cross-section showing the geological structure of the Parczew-Kodeń Heights (see Fig. 2)

For other explanations see Figure 3

The biogenic strata of the Mazovian (Holsteinian, MIS 11c) Interglacial in Podedwórze have a thickness of 3.4 m (Fig. 6C). They comprise peats and gyttja with crushed shell fragments. Above these lie lacustrine brown clayey silts, which terminate the lacustrine succession in the basin (Liviecian, Fuhne). These are overlain by 2.1 m of niveolimnic clayey silts from the Late Vistulian (MIS 2), overlain by Holocene biogenic silts (Table 2).

Analysis of a deep borehole (Fig. 6D) located in the vicinity of the site analysed, coupled with geological mapping, shows that below the deposits infilling the basin are glacial tills from the Sanian 2 (MIS 12) Glaciation, reaching few m in thickness. The lacustrine deposits infill a palaeobasin within the glacial tills, of melt-out origin, i.e. it originated from the melting of dead-ice blocks infilling an earlier depression on a glacial till surface (Błaszkiewicz, 2008, 2011).

Below the glacial tills occur glacifluvial sands and gravels of the Sanian 2 (MIS 12) Glaciation and ice-dammed clays correlated with the Sanian 1 (MIS 16) Glaciation. The thickness of Pleistocene strata in the vicinity of Podedwórze is ~35 m. Below there occur terrestrial Middle Miocene strata (12 m thick) and Upper Maastrichtian carbonate rocks (Pochocka-Szwarc and Żarski, 2023).

Gęś 3 (158 m a.s.l.) – this site is situated within the "Jabłoń Island", a glacial outlier with an incised palaeo-depression (Fig. 7A, B) infilled with lacustrine deposits of the Mazovian Interglacial. The site lies within a present-day isolated drainless depression, measuring ~80 m (E–W) by ~55 m (N–S). Most of the depression is covered by a lake; a borehole was sited on its western margin (Fig. 7B). Lacustrine (gyttja and silts) and bog deposits (peats) from the Mazovian (MIS 11c) Interglacial were drilled at the depth of 2.4 m, reaching a thickness of 3.35 m. Below the lacustrine deposits occur 0.25 m of ice-dammed silts from the Sanian 2 (MIS 12) Glaciation, underlain by glacial till from the same glaciation (Fig. 7C, D and Table 3).

Above the interglacial succession is 2.1 m of sands and silts, which probably accumulated during the Late Vistulian (MIS 2). Holocene peats with a thickness of 0.3 m occur on the surface (Fig. 7C, D and Table 2). This palaeobasin has a melt-out origin, forming due to melting of dead-ice blocks after the retreat of the Sanian 2 (MIS 12) ice-sheet.

The geological structure of Pleistocene strata near Gęś is similar to that near Podedwórze (Fig. 6C, D). The surface of the area is built of glacial tills from the Sanian 2 (MIS 12) Glaciation with thicknesses from several to 10 m, below which occur glacifluvial sands and gravels of the same glaciation. Below occur ice-dammed silts of the Sanian 1 (MIS 16) Glaciation and silts correlated with the Nidanian (MIS 22) Glaciation. The bedrock comprises Middle Miocene silts and Upper Maastrichtian marls (Pochocka-Szwarc and Żarski, 2023).

MATERIAL AND METHODS

Boreholes. Material for study was collected mainly during mapping linked with the preparation of the Detailed Geological Map of Poland at the scale of 1:50,000 (Żarski and Morawski, 2018, 2019; Pochocka-Szwarc, 2023; Pochocka-Szwarc and Żarski, 2023) and implementation the project of scientific research on Quaternary sediments in Western Polesie conducted by PIG-PIB. The sites described were documentedby boreholes, yielding samples for palaeobotanical and palaeofaunal studies. The Zahajki succession with a total depth of 15.6 m was documented by fully cored drilling in 2015. In Wygnanka, an Eijkelkamp hand-auger was used in 2022 to drill to 9 m depth. A similar borehole was drilled in Podedwórze in 2022 to 6.3 m depth in the eastern part of the depression. In Gęś 3 in the western part of the depression, a 6 m borehole was drilled in 2022. In 2023, a mechanically-drilled borehole in Sytyta reached the depth of 5 m. The deposits were sampled with a 5 to 10 cm resolution. The geological structure of the sites analysed is shown in geological cross-sections, whose location is shown in Figure 2.

PALAEOBOTANICAL ANALYSES

Pollen analysis. The samples were processed using the standard acetolysis method by Erdtman (1960) after removal of carbonates with 10% HCl, boiling in 10% KOH, and removal of the mineral fraction with 38% HF. Pollen spectra were counted in at least two microscopic slides or up to 500 pollen grains (excluding aquatic plants pollen). The only exception were preparations with a low frequency of palynomorphs (glacial intervals), in which 300 pollen grains were counted. The results are shown as percentage pollen diagrams with description. The basic sum for the percentage counts is the sum of tree and shrub pollen (Arboreal Plants – AP) and herbaceous plant pollen (NonArboreal Plants – NAP), excluding pollen of aquatic and reed plants, non-pollen palynomorphs (NPP), including Pteridophyta and Bryophyta spores, and redeposited sporomorphs.

The pollen diagrams were constructed in R Studio (R Studio Team, 2023) using the RiojaPlot package (Juggins, 2022) and are shown in Figures 8–12. Local Pollen Assemblage Zones (LAPZ) were distinguished using CONISS cluster analysis (Grimm, 1987), and corrected visually. Minor graphic changes in the diagrams were made using *CorelDRAW software* (Corel Corporation, 2023).

Plant macroremains. Plant macroremains were analysed in 19 samples (~30 cm^3 each) from Podedwórze. They were collected with a resolution of 5 or 10 cm. After boiling with KOH to reduce the amount of sediment and remove humic matter, the samples were wet sieved on a ∅ = 0.18 mm mesh. The material obtained, including seeds, fruits and vegetative plant fragments, was analysed using a *Carl ZEISS Stemi 508* stereoscopic microscope. The macrofossils were identified on the basis of manuals and keys (e.g., Kats et al., 1965; Berggren, 1969; Cappers et al., 2006; Velichkevich and Zastawniak, 2006, 2008), and compared with a reference collection of modern and fossil plants in the National Biodiversity Collection of Recent and Fossil Organisms stored at the W. Szafer Institute of Botany, Polish Academy of Sciences, in Kraków (KRAM herbarium). The results are shown in a macrofossil diagram using *POLPAL* software (Nalepka and Walanus, 2003). Based on the presence of one or more of the most abundant or characteristic taxa for particular zones, five plant macrofossil zones were distinguished in the diagram: Pd 1-5 LMAZ (Fig. 13). The boundaries between the zones were determined on the basis of changes in either index or the most abundant taxa. Photographs of macroremains are shown in Figure 14. A detailed description of the zones distinguished is provided in Table 3.

PALAEOFAUNAL ANALYSES

Mollusc and ostracod analyses. 46 samples of gyttja from Wygnanka were subject to macrofaunal analyses. The samples were collected with a resolution of 5 or 10 cm from the 2.7–6.3 m depth interval. Between 30 and 130 cm^3 of deposit per sample were taken for mollusc analysis, and bout 10 cm^3 for ostracod studies. Faunal remains were taxonomically determined under a low-power *Delta Optical IPOS 808* stereoscopic microscope at a magnification of up to 65×.

All mollusc shells and their fragments were picked from the dry residue after wet sieving through a 0.5 mm mesh following

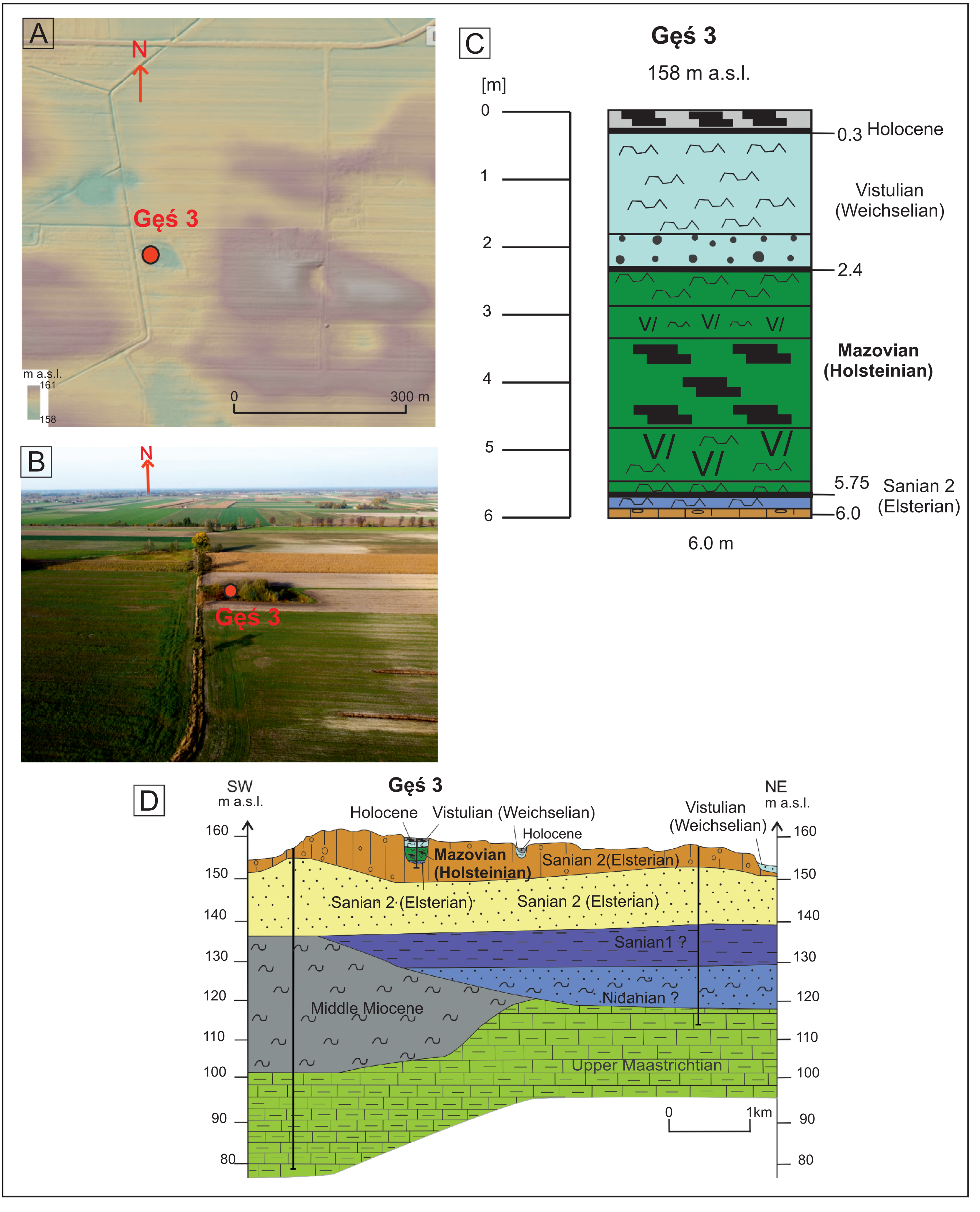

Fig. 7. Gęś 3 site: A – location on a Digital Terrain Model, B – location on an aerial photograph, C – lithological log, D – geological cross-section showing the geological structure of the Parczew-Kodeń Heights (see Fig. 2)

For other explanations see Figure 3

Table 3

Description of Local Macrofossil Assemblage Zones at Podedwórze

L MAZ depth [m]	Description of Local Macrofossil Assemblage Zones
PO-1a 6.3–6.1 3 samples	In the first subzone, the remains of *Larix decidua*, *Picea abies* and *Betula sect. Albae* trees were very numerous. Seeds of *Rubus idaeus* and *Rubus* sp. shrubs were also marked individually. Plants of wet and fresh habitats were present, although few. Single *Urtica dioica* and *Fragaria vesca* fruits and *Selaginella selaginoides* megaspores were determined. Peat plants were very abundant, including remains of *Menyanthes trifioliata*, *Comarum palustre*, *Lycopus europaeus*, as well as moss stems and numerous species of the Cyperaceae family, such as *Carex nigra*, *C. riparia*, *C. rostrata*, *C. elata*, *C. vesicaria* and *Carex* sp. div. *trigonous*. There were also numerous remains of reed and aquatic plants, mainly *C. pseudocyperus*, *Sparganium emersum*, *Nuphar lutea*, *Nymphaea cinerea*, *Sagittaria sagittifolia*, *Schoenplectus lacustris*, *Potamogeton natans* and *P. pannosus*. Sclerotia of *Cenococcum geophilum*, wood fragments and charcoal were also present in the zone.
PO-1b 5.8–5.6 3 samples	The subzone is characterized by a significant share of tree remains. There were still numerous remains of *Betula* sect. *Albae*, but less numerous were *Larix decidua* and *Picea abies*. Remains of *Abies alba*, *B. humilis* and *B. nana* appeared. Individually, *Rubus idaeus* and *Rubus* sp. were still present. In the group of plants from humid habitats, *Urtica dioica*, *Fragaria vesca* and *Ranunculus sceleratus*, *Polygonum aviculare* and *Alchemilla* sp. also appeared. As in the previous zone, there were still numerous remains of *Menyanthes trifioliata*, *Comarum palustre*, *Lycopus europaeus*, as well as moss stems. *Eleocharis palustris* and *Cicuta virosa* also appeared in the group of peat bog plants. Numerous remains of plants from the Cyperaceae family represented *Carex riparia*, *C. rostrata*, *C. elata*, *C. vesicaria* and *C.* sp. div. *trigonous*, *C.* sp. div. *biconvex*. Among rush and aquatic plants, *C. pseudocyperus*, *Sparganium emersum*, *Nuphar lutea*, *Nymphaea cinerea*, *Schoenoplectus lacustris*, *Alisma plantago-aqiuatica*, *Nuphar* sp., *Potamogeton natans*, *P. pannosus*, *P. praemaackianus* and *P. perfoliatus* were still present. Sclerotia of *Cenococcum geophilum*, wood fragments and charcoal were also present.
PO-2 5.3–5.0 3 samples	The share of trees and shrubs is decreasing, except for *Abies alba*, which was the most numerous in this zone, as well as *Betula* sect., Albae and *Rubus* sp. in the top of the zone. Plants of humid habitats were represented by *Urtica dioica* and *Eupatorium cannabinum*. The share of remains in the group of peat plants also decreased, including stems of mosses and plants from the Cyperaceae family, of which only *Carex riparia* and *Carex* sp. were still present. *Menyanthes trifioliata* and *Lycopus europaeus* also occurred among peat bog plants. The most characteristic feature of this zone was the presence of numerous *Juncus* sp. and *Typha* sp. seeds among the swamp vegetation. There were also numerous *Salvinia natans* megaspores and *Lemna trisulca* fruit. Additionally, one megaspore of Isoëtes lacustris and single fruits of *Sparganium emersum*, *Sagittaria sagittifolia*, *Nuphar* sp., and *Batrachium* sp. were also marked. Sclerotia of *Cenococcum geophilum*, wood fragments and charcoals also occurred.
PO-3 4.9–4.7 2 samples	In this zone, the share of plant remains in all ecological groups decreases. Among the shrubs, single seeds of *Rubus* sp. were marked, and in the group of plants of wet habitats, fruits of *Ranunculus reptans*. The share of peat plants also decreased, with only single *Carex elata* fruits remaining. The fruits of *Lemna trisulca* dominated the group of aquatic plants. One megaspore of *Azolla interglacialis* was also present. Other plant remains included wood fragments, charcoal and *Cenococcum geophilum* sclerotia.
PO-4 4.4–3.9 4 samples	The remains of *Larix decidua* and *Betula* sect. *Albae*, *B. humilis* and *B. nana* reappeared in the zone. For the first time in the succession, the fruits of *Alnus glutinosa* and *Arctostaphylos uva-ursi* appeared. The vegetation of humid habitats was represented only by *Ranunculus reptans* fruit. The share and species composition among boggy plants increased slightly. Fruits of *Carex nigra*, *C. riparia*, *C. rostrata*, *C. elata*, *C. caespitosa* and *C.* sp. div. *trigonous* and *C.* sp. div. *biconvex* were marked. *Comarum palustre* and *Eleocharis palustris* were also present. Among the swamp vegetation, a single seed of *Typha* sp. was recorded. The composition of aquatic vegetation changed, with the fruits of *Myriophyllum spicatum*, *M. verticillatum*, *Myriophyllum* sp., and *Batrachium* sp. dominating. There were also single *Potamogeton gramineus* endocarps, *Callitriche autumnalis* fruits, and *Azolla interglacialis* megaspores. The top of the zone was dominated by fragments of wood and charcoal, as well as *Cenococcum geophilum* sclerotia.
PO-5 3.5–3.1 4 samples	In the trees and shrubs group, the number of remains increased, especially *Larix decidua* and *Betula* sect., *Albae*, *B. humilis* and *B. nana* were still present in the zone. Single fruits of *Urtica dioica*, *Ranunculus sceleratus*, *R. reptans*, *Fragaria vesca*, *Mentha aquatica*, *Polygonum lapathifolium*, *P. amphibium* and megaspores of *Selaginella selaginoides* were marked. In this zone, the most numerous group of boggy plants was dominated by remains of plants from the Cyperaceae family, especially *Carex nigra*, *C. rostrata*, *C. elata* and, in smaller numbers, *C. riparia*, *C. pseudocyperus*, and *C.* sp. div. *biconvex*. Remains of *Menyanthes trifioliata*, *Comarum palustre*, *Eleocharis palustris* and *Filipendula ulmaria* were also present. The share of remains representing aquatic vegetation such as *Myriophyllum spicatum*, *M. verticillatum,* and *Batrachium* sp. was similar to the previous zone. There were also endocarps of *Potamogeton natans*, *P. praemaackianus*, and *P. perfoliatus*. *P. gramineus*, *P. perforatus*, *P. friesii*, *P. compressus*, *P. pussilus*, *P. alpinus*, *P. rutilus*, *P. obtusifolius*, *P. coloratus* and fruits of *Callitriche autumnalis*, *Hippuris vulgaris* and *Aracites interglacialis*. Aquatic vegetation was also represented *by Nymphaea candida, Elatine hydropiper*, *Sagittaria sagittifolia*, *Nuphar* sp. seeds, *Stratiotes* sp. spines, and *Sparganium emersum* and *S. angustifolium* fruits.

standard malacological procedures established by Ložek (1964), and Alexandrowicz and Alexandrowicz (2011). They were identified according to Welter-Schultes (2012), and Piechocki and Wawrzyniak-Wydrowska (2016). Complete shells, apices or apertures (as equivalent to one shell), and shell fragments suitable for unambiguous identification were counted following Ložek's method for broken individuals (Ložek, 1964; Alexandrowicz and Alexandrowicz, 2011). Some incomplete specimens (usually comprising the initial 1–1.5 whorls) were assigned to family or genus level.

For palaeoenvironmental purposes, the molluscs were grouped according to their ecological preferences based on Alexandrowicz and Alexandrowicz (2011). Five ecological groups were distinguished: mesophilous species, typical of moist substrate (8), hygrophilous species preferring very moist and swampy habitats (9), species of temporary water bodies (10), species of permanent water bodies of stagnant waters (11), and species of flowing waters (12) (Table 3). The structure of the mollusc assemblage is presented as the malacological spectra of species (MSS) and individuals (MSI) (Fig. 15). The malacological succession is illustrated by a frequency bar diagram, which is composed of both the percentages of the total sum for samples containing >50 individuals, and the absolute numbers of shells for those with <50 individuals (Fig. 16).

The ostracod material was subject to a standard procedure described by Löffler (1986). All the valves were extracted from sediments disaggregated with water and washed through a 0.1 mm mesh sieve. They were identified according to Sywula (1974), Meisch (2000) and Fuhrmann (2012), and counted (Table 4).

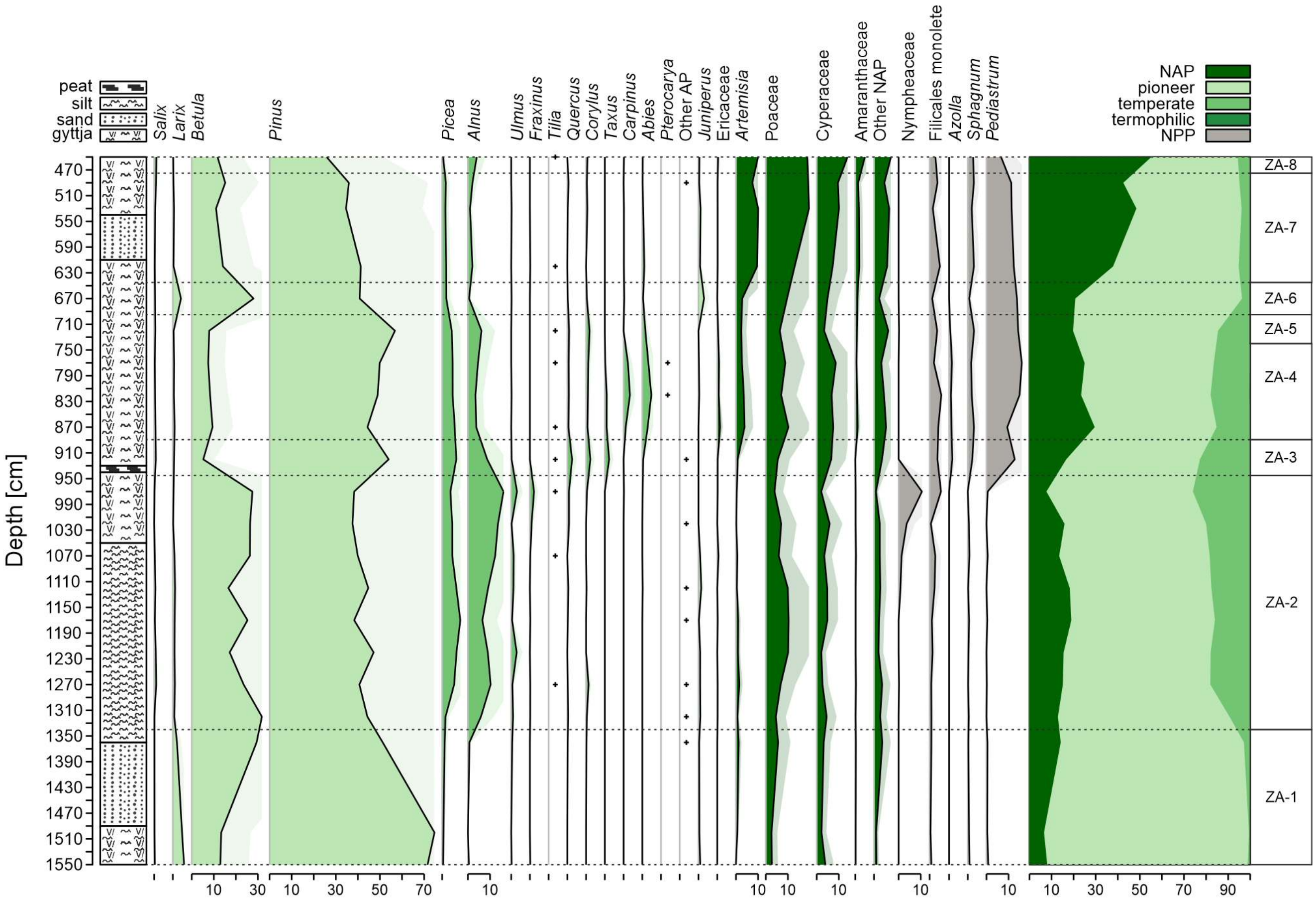

Fig. 8. Pollen diagram for Zahajki (Żarski et al., 2023b modified by A. Hrynowiecka)

RESULTS

PALAEOBOTANICAL ANALYSES

ZAHAJKI SITE

The palynomorph abundance and preservation state were very good. The pollen diagram (Fig. 8) representing analyses of 21 samples was subdivided into Local Pollen Assemblage Zones (LPAZs) and numbered consecutively from ZA-1 to ZA-7 from the base of the succession. The phases of lake development documented (Fig. 8) indicate a complete record of the Mazovian Interglacial. The oldest documented interval of vegetation evolution in the Zahajki Basin is the pine phase, typical of the beginning of each interglacial (*Pinus* ZA-1 LPAZ). The ZA-2 LPAZ, characterized by the co-occurrence of high amounts of alder (*Alnus*) and spruce (*Picea*) in the first part of the climate optimum, points to the Mazovian Interglacial. Later, the content of *Pinus* pollen rises (ZA-3 LPAZ), which may correspond to the Older Holsteinian Oscillation (OHO; Koutsodendris et al., 2012); at the same level there appear higher amounts of yew (*Taxus*) pollen. Due to its thickness, the Zahajki succession was analysed with low resolution, which probably caused that the high abundance of yew was not noted prior to the OHO, as it was in successions analysed at high resolution (e.g., Hrynowiecka-Czmielewska, 2010). The succeeding characteristic phase includes the co-occurrence of hornbeam (*Carpinus*) and fir (*Abies*) in the younger part of the climate optimum along with the appearance of pollen of trees with higher thermal requirements, such as *Pterocarya* (ZA-4 LPAZ). The Mazovian Interglacial terminates with the post-optimum *Pinus* phase with a clearly marked Birch Holsteinian Oscillation (BHO; ZA-5 LPAZ; Hrynowiecka and Szymczyk, 2011; Górecki et al., 2022), after which cooling related to the Early Liviecian Glaciation took place. During the entire interval described, the Zahajki Basin functioned as a shallow lake, as shown by the remains of the Nympheaceae and *Pediastrum* algae.

The Zahajki succession differs slightly from those typical for the Mazovian Interglacial in the continuous prevalence of *Pinus* over the pollen grains of other trees. This is a local feature, but typical of the extensive present-day Holocene basins in Western Polesie (e.g., Krowie Bagno; Bałaga et al., 1983).

WYGNANKA SITE

Palynomorph abundance and preservation were very good in all samples analysed. The pollen diagram (Fig. 9) illustrates the results from 14 samples, subdivided into LPAZs and numbered from WY-1 to WY-5 from the base of the succession. Characteristic features of the pollen diagram (Fig. 9) point to sedimentation during the Mazovian Interglacial. The age de-

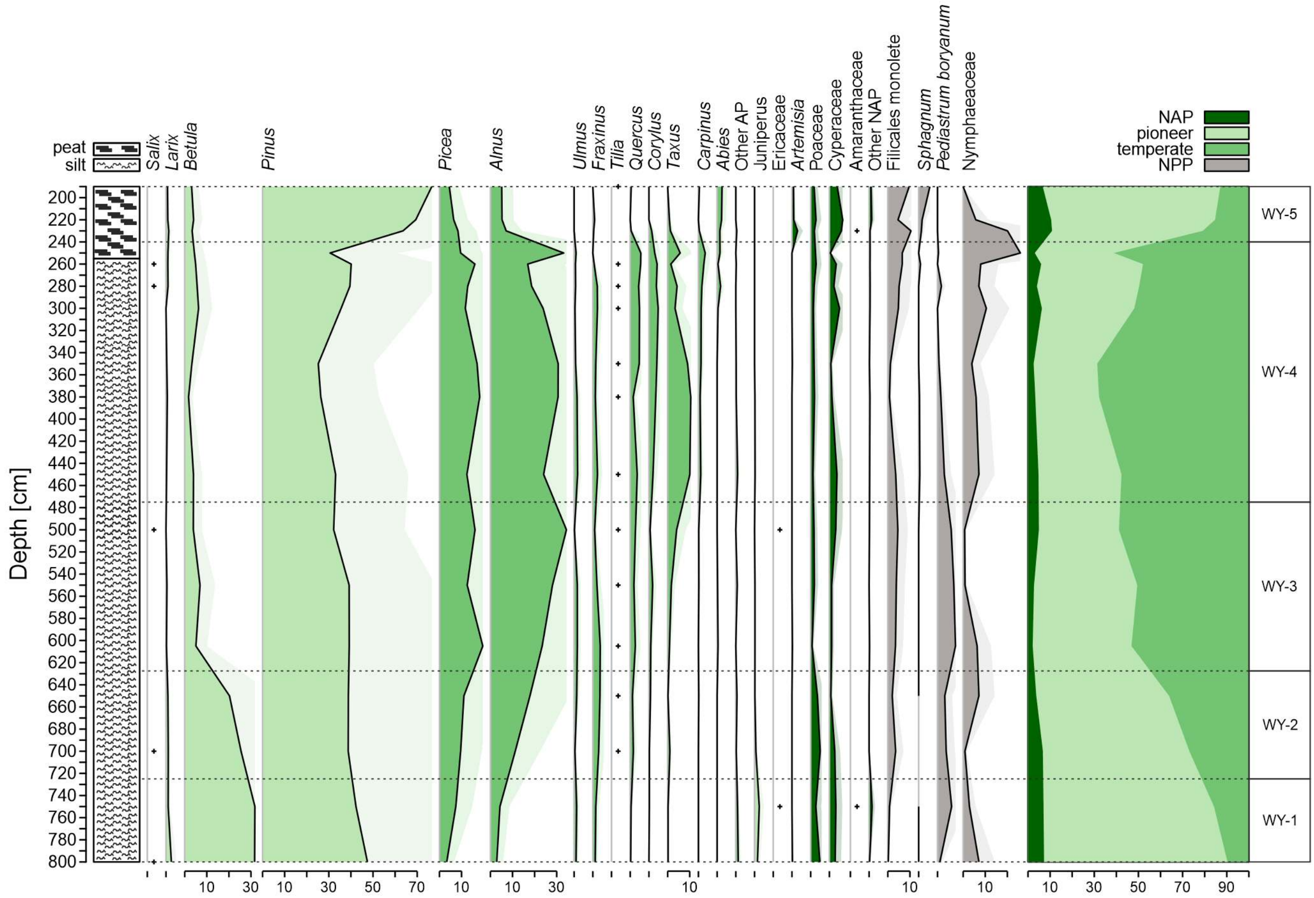

Fig. 9. Pollen diagram for Wygnanka (I.A. Pidek)

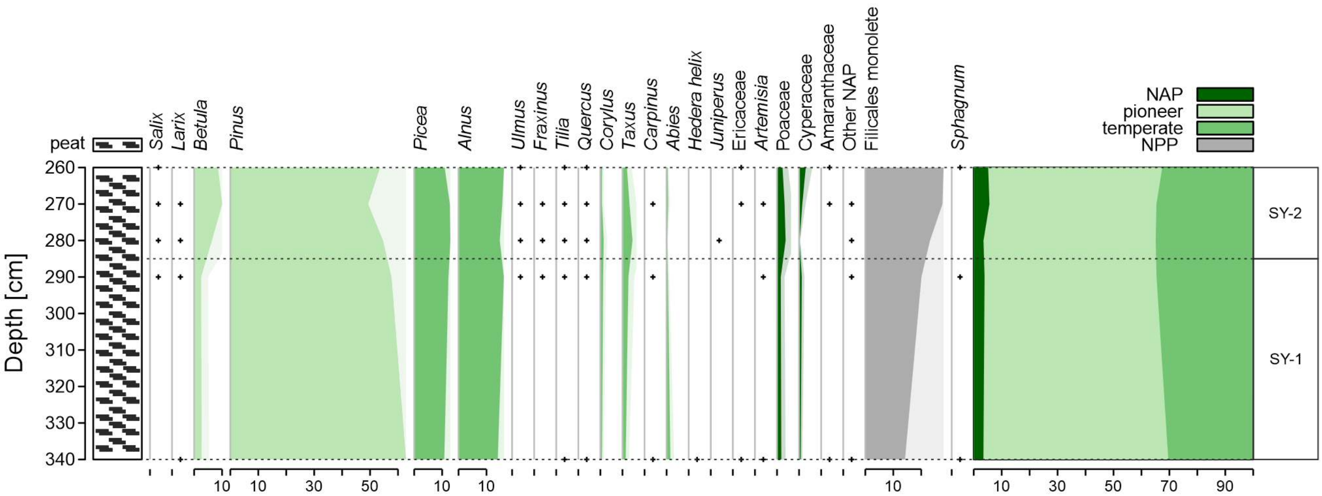

Fig. 10. Pollen diagram for Sytyta (A. Hrynowiecka)

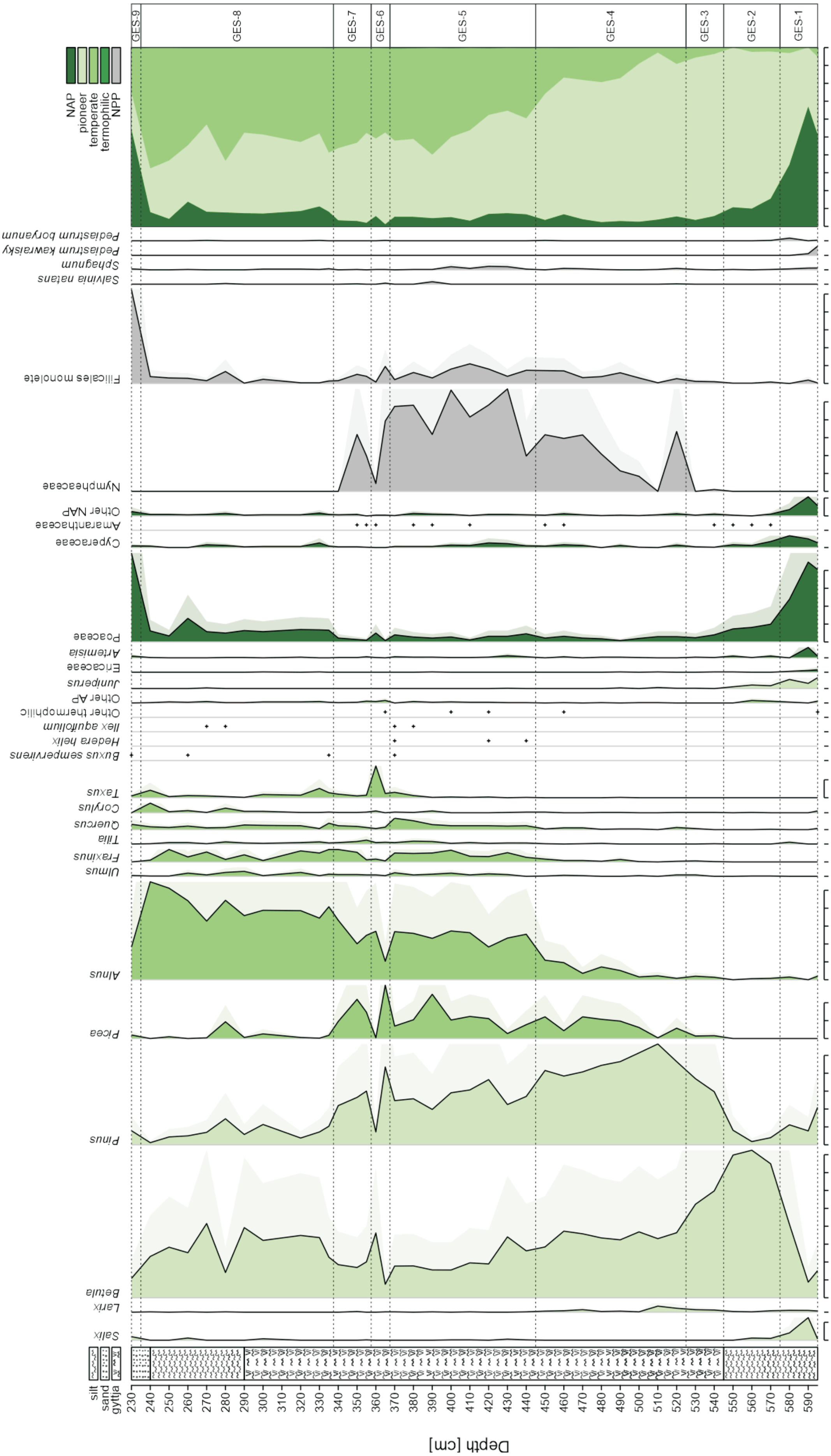

Fig. 11. Pollen diagram for Gęś 3 (A. Górecki)

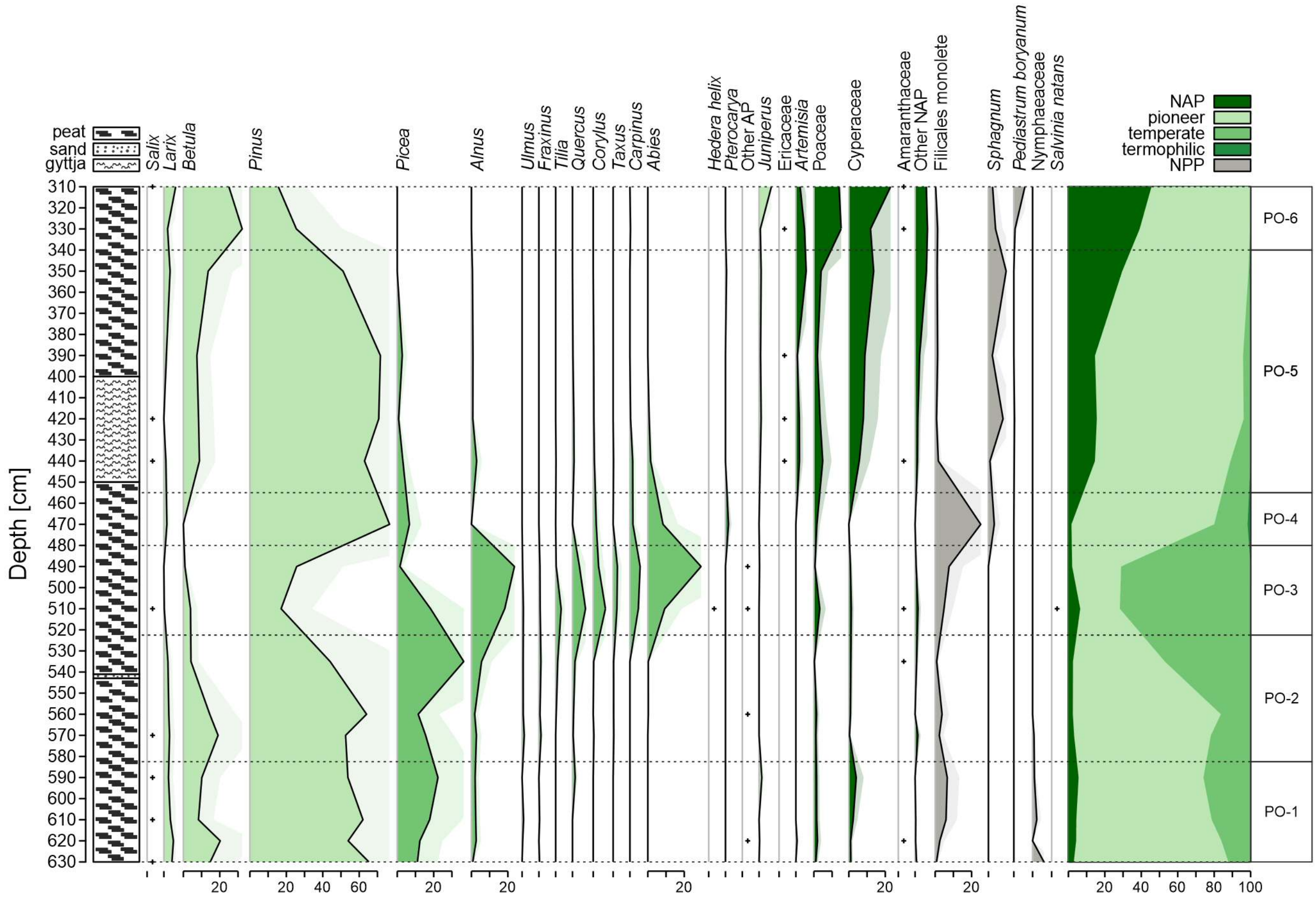

Fig. 12. Pollen diagram for Podedwórze (I.A. Pidek)

termination is reliable because it spans an interval in which *Taxus* pollen dominates, accompanied by abundant pollen of *Alnus* and *Picea*. The diagram (Fig. 9) spans a large fragment of the Mazovian succession, with the interglacial's beginning (WY-1 and WY-2 LPAZ), the older part of the climate optimum (WY-3 and WY-4 LPAZ, i.e. the *Taxus* zone with a high abundance of *Alnus* and *Picea*, and with warm climate indicators (e.g., *Viburnum* and *Humulus lupulus*), and the younger part of the hornbeam-fir interglacial optimum (WY-5 LPAZ). The diagram (Fig. 9) does not cover the youngest part of the Mazovian Interglacial optimum with the characteristic presence of *Pterocarya* pollen. Most probably, the lack of this interval in the analysed succession results from a depositional hiatus between gyttja and peats. This assumption is based on the rapidly terminating curves of percentage content of most trees, and an equally rapid increase in *Pinus* pollen values. In Wygnanka, as in Zahajki, there was a continuously high abundance of *Pinus* pollen.

SYTYTA SITE

Palynomorph abundance and preservation were very good in all samples analysed. The pollen diagram (Fig. 10) illustrating the results from 5 samples was subdivided into LPAZs, and numbered from SY-1 to SY-2 from the base of the succession. The phases of basin development documented (Fig. 10) span part of the Mazovian Interglacial, referred to the alder-spruce phase, i.e. the older part of the climate optimum of this interglacial, in which *Alnus* and *Picea* occur at high abundances (SY-1 LPAZ), followed by an increase in *Taxus* pollen percentages (SY-2 LPAZ). A very high abundance of *Pinus* pollen is observed again, which is not a feature characteristic for this interglacial but a local exception. The peats in Sytyta were formed in humid fern reed conditions.

GĘŚ 3

Palynomorph abundance and preservation were very good in all samples analysed. The palaeolake in Gęś 3 began functioning during the Elsterian (MIS 12) Glaciation with NAP values reaching up to 70% within the GES-1 LPAZ (Fig. 11). At that time, the lake was surrounded by steppe-like vegetation, among which dominated grasses and other herbaceous plants, including mugwort (*Artemisia*) and sedges (Cyperaceae). The first phase of the Mazovian Interglacial is typical and linked with the appearance of birch forests (*Betula* GES-2 LPAZ), in which *Pinus* appeared later as an admixture (GES-3; Fig. 11).

Within GES-4, species of temperate climate appeared in the local vegetation, mainly *Picea* and *Alnus* (Fig. 11). At that time, shallowing of the basin began, as shown by the high percentage content of palynomorphs related to the Nymphaeaceae (trichosclereids and tissue fragments).

Furthermore, appearance of Filicales monolete spores may testify to the formation of fern reeds. The vegetation in GES-5 is typical of the older part of the climate optimum of the Mazovian Interglacial, i.e. the *Picea-Alnus* phase (Fig. 11). As in the case

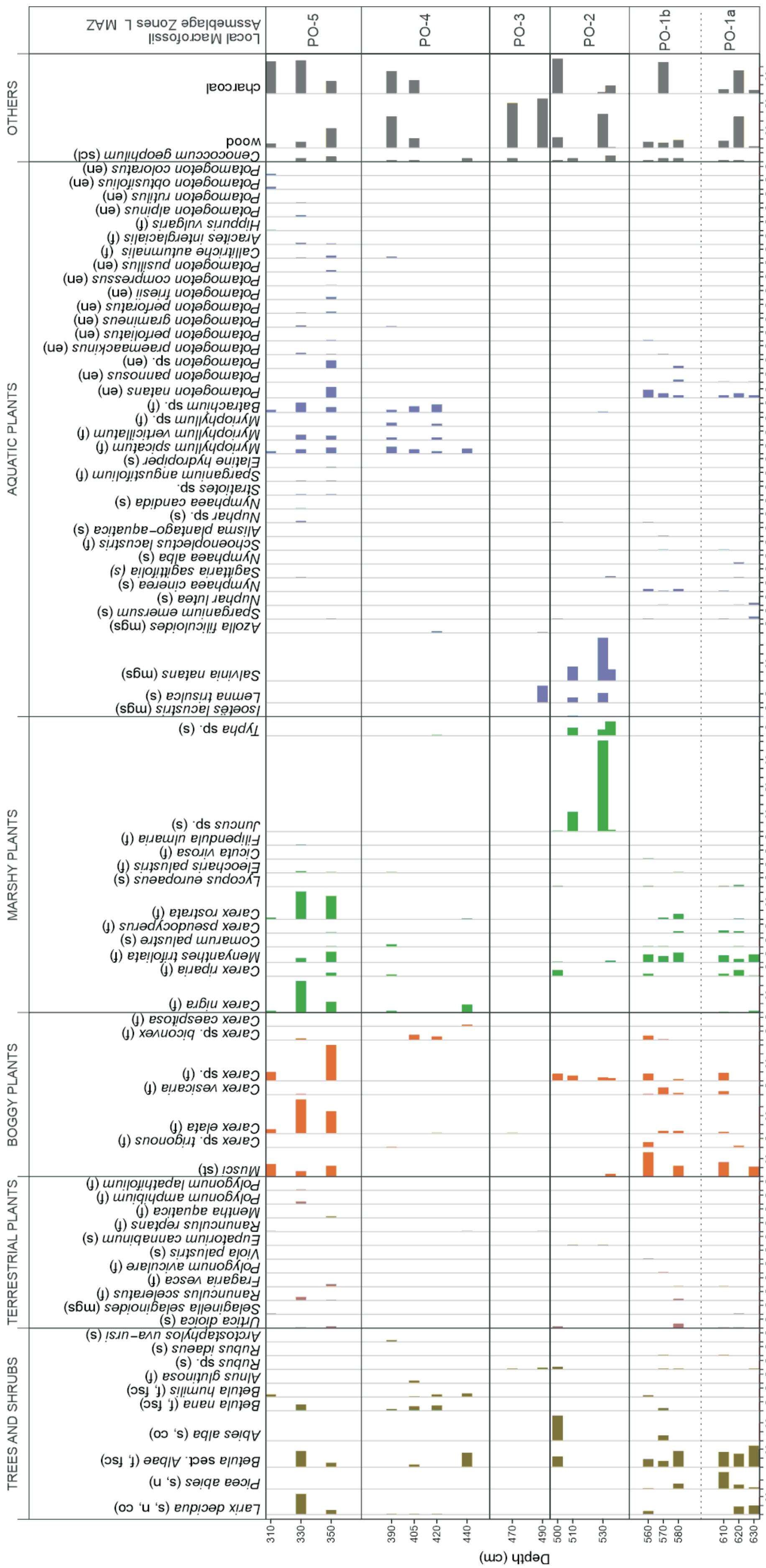

Fig. 13. Macrofossil diagram for Podedwórze (R. Stachowicz- Rybka, S. Skoczylas-Śniaz, K. Stachowicz)

mgs – megaspore, f – fruit, s – seed, fsc – fruit scale, n – needle, en – endocarp, l – leaf, scl – sclerotia, co – cone of other sites with MIS 11c in eastern Poland, riparian species become significant, mainly ash (*Fraxinus*) and elm (*Ulmus*). The lake margins were probably overgrown by alder forests. Climate conditions were optimal for the growth of thermofilous plants, such as boxwood (*Buxus sempervirens*), ivy (*Hedera helix*), and holly (*Ilex aquifolium*). Microsporangia of the thermophilous aquatic fern *Salvinia natans* were also noted; its presence together with Nymphaeaceae palynomorphs and Filicales monolete spores points to further shallowing of the lake.

The subsequent stage of vegetation development, i.e. with the high content of *Taxus* pollen (Fig. 11) is typical of the Mazovian Interglacial. This interval is linked with the prevalence of a warm and humid climate, marine in character, which probably led to a rise of water level in the fossil lake (with decrease in the percentage content of both Nymphaeaceae and Filicales monolete spores).

Repeated shallowing took place during the subsequent pollen zone (GES-7), which may be correlated with OHO (Fig. 11). Climate cooling is suggested by the disappearance of *Taxus* and a rising content of *Pinus*. Compared to the OHO record from other sites in eastern Poland, increase in the percentage content of pioneer taxa is not rapid (see Górecki et al., 2022). The atypical OHO record may result from the low sampling resolution, as well as from environmental conditions related to lake overgrowth. This translates also into a lack of precise correlation of GES-8 and 9 deposits. The pollen record may suggest overgrowth of the water body by an alder forest, therefore it is very local in character and does not represent regional vegetation changes. With regard to biostratigraphy, there is a lack of hornbeam (*Carpinus*) and fir (*Abies*) pollen, which are characteristic for the Mazovian Interglacial directly after the OHO. A rapid increase in herbaceous taxa content (NAP >50%) within GES-9 should be interpreted not as a rapid cooling, potentially linked with the beginning of the Liviecian (MIS 11b) Glaciation, but rather as the final stage of the lake succession within the *Carpinus-Abies* phase (Fig. 11).

PODEDWÓRZE SITE

This pollen diagram (Fig. 12) was subdivided into 6 Local Pollen Assemblage Zones (LPAZs), from PO-1 to PO-6, beginning from the base of the succession. The pollen zones span a large part of the Mazovian succession, with the beginning of the spruce-alder phase (PO-1 LPAZ), the younger part of the climate optimum (PO-2 LPAZ), i.e. the spruce zone with gradually encroaching thermophilous trees, such as *Ulmus*, *Fraxinus*, *Taxus*, *Quercus* and *Tilia*, and a younger part of the interglacial optimum, of the hornbeam-fir phase (PO-3 LPAZ). Expansion of fir forrest communites took place at that time (maximum content of *Abies* in PO-3), with a complete disappearance of spruce and pine, which previously occurred in high pollen values. *Carpinus* is present but in relatively low percentages. Among other thermophilous trees are present *Tilia platyphyllos* and maple (*Acer*). The pollen curves of most trees rapidly fall in the next zone. A subsequent increase in *Pinus* and numerous sporomorphs indeterminable due to poor preservation (Indeterminable) were noted in this zone (PO-4 LPAZ). There is an evident hiatus between PO-3 and PO-4. The percentage contents of fern spores Filicales rise rapidly, together with spores of sphagnum mosses (*Sphagnum*). This increase is preceded by the appearance of bog myrtle (*Menyanthes trifoliata*) pollen, pointing to a clear change of the habitat. At first, this was a shallow lake with *Potamogeton*, *Ceratophyllum*, and Nymphaeaceae, which was later overgrown (maximum of nympheids, microsporangia of the aquatic fern *Salvinia natans*), and transformed into a transitional bog with *Menyanthes trifoliata*, *Sphagnum*, and Filicales. A plant succession of an overgrowing alder forest was probably recorded in PO-4 LPAZ. This might explain the rapid disappearance of alder (*Alnus*) content at the PO-3/PO-4 boundary. Therefore it is evident that the diagram (Fig. 12) does not span the youngest part of the optimum of the Mazovian Interglacial with a characteristic continuous curve of *Pterocarya*. Instead, the latter taxon appears in Podedwórze as single pollen grains already in zones not representing the interglacial climate optimum. This is further evidence suggesting a Mazovian Interglacial age for these deposits. Most probably the PO-5 LPAZ represents the terminal part of the interglacial, when pine assemblages expanded. The zone is registered in peat deposits. Subsequent cooling is indicated by the presence of juniper (*Juniperus*, a continuous curve), dwarf birch (*Betula nana* t.), as well as an increased contribution of sagebrush (*Artemisia*), grasses (Poaceae), and sedges (Cyperaceae). The youngest zone (PO-6 LPAZ) represents vegetation typical of cool climate and open habitats.

Nineteen plant macrofossil samples were analysed in Podedwórze. Five local assemblage zones and one subzone were distinguished (Fig. 13 and Table 3). In the fossil flora analysed from Podedwórze, 78 taxa of various ranks were identified. Most taxa (64) have been recognised at species level, one at section level, 8 at genus level, and 5 at more general levels. The ecological requirements of the taxa analysed allowed detailed conclusions regarding the palaeoenvironment of the Podedwórze palaeolake and its direct vicinity.

The succession of local vegetation in the Podedwórze palaeolake resembles the succession in the stratotype section in Nowiny Żukowskie (Hrynowiecka and Szymczyk, 2011). The beginning of sedimentation, recorded in the PO-1 a, b LMAZ took place in a relatively shallow lake surrounded by a pine-birch forest with spruce (*Picea abies*) and larch (*Larix decidua*). A cool climate is shown by communities with boreal climate indices such as *Betula nana*, *B. humilis* and *Selaginella selaginoides* (Fig. 14: 4). Communities of low-sedge bog meadows with *Carex nigra*, *Menyanthes trifoliata*, and *Comarum palustre*, as well as high-sedge reeds (*Magnocaricion;* Koch 1926) with *Carex pseudocyperus*, *C. rostrata* and *C. riparia* developed on marshy margins near the lake.

Gradual shallowing took place in the interglacial optimum recorded in the PO-2 LMAZ; the earlier occurring macrophytes, e.g., *Nymphaea alba*, *N. cinerea* (Fig. 14: 11, 12), and *Nuphar lutea* (Fig. 14: 10), as well as *Potamogeton natans*, *P. praemackianus*, (Fig. 14: 7) *P. perfoliatus* and *P. pannosus* (Fig. 14: 5, 6) withdrew from the lake (Matuszkiewicz, 2008). This vegetation was almost completely replaced by pleuston communities of *Lemno minoris-Salvinion natantis* type (Slavnić, 1956 em. R. Tx. et A. Schwabe 1981), which covers exclusively aquatic plant communities composed of pleuston plants with the aquatic ferns *Salvinia natans* (Fig. 14: 4) and *Lemna minor*. The communities dwell in warm standing or flowing waters (Michalska-Hejduk and Kopeć, 2002), and often co-occur with better developed communities of water plants and coastal reeds with e.g. *Sparganium emersum* (Fig. 14: 14) and *Typha* sp., which were also identified in this zone.

In the PO-3 LMAZ in the sample from 4.9 m, high contents of *Alnus glutinosa* pollen and wood fragments document a subsequent phase of lake shallowing, which was then successively filled with organic sediments. A single megaspore of *Azolla filiculoides* (Fig. 14: 1) was identified in the zone; this taxon is crucial for determining the conditions prevailing in the lake. The appearance of *Azolla filiculoides* megaspores and numerous fruits of *Lemna minor* point to higher water temperature and trophic level (Stachowicz-Rybka, 2011).

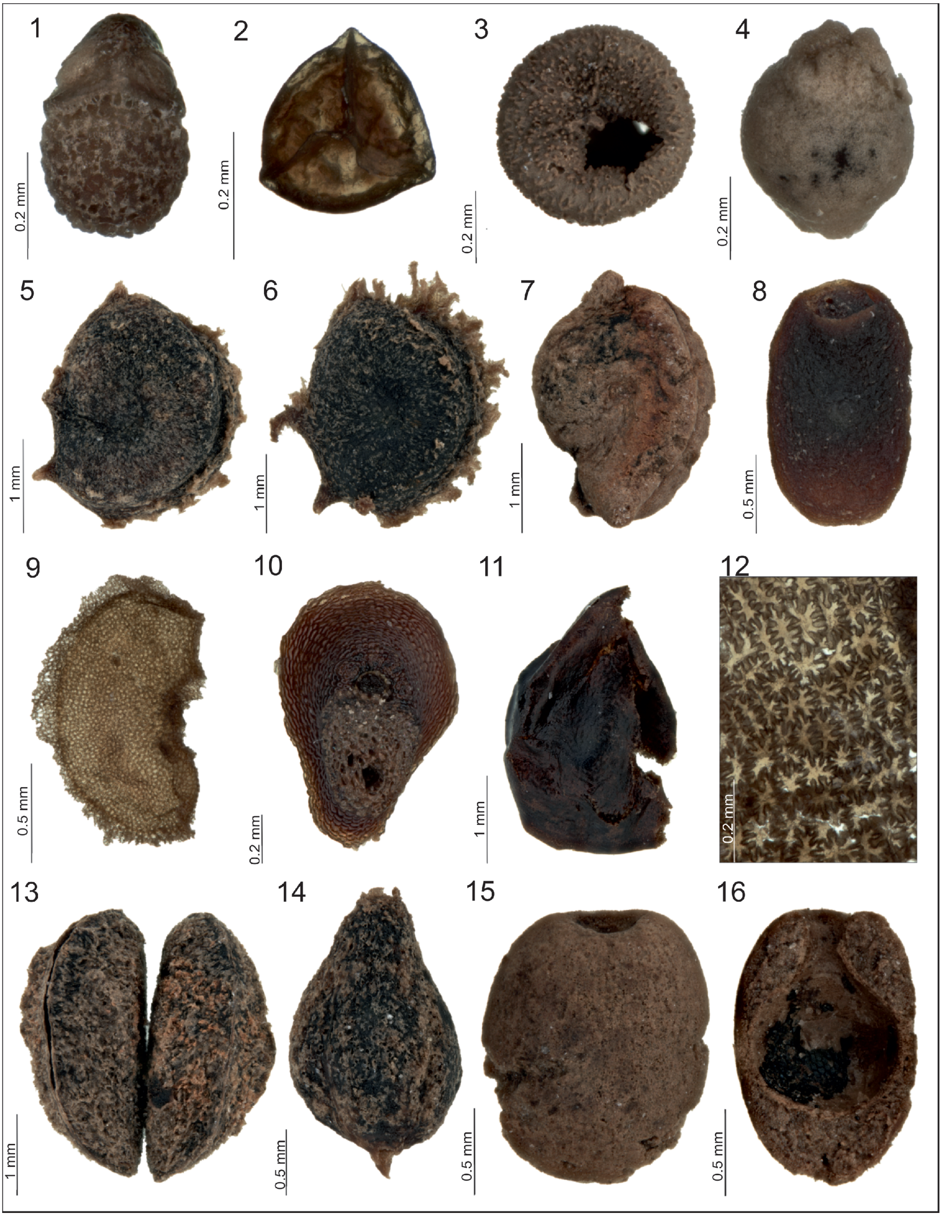

Fig. 14. Macrofossil plant remains from Podedwórze

1 – *Azolla filiculoides* megaspore*;* **2** – *Isoëtes lacustris* megaspore; **3** – *Selaginella selaginoides* megaspore*;* **4** – *Salvinia natans* megaspore*;* **5, 6** – *Potamogeton pannosus* endocarps; **7** – *Potamogeton praemaackianus* endocarp; **8** – *Hippuris vulgaris* fruit; **9** – *Callitriche autumnalis* fruit; **10** – *Nuphar lutea* seed; **11** – *Nymphaea cinerea* seed; **12** – *Nymphaea cinerea* details of the seed surface sculpture; **13 –** *Arctostaphylos uva-ursi* seed; **14** – *Sparganium emersum* fruit; **15** – *Aracites interglacialis* fruit;, **16** – *Aracites interglacialis* cross-section of fruit (fot. K. Stachowicz)

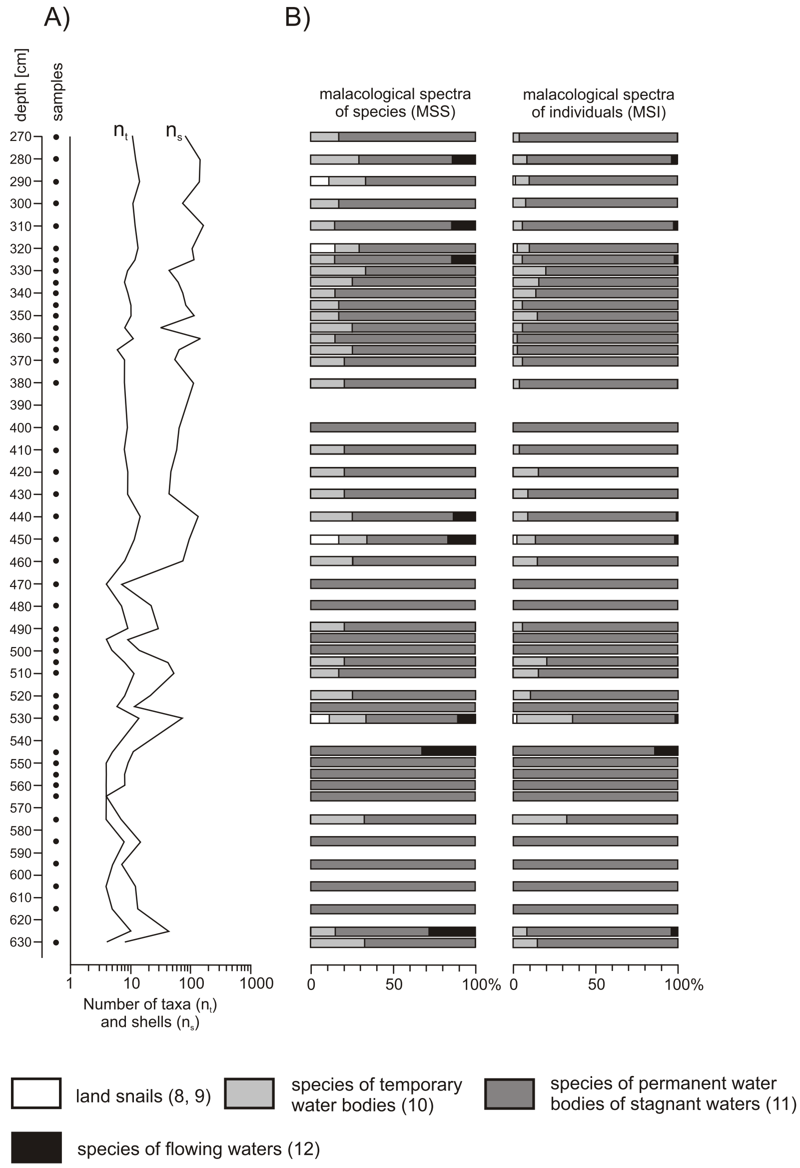

Fig. 15. Numbers of taxa and shells per sample (A) and ecological structure of the assemblage at Wygnanka (B)

For other explanations see Table 4

The reappearance of communities preferring deeper waters, with the endocarps *Myriophyllum spicatum*, which may occur in lakes to a depth of 6 m, and *M. verticillatum* which prefers more eutrophic waters with a low carbonate content and shallower conditions, up to 3–5 m deep (Podbielkowski and Tomaszewicz, 1982), took place in the PO-4 LMAZ. A cooler climate and better light conditions caused by thinning of the tree stands around the lake are shown by the return of a shrub tundra with dwarf birch (*Betula nana*), shrubby birch (*Betula humilis*), and *Arctostaphylos uva-ursi* (Fig. 14: 13).

The PO-5 LMAZ may correspond to the Early Liviecian (or the Birch Oscillation BHO within the pine phase of the Mazovian Interglacial) and is characterized by an increased content of *Betula* sect. *Albae* and *Larix decidua*, both in pollen and plant macroremains. The contribution of birch and larch also increased around Nowiny Żukowskie in the same interval. In comparison to the earlier zone, the water level in the lake increased, causing the development of high-sedge reed with *Carex rostrata*, *C. vesicaria*, *C. riparia*, *C. elata* and *C. nigra*. *Aracites interglacialis* (Fig. 14: 15, 16) appeared in marshy habitats near the lake margin. This taxon appears in mass amounts in the same interval at Nowiny Żukowskie. Its presence was also observed in Konieczki (Nita, 1999) in interval IV and in the early glacial of the Liviecian, in Białe Ługi 2 and 3 (Nita, 2009) in interval IV, and in Nowiny Żukowskie (Hrynowiecka and Szymczyk, 2011) in intervals III and IV of the Mazovian Interglacial. *Aracites interglacialis* Wieliczk. is an extinct species described for the first time by Velichkevich (1977) from the Ruba site in Belarus. It is also known from other sites in Belarus, e.g. Gralevo (Velichkevich, 1982), Vily Villago, and Zhidovshchizna (Dorofeev, 1960, 1963), Poland, e.g., Maków Mazowiecki, Olszewice, Stanowice, Katowice (Mamakowa and Velichkevich, 1993), Konieczki (Nita,

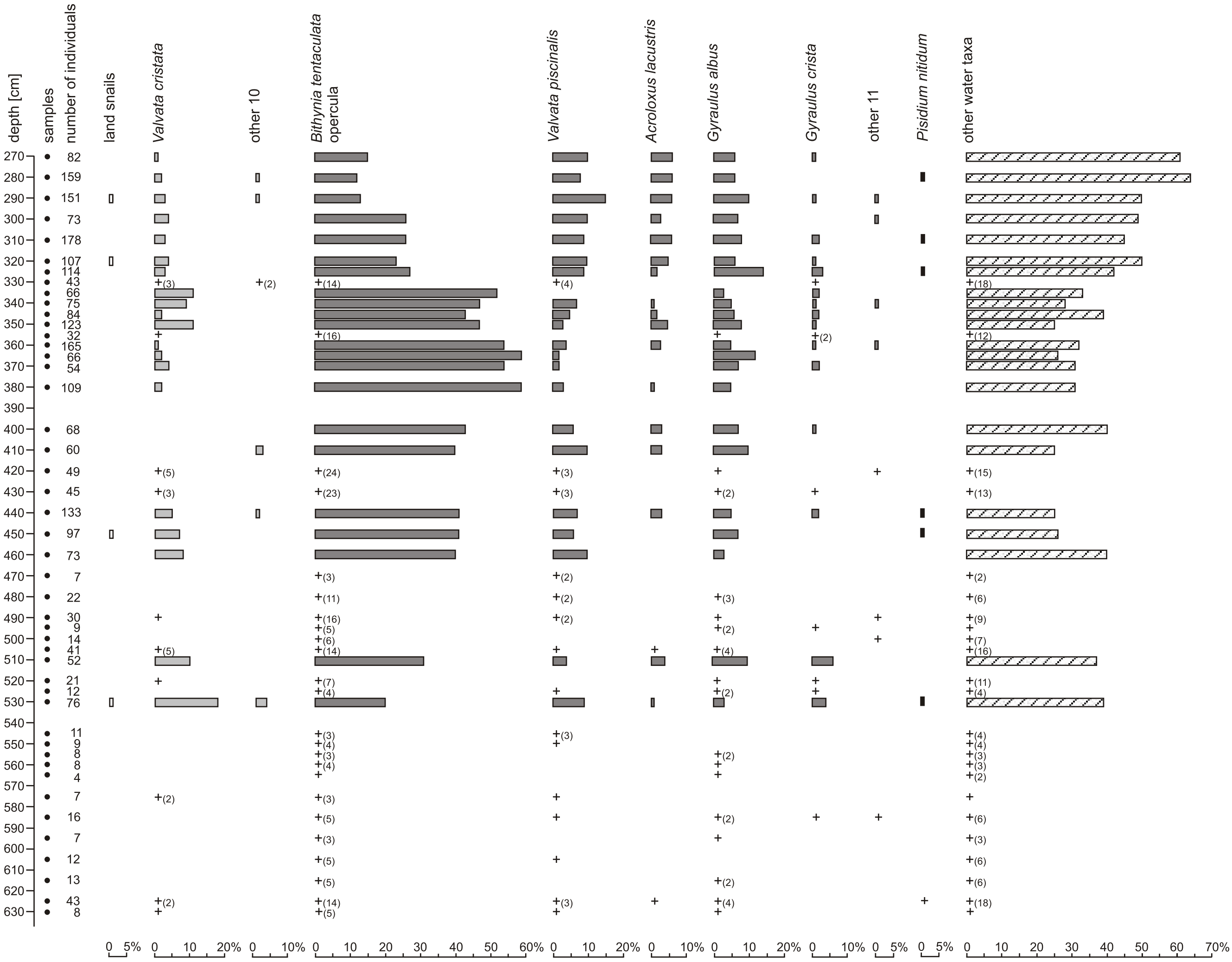

Fig. 16. Malacological diagram for Wygnanka

Representation of taxa reflects the percentage of individuals; "+" means that the taxon is represented in the given layer but the number of individuals for the layer is lower than 50; numbers in parentheses indicate a number of individuals higher than 1; for other explanations see Figure 15

1999), Białe Ługi (Nita, 2009), and Nowiny Żukowskie (Hrynowiecka and Szymczyk, 2011), Finland, e.g. Naakenavaara (Aalto et al., 1992), and England, e.g. Gilson (Field et al., 2017). Water level rise and probably trophic level increase allows reconstruction of diverse phytocoenoses with *Potamogeton natans*, *P. rutilus*, *P. filiformis*, *P. pusillus*, *P. obtusifolius* and *Batrachium* sp. Such species composition suggests mesotrophic waters. Bog and aquatic communities were enriched in *Cicuta virosa*, *Hippuris vulgaris*, (Fig. 14: 8), *Callitriche autumnalis* (Fig. 14: 9), *Nymphaea candida*, *Elatine hydropiper*, *Sagittaria sagittifolia*, *Nuphar* sp. and *Sparganium emersum.*

PALAEOFAUNAL ANALYSES

Altogether, 22 mollusc taxa (19 snails and 3 bivalves) and 6 ostracod taxa were identified at Wygnanka. They include 13 and 5 species, respectively (Table 4). Mollusc shells were poorly preserved and often crushed; however, complete or only slightly damaged specimens were also present. Ostracods were represented by single valves (a total of 13 individuals) found in only 8 samples (Table 4). Thus, they are of minor importance in this analysis.

The mollusc assemblage contained 2635 individuals. The maximum numbers of taxa and specimens per sample varied from 4 to 15 and from 4 to 178, respectively (Table 4). The abundance changed through the succession, with the most numerous shells noted in its upper part (2.7–4.6 m), within gyttja rich in plant detritus.

At Wygnanka, aquatic molluscs of permanent water bodies of stagnant waters (ecological group 11) dominated. They constitute at least 50% of all species and 61% of all individuals (Fig. 15). These species usually inhabit ponds, lakes and bays of slowly flowing rivers. *Acroloxus lacustris* and *Gyraulus albus* are most common in standing waters with rich vegetation (Welter-Schultes, 2012; Piechocki and Wawrzyniak-Wydrowska, 2016). Most abundant was the euryecological *Bithynia tentaculata* represented by lids (opercula) and their fragments (Fig.

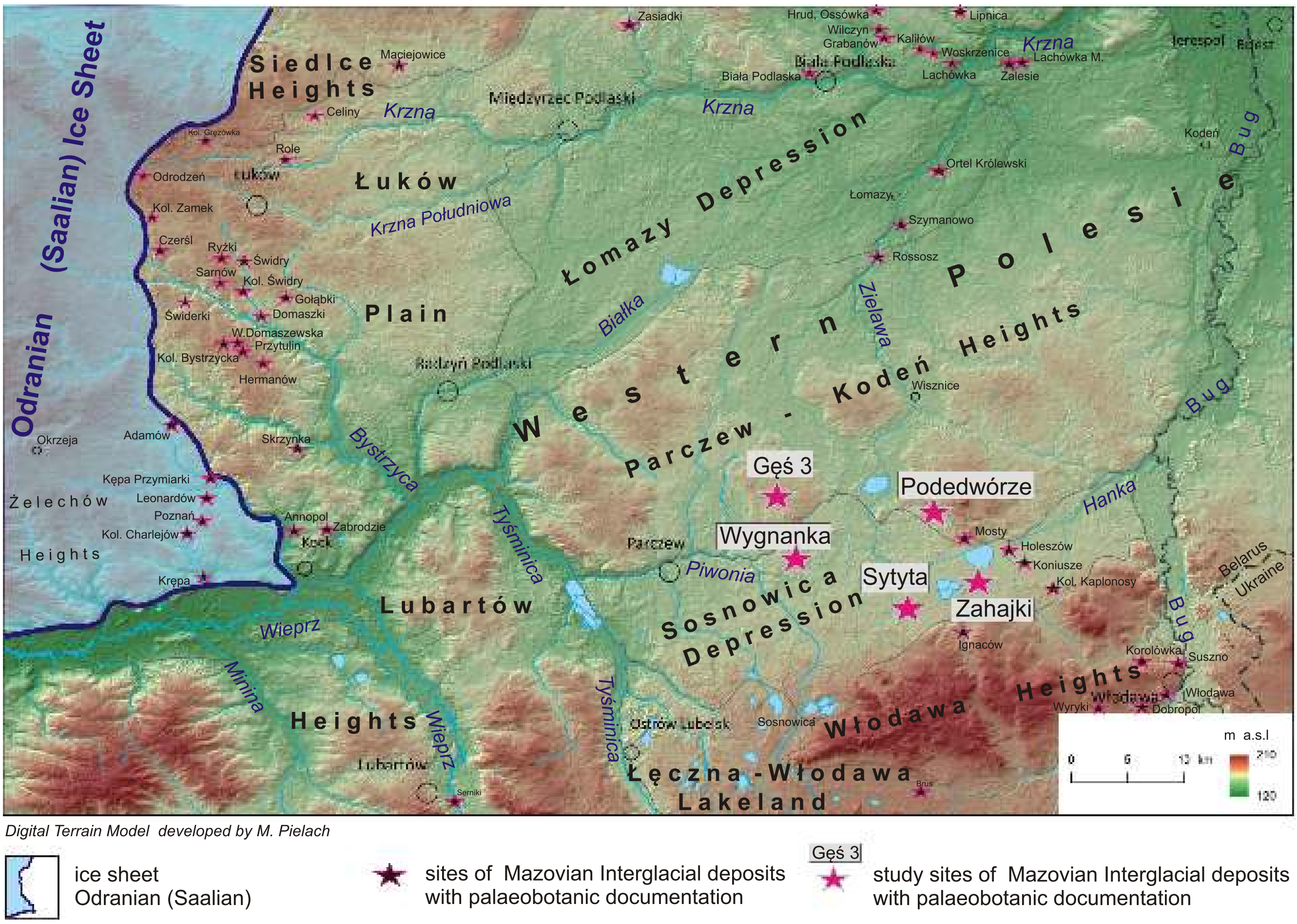

Fig. 17. Maximum range of the Odranian (Salian, MIS 6) ice-sheet (Żarski et al., 2009, 2024; Hrynowiecka et al., 2019; Górecki et al., 2022) with regard to the sites studied with the Mazovian Interglacial deposits

16 and Table 4). Some apical parts of shells were assigned to *Bithynia* sp. *Bithynia tentaculata* was accompanied by the relatively abundant *Valvata piscinalis*. Both species prefer well-oxygenated waters, but *V. piscinalis* usually prefers slightly deeper parts of the lakes (*B. tentaculata*: 0.7–1.8 m; *V. piscinalis*: 3–10 m; Welter-Schultes, 2012; Piechocki and Wawrzyniak-Wydrowska, 2016). Three species are typical of small, temporary and heavily overgrown water bodies (group 10): *Valvata cristata*, *Valvata* cf. *macrostoma* and *Planorbis* cf. *planorbis*. They constituted up to 35% of the assemblage (Fig. 15). However, due to the large proportion of initial whorls of *Valvata* sp. shells, it was impossible to clearly distinguish *V. piscinalis* from *V. macrostoma*. Rheophile species (group 12) were represented by single specimens of the euryecological *Pisidium nitidum* being an accessory element of the fauna (usually a few percent of all specimens) (Fig. 15 and Table 4). The mollusc assemblage was completed by single specimens of the moist-demanding land snails *Nesovitrea petronella* and *Carychium minimum*, a fragment of a Clausiliidae shell, and a calcareous slug plate (Limacidae). These were found in only four samples and were insignificant for the interpretation (Table 4).

Among ostracods were the extinct *Scottia browniana* and *S. tumida*, which are very common in Holsteinian deposits and indicative of moderately shallow zones of water bodies (Robinson, 1980; Skompski, 1991; Szymanek, 2014; Wasążnik, 2018; Czajkowska, 2022).

DISCUSSION

Sites with documented deposits of the Mazovian Interglacial (Holsteinian, MIS 11c) are of key significance for Pleistocene stratigraphy, because they separate deposits of the Sanian 2 (Elsterian, MIS 12) Glaciation from deposits of the Odranian (Saalian, MIS 6) Glaciation, i.e. from the Middle Polish Complex (Saale complex, MIS10–MIS 6; Table 1).

Palaeobotanical studies in Zahajki, Wygnanka, Sytyta, Podedwórze, and Gęś 3 point to the presence of lacustrine deposits from the Mazovian Interglacial (MIS 11c). The sites occur in the shallow subsurface and are characterized by the lack of a glacial cover (Table 2). Only occasionally are deposits of the Mazovian Interglacial overlain by Early Liviecian (Fuhne, MIS 11b) lacustrine deposits or upper Vistulian deluvial, biogenic or niveolimnic deposits. This is thus proof that the area of the Sosnowica Depression and the Parczew-Kodeń Heights described was not covered by the ice-sheet of the Odranian (Saalian, MIS 6) Glaciation, contrary to what was hitherto assumed. Therefore, the concept of Zaborski (1927) that the ice-sheet of this glaciation reached the Chełm-Rejowiec line cannot be sustained.

The sites located in Western Polesie supplement the list of 10 previously studied sites of this interglacial (located in the Łomazy Depression, Włodawa Heights and the Łęczna-Wło-

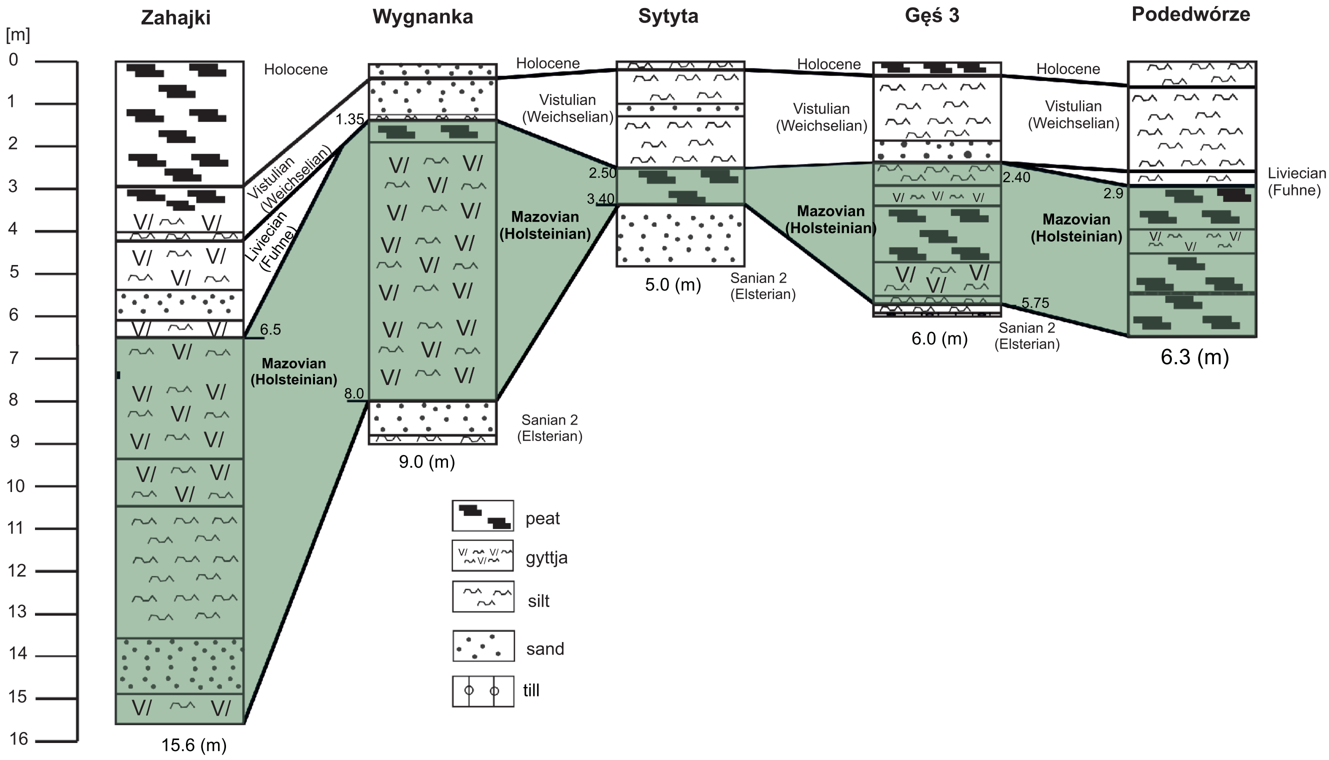

Fig. 18. Correlation of the successions analysed

dawa Lakeland) and the numerous sites of the Mazovian Interglacial with palaeobotanical and geological data from the southern part of the South-Podlasie Lowland (Żarski et al., 2023b, 2004; Fig. 17). Taking into account our results, we would like to sustain the inference (Żarski et al., 2023a, b; Hrynowiecka et al., 2019) that the Łuków Plain was not covered by the ice-sheet of the Odranian (Saalian, MIS 6) Glaciation and that the maximum range of this ice-sheet can be traced along the Siedlce-Łosice-Kornica line (Marks et al., 2018; Żarski and Kucharska, 2020; Kucharska et al., 2020; Żarski et al., 2024) and to the west of Łuków (Fig. 17).

The Parczew-Kodeń Heights do not represent a continuous plateau. They are composed of a series of isolated "islands" composed of glacial tills, weathered in their topmost part. The Gęś 3 and Podedwórze sites of the Mazovian Interglacial occur in the topmost parts of these weathered "islands" (Figs. 1, 2 and 17). The plateau was not shaped during the Middle Polish Odranian (MIS 6) Glaciation as previously thought (Zaborski, 1927; Lindner et al., 1985; Buraczyński, 1986), but during the Sanian 2 (Elsterian, MIS 12) Glaciation. Glacifluvial outwash covers linked with the runoff of meltwaters from the ice-sheet front of the Odranian (Saalian, MIS 6) Glaciation have been documented only in the northern part of the Parczew-Kodeń Heights (Pochocka-Szwarc et al., 2021; Pochocka-Szwarc and Żarski, 2023).

The Sosnowica Depression comprises a vast, sub-parallel surface reaching a width of ~15 km. As shown by the results of geological surveys (Żarski and Morawski, 2019; Pochocka-Szwarc, 2023; Żarski and Pochocka-Szwarc, 2023), it is a fossil outwash plain with thicknesses up to ~20–30 m (Figs. 5–7). The plain developed during the recessive phase of the Sanian 2 (MIS 12) Glaciation. Zahajki, Wygnanka and Sytyta, i.e. sites with a record of the Mazovian Interglacial, are located on its surface. The Sosnowica Depression is infilled with glacifluvial deposits, probably derived also from earlier glaciations, whereas the glacial tills are preserved as relics, e.g. near Kodeniec (Pochocka-Szwarc, 2023). Above these deposits commonly occur up to 2.5 m of fine silts and sands, whose OSL absolute age determinations are in the range of 68 to 13 ka (Pochocka-Szwarc et al., 2021; Pochocka-Szwarc, 2023). We infer that these sediments accumulated in periglacial conditions in the presence of permafrost, which existed in the study area during the Vistulian (Błaszkiewicz, 2005, 2008; Dobrowolski, 2006; Bogucki and Łanczont, 2018).

Therefore, the Sosnowica Depression was subject to glacifluvial runoff during the Middle Polish Odranian Glaciation (Zaborski, 1927; Buraczyński and Wojtanowicz, 1980/1981; Buraczyński et al., 1984; Buraczyński, 1986) or the Wartanian Glaciation (Harasimuk et al., 2004). It seems thus that the main route of outwash runoff, related to meltwater drainage from the proximal zone of the Odranian ice-sheet, took place towards the east (Fig. 17) mainly through the Łuków Plain and the Łomazy Depression (Żarski et al., 2023, 2024). Sites of the Mazovian Interglacial at Ortel Królewski, Szymanowo and Rossosz (Figs. 1 and 17; Albrycht et al., 1995; Szymanek et al., 2005; Szymanek, 2011, 2014; Czajkowska, 2022) are preserved along this route.

PALAEOECOLOGICAL IMPLICATIONS

The sections of organogenic deposits analysed document the Mazovian (Holsteinian, MIS 11c) pollen succession with its characteristic features. The record of this succession varies between the sites, but in each of them the pollen zones of the older part of the climate optimum, dominated by spruce and alder communities, followed by yew expansion, are well-developed. The percentage content of *Taxus* pollen is not high in any of the pollen diagrams analysed (Figs. 8–12), but there is a continuously high content of *Pinus* pollen. In comparison to the high-resolution pollen diagrams from Brus (Pidek, 2003), Ossówka (Krupiński, 1995; Nitychoruk, 2000; Nitychoruk et al., 2005, 2018), Biała Podlaska (Krupiński et al., 1988); Nowiny Żukowskie (Hrynowiecka-Czmielewska, 2010), and Skrzynka (Górecki et al., 2022), lower contents of *Taxus* and much higher contents of *Pinus* should be considered as a local feature. Such an interpretation is supported by the very high content of *Alnus*, which may suggest the presence of shallow drainless lakes, partly transforming into alder carrs, and partly into transitional bogs and raised bogs. Further evidence comes from the analy-

Table 4

Faunal assemblage at Wygnanka

	Nesovitrea petronella (Pfeiffer, 1853)	*Carychium minimum* (O.F. Müller, 1774)	Limacidae	Clausiliidae	*Valvata cristata* O.F. Müller, 1774	*Valvata* cf. *macrostoma* Mörch, 1864	*Planorbis* cf. *planorbis* (Linnaeus, 1758)	*Bithynia tentaculata* (Linnaeus, 1758)	*Valvata piscinalis* (O.F. Müller, 1774)	*Acroloxus lacustris* (Linnaeus)	*Lymnaea* cf. *stagnalis* (Linnaeus, 1758)	*Gyraulus albus* (O.F. Müller, 1774)	*Gyraulus crista* (Linnaeus, 1758)	*Pisidium hibernicum* Westerlund, 1894	*Pisidium nitidum* Jenyns, 1832	*Bithynia* sp.	*Valvata* sp.	*Radix* sp.	Planorbidae	*Anisus* sp.	*Gyraulus* sp.	*Pisidium* sp.	n_t	n_s	Volume [cm^3]	*Candona candida* (O.F. Müller, 1776)	*Candona* sp.	*Cyclocypris ovum* (Jurine, 1820)	*Herpetocypris* cf. *reptans* (Baird, 1835)	*Scottia browniana* (Jones, 1850)	*Scottia tumida* (Jones, 1850)	n_t	n_s	Volume [cm^3]
	Gastropoda (ecological groups after Alexandrowicz and Alexandrowicz, 2011)															Other Mollusca										Ostracoda								
	Land				Aquatic																													
	8	9			10			11							12																			
2.7					1			(12)	8	5		5	1			7 (5)	37	4	1		1		11	82	60									10
2.8					3		2	(19)	12	10		10			2	8 (26)	56	7			9	3	12	159	110									10
2.9			1		5		2	(19)	22	9	1	15	1			10 (8)	53	4		1	6	2	15	151	110									10
3.0					3			(19)	7	2		5		1		3 (4)	24	1			6	1	11	73	80									10
3.1					6			(46)	16	11		14	3		2	6 (6)	57	2			14	1	12	178	100									10
3.2	1				4			(25)	11	5		6	1			4 (7)	34	1		1	9	2	13	107	80									10
3.25					3			(31)	10	2		16	3		1	8 (9)	30	1			5	3	12	114	60			1				1	1	10
3.3					3	2		(14)	4	1			1			3 (5)	10				3		9	43	50									10
3.35					7			(34)				2	1			5 (11)	9	1			1		8	66	60									10
3.4					7			(35)	5	1		4	1	1		7 (13)	8						9	75	60				1			1	1	10
3.45					2			(36)	4	2		5	2			6 (16)	14	2		1			10	84	60									10
3.5					13			(58)	4	6		10	1			8 (10)	17				3	1	10	123	60									10
3.55					1			(16)				1	2			3 (5)	5				1	1	8	32	30									10
3.6					2			(89)	6	5	1	8	1			6 (29)	20	1			3		11	165	110	1			1		1	3	3	10
3.65					1			(39)	1			8				1 (13)	4						6	66	60									10
3.7					2			(29)	1			4	1			1 (7)	8				2		8	54	50									10
3.8					2			(64)	3	1		5				5 (25)	8	1					8	109	100									10
4.0								(29)	4	2		5	1			(11)	10				5	1	9	68	50									10
4.1						1		(24)	6	2		6				6 (5)	14					1	8	60	40									10
4.2					5			(24)	3		1	1				4 (8)	4	1				2	9	49	50									10
4.3					3			(23)	3			2	1			2 (5)	5	2			1		9	45	40		1					1	1	10
4.4					7		1	(54)	9	4		7	3		1	8 (11)	25	2	1	1	5	2	15	133	90									10
4.5		1			7			(40)	6			7			1	6 (13)	17	1		1	2	1	12	97	60									10
4.6					6			(29)	7			2				3 (6)	17				3	3	8	73	40						1	1	1	10
4.7								(3)	2							(1)	1						4	7	60						1	1	1	10
4.8								(11)	2			3				2	2	1				1	7	22	70									10
4.9					1			(16)	2		1	1				(2)	4				2	1	9	30	80									10
4.95								(5)				2	1			(1)							4	9	100									10
5.0								(6)			1					(4)	2			1			5	14	60									10
5.05					5			(14)	1	1		4					13	1				2	8	41	70	1						1	1	10
5.1					5			(16)	2	2		5	3			2 (3)	9	2		1	3	1	12	52	110									10
5.2					1			(7)				1	1			(5)	4			1		1	8	21	110									10
5.25								(4)	1			2	1			(1)	3						6	12	110									10
5.3				1	14	2		(15)	7	1		2	3		1	4 (8)	16	3	1			2	14	76	130									10
5.45								(3)	3						1	(1)	3						5	11	90					4		1	4	10
5.5								(4)	1							(1)	3						4	9	70									10
5.55								(3)				2					2					1	4	8	60									10
5.6								(4)				1					2	1					4	8	90									10
5.65								(1)				1					1				1		4	4	60									10
5.75					2			(3)	1							1							4	7	60									10
5.85								(5)	1		1	2	1				4				1	1	8	16	100									10
5.95								(3)				1				(1)	1					1	5	7	110									10
6.05								(5)	1								5	1					4	12	60									10
6.15								(5)				2				3 (1)	2		1				5	13	100									10
6.25					2			(14)	3	1		4			1	4 (5)	11	1	1				10	43	110									10
6.3					1			(5)	1								1						4	8	70									10

8 – mesophilous species typical of moist substrates, 9 – species of damp and swampy habitats, 10 – species of temporary water bodies, 11 – species of permanent stagnant water bodies, 12 – species of flowing waters; the number of opercula is given in parentheses; for bivalves and ostracods the number of valves is given; n_t – number of taxa, n_s – number of specimens

sis of plant macroremains and molluscs. Due to the shallow character and fast overgrowth of the lakes, most probably the cooler and more arid OHO climate oscillation ending the older part of the Holsteinian climate optimum terminated the functioning of these lakes. This is marked as a hiatus in the palaeorecord in each of the pollen diagrams, as well as in the analyses of macroremains and mollusc communities. A return to biogenic accumulation and thus reactivation of the palaeoecological record took place in the younger part of the climate optimum, which, as corroborated by sites with a complete Holsteinian succession, was characterised by a warm and humid climate. Fir and hornbeam communities with numerous shrubs and climbers indicative of a warm and humid climate, e.g., *Celtis*, *Juglans*, *Ilex aquifolium*, *Carya*, *Parrotia*, *Pterocarya*, *Buxus*, and *Vitis*, expanded at that time (Janczyk-Kopikowa, 1996; Bińka et al., 2003; Winter, 2008). Of particular attention is the much wider range of common silver fir *Abies alba* across the entire Polish Lowlands (Krupiński, 1995, 2000) compared to the present-day range covering only the sub-alpine forest of the Carpathians and the Central Polish Uplands.

The record of the younger part of the interglacial has been noted in Podedwórze (maximum of *Abies* at 29%). However, the plant macroremains and malacofauna do not indicate reactivation of a lake or of the presence of a marsh.

The mollusc assemblage at Wygnanka appears typical of a shallow stagnant body of water or a littoral zone with abundant vegetation. The presence of lids with no shells may point to a reed and bullrush zone of the lake (Alexandrowicz, 1999). Separation of lids and shells may also have been influenced by currents (e.g., Sanko et al., 2011), which were clearly minimal as indicated by the low number of species typical of running waters. A rich aquatic vegetation is supported by the plant-associated *Valvata cristata*, *Gyraulus albus*, *G. crista*, *Acroloxus lacustris* and *Scottia browniana*.

Better conditions for faunal development (or shell preservation) occurred in the upper part of the succession as indicated by the increased abundance of taxa and individuals (Fig. 15). The assemblage was rather uniform, though some changes in the proportions of *Bithynia tentaculata* and *Valvata piscinalis* (in the depth interval 2.7–3.25 m) may suggest a slight rise in water level (cf. Szymanek, 2012, 2013, 2014; Alexandrowicz et al., 2021, 2024).

No index species occurred in the assemblage. *Scottia browniana* and *S. tumida* used to be considered characteristic of the Holsteinian (Kempf, 1971; Robinson, 1980; Skompski, 1991) until being found in younger deposits in Germany and Poland (Pietrzeniuk, 1987; Kozydra and Skompski, 1995; Krzymińska and Namiotko, 2013). All species are common in lake deposits of various ages (e.g., Albrycht et al., 1995; Skompski, 1996, 2009; Alexandrowicz, 2002; Sanko et al., 2010; Szymanek, 2011, 2012, 2013; Alexandrowicz and Alexandrowicz, 2010; Alexandrowicz et al., 2021, 2024; Czajkowska, 2022).

PALAEOGEOGRAPHIC AND PALAEOENVIRONMENTAL IMPLICATIONS FOR THE MIS 12-MIS 2 INTERVAL IN THE STUDY AREA

The last Pleistocene ice-sheet that covered Western Polesie was from the Sanian 2 (Elsterian, MIS 12) Glaciation, whose maximum range reached to the foot of the Carpathians according to some authors (Lindner, 2001; Łanczont, 1997; Lindner et al., 2006), and only to the vicinity of Chełm according to others (Marks, 2023a). During its recession, the ice-sheet limit was recorded as frontal moraines, e.g. in the Włodawa Heights (Pochocka-Szwarc, 2023) or near Góra Grabowska in the Parczew-Kodeń Heights (Pochocka-Szwarc and Żarski, 2023; Żarski et al., 2023). The formation of the Sosnowica Depression can be linked with the ice-sheet limit near Góra Grabowska: waters flowing from the melting ice-sheet formed a subparallel, wide runoff zone towards the east (Pochocka-Szwarc and Żarski, 2023; Żarski et al., 2023b, 2024), at the same time eroding older glacial or ice-dammed deposits.

Glacifluvial sands and gravels covered dead-ice blocks, probably preserving small post-glacial troughs (Wygnanka) or depressions (Zahajki). Small depressions carved in the glacial tills were formed during the recession. These depressions are probably the result of meltwater evorsion activity (Piotrowski, 1997; Ravier and Buoncristiani, 2018). They were later infilled with dead-ice blocks during ice-sheet melting. The presence of dead ice is common in zones of deglaciation (Böse, 1995; Błaszkiewicz, 2008, 2011; Schomacker and Benediktsson, 2018).

After the retreat of the Sanian 2 ice-sheet towards the north, glacial tills building the Parczew-Kodeń Heights were exposed and the plateau was incised by meltwater from the ice-sheet.

Climate warming during the late glacial of the Sanian 2 Glaciation caused melting of ice in depressions occurring within the Sosnowica Depression and the Parczew-Kodeń Heights. The former depressions (troughs, meltout water bodies) became lakes accumulating silts, sands and gyttja (Pochocka-Szwarc et al., 2021).

During the Mazovian (Holsteinian, MIS 11c) Interglacial the post-glacial meltouts were transformed into lakes. A lake functioned throughout the entire documented Mazovian Interglacial in Zahajki, with gyttja infilling the palaeobasin, existing also during the early Liviecian (MIS 11b; Fig. 18 and Table 5).

In Podedwórze a bog existed from the early Mazovian until the late Mazovian (Holsteinian, MIS 11c; Fig. 18 and Table 5). In the early Liviecian, the bog transformed into a lake. Analysis of the lithological log suggests that a water body had already existed in the Late Sanian 2 (Elsterian); in the earliest part of the Mazovian Interglacial it transformed into a lake (gyttja) and later into a bog (Fig. 18). In Wygnanka, the lake existed from the early part of the Mazovian Interglacial (MIS 11c) until the middle of the younger part of the climate optimum. Deposits from the younger part of the Mazovian Interglacial are not preserved. Probably the lake was sediment-filled and completely disappeared. In Gęś 3 a lake existed in the late Sanian 2 (Elsterian) and gyttja sedimentation took place through the entire Mazovian Interglacial (Fig. 18 and Table 5). The older part of the climate optimum is preserved in the pollen spectra. Afterwards the lake shallowed and disappeared. In Sytyta, only a bog was documented; it spans the climate optimum of the Mazovian Interglacial (MIS 11c; Fig. 18 and Table 5).

Based on the spatial distribution of sites with lacustrine deposits of the Mazovian Interglacial (Holsteinian, MIS 11c) it can be inferred that they were part of a palaeolakeland streching from Biała Podlaska to Łuków, and covering the northern part of Western Polesie (Fig. 17).

There is scarcely any sedimentary record in the interval between MIS 9 and MIS 6 in the sections analysed. We therefore infer that there was only one advance of the Odranian (Saalian, MIS 6) ice-sheet (Marks, 2023a) after the Mazovian Interglacial in the study area. As during the glacial periods correlated with MIS 10, MIS 8 and MIS 6, the study area was not covered by ice, and periglacial conditions related with the presence of permafrost prevailed in its subsurface zone (Dobrowolski, 2006), post-glacial lakes with lacustrine deposits did not originate during the warmer intervals correlated with MIS 9 and MIS 7. The lack of lacustrine deposits does not allow for the reconstruction of the vegetation successions of these interglacials (MIS 9 and

Table 5

Tentative stratigraphic correlation of the successions studied with the records at: Hermanów (Hrynowiecka et al., 2019), and Nowiny Żukowskie (Hrynowiecka-Czmielewska, 2010) and the Mazovian Interglacial zonation in Poland (Krupiński, 1995; Janczyk-Kopikowa, 1996; Winter, 2008)

Marine Isotope Stage	Hermanów	Nowiny Żukowskie	Skrzynka	Zahajki	Podedworze	Gęś	Wygnanka	Sytyta	Mazovian Interglacial palynostratigraphy
11a	HE-21								Early Liviecian Glaciation
	HE-20								
	HE-19								
	HE-18								
	HE-17								
	HE-16								
11b	HE-15	NŻ-14		ZA-8					
	HE-14	NŻ-13		ZA-7					
	HE-13 HE-12	NŻ-12	SK-14	ZA-6					
11c	HE-11	NŻ-11	SK-13	ZA-5					*Pinus*
		NŻ-10	SK-12		PO-6				BHO
		NŻ-9	SK-11 SK-10		PO-5 PO-4				*Pinus*
	HE-10	NŻ-8e	SK-9	ZA-4	PO-3				*Carpinus-Abies*
	HE-9	NŻ-8d	SK-8						
	HE-8	NŻ-8c	SK-7						YHO
	HE-7	NŻ-8b	SK-6						*Carpinus-Abies*
	HE-6	NŻ-8a				GES-9? GES-8?			
	HE-5	NŻ-7	SK-5			GES-7	WY-5		OHO
	HE-4	NŻ-6	SK-4	ZA-3		GES-6	WY-4	SY-2	*Picea-Alnus-Taxus*
		NŻ-5							
	HE-3	NŻ-4	SK-3	ZA-2	PO-2 PO-1	GES-5	WY-3	SY-1	*Picea-Alnus*
		NŻ-3	SK-2			GES-4	WY-2		
	HE-2	NŻ-2	SK-1	ZA-1		GES-3	WY-1		*Betula-Pinus*
	HE-1					GES-2			*Betula*
12		NŻ-1				GES-1			Late Sanian 2 Glaciation

MIS 7). Based on an overview of interglacial successions in Poland (Pidek et al., 2022), it can be assumed that these warmer intervals were in fact colder than the Mazovian (MIS 11c) and the Eemian interglacial (MIS 5e), which are represented by sites in Poland that have good palynological documentation (Mamakowa, 1989; Krupiński, 2000; Granoszewski, 2003; Kupryjanowicz et al., 2018). The sequence of warmings and coolings in SE Poland and western Ukraine is recorded in loess-paleosol successions (Lindner et al., 2004; Bogucki and Łanczont, 2018; Komar et al., 2018; Valde-Nowak and Łanczont, 2021; Marks, 2023a).

During the Late Vistulian, lake deposits from the Mazovian Interglacial were subject to compaction. Deluvial, lacustrine and bog sediments accumulated in small depressions and on shallow flood plains. Such extensive inundations, practically without bottom erosion, are a common feature of areas subject to arctic climate (Zieliński, 2015). Peatlands reactivated in the depressions during the Holocene, from the Atlantic period (Hrynowiecka et al., 2019).

CONCLUSIONS

1. Palaeobasins filled with Mazovian Interglacial (Holsteinian, MIS 11c) deposits occur in the subsurface of the Sosnowica Depression and the Parczew-Kodeń Heights; their presence has been corroborated by palaeobotanical and palaeofaunal studies. They are overlain by Early Liviecian (Fuhne, MIS 11b) lacustrine and bog deposits, or upper Vistulian (MIS 2) mineral and bog deposits. Above, there occur Holocene strata.

2. The Sosnowica Depression and the Parczew-Kodeń Heights, i.e. the entire area of Western Polesie, were not covered by the ice-sheet of the Odranian (Saalian, MIS 6) Glaciation. The last ice-sheet that covered the area and played the main role in shaping the geological setting and geomorphology of the area was from the Sanian 2 (Elsterian, MIS 12) Glaciation.

3. The Sosnowica Depression developed during erosion by glacial meltwaters, and accumulation of glacifluvial sands and gravels. This was the area of an extensive outwash plain which functioned during the recession of the Sanian 2 (Elsterian, MIS 12) Glaciation. The flow was towards the east.

4. The surface of the Parczew-Kodeń Heights is composed of glacial deposits of the Sanian 2 (Elsterian, MIS 12) Glaciation, which were dissected by glacial meltwaters that formed isolated patches ("islands") of post-glacial plateaus.

5. The study area was not covered by the Liviecian (Fuhne, MIS 11b-10) or the Krznanian (MIS 8) ice-sheets. Glacial deposits suggesting the presence of these glaciations in Western Polesie, as well as lacustrine interglacial deposits of the Zbójnian (MIS 9) and Lublinian (MIS 7) interglacials were not documented.

6. Palaeolake depressions located in the Sosnowica Depression were eroded in glacifluvial sands and gravels of the Sanian 2 (Elsterian, MIS 12) Glaciation, and in the Parczew-Kodeń Heights, in the glacial tills of that glaciation. The basins have a melt out or trough-meltout origin.

7. The paleolakes were formed in the late part of the Sanian 2 (Elsterian, MIS 12) Glaciation and functioned as lakes during the Mazovian Interglacial (Holsteinian, MIS 11c), with some (Zahajki and Podedwórze) existing until the Early Liviecian (Fuhne, MIS 11b) Glaciation, in places transforming into peatlands.

8. The palaeobasins analysed were part of an extensive palaeolakeland from the Mazovian Interglacial, stretching from the southern part of Podlasie to the northern part of Western Polesie.

9. Overlying the Mazovian Interglacial sediments in Zahajki are lacustrine deposits (peats, silts, and gyttja with sand intercalations) correlated with the Early Liviecian (Fuhne, MIS 11b) Glaciation, above which occur biogenic and niveolimnic deposits of the Vistulian (Weichselian, MIS 2). In Wygnanka, Gęś 3, and Sytyta, the Mazovian Interglacial strata are overlain by deluvial and niveolimnic deposits of the Late Vistulian (MIS 2).

10. Palynological analysis of deposits from the sites studied have indicated palaeoenvironmental changes of the area from the end of the Sanian 2 (Elsterian, MIS 12) Glaciation, through the Mazovian Interglacial (Holsteinian, MIS 11c), to the cool interval of the Liviecian (Fuhne, MIS 11b) Glaciation. In all successions analysed there were at least two features typical for the Mazovian. These included the younger part of the interglacial optimum with the dominance of alder-spruce communities and a high content of *Taxus*. A third feature was noted in Zahajki and Podedwórze: the occurrence of a hornbeam-fir phase with pollen of trees with high thermal requirements, e.g. *Pterocarya* and *Buxus*.

11. The palaeobotanical and palaeofaunal analyses have allowed determination of the conditions in the palaeolakes studied. Those in Zahajki and Gęś 3 functioned as shallow lakes throughout the Mazovian Interglacial. The palaeolake in Wygnanka transformed into a marsh as late as in the *Abies-Carpinus* phase. A part of the Sytyta succession represents palaeobasin filling with fern reed. The palaeolake in Podedwórze was at first boggy and then transformed into a peatland at the end of the pine phase. Taxa typical of the Mazovian Interglacial such as *Aracites interglacialis*, *Azolla filiculoides* and *Nymphaea cinerea* were found in the flora from Podedwórze.

12. Our research also allowed reconstruction of the conditions prevailing in the surroundings of the palaeolakes analysed. This area was characterized by significant humidity, which meant that the plant communities inhabiting it differed to some extent from those typical for MIS 11c. These conditions included more widespread alder riparian forests and rushes, mainly sedges, but also ferns, which strongly overgrew the lake shores. *Pinus* was also much more widespread and, as a pioneer species, grew in areas where other trees could not due to the unfavourable conditions. A similar situation occurred in this area also during the Holocene, indicating that Polesie Region has not changed much since MIS 11c.

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