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Evidence for the presence of the Sanian 2 Glaciation (MIS 12) ice-sheet – a case study of palaeobasins from the Mazovian Interglacial (MIS 11c) and terrain relief in Wantopol site (E Poland)

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ABSTRACT:

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In the vicinity of Wantopol (Western Polesie, E Poland), present-day depressions in the landscape (Wantopol sites A, D and E) contain limnic and peat sediments with palynologic spectra and local macrofossil assemblages diagnostic of the Mazovian (Holsteinian, MIS 11c) Interglacial. The palaeobasins were carved in glacial tills of the Sanian 2 (Elsterian, MIS 12) Glaciation covering the entire area. The sediments covering the interglacial deposits are mostly of dilluvial origin and correlated with the Vistulian (Weichselian) Glaciation. The palaeobasins were formed as a result of aerial deglaciation of the Sanian 2 (Elsterian, MIS 12) ice-sheet by melting of dead-ice blocks in a depression (Wantopol A) and a shallow post-glacial trough (Wantopol D and E). Moreover, further evidence for this type of deglaciation of the Sanian 2 ice-sheet is a kame located in the vicinity of the studied sites, composed mainly of sandy sediments topped with a gravel layer. Sediments building the kame were deposited in a crevasse within the melting ice-sheet. The presence of glacial tills and the geological context of the interglacial sediments overlying them are proof of the presence of the Sanian 2 ice-sheet and for this being the last one that occurred in the study area.

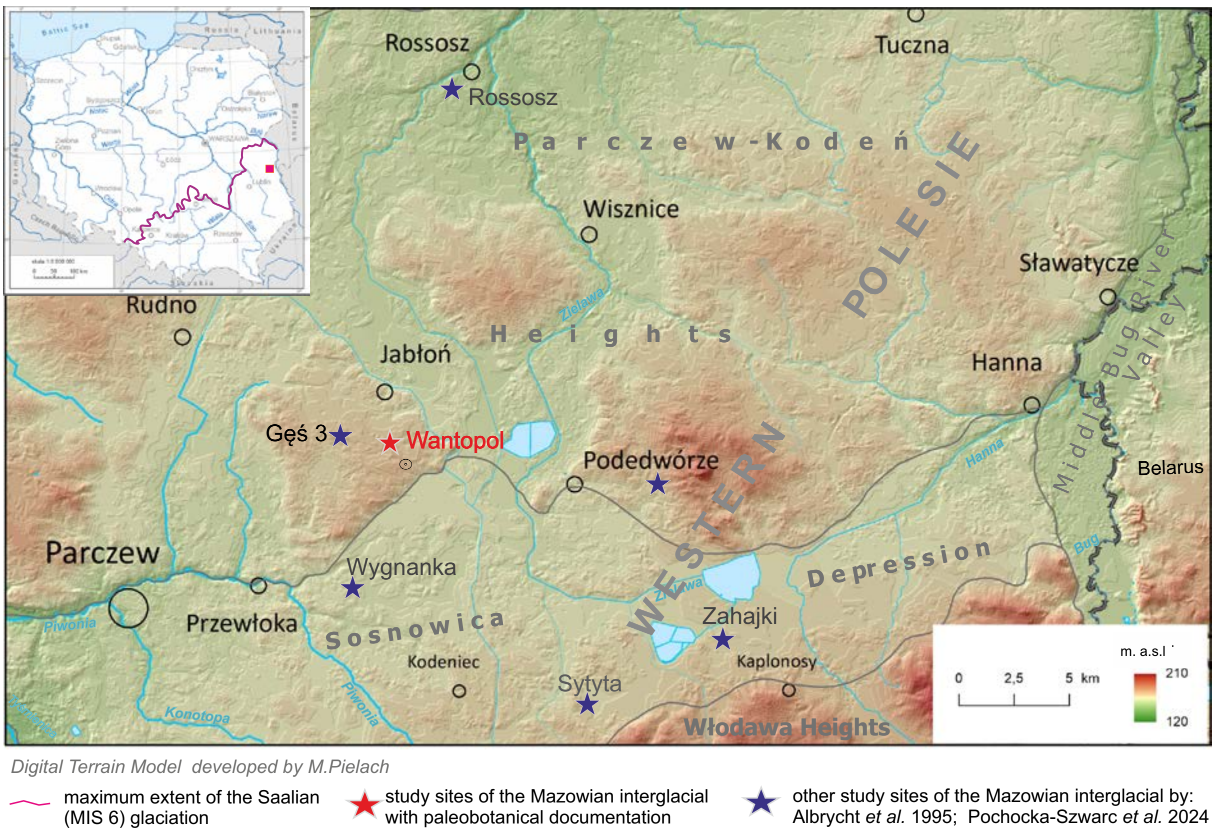
Key words: Mazovian (Holsteinian, MIS 11c); Sanian 2 (Elsterian, MIS 12); OHO; Palaeolakes; Kame; Western Polesie (E Poland).

INTRODUCTION

History of research

The most recent results of detailed palaeoenvironmental and geological studies unequivocally indicate that the Sanian 2 (Elsterian, MIS 12) ice-sheet was the last one that covered the area of Western Polesie in eastern Poland (Pochocka-Szwarc *et al.* 2021, 2024; Żarski *et al.* 2024; Orłowska *et al. in press*) (Text-fig. 1). These studies have questioned the validity of concepts existing for the last hundred years (Zaborski 1927; Trembaczowski 1957; Różycki 1980; Lindner 1984, 1991, 2001; Lindner *et al.* 2007), which assumed that the area of Western Polesie, and thus its landscape, was shaped by the ice-sheet of the Odranian (Saalian, MIS 6) Glaciation. An important conclusion of these recent works was the indication that the maximum range of the Odranian Glaciation ice-sheet was located several tens of kilometres to the north of the study area (along the Siedlce-Łosice-Sarnaki line) and continued further to the south towards the Wieprz river valley (Żarski *et al.* 2024). The present work unambiguously confirms the hypotheses of Żarski *et al.* (2024) and Pochocka-Szwarc *et al.* (2024) that the study area was not covered by the Odranian (Saalian, MIS 6) ice-sheet.

The study area located in Western Polesie is of unique significance for Pleistocene geomorphology and stratigraphy. Unique in Poland, Europe and most probably in the world, it preserves a terrain landscape that was formed over 400 000 years ago after the retreat of the Sanian 2 ice-sheet. Palaeobasins filled with limnic and marsh sediments of the Mazovian Interglacial are preserved just below the surface (Stachurska 1961, Mojski and Trembaczowski 1961; Buraczyński and Wojtanowicz 1980, 1981; Wojtanowicz 1983, 1995; Pochocka-Szwarc *et al.* 2024). They form a part of a vast palaeolakeland covering also Southern Podlasie, located to the north of the study area (Lindner 1988; Lindner *et al.* 1990; Nitychoruk 1994, 2000; Albrycht *et al.* 1995; Skompski 1996; Linder and Marciniak 1997, 1998; Krupiński 2000; Albrycht 2002; Pidek 2003; Nitychoruk *et al.* 2005, 2006; Szymanek *et al.* 2005; Małek and Pidek 2007; Hrynowiecka *et al.* 2014, 2019; Terpiłowski *et al.* 2014; Hrynowiecka and

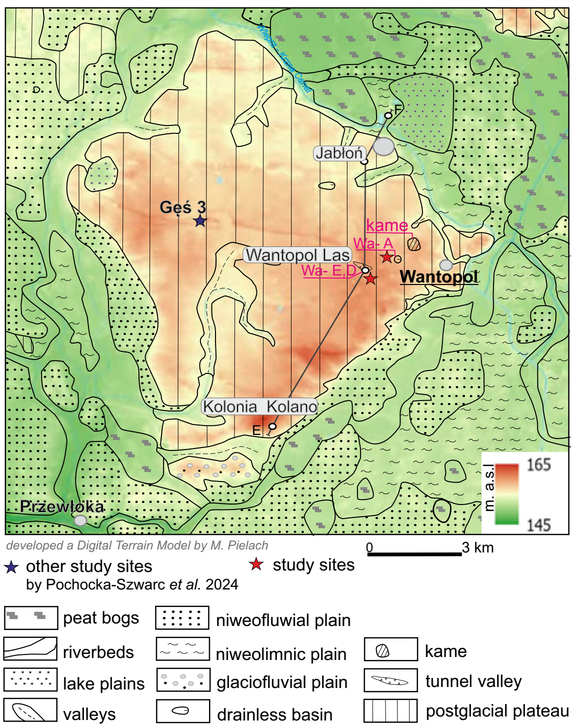


Text-fig. 1. Western Polesie; study sites of the Mazovian Interglacial (MIS 11c) with palaeobotanic documentation; other study sites of the Mazovian Interglacial after Albrycht *et al.* (1995) and Pochocka-Szwarc *et al.* (2024). Maximum extent of the Saalian glaciation after Żarski *et al.* (2024) and Lindner and Marks (2007).

Pidek 2017; Marks *et al.* 2018; Górecki *et al.* 2022). Sites documenting the Mazovian Interglacial deposits which are not covered by glacial tills occur also on the eastern side of the Bug river valley in Belarus and Ukraine (Lindner *et al.* 2004, 2007; Gozhik *et al.* 2012; Marks *et al.* 2018). Although these sites document the presence of the Mazovian Interglacial, many authors did not correlate this fact with the absence of the Odranian (Saalian, MIS 6) Glaciation in the area.

A characteristic feature of the landscape in Western Polesie is the fact that most contemporary (Holocene) hollows precisely reflect the outline of the lake palaeobasins and peatlands from the Mazovian Interglacial. In the study area, the lake palaeobasins are accompanied by the Wantopol kame, i.e., the result of fluvioglacial accumulation, related with the presence of the ice-sheet of the Sanian 2 (Elsterian, MIS 12) Glaciation in the area.

This work is aimed at presenting subsequent lines of evidence for the presence of the Sanian 2 (Elsterian, MIS 12) Glaciation in the vicinity of Wantopol near Jabłoń in Western Polesie based on results of palaeobotanic studies in Wantopol A and Wantopol E sites containing sediments of the Mazovian Interglacial (Holsteinian, MIS 11c), analysis of their geological setting, and analysis of post-glacial landforms against a palaeogeographic background (Text-fig. 2).



Text-fig. 2. Geomorphological sketch of the Wantopol area with location of the geological cross-section E-F; see Text-fig.14

Middle Pleistocene in Poland

During the Sanian 2 Glaciation, the Pleistocene ice-sheet had one of its widest ranges (Hughes *et al.* 2020). The ice-sheet covered a vast part of the Central European Lowlands, reaching the Carpathian foothills (Lindner 1988, 1991, 2001; Łanczont *et al.* 2003, 2019; Gozhik *et al.* 2012; Lindner *et al.* 2013). Marks (2023) presented a hypothesis on the smaller range of this ice-sheet, whose maximum range was supposed to reach the region of Lublin, i.e., 51º N. The range of this ice-sheet in the Polish-Ukrainian borderland has been discussed e.g., by Łanczont (1997) and Łanczont *et al.* (2003, 2019).

The Elsterian Glaciation is correlated with the Middle Pleistocene (Cromerian complex, MIS 12–15), the Brunhes Epoch (Cohen and Gibbard 2019), and MIS 12 (Lisiecki and Raymo 2005). In the Polish climatostratigraphic scheme (Table 1), the Sanian 2 Glaciation is located between the Ferdynandovian Interglacial (MIS 13–15) and the Mazovian Interglacial (Holsteinian, MIS 11c) (Janczyk-Kopikowa 1991; Lindner *et al.* 2013). These climatostratigraphic units are documented by limnic and peatland sediments representing the Ferdynandovian (Cromerian complex, MIS 12–15) and Mazovian interglacials, and by glacial and fluvioglacial sediments representing the Sanian 2 Glaciation.

Sites with documented sediments of the Ferdynandovian Interglacial, i.e., Sosnowica, Ferdynandów, Budziska, Kosiorki, Gołowierzchy, and Łuków, occur in Western Polesie and the neighbouring Southern Podlasie (Dolecki *et al.* 1991; Rzechowski 1996; Pidek 2003; Żarski *et al.* 2004, 2009; Małek and Pidek 2007; Pidek and Małek 2010; Pidek *et al.* 2015). Limnic deposits documenting the Ferdynandovian Interglacial were noted in drillings between two horizons of glacial deposits, i.e., glacial tills of the Sanian 1 (Glacial B, MIS 16) and Sanian 2 (Elsterian, MIS 12) glaciations (Table 1). The lower lithostratigraphic boundary of the Sanian 2 (Elsterian, MIS 12) Glaciation has been precisely determined in these drillings (Janczyk-Kopikowa 1984, 1991; Rzechowski 1996; Pidek 2003, 2015; Pidek and Małek 2010; Pidek *et al.* 2015; Stachowicz-Rybka 2015a, b; Stachowicz-Rybka *et al.* 2017; Żarski *et al.* 2004; Marks 2023). In turn, the upper lithostratigraphic boundary of the Sanian 2 Glaciation is documented by limnic deposits of the Mazovian Interglacial (Table 1) at the studied sites in Western Polesie (Pochocka-Szwarc *et al.* 2024), as well as new sites presented in this work.

The Mazovian Interglacial is widely correlated with the Holsteinian Interglacial of Western Europe,

<table>
<tr><th>Age (ka BP)</th><th colspan="2">Stratigraphy</th><th>North West Europe</th><th>South East Poland</th><th>Belarus</th><th>Ukraine</th><th>MIS</th></tr>
<tr><td>11.7</td><td colspan="2">Holocene</td><td>Holocene</td><td>Holocene</td><td>Holocene</td><td>Holocene</td><td>1</td></tr>
<tr><td rowspan="2">130</td><td colspan="2" rowspan="2">Upper Pleistocene</td><td>Weichselian</td><td>Vistulian</td><td>Poozierian</td><td>Valday</td><td>2-5d</td></tr>
<tr><td>Eemian</td><td>Eemian</td><td>Muravian</td><td>Pryluky</td><td>5e</td></tr>
<tr><td rowspan="14">780</td><td rowspan="14">Middle Pleistocene</td><td rowspan="5">Saalian Complex</td><td>Warthe + Drenthe</td><td>Odranian (Odranian+Wartanian)</td><td>Pripyatian (Dnieperian+Sozhian)</td><td>Dnieperian 2</td><td>6</td></tr>
<tr><td>Schöningen</td><td>Lublinan</td><td>Shklovian</td><td>Kaydakay</td><td>7</td></tr>
<tr><td>?</td><td>Krznanian*</td><td>?</td><td>Dnieperian 1</td><td>8</td></tr>
<tr><td>Dömitz-Wacken</td><td>Zbójnian</td><td>Smolenskian</td><td>Potagylivka</td><td>9</td></tr>
<tr><td>Fuhne</td><td>Liviecian*</td><td>?</td><td>Orelian</td><td>10</td></tr>
<tr><td>Holsteinian</td><td>Holsteinian</td><td>Mazovian</td><td>Alexandrian</td><td>Likhvinian</td><td>11c</td></tr>
<tr><td rowspan="8">Cromerian Complex</td><td>Elsterian</td><td>Sanian 2</td><td>Berezinian</td><td>Okaan</td><td>12</td></tr>
<tr><td>Cromerian IV</td><td rowspan="3">Ferdynandovian</td><td rowspan="3">Belovezhian</td><td rowspan="3">Lubenian</td><td>13</td></tr>
<tr><td>Glacial C</td><td>14</td></tr>
<tr><td>Cromerian III</td><td>15</td></tr>
<tr><td>Glacial B</td><td>Sanian 1</td><td>Narevian</td><td>Sulian</td><td>16</td></tr>
<tr><td>Cromerian II</td><td rowspan="3">Podlasian</td><td rowspan="3">Różan</td><td rowspan="3">Martonoshian</td><td>17</td></tr>
<tr><td>Glacial A</td><td>18</td></tr>
<tr><td>Cromerian I</td><td>19</td></tr>
</table>

Table 1. Chronostratigraphic correlation of the Middle and Upper Pleistocene in north-western Europe (Lit *et al.* 2007; Head and Gibbard 2015), south-eastern Poland (Lindner *et al.* 2006, modified; Marks *et al.* 2016, modified), Belarus (Velichkevich *et al.* 2001), Ukraine (Lindner *et al*. 2004, 2006, 2007), and marine isotope stages (MIS). Modified after Pochocka-Szwarc *et al.* (2024). * – area not covered by ice-sheets.

the Alexandrian Interglacial of Belarus, the Likhvinian Interglacial of Ukraine, and the Mindel/Riss in the Alps (Nitychoruk *et al.* 2005; Marks *et al.* 2019). The Holsteinian corresponds to MIS 11c (Koutsodendris *et al.* 2012; Cohen and Gibbard 2019; Hrynowiecka *et al.* 2019; Marks *et al.* 2019) and is classified within the Middle Pleistocene. In the Polish chronostratigraphic scheme, the Mazovian Interglacial distinctly separates the Sanian 2 (Elsterian, MIS 12) Glaciation from the subsequent Liviecian (Fuhne, MIS 11a–b) Glaciation (Hrynowiecka *et al.* 2019; Marks *et al.* 2019).

Palynological analyses across numerous sites highlight the distinct pollen succession of the Mazovian Interglacial (e.g., Krupiński 1995; Winter 2008; Hrynowiecka *et al.* 2014; Hrynowiecka and Pidek 2017; Nitychoruk *et al.* 2018; Pochocka-Szwarc *et al.* 2024; Żarski *et al.* 2024). The key phases of this interglacial include initial forests dominated by *Betula*, transitional *Betula–Pinus* forests, temperate forests dominated by *Picea* and *Alnus*, a distinct phase characterised by a significant representation of *Taxus*, a climatic optimum defined by the co-occurrence of *Abies* and *Carpinus* along with multiple thermophilic taxa, and a concluding *Pinus* phase associated with preglacial cooling (Krupiński 1995; Janczyk-Kopikowa 1996). Among the thermophilic taxa typical for the Mazovian Interglacial, *Pterocarya fraxinifolia* serves as the primary marker, achieving high abundances in profiles from eastern Poland (Winter, 2008). Other significant thermophilic taxa include *Buxus*, *Parrotia persica*, *Ilex*, *Celtis*, and *Carya*, none of which were native to eastern Poland during the Holocene (Winter 2008; Górecki *et al.* 2022; Pochocka-Szwarc *et al.* 2024; Żarski *et al*. 2024). The widespread presence of these thermophilic taxa aligns well with climatic reconstructions, indicating that the MIS 11c interglacial was a notably warm period (Nitychoruk *et al.* 2005; Candy *et al.* 2024).

Besides the established pollen phases, recent studies have identified several notable climatic oscillations within MIS 11c based on northern European pollen records (Koutsodendris *et al.* 2010, 2012; Nitychoruk *et al.* 2018; Górecki *et al*. 2022). The first one, referred to as the Older Holsteinian Oscillation (OHO), is associated with an intra-interglacial cooling before the *Carpinus–Abies* phase, widely recognised across European sites, and characterised by a significant vegetation regression towards pioneer taxa such as *Betula* and *Pinus* (Koutsodendris *et al.* 2010, 2012; Hrynowiecka *et al.* 2019; Schläfli *et al.* 2023). This event is hypothesised to be analogous to the Holocene 8.2 ka event, possibly triggered by a meltwater-induced slowdown of the North Atlantic Deep Water formation (Koutsodendris *et al.* 2012). The second, less prominent oscillation is the Younger Holsteinian Oscillation (YHO), which is interpreted either as being significantly dryer (Koutsodendris *et al.* 2010) or wetter (Górecki *et al.* 2022), and connected to the sudden decline in *Carpinus* in the forest vegetation. The Birch Holsteinian Oscillation (BHO), so far documented only in two sites in eastern Poland, is interpreted as being a rapid cooling occurring within the *Pinus* phase and immediately preceding the onset of the next glaciation (Hrynowiecka-Czmielewska 2010; Górecki *et al.* 2022).

STUDY AREA

The study area is located in the northern part of Western Polesie, directly adjacent to the eastern state border of Poland (Text-fig. 1). Western Polesie is the Polish part of Polesie, i.e., a vast geographic region continuing to the east into Ukraine and Belarus for several hundreds of kilometres, along the Pripyat river valley up to the Dnieper river valley. A characteristic feature of Polesie is the presence of small denivelations and the occurrence of numerous wetlands and peatlands.

The old-glacial terrain of Western Polesie (after the retreat of the Elsterian ice-sheet) is largely characterised by the presence of flat post-glacial plateaus, composed of glacial tills and diversified by single kames, i.e., forms indicating aerial deglaciation of the area (Bartkowski 1953). This is typical of the Wantopol post-glacial plateau, where apart from a kame, there occur melt-out depressions infilled with limnic and peat deposits of the Mazovian Interglacial.

Kames are important evidence of aerial ice-sheet deglaciation, commonly documented in old-glacial plateaus of eastern Europe, as well as in Podlasie and Polesie in Poland (Terpiłowski 2007; Bitinias *et al.* 2004; Bitinias 2012; Godlewska and Terpiłowski 2012; Gruszka and Terpiłowski 2015). Their presence indicates that aerial deglaciation was widespread in this part of Europe.

The studied sites (Text-fig. 1) with interglacial deposits and the kame in Wantopol (near Jabłoń) are situated within a minor geographic unit, i.e., the Parczew-Kodeń Heights (Richling *et al.* 2021). The terrain has an erosional-accumulation character. The described sites are located on a strongly denuded post-glacial plateau (Text-fig. 2), whose surface is composed of glacial tills of the Sanian 2 Glaciation, occasionally covered by silty-sandy sediments representing the weathering covers of these tills. Near Jabłoń, the post-glacial plateau forms an isolated 'island' covering an area of 57 km^2 (Text-fig. 2). It represents an outlier that developed due to the erosive activity of fluvioglacial waters of the Sanian 2 (Elsterian, MIS 12) Glaciation (Żarski and Pochocka-Szwarc 2024). It is referred to as the Jabłoń Island by those authors and is one of the three forms of this type in the Parczew-Kodeń Heights. The studied sites with palaeobasins in Wantopol and the kame are located on the surface of Jabłoń Island. The kame culmination occurs at about 162.5 m a.s.l. and is one of the highest points in the entire post-glacial plateau. The described surface is rather monotonous, and only in some areas it is diversified by small erosional valleys, at present filled mostly with dilluvial sediments, and melt-out depressions (Text-fig. 2).

Jabłoń Island (Text-fig. 2) is at present surrounded by depressions that are 2 to 8 km wide. These are the remains of ancient erosional incisions filled with Holocene biogenic sediments (peat bogs), limnic sediments (lake plains), fluvial deposits (Zielawa river) and Vistulian (Weichselian) fine niveofluvial and niveolimnic (floodplain) sediments (Marks *et al.* 2024; Pochocka-Szwarc *et al.* 2024).

GEOLOGICAL SETTING

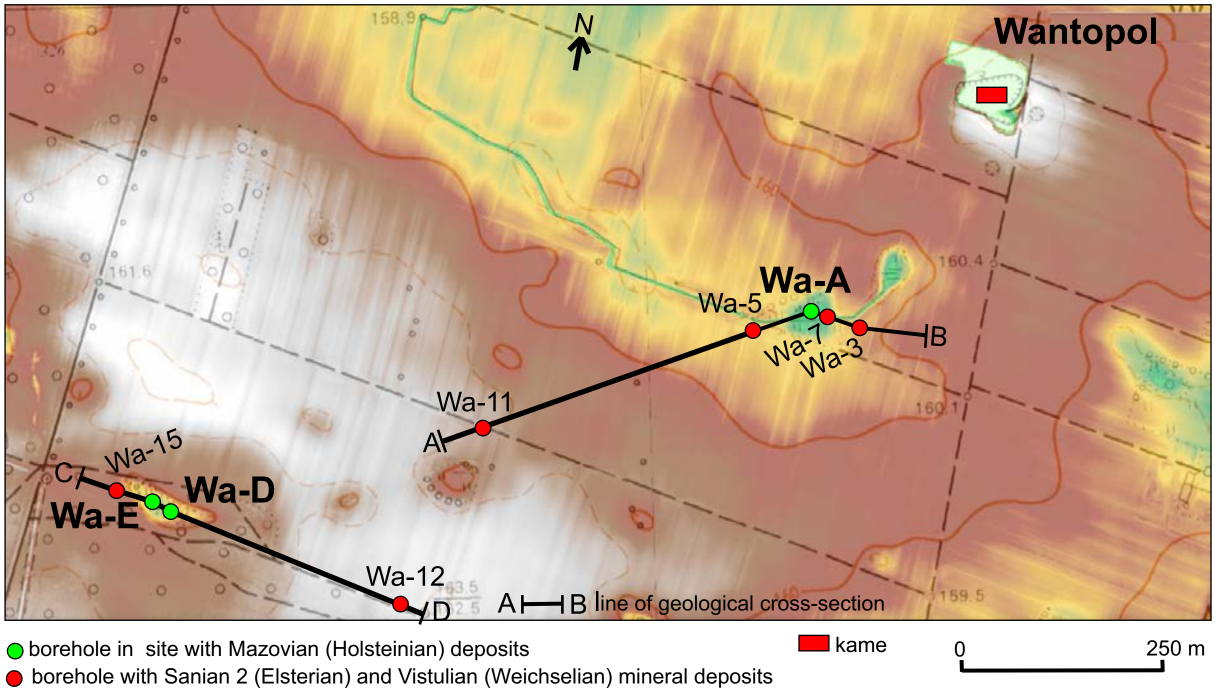
A characteristic feature of the study area is the presence of small depressions and one strongly denuded kame hillock (Dolecki *et al.* 1995), whose structure is presented herein. An excavation which documents its geological structure was made in the kame culmination; it is described in detail below. At about 300 m to the south-west of the kame occurs site Wantopol A (Wa-A), and at about 1 km – sites Wa-E and Wa-D (Text-figs 3 and 4), documenting the palaeobasins of the Mazovian Interglacial (Holsteinian, MIS 11c).

Wantopol Wa-A

Site Wa-A is located in a small depression carved in glacial tills. Its bottom is situated at 158 m a.s.l., i.e., about 2 m below the surrounding plateau surface. The longer axis of the depression, 85 m long, has a NE-SW orientation, whereas the shorter axis, 50 m long, has a WNW-ESE orientation (Text-figs 3 and 4). A periodical watercourse flows out from the western part of the depression; it is captured in a melioration channel. A 5 m long, fully cored drilling was made in the depression using a mechanical drill.

Wantopol Wa-E and Wa-D

Site Wa-E and the nearby site Wa-D are situated in an elongated, land-locked depression which is a post-glacial trough (Text-figs 3 and 4). The W-E-oriented longer axis of this depression is about 150 m long, whereas the N-S-oriented shorter axis is 30



Text-fig. 3. Location of geological cross-sections A-B and C-D, boreholes and the kame in Wantopol (hypsometric terrain model).

to 44 m long. The bottom of the depression lies at 159 m a.s.l., i.e., 1 to 1.5 m below the surface of the surrounding plateau. Two drillings were made in the central part of the depression: in Wa-E to the depth of 6.3 m using a hand probe (Eijkelkamp) and in Wa-D to the depth of 8.3 m using mechanical drillings; samples for pollen analysis were collected from the cores.

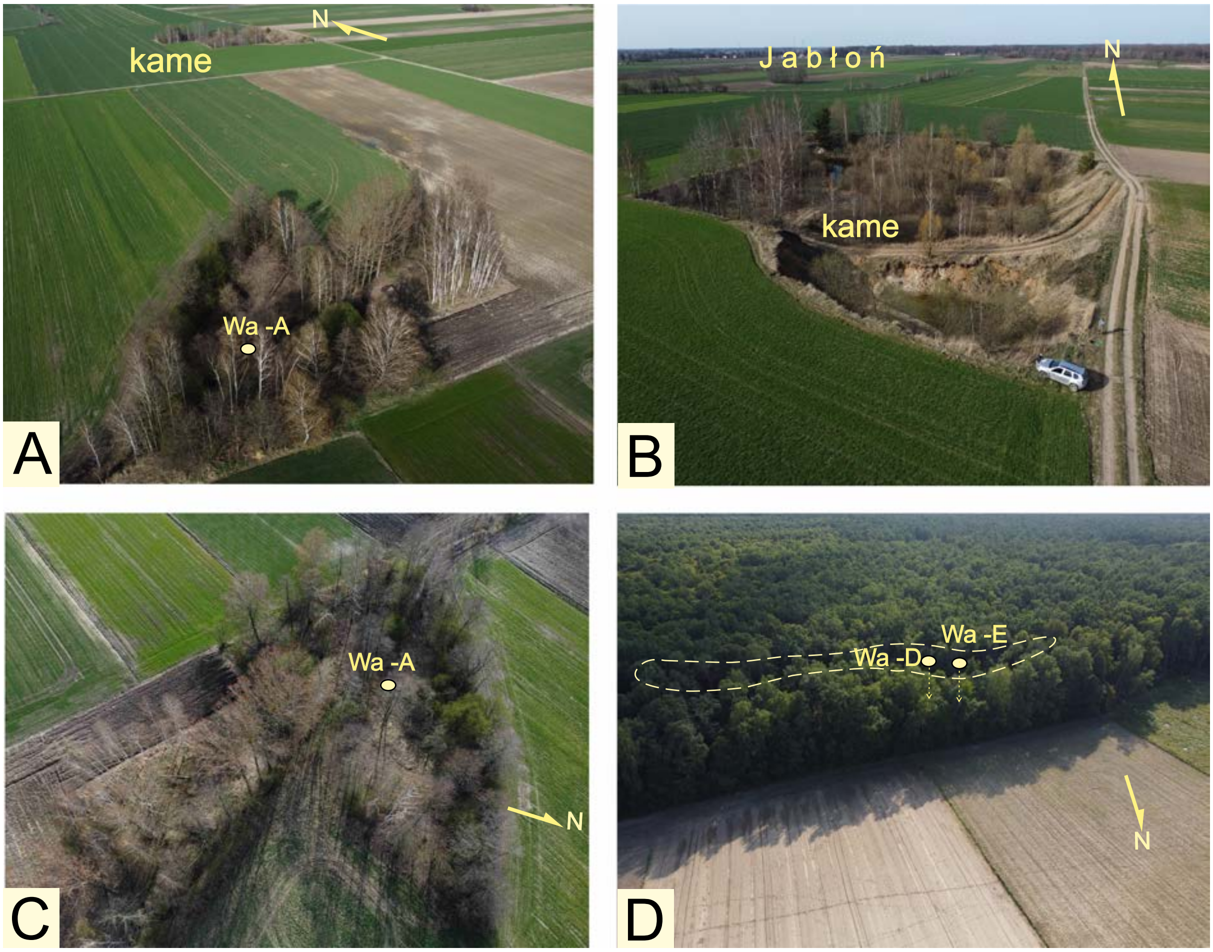
METHODOLOGY

Drillings

Fully cored drillings were made with a hand probe (Eijkelkamp) and a mechanical probe WH to document the geological structure and collect samples for palaeobotanic analyses. Supplementary probes were drilled to obtain sediments for lithological studies and construction of cross-sections A-B and C-D (Text-figs 3 and 4), i.e., Wa-3, Wa-7, Wa-5, Wa-11, Wa-12, and Wa-15 with depths from 1.9 to 3.3 m (Table 2). Probe Wa-7 was drilled directly in the vicinity of drilling Wa-A to determine the lithology and origin of sediments overlying the biogenic series. Moreover, to recognise the geological setting of Quaternary sediments in the study area, a cross-section through Jabłoń Island was constructed based on 3 hydrogeological drillings in Kolonia Kolano and Jabłoń

Palynological analysis

The sampling procedure for palynological analysis was consistent across all examined profiles. Samples of 1 cm³ were collected from peat and gyttja, whereas 3 cm³ samples were taken from mineral deposits (silts) due to the anticipated low concentration of pollen grains. All profiles were initially analysed at a preliminary resolution to determine the general palynostratigraphy of the succession. Each sample was subject to acetolysis following the methodology described by Erdtmann (1960). Additionally, pollen was extracted using the dense-media method with a zinc chloride solution ($ZnCl_2$) of 1.88 g/cm³, following Nakagawa *et al.* (1998). In total, 44 samples were analysed: 16 from Wa-A, 12 from Wa-D, and 16 from Wa-E. The palynological analyses were carried out using a light microscope, supported by POLPAL software (Nalepka and Walanus 2003). In most cases, up to 500 pollen grains of arboreal (AP) and herbaceous (NAP) plants were counted, excluding aquatic and reedbed taxa. All samples are archived at the Institute of Botany, Jagiellonian University in Kraków.



Text-fig. 4. Aerial photographs of sites Wa-A, Wa-D and Wa-E, and the kame in Wantopol: Fot. 4A, 4B, 4C sites Wa-A (see Text -fig. 12); kame (see Text-fig. 10); Fot. 4D sites Wa-D and Wa-E (see Text-fig. 13). All photographs by M. Żarski.

Plant macroremains

Plant macroremains were analysed in 16 samples (~100 cm^3 each) from Wa-A. 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 an Ø = 0.18 mm mesh. The obtained material, including seeds, fruits, and vegetative plant fragments, was analysed with application of 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 diasporas, as well as specimens of fossil flora from the National Biodiversity Collection of Recent and Fossil Organisms stored at the W. Szafer Institute of Botany, Polish Academy of Sciences, in Kraków (herbarium KRAM). The results are presented in a macrofossil diagram using POLPAL software (Nalepka and Walanus 2003).

Sedimentological analysis

The sedimentological analysis of glacigenic deposits was carried out on the basis of a detailed reconnaissance in the walls of the outcrop dissecting the kame hillock. It aimed to determine the spatial distribution of sedimentary and structural features, e.g., bedding, unconformities or faults. Additional data were collected from the sedimentological profiles, i.e., sediment texture (T – silt, S – sand, G – gravel, D – diamicton) and structure, scale, geometry and contacts between the sedimentary units, and analysis of sediment deformation features (type, scale and azimuth of faults). This

Supplementary probe	Depth (m)	Lithology	Stratigraphy
Wa-3	0.0–0.8	sandy dust	Vistulian (Weichselian)
	0.8–1.4	silty sand with gravels	
	1.4–2.8	clayey silt	Sanian 2 (Elsterian)
	2.8–3.3	till	
Wa-5	0.0–1.1	silt	Vistulian (Weichselian)
	1.1–1.4	sand with gravels	
	1.4–2.2	till	Sanian 2 (Elsterian)
Wa-7	0.0–0.4	peaty silt	Holocene
	0.4–1.35	sandy silt	Vistulian (Weichselian)
	1.35–1.7	fine and medium sand with silty sand	
	1.7–2.2	peat	Mazovian (Holsteinian)
Wa-11	0.0–1.3	fine sand	Vistulian (Weichselian)
	1.3–3.0	till	Sanian 2 (Elsterian)
Wa-12	0.0–1.4	silt with gravels	Vistulian (Weichselian)
	1.4–3.0	till	Sanian 2 (Elsterian)
Wa-15	0.0–0.7	silt	Vistulian (Weichselian
	0.7–1.0	silt	
	1.0–1.2	sand with gravels	
	1.2–1.9	sandy till	Sanian 2 (Elsterian)

Table 2. Lithological description of the supplementary probes (for location see Text–fig. 3).

analysis was based on macroscopic recognition of sedimentary structures and structural features.

The sedimentological interpretation was based on a three-stage division of the sedimentological units (lithofacies, lithofacies associations and lithofacies complexes) according to Zieliński (1995). Sedimentological units were labelled with lithofacies codes following Miall (1977) and modified according to Zieliński and Pisarska-Jamroży (2012). This enabled the determination of the general characteristics of the sediments, as well as their sedimentary environments and post-sedimentary transformations.

Grain-size analysis

The sieve method was used to determine the grain-size composition (Racinowski 1973). A sieve set with meshes ranging between 0.06–2.5 mm was used (Racinowski 1969; Racinowski *et al.* 2001). The grain-size composition was analysed to determine the basic lithological and genetic properties of sediments occurring above the deposits of the Mazovian Interglacial, on samples collected from probes Wa-7 and Wa-3 (Tables 3–5) in the PGI-NRI laboratories following norm PN-EN ISO 14688-1:2018-05 (Majer *et al.* 2021).

The aerometric method was applied to determine the grain-size composition of sediments with particles whose equivalent grain diameter was below 0.063 or 0.071 mm (Myślińska 2021; Dołżyk and Szypcio 2014). The analysis includes determining the grain-size composition of soil based on the velocity at which the mineral particles suspend in an aqueous solution using an aerometer. The analyses were performed on sediments that occurred directly above the deposits of the Mazovian Interglacial, as well as on sediments that overlay the glacial tills. The aerometric analysis was conducted in PGI-NRI according to norm PN-EN ISO 17892-4: 2017-01.

Profile	Sample depth (m)	Lithology
Wa-11	1.5–2.0 2.4–2.7	till
Wa-12	1.5–2.0 2.5–3.0	till

Table 3. Sample list for petrographic determination of gravels from glacial tills.

Marine Isotope Stage	Wa-A	Wa-D	Wa-E	Mazovian Interglacial palynostratigraphy
MIS 11c	Wa-A-6		Wa-E-5	*Carpinus–Abies*
	Wa-A-5			OHO
	Wa-A-4		Wa-E-4	*Picea–Alnus–Taxus*
	Wa-A-3	Wa-D-3	Wa-E-3	*Picea–Alnus*
	Wa-A-2	Wa-D-2	Wa-E-2	*Betula–Pinus*
		Wa-D-1	Wa-E-1	*Betula*
MIS 12	Wa-A-1			Late Sanian 2 Glaciation

Table 4. Stratigraphic correlation of the studied successions with the Mazovian Interglacial palynostratigraphic scheme of Poland (Krupiński 1995; Janczyk-Kopikowa 1996; Winter 2008). MIS – Marine Isotope Stages after Lisiecki and Raymo (2005) and Hrynowiecka *et al.* (2019); OHO – Older Holsteinian Oscillation.

Petrographic analyses of gravels

The quantitative analysis of the petrographic composition of gravels washed out from glacial tills was performed on material collected from probes Wa-11 and Wa-12. The sampling depths of the gravels washed out from glacial tills are presented in Table 3. Macroscopic analyses of the petrographic composition of gravels washed out from glacial tills have been performed for profiles Wa-11 and Wa-12 from depth interval 1.5–2.0 m. The gravels were analysed under a digital microscope with 1000 x magnification. Furthermore, the glacial tills were characterised using data from the Explanations to the Detailed Geological Map of Poland, Wisznice sheet (Dolecki *et al.* 1995).

RESULTS

Palynological analysis

Analysis of all three profiles yielded viable pollen successions, with the exception of two basal samples from Wa-A and Wa-D, which were too poor in pollen content for a reliable assessment (Text-figs 5–7). All three profiles represent the Mazovian Interglacial, with only the lowest sample from Wa-A corresponding to the late MIS 12 (Table 4).

The *Betula* and *Betula–Pinus* phases are present across all profiles and exhibit all characteristics typical of eastern Poland (Winter 2008; Pochocka-Szwarc *et al.* 2024; Żarski *et al.* 2024). The *Picea–Alnus* phase is also evident in all records; however, in Wa-D, it marks the final stage of the succession and is atypically developed, with a strong dominance of *Alnus* pollen. The lack of significant *Taxus*, *Carpinus*, and *Abies* pollen suggests that the sedimentary record in Wa-D terminates within the *Picea–Alnus* phase. As Wa-D and Wa-E originate from the same palaeolake, the more complete succession preserved in Wa-E indicates that Wa-D was likely located closer to the shoreline. The *Picea–Alnus–Taxus* phase is documented in both Wa-A and Wa-E, although *Taxus* pollen values do not exceed 5%. Such low abundances are consistent with other records from the region (Pochocka-Szwarc *et al.* 2024).

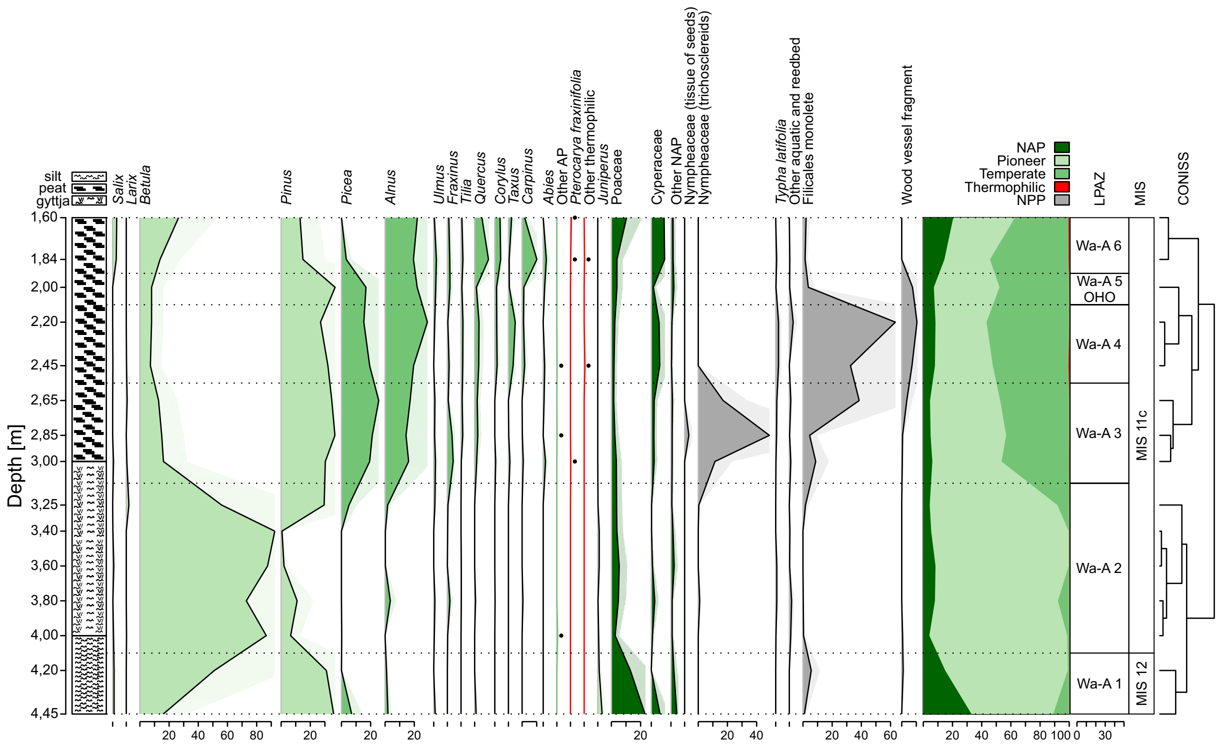
The OHO oscillation is recorded only in Wa-E, marked by a rise in *Pinus* pollen following the *Taxus* phase. Its absence in Wa-A is likely due to a low sampling resolution. The final phase of the Mazovian Interglacial in all records is the *Carpinus–Abies* phase, although its development appears to be influenced by local environmental factors. The occurrence of thermophilic taxa such as *Pterocarya fraxinifolia*, *Juglans*, *Ilex*, *Viscum*, and *Buxus* (apart from *P. fraxinifolia* included in the diagrams in the Other thermophilic grouping) further supports the palynostratigraphic position of the studied sediments.

Plant macroremains

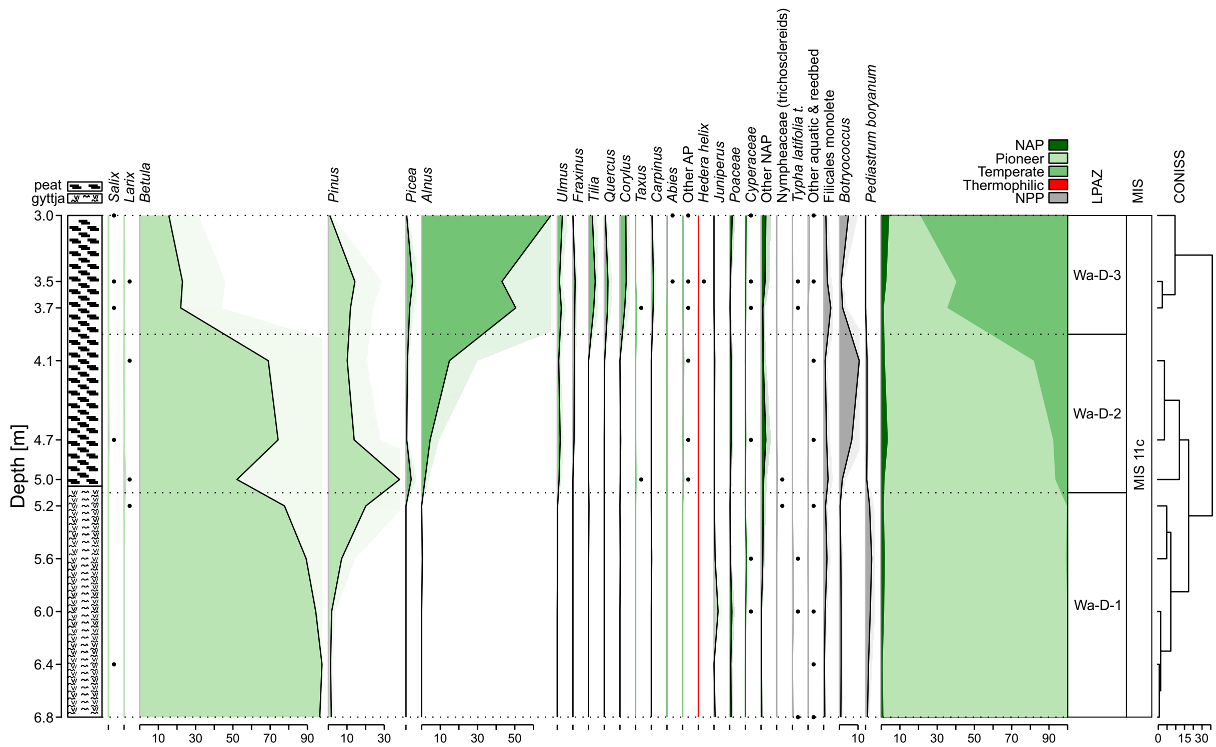
Based on the presence of one or more of the most abundant or characteristic taxa for particular zones, five plant macrofossil zones Wa-A 1-6 LMAZ were distinguished in the diagram (Text-fig. 8). The boundaries between the zones were determined based on-changes in either the index or the most abundant taxa. Ecological requirements of the analysed taxa allowed for the drawing of detailed conclusions regarding the palaeoenvironment of the Wantopol Wa-A palaeolake and its direct vicinity. The succession of local vegetation in the Wantopol Wa-A palaeolake resembles the succession in the Podedwórze section and in the Nowiny Żukowskie stratotype section (Hrynowiecka and Szymczyk 2011; Pochocka-Szwarc *et al.* 2024). Wa-A 1LMAZ in the base of the succession may be correlated with the late glacial of the Sanian 2 Glaciation. Apart from the numerous sclerotia of the fungi *Cenococcum geophilum*, other plant macrofossils are lacking. Such a taxonomic composition usually occurs in sediments that developed in a cool climate and at a not very dense vegetation cover. The remaining zones marked as Wa-A 2-6 LMAZ were deposited at first in cold climate conditions with *Betula nana* (Text-fig. 9G) and *Betula humilis*, and later in a warm and humid climate. Several species characteristic of the Mazovian Interglacial were distinguished, including *Azolla filiculoides* (Text-fig. 9A), *Salvinia natans* (Text-fig. 9B), *Caulinia* = *Najas goretskyi*, *Caulinia interglacialis* and *Potamogeton pannosus* (Text-fig. 9D).

Sedimentological analysis

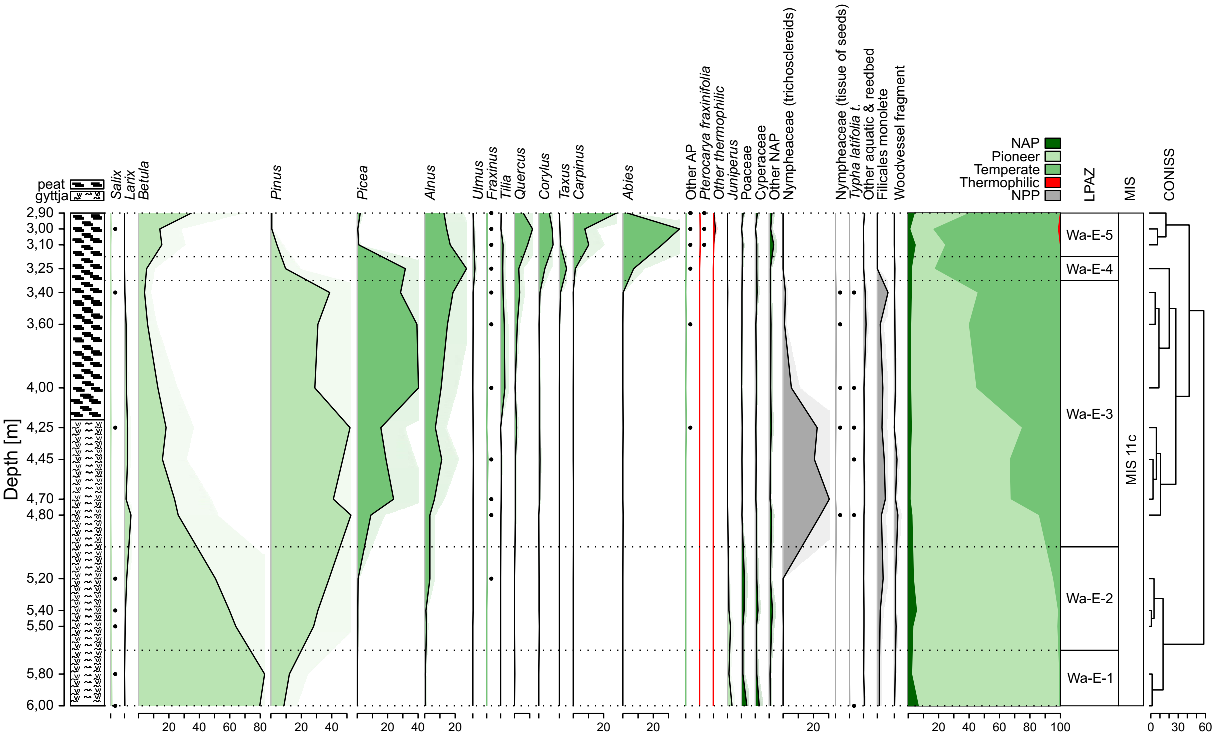
Glaciogenic sediments, composing numerous kame elevations in the Parczew-Kodeń Heights, are currently exposed in the vicinity of Wantopol, located to the SW of Wisznice village. They form a hillock reaching 162.5 m a.s.l. According to Dolecki *et al.* (1995), the succession of glaciogenic sediments in the kames reaches here its greatest thickness of over 10 m. In the current state of exposure, their apparent thickness of about 5 m was recorded. Four lithofacies sets were documented in two profiles, distributed in the core (profile A, at 160.5 m a.s.l.) and on the slope of the form (profile B, at 156.2 m a.s.l.): W-1, W-2, W-3 and W-4 (Text-fig. 10).



Text–fig. 5. Simplified pollen diagram for Wa-A (analysis by A. Górecki).



Text–fig. 6. Simplified pollen diagram for Wa-D (analysis by A. Górecki).



Text–fig. 7. Simplified pollen diagram for Wa-E (analysis by A. Górecki).

In the basal part of the succession occur fine-grained sediments of lithofacies association W-1. They include small (10–30 cm) and medium (30–50 cm) scale individual layers of fine sands (Sm), sandy silts (TSm, TSh) and silty sands (STm), massive or with poorly horizontal lamination. The thickness of the exposed lithofacies association in profile A (Text-fig. 10) reaches up to 1 m, whereas in profile B (Text-fig. 10) – up to 30–50 cm. In the profile B sediments of this lithofacies association take the form of rhythmites Sm and STm, i.e., fine-grained massive sands and massive silty sands with a rhythmite thickness of up to 10 cm.

The largest thickness – about 3 m – was noted in sediments of lithofacies association W-2. They include poorly sorted sands (mainly medium and coarse), massive or horizontally laminated (Sm and Sh), with a thickness of individual sets from 5 to 35 cm. In the lower part of the unit (profile B), they are overlain by sediments of lithofacies association W-1 (sandy silts or horizontally laminated silty sands), whereas in the upper part of the unit (profile A) – by massive sandy gravels of lithofacies association W-3. Sediments of lithofacies association W-3 reach a maximum thickness of up to 1 m. They include massive sandy gravels (GSm) occurring in individual packages of small and medium thickness from 10 to 50 cm. In profile A (the core of the form) they occur as high forming rhythmites with Sh sediments of lithofacies association W-2. The thickness of the rhythmites reaches up to a maximum of 40 cm (lower GSm packet about 10 cm; upper Sh packet – about 30 cm). In profile B they occur at a lower level, also surrounded by sediments of lithofacies association W-2, forming a thicker sedimentary package up to 1 m.

The topmost part of both profiles is composed of sediments of lithofacies association W-4. They include a sandy massive diamicton (DSm) with single gravels. In the core of the form (profile A) this lithofacies is characterised by sandy interbeds and a lower thickness, i.e., in a single package of average scale of about 50 cm. On the slope of the hillock (profile B) it floods in the form of DSm and Sm rhythmites, i.e., small and medium scale massive sandy diamicton (10–40 cm), interbedded with small and medium scale massive sands (5–15 cm). The entire succession of sediments is deformed, with sets of complementary faults reaching values: 208/57/130 and 271/47/345.

Grain-size composition

Glacial tills occurring on the surface of the area are overlain by silty weathering covers (Żarski and Pochocka-Szwarc 2024). The successions obtained from supplementary profiles Wa-3 and Wa-7 were subject to grain-size analysis (Tables 5 and 6). In profile Wa-3 sandy silts occur to the depth of 0.8 m, and below to the depth of 1.4 occur silty sands with gravels, underlain by clayey silts to the depth of 2.8 m (Table 2). Glacial tills were noted below 2.8 m. Grain-size analysis of a sample collected from depth interval 1.05–1.20 m has indicated an even contribution (30% each) of three fractions: silty-clay, fine sand and medium sand. Coarse sand contributes to 6%, whereas fine gravel – 3%. Such a grain-size composition corresponds to that typical for glacial tills (Racinowski 1969; Boulton 1976) with the only difference that usually in glacial tills there is a much higher content of the silt-clay and gravel fractions. Both the overlying sandy silts and silty sands should be linked with the weathering of glacial tills that took place in the cool intervals of the Pleistocene, beginning in the Liviecian (Fuhne, MIS 10), through the Odranian (Saalian Complex, MIS 8 and 6), to the Vistulian (Weichselian, MIS 2–5d). Therefore, it was assumed that the age of these sediments should be correlated with the Last Glaciation (MIS 2–5d).

A slightly different development and origin was determined for sediments occurring above the peat and limnic sediments of the Mazovian Interglacial. Samples for grain-size analysis were collected from profile Wa-7 from depth intervals 0.9–1.1, 1.4, and 1.55–1. 6 m (Tables 5 and 6). In samples from 1.4 m and depth interval 1.55–1.6 m the dominating fraction is medium sand with a percentage contribution of 41%, with a high contribution of fine sand (29 to 34%), a lower contribution of coarse sand (7 to 8%), and an admixture of fine gravel (2–4%) (Table 6). The contribution of the silt and clay fraction varies within 16–18%. In general the sediment is poorly sorted, indicating a dilluvial origin. This is a characteristic sediment occurring in numerous profiles (Pochocka-Szwarc *et al.* 2024) above sediments of the Mazovian Interglacial and their time of accumulation is linked with the Vistulian Glaciation (Weichselian, MIS 2–5d) (Marks *et al.* 2024).

The sample collected from depth interval 0.9–1.1 m in profile Wa-7 is dominated by the silt fraction (89%) with an admixture of clay (5%) and sand (6%). The sediment can be determined as silt. The origin of these silts can be linked with lakes existing in a cool climate (MIS 2). The OSL absolute age of similar sediments in profile Sytyta located in the Sosnowica Depression is 31±7 ka, indicating the Late Vistulian (Pochocka-Szwarc *et al.* 2024). Holocene peats occur above.

Results of petrographic analyses

Glacial tills were documented in profiles Wa-A and Wa-D and all other remaining supplementary profiles (Wa-11, Wa-12) (Table 3). Gravels were washed out for macroscopic petrographic assessment from samples collected from these tills.

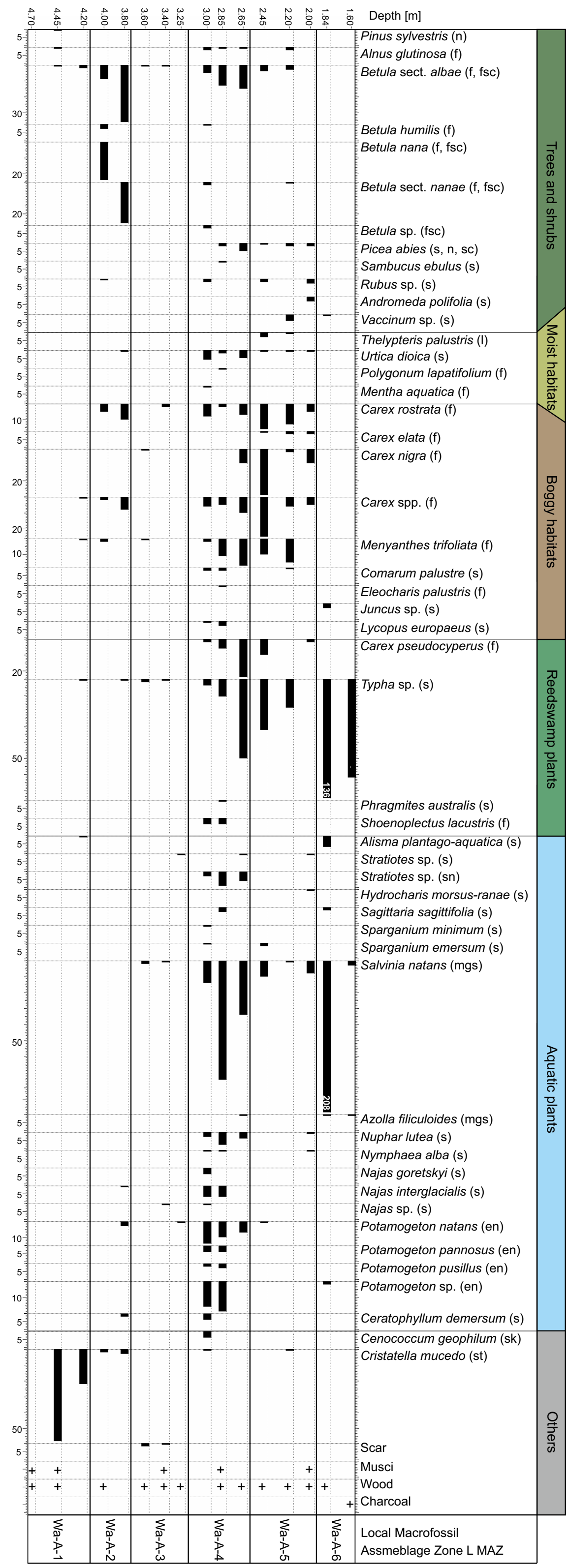
The petrographic composition of gravels (in both samples from depth interval 1.5–2.0 m in profiles Wa-11 and Wa-12) is characterised by the dominance of crystalline rocks over quartz grains and sandstones. Carbonates were not observed. The diameters of the gravels of crystalline rock vary within 1 mm to 2 cm. Gravels of red granitoid rocks prevail over gravels of grey granitoid rocks in the analysed samples (Text-fig. 11). Both types of rock occur in Scandinavia, where they crop out and from where they were transported by the ice-sheet in glacial tills. There are no exposures of crystalline rocks in northern Poland (north of the study area). The gravels have a similar petrographic composition to that of the erratic boulders commonly occurring within the post-glacial Parczew-Kodeń Heights. Most gravels are sharp-edged or partly rounded.

The second group includes quartz gravels with dimensions from 1 to 5 mm. Grey transparent quartz grains with an admixture of yellowish and pink quartz grains dominate the samples (Text-fig. 11). Quartz gravels are mostly very well, well and medium rounded. Shining, semi-mat and mat gravels are present. The gravels derive from the weathering of granitoid rocks, and prior to being accumulated by the ice-sheet they occurred in fluvial and eolian settings.

The third group comprises sandstone gravels (Text-fig. 11), which also are exposed in Scandinavia. The gravel diameters vary within 1–5 mm. Dark grey conglomeratic sandstones with distinct grains of sand and even very fine gravels prevail in the samples. They are accompanied by light grey sandstones composed of uniform quartz grains.

Petrographic analyses of gravels washed out from glacial tills have indicated that they are derived from Scandinavia, which evidently points to the glacial origin of the analysed tills.

The tills are sandy, grey with a green tint (Dolecki *et al.* 1995). Gravels washed out from these glacial tills (from samples collected from cores and from exposures near Jabłoń) are characterised by a dominance of crystalline rocks and quartz grains derived from Scandinavia over carbonate rocks (Dolecki *et al.* 1995). The prevalence of crystalline rocks points to intense chemical weathering which contributed to the dissolution of carbonate rocks. The calcium



Text-fig 8. Diagram of plant macroremains for Wantopol Wa-A profile (analysis by S. Skoczylas-Śniaz and R. Stachowicz-Rybka). f – fruit; fsc – fruit scale; sc – scales; ssc – seed scale; en – endocarp; n – needle; sk – sclerotium; st – statoblast; l – leaf; mgs – megaspore.

carbonate content in these glacial tills is up to 20% (Dolecki *et al.* 1995). According to older concepts, the tills were linked with the Odranian (Saalian) Glaciation (Buraczyński and Wojtanowicz 1980/81; Buraczyński 1986; Lindner 1988, 1991). Current knowledge (Pochocka-Szwarc 2024; Żarski *et al.* 2024) suggests that the tills should be correlated with the Sanian 2 (Elsterian, MIS 12) Glaciation as indicated by the superposition of Sanian 2 (Elsterian) sands or silts on glacial till, which in turn are overlain by documented limnic deposits of the Mazovian (Holsteinian) Interglacial in profiles Wa-A and Wa-B.

Geological setting of Quaternary deposits in the study area

The main stratigraphic horizon to present a model of the geological setting of the Pleistocene deposits are the limnic and peat deposits of the Mazovian (Holsteinian, MIS 11c) Interglacial documented by palaeobotanic analyses in the studied sites. The lithological successions of drillings Wa-A, Wa-E, and Wa-D are presented in Table 7.

Wantopol Wa-A – the succession begins with a glacial till of the Sanian 2 (Elsterian) Glaciation with a thickness exceeding 0.2 m, overlain by fluvioglacial sands (0.1 m) and silts (0.6 m) of the same age. The thickness of limnic and peat deposits of the Mazovian (Holsteinian) Interglacial reaches 2.6 m and begins with silts, overlain by gyttja and peats. The series is overlain by sands and silts correlated with the Vistulian (Weichselian) Glaciation. The succession is capped by Holocene peats (Table 7, Text-fig. 12).

Wantopol Wa-D – the succession begins with glacial tills of the Sanian 2 Glaciation, overlain by silts of the same age. The thickness of limnic and peat deposits of the Mazovian Interglacial reaches 4.2 m (between 7.2 and 3.0 m) and comprises gyttja and overlying peats, above which occur Vistulian sands and silts. The succession terminates with Holocene peats (Table 7, Text-fig. 13).

Wantopol Wa-E – the entire series of limnic and bog deposits of the Mazovian Interglacial has not been drilled through, and the documented thickness exceeded 3.6 m. It includes gyttja and overlying peats. Above deposits of the Mazovian Interglacial occur Liviecian (MIS 10) and Vistulian sands and silts and Holocene peats (Table 7).

Furthermore, strongly compressed shales have been noted in the biogenic series within the analysed successions (Table 7). They occur within peats and

Text-fig. 9. Plant macroremains in Wantopol Wa-A profile. **A** – *Azolla filiculoides*; **B** – *Salvinia natans*; **C** – *Potamogeton pusillus*; **D** – *Potamogeton pannosus*; **E** – *Sagittaria sagittifolia*; **F** – *Schoenoplectus lacustris*; **G** – *Betula nana*; **H** – *Alnus glutinosa*; **I** – *Sambucus ebulus*. Photographed by K. Stachowicz.

gyttja, and often hamper the drilling process. They are known from many interglacial sites in the Sosnowica Depression and Łuków Plain (Hrynowiecka *et al.* 2019; Pochocka-Szwarc *et al.* 2024).

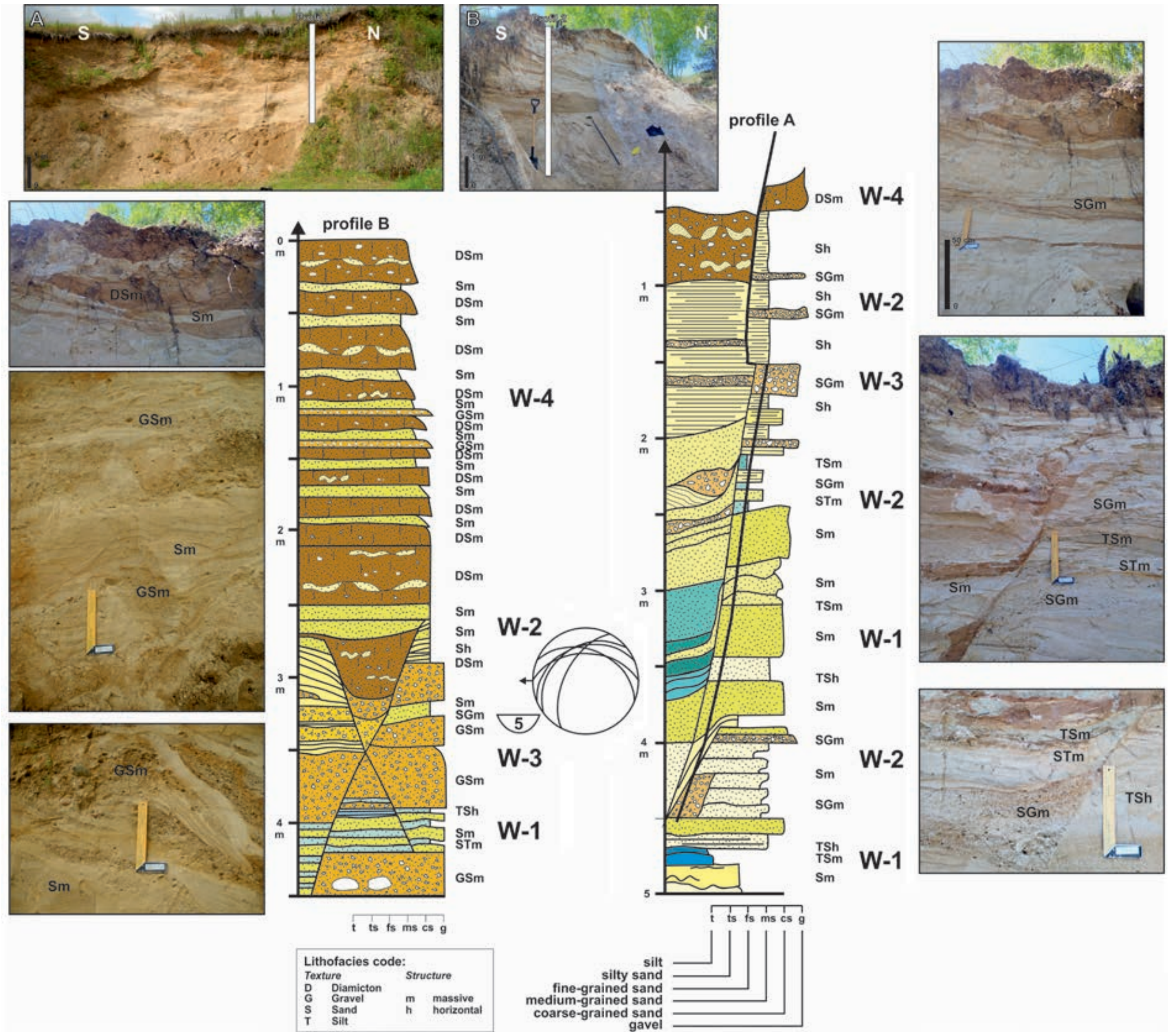
Three geological cross-sections have been constructed to show the geological context of the study area near Wantopol and Jabłoń (Text-figs 12–14). Cross-sections A-B (Text-fig. 12) and C-D (Text-fig. 13) present the geology of limnic and peat deposits of the Mazovian Interglacial (Wa-A and Wa-E). In turn, cross-section E-F (Text-fig. 14) documents

Profile	Depth (m)	Sand % 0.063–2 mm	Silt (dust) % 0.002–0.063 mm	Clay % ≤0,002	Lithology
Wa-7	0.9–1.1	16	89	5	silt

Table 5. Determination of the grain-size composition using the aerometric method, by Roguski (2024).

Profile	Depth (m)	silt + clay ≤ 0.063 mm	fine sand (%) (0.063–0.2> mm)	medium sand (%) (0.2–0.63) > mm	coarse sand (%) (0.6–2.0) > mm	fine gravel (%) (2.06–3) > mm	Lithology
Wa-3	1.05–1.2	30	31	30	6	3	medium and fine sand with silt
Wa-7	1.4	16	34	41	7	2	medium and fine sand with silt
	1.55–1.6	18	29	41	8	4	medium and fine sand with silt

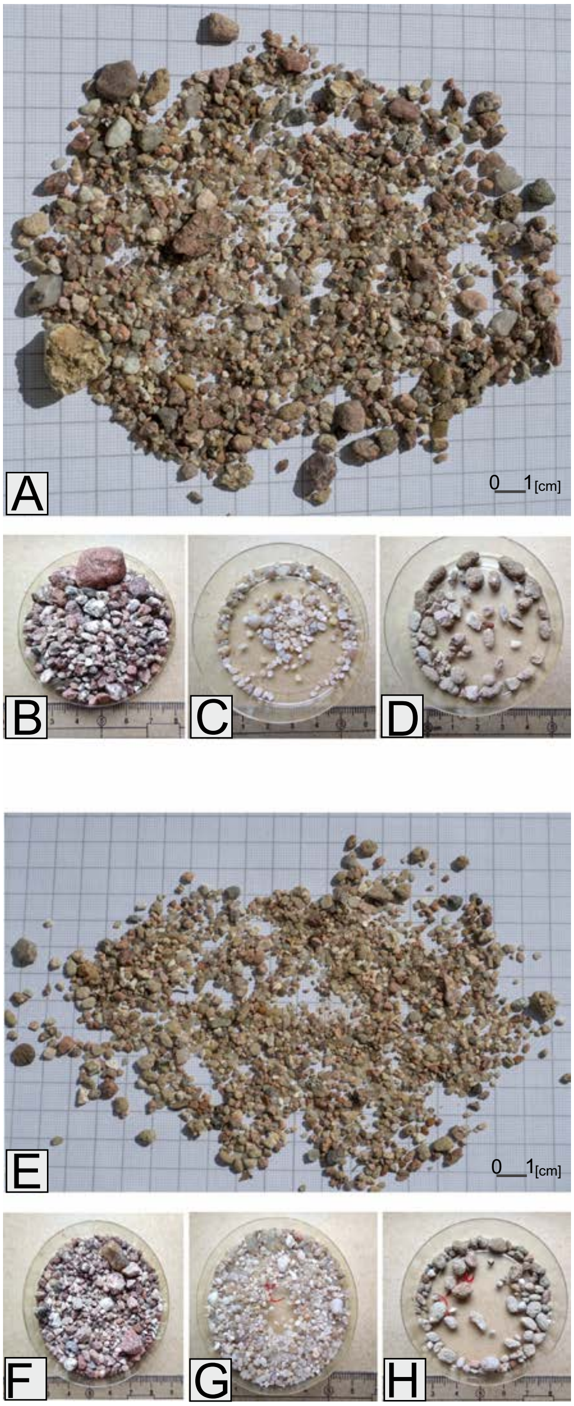
Table 6. Grain-size composition determined from sieve analysis by Roguski (2024).



Text-fig. 10. The Wantopol kame: lithological profiles A and B with lithofacies, lithofacies associations and photographic documentation. All photographs by A. Orłowska

the geology of Pleistocene sediments and their direct bedrock in the post-glacial plateau ('Jabłoń Island').

The thickness of Quaternary sediments in the post-glacial plateau reaches 30–40 m, and exceeds 41 m in depressions between the plateaus (Text-fig. 14). The bedrock of the Quaternary sediments in Kolonia Kolano comprises Neogene quartz sands with lignite fragments, and in Jabłoń – Upper Maastrichtian marls and chalk (Text-fig. 14). In both sites, these rocks are overlain by Pleistocene sediments, represented by ice-dammed clays overlain by fluvioglacial sands of the Sanian 1 Glaciation (MIS 16), 11 and 8 m thick, respectively. In Kolonia Kolano there occurs 1.5 m of glacial till correlated with the Sanian 1 Glaciation (Glacial B). The series representing the Sanian 2 Glaciation in Jabłoń includes a 6-m thick horizon of ice-dammed clays and about 9 m of fluvioglacial sands and gravels, followed by 4 m of glacial tills. In other successions the thickness of glacial till occasionally exceeds 10 m. Palaeobasins with the limnic and peat deposits of the Mazovian Interglacial are carved in these tills (Pochocka-Szwarc *et al.* 2024; Żarski *et al.* 2024). The succession of the Jabłoń drilling, located in the depression zone, documents (Text-fig. 14) two series of fluvioglacial sands and ice-dammed deposits correlated with the Sanian 1 (Glacial B, MIS 16) and Sanian 2 glaciations. The geological setting of



Text-fig. 11. Analysis of petrographic composition of glacial till gravels, profiles: Wa-11 (A–D) and Wa-12 (E–H); **A** – gravels of crystalline rocks, quartzes and limestones from a depth of 2.4–2.7 m; **B** – gravels of crystalline rocks from a depth of 1.5–2.0 m; **C** – quartz grains from a depth of 1.5–2.0 m; **D** – sandstones from a depth of 1.5–2.0 m; **E** – gravels of crystalline rocks, quartzes and limestones from a depth of 2.5–3.0 m; **F** – gravels of crystalline rocks from a depth of 1.5–2.0 m; **G** – quartz grains from a depth of 1.5–2.0 m; **H** – sandstones from a depth of 1.5–2.0 m. All photographs by A.Tekielska and M. Żarski.

this depression resembles the Sosnowica Depression (Pochocka-Szwarc *et al.* 2024). Below the terrain surface composed of niveolimnic silts and sands (Marks *et al.* 2024) occur over 10 m of fluvioglacial sands and gravels of the Sanian 2 (Elsterian) Glaciation.

DISCUSSION

Palaeogeographic evolution in the Late Sanian 2 (Elsterian)

The presented results of palaeobotanic, geological and sedimentological analyses unequivocally point to the fact that the Sanian 2 (Elsterian, MIS 12) ice-sheet was the last that covered the study area, which may be confirmed by the results of recent studies (Pochocka-Szwarc *et al.* 2024; Żarski *et al.* 2024). Those studies suggest that the main elements of the landscape were established during the melting of the Sanian 2 ice-sheet. This glaciation reached down south as far as to the San and Wisłok catchment area, i.e., to 50º N (Łanczont *et al.* 2003, 2019).

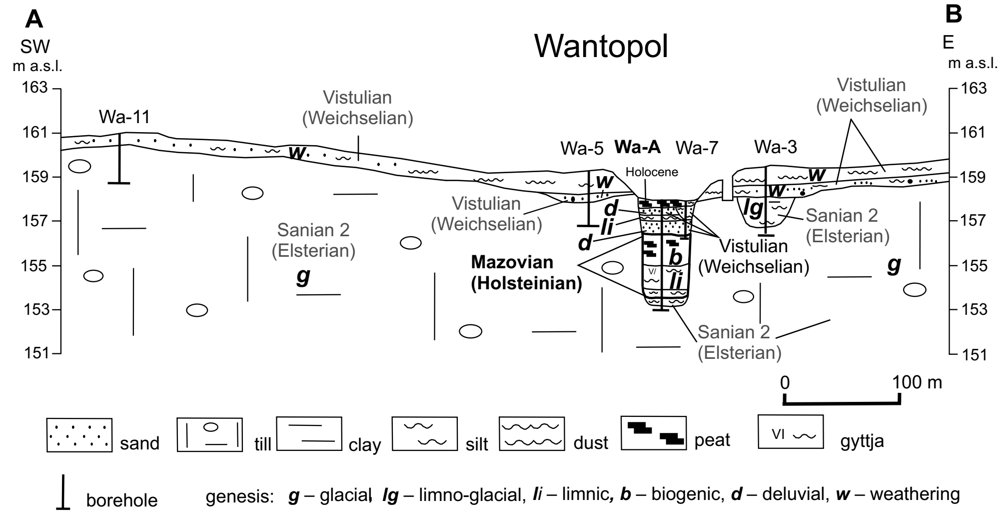
In a wider palaeogeographic context, the recession of the Sanian 2 ice-sheet is recorded as stoppage of the ice-sheet front along the Włodawa Ridge (Marianka and Pieszowola moraines) (Pochocka-Szwarc and Żarski 2023; Żarski *et al.* 2023; Pochocka-Szwarc 2024). Recession and activity of melt-waters lead to the incision of the plateaus (resulting in the formation of outliers, e.g., Jabłoń Island) and creation of a vast depression, e.g., the Sosnowica Depression.

Accumulation of fluvioglacial sands and gravels from the Sanian 2 Glaciation took place after plateau erosion. Below these fluvioglacial sediments occur fluvioglacial sands and gravels linked with the Sanian 1 (Glacial B, MIS 16) Glaciation. In the Sosnowica Depression, biogenic deposits of the Mazovian Interglacial were documented in the top of these sediments, e.g., in the previously studied Wygnanka, Zahajki and Sytyta sites (Pochocka-Szwarc *et al.* 2024) (Text-fig. 1).

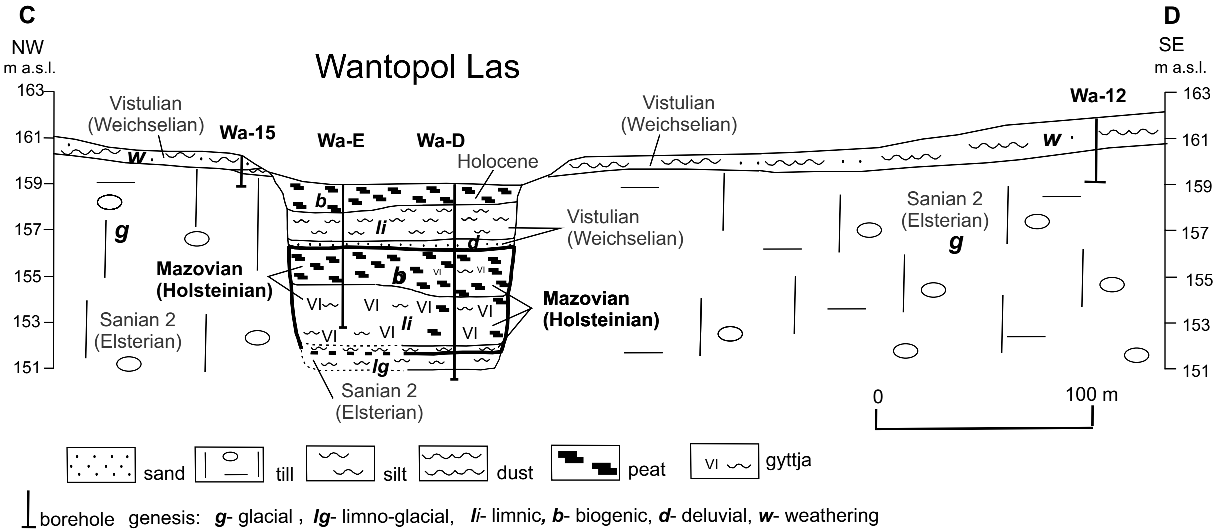
In the kataglacial phase of the Sanian 2 Glaciation near Jabłoń, glacial waters eroded the basement composed mainly of lodgement till, which resulted in the formation of small evorsion potholes, 5–6 m deep, filled with the overlying ice (Wa-A). In places, under high and variable pressure, water flowing in the ice-sheet (Kirkham *et al.* 2024) eroded small, about 7 m deep troughs, e.g., documented in Wa-E and Wa-D. During deglaciation, the troughs were also filled with dead-ice blocks (Kirkham *et al.* 2024).

The aerial melting of the Sanian 2 ice-sheet began with surficial melting of ice layers, leading to the formation of a crevasse, which was the initial form of a future kame. At first, shallow post-glacial lakes were formed, in which, when melting ceased for example during winter, fine sediment was accumulated from suspension. During intense melting, these shallow lakes were filled with sand and sand-gravel in glaciofluvial fans dominated by sheet floods. In effect, the kame hillock in Wantopol was formed (Text-fig. 15).

Further climate warming caused complete disappearance of the ice-sheet and exposure of the surface, mostly built of glacial tills. The surfaces of these post-glacial plateaus contained small depressions filled with dead-ice blocks (melt-outs) and post-glacial tunel valley. Successive climate warming resulted in melting of the dead-ice blocks, unblocking of the aquifer systems and formation of small lakes with mineral sediments accumulated in the terminal part of the Sanian 2 Glaciation but still in cold climate conditions. In succession Wa-A, they are represented by dark grey silts in depth interval 4.1–4.7 m occurring below the limnic series from the Mazovian Interglacial (Table 7, Text-fig. 12). Directly below the silts occurs a 10-cm thick horizon of fluvioglacial sands, and below – glacial till of the Sanian 2 Glaciation. In succession Wa-D, the termination of the Sanian 2 (Elsterian) Glaciation is recorded by grey silts occurring in depth interval 7.2–7.9 m (Table 7, Text-fig. 12), lying directly on glacial tills of the same age. These silts underlie limnic deposits of the Mazovian Interglacial.



Text-fig. 12. Geological cross-section A-B through drilling Wa-A. See Text-figs 3, 4A, C.



Text-fig. 13. Geological cross-section C-D through drillings Wa-D and Wa-E (Wantopol Las). See Text-figs 3, 4D.

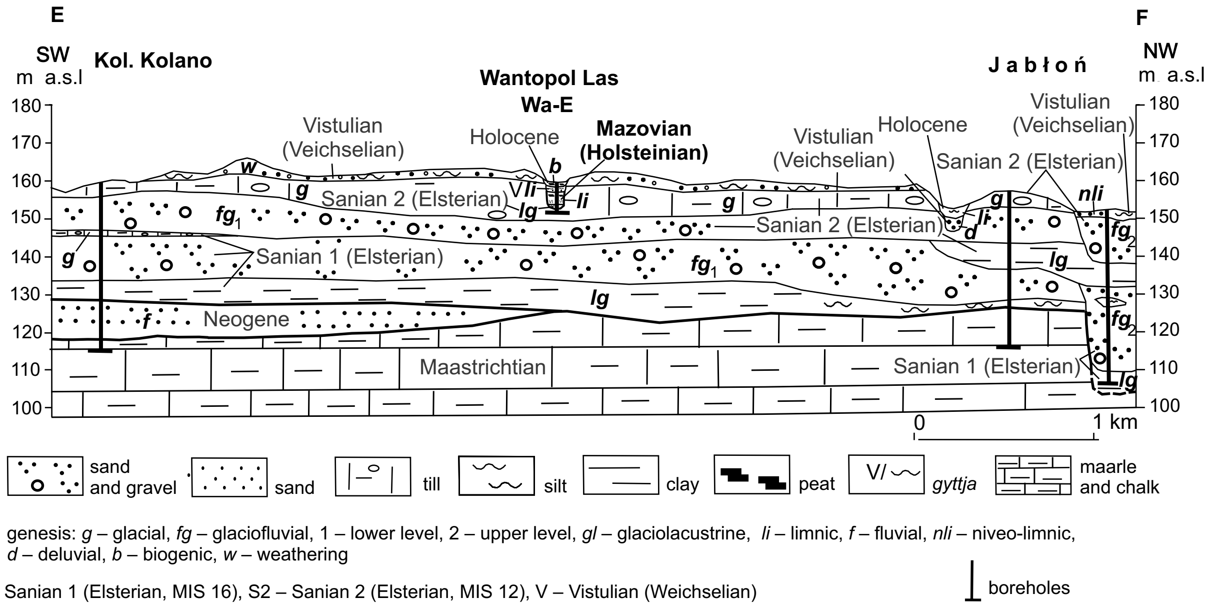
Site	Depth (m)	Deposits	Origin	Stratigraphy	MIS
Wa-A 51°42'1.7"N 23°5'43.6"E 158 m a.s.l.	0.0–0.20	well-decomposed peat, brown	bio	Holocene	1
	0.20–0.70	fine sand with silty sand, grey-beige	d	Vistulian (Weichselian)	2
	0.70–1.20	sandy silts, grey, -HCL	li		
	1.20–1.50	fine sand with humus, brown-beige, -HCL	d		
	1.50–2.0	well-decomposed peat, black, -HCL	bio	Mazovian (Holsteinian)	11c
	2.0–3.0	poor-decomposed peat, with macrofossils	bio		
	3.0–3.7	gyttja, grey-olive, -HCL	li		
	3.7–4.0	gyttja, grey-olive, with peat and shales intercalation	li		
	4.0–4.1	dark-grey silt	li		
	4.1–4.7	dark-grey silt	li	Sanian 2 (Elsterian)	12
	4.7–4.8	brown clayey sand	fg		
	4.8–5.0	grey till	g		
Wa-D 51°41'55.1"N 23°4'58.5"E 159 m a.s.l.	0.0–1.0	well-decomposed peat, brown-black	bio	Holocene	1
	1.0–1.1	fine, silty sand, grey-beige	d	Vistulian (Weichselian)	2
	1.1–2.5	brown silt	li		
	2.5–3.0	fine, beige sands with single gravels	d		
	3.0–3.6	rotting peat, black	bio	Mazovian (Holsteinian)	11c
	3.6–4.0	peaty gyttja, on 3.6 m shales intercalation	li		
	4.0–5.05	brown-black peat	bio		
	5.05–7.0	peaty gyttja, passing to olive with single malacofauna	li		
	7.0–7.2	brown silt	li		
	7.2–7.9	grey silt	li	Sanian 2 (Elsterian)	12
	7.9–8.3	grey till	g		
Wa-E 51°41'55.4"N 23°4'57.9"E 159 m a.s.l.	0.0–0.80	rotting peat, black	bio	Holocene	1
	0.8–1.2	dry peaty silt, black	li		
	1.2–1.7	beige silt	li	Vistulian (Weichselian)	2
	1.7–2.5	beige-rusty silt with macrofossils, sandy in the bottom	li		
	2.5–2.7	fine, silty sand, beige	d		
	2.7–2.8	brown silty sand, in the bottom brown-black	d	Liviecian (Fuhne)	10
	2.8–2.9	loamy black peat with sandy intercalation	bio	Mazovian (Holsteinian)	11c
	2.9–3.55	sandy peat, brown-black	bio		
	3.55–4.2	well-decomposed peat with shales, brown-black	bio		
	4.2–5.0	shale gyttja, olive-brown	li		
	5.0–6.3	brown gyttja	li		

Table 7. Lithological and stratigraphic characteristics of the analysed successions of drillings Wa-A, Wa-D, and Wa-E. Explanations: li – limnic, bio – biogenic, d – diluvial, fg – fluvioglacial, g – glacial.

Regional and local vegetation changes during the Masovian Interglacial (MIS 11c)

In the early interglacial, lake basins occurred both in the depressions (Wa-A) and (Wa-E and Wa-D). Limnic sediments, comprising silts and predominantly gyttja from the Mazovian (Holsteinian) Interglacial, were documented in Wa-A in depth interval 4.0–3.0 m, providing evidence for the existence of a lake till the early *Picea–Alnus* phase. In Wa-E, gyttja was recorded in depth interval 6.3–4.2 m, whereas in Wa-D, lacustrine silts and gyttja occur in depth interval 7.0–5.05 m (Table 7, Text-fig. 6). The lacustrine phase ended in general within the *Picea–Alnus* phase; however, in Wa-D, a transition to peat sedimentation occurred earlier, during the *Betula–Pinus* phase, suggesting that the profile was located closer to the basin palaeoshoreline. Due to changes in the hydrological regime, both basins eventually became overgrown and were transformed into peat bogs. Peat accumulation persisted through most of the climatic optimum, from the *Picea–Alnus* to the *Carpinus–Abies* phases.

Other basins described by Pochocka-Szwarc *et al.* (2024) from the same region share a similar origin, although they have different developmental histories. Only in Wygnanka did the lake transform into a peat bog, but this transition occurred only after the *Picea–Alnus–Taxus* phase. In Gęś 3, environmental changes occurred during the same phase (marked by the decline of the Nymphaeaceae), but despite the basin becoming shallower, it did not transition



Text-fig. 14. Geological cross-section E-F through drilling Wa-E (Kolonia Kolano-Wantopol Las-Jabłoń). See Text-fig. 2.

into a peat-forming environment. The palynological record of this phase in Gęś 3 resembles that of Wa-D, particularly due to the dominance of *Alnus*, which is atypical for this stage of the succession. These observations support the hypothesis of Pochocka-Szwarc *et al.* (2024) that, as in present-day Polesie, the region had favourable conditions for the development of riparian forests during this period.

Due to the preliminary nature of the studies in the Wantopol area, broader palynological interpretations are currently not justified. However, the region shows a significant potential for future research on regional vegetation changes.

Studies of plant macroremains in Wa-A point to a large similarity of lake basin development to that in the Podedwórze succession (Pochocka-Szwarc *et al.* 2024). Worth noting is the climate optimum phase recorded in zones Wa-A 4-5 LMAZ, dominated by multi-species assemblages of aquatic plants with floating plants and plants rooted in the lake bottom, such as *Sagittaria sagittifolia* (Text-fig. 9E), *Nuphar* sp., *Potamogeton natans*, *P. pannosus*, *P. pusillus* (Text-fig. 9C), *Ceratophyllum demersum*, *Caulinia goretskyi* and *Caulinia interglacialis*. Similarly, as in Podedwórze, following shallowing and eutrophication, aquatic macrophytes in this interval are replaced by the intense development of *Salvinia natans* (Pochocka-Szwarc 2024). The interglacial character and warm climate are also evidenced by *Azolla filiculoides*, whose presence in sediments is linked with the Mazovian Interglacial and described from several sites in Europe (Field *et al.* 2000; Sanko *et al.* 2006; Velichkevich and Zastawniak 2006; Panin *et al.* 2024). In terrestrial plant assemblages, humid habitats were dominated by *Alnus glutinosa* (Text-fig. 9H) and *Sambucus ebulus* (Text-fig. 9I), with accompanying *Urtica dioica*, *Rubus* sp., *Thelypteris palustris*, *Polygonum lapatifolium* and *Mentha aquatica*. Closer to the water body there was domination of vegetation similar to the present-day Magnocarion elate assemblage (after Koch 1926), and the reed zone surrounding the lake was overgrown by *Typha* sp., *Lycopus europaeus* and *Shoenoplectus lacustris* (Text-fig. 9F).

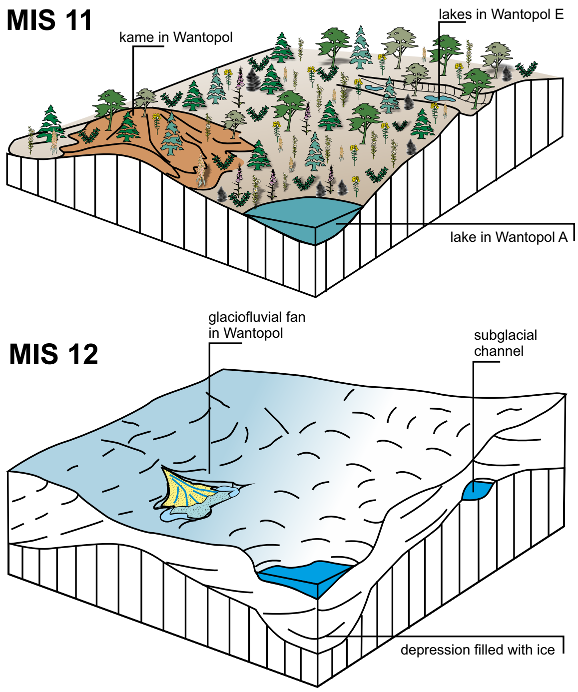
The results of the palaeobotanic analyses are evidence for the existence of an area of post-glacial lakes during the Mazovian Interglacial, which originated from the melting out of the Sanian 2 ice-sheet in Western Polesie (Pochocka-Szwarc *et al.* 2024; Żarski *et al.* 2024). Unambiguous evidence for the ice-sheet presence are glacial tills building the terrain surface, with the occurrence of Scandinavian rocks in their composition as testified by their petrographic analysis.

Landscape changes in the Wantopol region from the Middle Pleistocene till present

Evidence for the presence of the ice-sheet is recorded in the internal structure of the kame, with sedimentary structures characteristic of its formation in the zone of aerial deglaciation. However, the most important stratigraphic proof for the presence of the Sanian 2 Glaciation are deposits of the Mazovian Interglacial occurring directly below the surface (without a cover of glacial deposits) (Text-figs 12–14). The development of these sediments which overlie interglacial deposits, as well as the results of their lithological analyses, unambiguously exclude a glacial origin, similarly as in the case of other successions in Polesie (Marks *et al.* 2024; Pochocka-Szwarc *et al.* 2024). Therefore, this is indirect evidence for the age of sediments building the post-glacial plateaus (Sanian 2, Elsterian, MIS 12), in which palaeobasins from the Mazovian (Holsteinian, MIS 11c) Interglacial occur. In consequence, the hypothesis of the covering of the study area by the Odranian (Saalian, MIS 6) Glaciation has been fully revised (Żarski *et al.* 2024).

A separate issue of high significance is the fact that the palaeobasins infilled with sediments from the Mazovian Interglacial occurring on the post-glacial plateau are practically 1:1 reflected in the contemporary relief. A question thus arises: what are the processes that took place for such a long time from the end of the Mazovian Interglacial till the Holocene, i.e., for over 300 000 years. With the end of the Mazovian (Holsteinian, MIS 11c) Interglacial, with infilling of the palaeobasins, the natural depression ceased to exist. During the following cold intervals (glaciations from MIS 10, 8, 6, 5d-2; Lisiecki and Raymo 2005; Hughes *et al.* 2022), the study area was not covered by an ice-sheet, and the plateaus were subject to intense weathering and mechanical denudation. This is evidenced by numerous weathering covers reaching in places up to 2 m in thickness. The relief of the study area became levelled except for the highest elevations, such as the Wantopol kame, which also currently stands out in the landscape (initially it must have been much higher). In the mentioned cold intervals, multiannual permafrost was most probably developed in the area (Dobrowolski 2006), which preserved also the limnic deposits of the Mazovian Interglacial (Pochocka-Szwarc *et al.* 2024).

Most probably in the warm intervals (MIS 9, 7, 5e; Lisiecki and Raymo 2005), as well as in the terminal part of the Vistulian (Weichselian, MIS 2), mainly in the Alleröd and Böling, permafrost was subject to degradation (Böse 1995; Błaszkiewicz 2005, 2008; Dobrowolski 2006; Słowiński *et.al.* 2015, Woronko *et al.* 2024). Within the biogenic sediments infilling the palaeobasins, complex processes related with hydrocarbon release resulted in the development of shales (Łyczewska 1966; Sieradz *et al.* 2024), often observed in the analysed successions (Pochocka-Szwarc *et al.* 2024). They could be of post-sedimentary origin, be-



Text-fig. 15. Model of kame and palaeolake development near Wantopol (A. Orłowska).

cause there are no shales in Holocene limnic sediments, which may point to the fact that they developed as a result of secondary geochemical processes after the accumulation of sediments (Łyczewska 1964).

In the mentioned warm intervals (MIS 9, 7, 5e; Lisiecki and Raymo 2005), the lake palaeobasins from the Mazovian Interglacial were not reconstructed. Preliminary palaeobotanic analyses of the overlying deposits suggest that this process took place along with permafrost degradation in the terminal part of the Vistulian (Weichselian) (Dobrowolski 2006; Błaszkiewicz 2008, 2011), as well as in later parts of the Holocene (unpublished data). Only then was the degree of compaction of the limnic and peat sediments high enough to cause slight terrain deflection, up to 2–3 m. Following these processes, the palaeobasins were replaced by often drainless depressions, in which accumulation of mineral dilluvial sediments took place, followed by periodical basins with organic accumulation. Peatlands were formed in them in the Holocene. For example, the absolute age of such peats is known from Hermanów in the Łuków Plain (in the extraglacial zone of the Saalian ice-sheet lobe) and reaches 5 600–5 265 of calibrated calendar age (Michczyński 2017; Hrynowiecka *et al.* 2019). At present, the depressions are often filled with water during spring.

CONCLUSIONS

- The Sanian 2 (Elsterian, MIS 12) ice-sheet was the last one that covered the area in the vicinity of Wantopol, and thus the entire Western Polesie. The obtained results confirm the hypotheses posed in an earlier work on the Parczew-Kodeń Heights and Sosnowica Depression (Pochocka-Szwarc *et al.* 2024).
- Sites Wa-A, Wa-D and Wa-E with limnic and peat sediments of the Mazovian Interglacial (Holsteinian, MIS 11c) and a vegetation succession typical for this interglacial were documented near Wantopol.
- The recognised vegetation succession follows a similar pattern to that observed in the nearby sites in Eastern Poland, particularly in other palaeolakes of analogous origin in Western Polesie.
- The local conditions in palaeolake Wantopol Wa-A, which functioned as a shallow reservoir from the end of the Sanian 2 Glaciation to the end of the optimum of the Mazovian Interglacial, were determined. Sedimentation in palaeobasin Wantopol Wa-A ended in the *Carpinus–Abies* phase. Locally, a pleuston assemblage with *Salvinia natans* dominated at that time.
- The studied palaeobasins underwent rapid overgrowth, resulting in an atypical stratigraphic record of the most recent phases recorded in the analysed profiles.
- The terrain surface is built of glacial tills of the Sanian 2 (Elsterian, MIS 12) Glaciation, which are direct evidence of the presence of this ice-sheet in the study area.
- Sediments of the Mazovian Interglacial occur directly below the surface and fill palaeobasins carved in glacial tills of the Sanian 2 Glaciation, forming a palaeolakeland. It includes lakes formed due to the melting of melt-out blocks (ice-sheet deglaciation) in small melt-outs and in post-glacial troughs.
- The aeral ice-sheet deglaciation in the study area can be confirmed by the presence of melt-out depressions and the kame hillock in Wantopol, which was formed in a crevasse in the ice-sheet, where fine sediments of a post-glacial lake were covered by sediments of fluvioglacial fans.
- The location of the documented sediments of the Mazovian Interglacial within glacial tills and covered by only a thin cover of dilluvial and biogenic sediments, 1.5 m and 2.8 m thick, respectively (Vistulian, Weichselian, MIS 2 and Holocene) represent the most crucial evidence for the Sanian 2 (Elsterian, MIS 12) age of glacial tills building the terrain surface.
- The lithology of the mineral sediments which overlie the Mazovian Interglacial series unequivocally excludes the possibility of the covering of the area by the ice-sheet of the Odranian (Saalian, MIS 6) Glaciation.
- Sandy-silty weathering covers the overlying the Sanian 2 glacial tills are evidence for intense weathering of the glacial tills, which took place in the study area between MIS 10 and MIS 2.
- Reactivation of drainless depressions in place of the Mazovian Interglacial palaeobasins took place in the end of the Vistulian Glaciation and even in the Holocene, due to deflection of the terrain caused by compaction of limnic and bog deposits, and permafrost degradation.

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