

## Vistulian periglacial and glacial environments in central Poland: an overview

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Vistulian climatic changes are recorded in various sedimentary environments of central Poland, both in the extraglacial zone of the last glaciation and also in the area occupied by the last Scandinavian Ice Sheet, being reflected by palaeobotanical, palaeozoological, sedimentological and geochronological data. The most pronounced morphogenetic processes are linked to a glacial succession in the northern part of the study area, referred to the Upper Plenivistulian. For most of the study area, located in the extraglacial zone, the climatic changes are reconstructed from lake-bog, fluvial, slope and aeolian sedimentary successions. In central Poland, no site has been documented so far where there would be a continuous biogenic record through the whole Vistulian. Environmental changes recorded through the Vistulian include temperature, vegetation and the dynamics of morphogenetic processes, and sedimentary environments most useful for assessing changes occurring at that time may be indicated. The Early Vistulian is best recognized within biogenic deposits, as in the older part of Plenivistulian. The conditions in the earlier part of the Plenivistulian are best reported from fluvial and slope deposits with evidence of permafrost and of glacial conditions, though only in the northern part of the study area. Changing conditions of the Late Vistulian are expressed via well-documented morphogenetic processes occurring in all (except glacial) sedimentary environments, lake-bog and aeolian environments providing the most complete information about the nature of this period. Most of the Vistulian deposits reflect cold periods. There is a distinctive increase in periglacial impacts throughout the Plenivistulian with the apogee during the Upper Plenivistulian and interstadial warmings did not influence this trend. Each sedimentary environment provides significant data about the climate evolution, and processes playing a leading role vary according to the Vistulian stratigraphic unit. The consolidation of findings from regional research has provided new directions for further interdisciplinary studies.

Key words: sedimentary record, cold-related conditions, last glacial event, MIS 5d-a–MIS 2, Late Pleistocene, Central European Lowland.

### INTRODUCTION

During the Vistulian (Weichselian), climatic changes caused environmental processes to vary greatly in space and time as well as in intensity. The evidence of this high variability and dynamics is reflected in different sedimentary environments and landforms. This paper focuses primarily on the characteristics of both glacial and extraglacial natural archives, including lake-bog, fluvial, slope and aeolian deposits laid down in cold Vistulian conditions. Periglacial environments *sensu lato*, with permafrost playing a significant role, were active continuously, although with varied intensity, while glacial ones were restricted to only a few thousand years of the last Scandinavian Ice Sheet (SIS) advance.

Central Poland is an area where data from the extraglacial area, combined with archives from the zone covered by the last Scandinavian Ice Sheet (SIS), complete the picture of past events (e.g., Klatkova, 1965, 1996, 1997; Dylík, 1967; Turkowska, 1988, 2006; Goździk, 1995, 2007; Manikowska, 1995a; Petera, 2002; Forsyjak, 2005; Roman, 2010; Roman et al., 2014). The compilation of results of these investigations, carried out for decades at many locations in central Poland, with independent chronologies, gives an opportunity to relate regional variations to the global system of Vistulian environmental changes. Insufficiencies of data from one sedimentary environment are compensated by more comprehensive records from other ones, which made it possible to provide a coherent Vistulian history of central Poland, with small-scale events included.

An increasing number of proxies, such as continuously improved climate qualitative and quantitative data (e.g., NGRIP Members, 2004; Wohlfarth, 2013; Helmens, 2014; Marks et al., 2016) makes it possible to answer the questions regarding the nature of processes frequently described in source materials in qualitative terms only, and relate environmental data more precisely to global changes. This article describes individual fea-

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tures of sedimentary environments, mostly “cold” in nature, and reconstructs depositional changes in central Poland during the Vistulian by consolidation of findings from regional research. We assume that defining the Vistulian permafrost-related and glacial events in different sedimentary archive records will contribute to achieving progress in the comprehensive understanding of this palaeoenvironment. The study also highlights research aspects which are still obscure and are expected to be explained using more advanced methods in the future.

## REGIONAL SETTING

Central Poland is part of the northern Central European Lowland constituting, during the Vistulian, a transitional zone between the extraglacial region and the area within the reach of the last Scandinavian Ice Sheet. The region is situated in the central part of the European sand belt (Koster, 1995; Zeeberg, 1998), formed at the end of last glacial period. The area discussed is limited to the south by the maximum extent of the Saalian ice sheet (Warta Stadial of the Odranian Glaciation in Polish stratigraphy) while in the north it extends up to the marginal zone of the Vistulian ice sheet. It is bounded by the Warta River valley in the west and the Pilica and Bzura River valleys in the east (Fig. 1).

The area under consideration has an elevation of over 200 m a.s.l. with culminations of >250 m a.s.l. concentrated in its central and southern parts. Most of the area has a flat or slightly undulating lowland landscape with long and gentle slopes <5°. Intermittently, the relief changes significantly e.g., in the “edge zone” of the Łódź Plateau (Fig. 1), where the terrain descends northwards through a series of broad flat levels separated by zones of steeper slopes, which made it particularly predisposed to intense geomorphological processes. Farther to the north, the area is occupied by an approximately east-west oriented depression of the Warsaw–Berlin ice-marginal valley (<100 m a.s.l.). The northernmost part of the area discussed is more diverse, with well-pronounced glacial landforms shaped by the last Scandinavian Ice Sheet advance. Through the area of central Poland, from north to south, there runs a first-order watershed, between the Odra and Vistula Rivers. Most of the area is located in the Odra drainage basin, with the middle section of the Warta River as its biggest tributary. The northeastern part of the area is drained by minor tributaries of the Vistula. The Vistula River uses here a broad depression of the Plock Basin.

## MATERIALS AND METHODS

In interpreting these Vistulian cold environments, we used scientific investigations carried out for decades at many localities in central Poland, available in published and unpublished sources – journal articles, books, theses, geological survey reports and maps. Much information, acquired over >40 years, was obtained from fundamental studies of individual Vistulian sedimentary environments, while available techniques have improved during this time. The most important research material comes from long and undisturbed Eemian–Vistulian lake-bog successions (Kubłowo and Zgierz-Rudunki sites) and from extensive excavations available in the open brown coal mines at Bełchatów and Adamów, as well as exposures in the high scarps of the Vistula River (Fig. 1). Moreover, the materials gathered from dozens of individual sites provided further valuable and detailed information.

Among methods and data used for reconstructions, only those which provided the most information of cold events during the Vistulian were selected. However, some are only applicable in the area covered by the last SIS.

### PALAEOBOTANICAL AND PALAEOZOOLOGICAL DATA

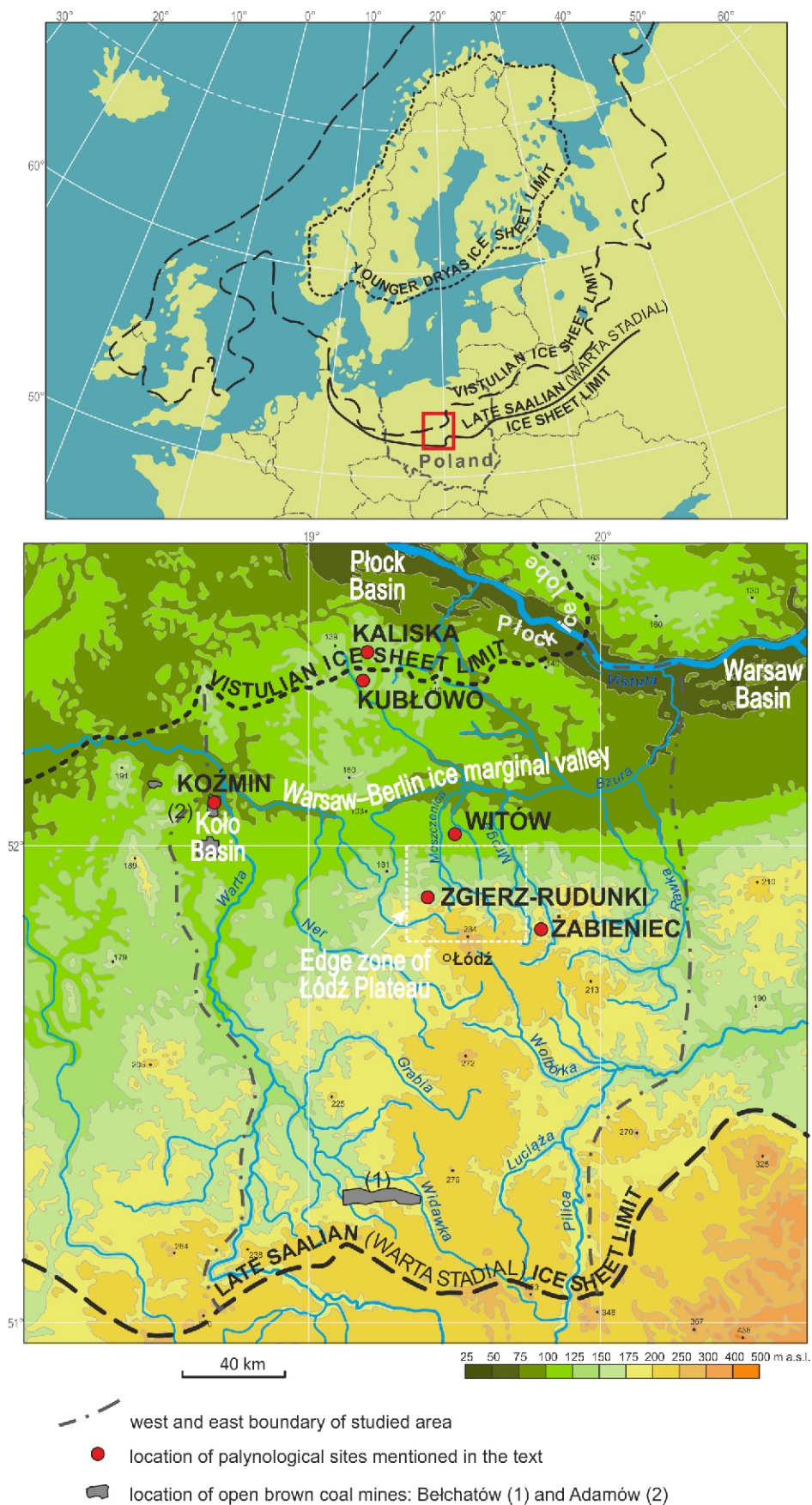
Palaeontological documentation of the Vistulian history of central Poland lacks continuous records. Palaeobotanical data, i.e. pollen records, are applied commonly for reconstruction of vegetation history, climate changes and for stratigraphic correlation. Using plant indicators, we can glean indirect information about the mean temperature of the warmest month (MTWM) and the mean temperature of the coldest month (MTCM); however, those indices may include additional uncertainty because plants may have had different tolerances to temperature, of up to a few degrees centigrade (Aalbersberg and Litt, 1998). In the study area the most reliable data is provided by organic and mineral deposits of large isolated palaeolakes known from several Eemian–Vistulian sites (Klatkowska, 1997; Kołaczek et al., 2012; Roman, 2016), including Zgierz-Rudunki (Jastrzębska-Mamełka, 1985) and Kubłowo (Roman and Balwierz, 2010) in which lake-bog deposition lasted the longest, reaching the Middle Plenivistulian. For the upper part of the Middle Plenivistulian and the Upper Plenivistulian, corresponding to the apogee of cold, there are only scattered records (Balwierz, 2007). Further palynological data (Witów, Żabieniec sites) refer only to the Late Vistulian (Wasylikowa, 1964; Majecka et al., 2018). Considerable detail can be seen in the original pollen spectra.

The Cladocera and Chironomidae reacted more quickly to environmental changes than did plants (Huijzer and Isarin, 1997). Their assemblages provide information on climatic phases as well as habitat changes such as lake level fluctuations and eutrophication (Birks and Birks, 1980; Tobolski, 2000). Well-preserved fossils and abundant cladoceran remains are present through the Eemian Interglacial and, for warm/cold Vistulian episodes, are recognized only at the Kubłowo site (Niska and Roman, 2014; Mirosław-Grabowska et al., 2018). The Cladocera record also provides reliable reconstruction of environmental conditions of the Late Vistulian from many localities in central Poland (Forysiak et al., 2010; Dzieduszyńska et al., 2014a; Pawłowski et al., 2015). Fossil Chironomidae also enable estimation of the mean July palaeotemperature. Such reconstruction has been performed for the Late Vistulian warm/cold phases (Płóciennik et al., 2011; Dzieduszyńska et al., 2014a).

### AEOLIAN ACTIVITY FEATURES AND QUARTZ GRAIN ABRASION

Vistulian cold and dry climate conditions in the northern European Lowland area were expressed as wind-driven sediments, with a number of features and landforms (cover sands, loesses, wind-abraded quartz grains, ventifacts, dunes, deflation depressions) being regarded as formed by episodes of aeolian activity operating on poorly-vegetated terrain (Goździk, 2007; Zieliński et al., 2015).

Analysis of the shape and surface of quartz grains (size 0.63–0.8 and 0.8–1.0 mm) is based on the Cailleux (1942) method with modification by Klatkowska (1976), Goździk (1980) and Manikowska (1985). Five types of quartz grain roundness and grain surface include: very well rounded and matt grains of aeolian origin (RM), moderately rounded grains, with aeolian abrasion at their edges only (M), very well rounded, shiny glossy grains of fluvial origin (EL), broken grains reflecting periglacial or glacial conditions (C) and unprocessed fresh,



**Fig. 1.** Location of study area in relation to selected glacial limits

sharp-edged grains (NU). The degree of wind-abrasion of quartz grains depends on the intensity and time of the process. RM type grains indicate long (millenia) and intense wind-transport, while M grains mark short-term (several hundred years) wind activity.

#### PERMAFROST INDICATORS

Climate-controlled terrestrial sedimentary records of stadial-interstadial cycles during the Vistulian, as regarding cold units, are sometimes expressed in the form of periglacial structures, associated with the presence of permafrost. The most significant are ice-wedge casts, cryogenic wedges with primary mineral infills and large cryoturbations (cf. Washburn, 1980; Vandenberghe, 1988); however, discussion about their usefulness to assess former mean annual air temperature (MAAT) is still ongoing (Murton and Kolstrup, 2003; Matsuoka, 2011). A combination of several periglacial features, often coupled with other palaeoclimate indicators (e.g., biological, content of wind-abraded quartz grains), provides more precise constraints to distinguish cryohorizons interpreted in the context of Vistulian-age permafrost occurrence (cf. Vandenberghe et al., 1998).

#### SEDIMENTOLOGICAL ANALYSIS

A palaeogeographical reconstruction based on non-biotic proxies was the main approach for recognition of the Vistulian sedimentary successions and landforms. Lithological examinations were preceded by geological mapping and geomorphological survey of landforms.

At field sites (outcrops, excavations or natural exposures, boreholes), sedimentary (sub)environments were determined on the basis of several standard analyses including grain size, CaCO<sub>3</sub> content, and heavy mineral composition (grain size 0.1–0.2 mm). Petrographic analysis of the fine gravel fraction (5–10 mm) of tills was carried out to distinguish till lithotypes and use these for lithostratigraphic correlation. In exposures, lithofacial analyses were performed to interpret conditions of sedimentation (cf. Zieliński, 2014). The studies included characteristics of texture, structure, directional elements (palaeocurrents, till clast fabric, striae orientation and lee end turns in sub-till boulder pavements), and post-depositional changes.

#### MESOSTRUCTURAL ANALYSIS OF GLACIOTECTONIC DEFORMATION

Glaciotectonic deformation investigations concerned the type and scale of structures, measuring their orientation and vergence to determine the glaciotectonic stress (transport) direction, the relation of disturbance occurrences *versus* palaeorelief and glacial landforms and also the age of the structures. The relative sequences of structural generations were defined and correlated with deformation stages related to consecutive ice advances, allowing the recognition of kinostratigraphic units (cf. Berthelsen, 1978; Pedersen, 1993; Roman, 2019). Structural analysis was also an important link in determining the ice-sheet movement direction.

#### AGE CONTROL

Geochronological analysis comprises conventional radiocarbon dating of organic deposits and thermoluminescence (TL) and optically-stimulated luminescence (OSL) age determination of sandy deposits of aeolian, fluvial, slope or glaciofluvial

origin. In glaciated areas, the luminescence dating method identifies sands resting below and above the LGM till. Radiocarbon ages are given as years BP (i.e. before 1950). Luminescence ages are reported to the year of sampling.

The chronology of the palaeoenvironmental events discussed is based on age determinations made over the last 60 years, during which analytical techniques continuously improved. This is why the quality of the dates cited in this paper were assessed considering their geological context, for assumptions of reliability. As a rule, in the text the authors refer to non-calibrated radiocarbon ages, and only for the Late Vistulian are values additionally converted into calendar years. This approach is for two reasons. Firstly, authors of the source publications formulate general statements and operate within wide age intervals (*vide* Goździk and Zieliński, 1996). Secondly, the Late Vistulian chronology, as established on annually laminated deposits or a well-defined part of the radiocarbon calibration curve (Reimer et al., 2013), is commonly used in the literature. However, as palaeoenvironmental considerations require a uniform time scale, a full record of the dates used in this contribution, for radiocarbon ages as both conventional and calendar, are listed in Table 1. Recalculation of radiocarbon ages was performed with the IntCal 13 calibration curve (Reimer et al., 2013) using the OxCal v.4.2. software.

### STRATIGRAPHIC SUBDIVISION OF THE VISTULIAN FOR CENTRAL POLAND

Taking the traditional approach to the palaeogeographical development of the study area (Mojski, 2005; Turkowska, 2006; Roman et al., 2014; Marks et al., 2016; Dzieduszyńska, 2019), the stratigraphy of the last cold stage may be outlined in general. The approach provided relies on the assumption that palaeoenvironmental changes are synchronous with the oxygen isotope records of marine successions (MIS) and, for the Late Vistulian, also with Greenland ice cores (Greenland Stadials – GS and Interstadials – GI; NGRIP Members, 2004; Svensson et al., 2008; Rasmussen et al., 2014; Hughes and Gibbard, 2015).

The chronostratigraphy of the Vistulian comprises three basic units: Early Vistulian, Plenivistulian and Late Vistulian. This is based on the variability of palaeoenvironmental transformation corresponding to climate fluctuations (Fig. 2). This subdivision derives from the climatic curve developed for the continental part of NW Europe (van der Hammen et al., 1967), and then adapted for Poland by Kozarski (1981). Progress in identification of cooling and warming phases resulted in a more precise chronostratigraphic scheme (Marks et al., 2016, 2019; see also references in Fig. 2).

The Early Vistulian spans the period of ~115–75 ka (MIS 5d-a) and consists of two distinct coolings (VS1 – MIS 5d and VS2 – MIS 5b, comparable respectively with the Herning and Rederstall in Western European stratigraphy) and interstadial warmings: Amersfoort + Brørup (MIS 5c) and Odderade (MIS 5a). The cool periods of the Lower Plenivistulian (VS3, at ~75–60 ka, MIS 4) and Upper Plenivistulian (~30–15 ka BP, MIS 2) were characterized by a decrease in the average July temperature of <5°C (Kozarski and Nowaczyk, 1999), which paused vegetation growth. MIS 4 cooling resulted in ice sheet advance, which did not reach central Poland (Wysota et al., 2009; Roman, 2010; Marks, 2012). The Middle Plenivistulian, at ~60–30 ka BP (MIS 3), had several warm and cold phases in central Poland (Fig. 2), which correspond to Dansgaard-Oeschger events (Dansgaard et al.,

Table 1

## Results of radiocarbon and luminescence dating of the Vistulian deposits mentioned in text and figures

Radiocarbon dates				
Site name	Age <sup>14</sup> C ka BP	Lab code	95.4 prob. cal kyr BP	References
Koźmin Las	9.78 ± 0.11	MKL-1077	11.6–10.77	<a href="#">Dzieduszyńska et al. (2014a)</a>
Koźmin Las	9.78 ± 0.15	MKL-1076	11.75–10.71	<a href="#">Dzieduszyńska et al. (2014a)</a>
Koźmin	10.20 ± 0.43	Gd-9740	12.94–10.66	<a href="#">Forysiak et al. (1999)</a>
Koźmin	10.35 ± 0.90	Lod-1389	12.54–11.95	<a href="#">Petera-Zganiacz and Dzieduszyńska (2007)</a>
Koźmin	10.68 ± 0.10	Lod-1396	12.84–12.40	<a href="#">Petera-Zganiacz and Dzieduszyńska (2007)</a>
Koźmin	10.83 ± 0.17	Lod-764	13.12–12.42	<a href="#">Petera (2002)</a>
Koźmin Las	10.84 ± 0.10	MKL-1075	12.97–12.56	<a href="#">Dzieduszyńska et al. (2014a)</a>
Koźmin	10.87 ± 0.17	Lod-699	13.14–12.52	<a href="#">Petera (2002)</a>
Kamion	14.59 ± 0.27	Lod-85	18.43–17.07	<a href="#">Manikowska (1985)</a>
Koźmin	18.48 ± 0.23	Lod-768	22.511–21.446	<a href="#">Petera (2002)</a>
Koźmin	24.20 ± 0.30	Lod-659	29.596–28.338	<a href="#">Forysiak et al. (1999)</a>
Koźmin	26.29 ± 0.56	Lod-879	31.678–30.136	<a href="#">Petera (2002)</a>
Koźmin	28.60 ± 0.26	Lod-700	34.07–31.985	<a href="#">Forysiak et al. (1999)</a>
Warszyce	28.90 ± 0.70	Lod-439	34.29–31.40	<a href="#">Kamiński (1993)</a>
Koźmin	29.95 ± 0.90	Lod-769	36.646–32.487	<a href="#">Petera (2002)</a>
Koźmin	31.74 ± 1.10	Lod-878	39.439–34.547	<a href="#">Petera (2002)</a>
Swędów	32.80 ± 0.90	Lod-339	39.28–35.04	<a href="#">Kamiński (1993)</a>
Koźmin	36.31 ± 1.86	Lod-881	45.294–37.563	<a href="#">Petera (2002)</a>
Koźmin	> 29.00	Lod-662		<a href="#">Petera (2002)</a>
Koźmin	>30.00	Lod-694		<a href="#">Petera (2002)</a>
Koźmin	> 31.20	UG-2294		<a href="#">Petera (2002)</a>
Koźmin	> 32.00	Lod-701		<a href="#">Forysiak et al. (1999)</a>
Koźmin	> 37.20	Gd-7969		<a href="#">Petera (2002)</a>
Luminescence dates				
Site name	Age OSL/TL	Lab code		References
Koźmin Las	5.75 ± 0.35 OSL	GdTL-1411		<a href="#">Dzieduszyńska et al. (2014b)</a>
Koźmin Las	12.78 ± 0.62 OSL	GdTL-1410		<a href="#">Dzieduszyńska et al. (2014b)</a>
Zgierz-Rudunki	12.80 ± 1.90 TL	Lub-769		<a href="#">Klatkova (1997)</a>
Koźmin Las	13.69 ± 0.68 OSL	GdTL-1516		<a href="#">Dzieduszyńska et al. (2014b)</a>
Koźmin Las	14.31 ± 0.66 OSL	GdTL-1515		<a href="#">Dzieduszyńska et al. (2014b)</a>
Koźmin Las	14.33 ± 0.74 OSL	GdTL-1517		<a href="#">Dzieduszyńska et al. (2014b)</a>
Zgierz-Rudunki	17.50 ± 2.60 TL	Lub-607		<a href="#">Klatkova (1997)</a>
Korzeń Królewski	18.7 ± 0.8 ka OSL	GdTL-900		<a href="#">Roman (2010)</a>
Otmianowo	22.9 ± 1.1 OSL	GdTL-865		<a href="#">Roman (2010)</a>
Lisica	41.2 ± 2.0 ka OSL	GdTL-851		<a href="#">Roman (2010)</a>
Koźmin	102.85 ± 15.40 TL	UG-2291		<a href="#">Forysiak et al. (1999)</a>
Koźmin	105.45 ± 14.80 TL	UG-2293		<a href="#">Forysiak et al. (1999)</a>

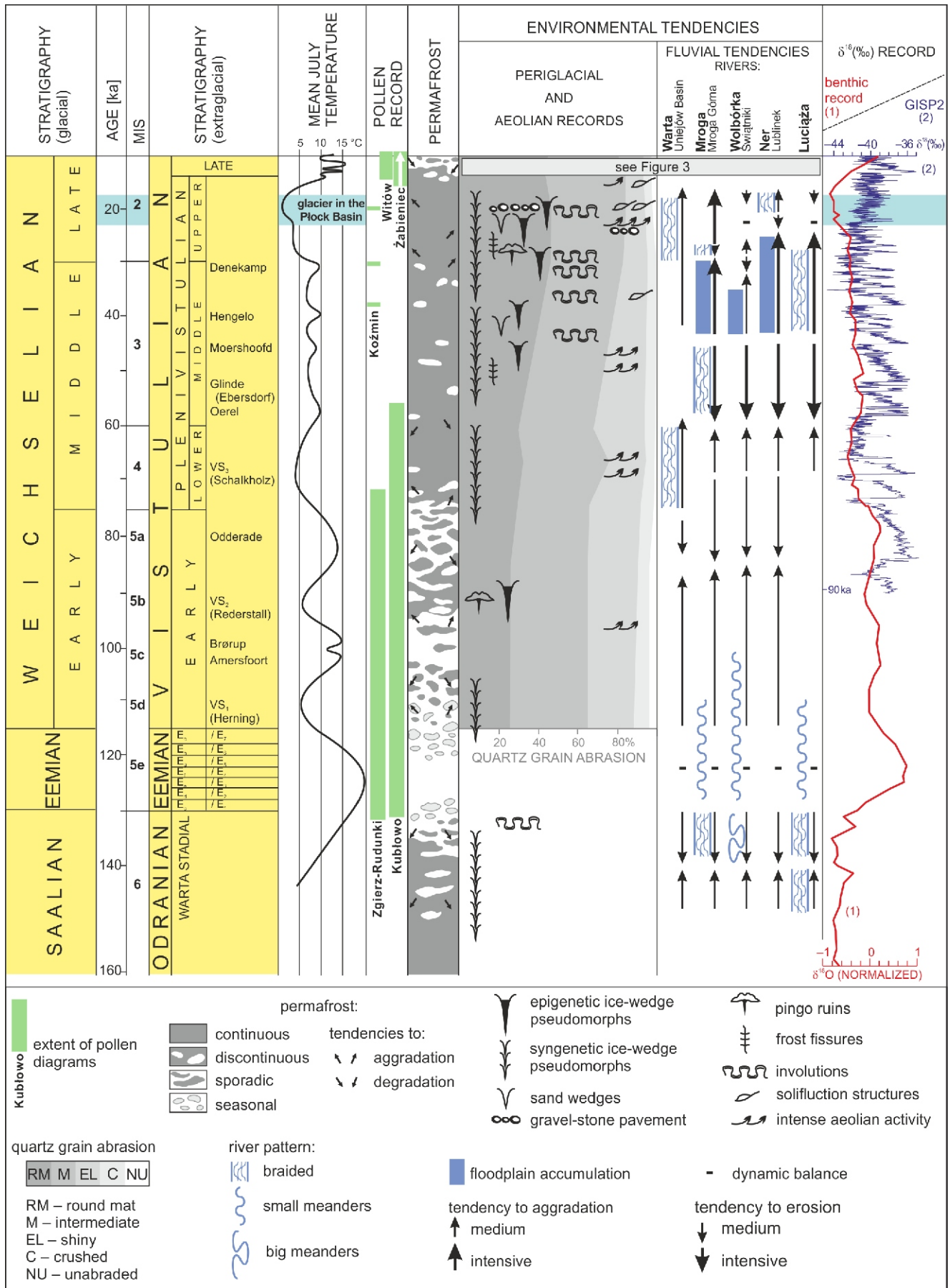
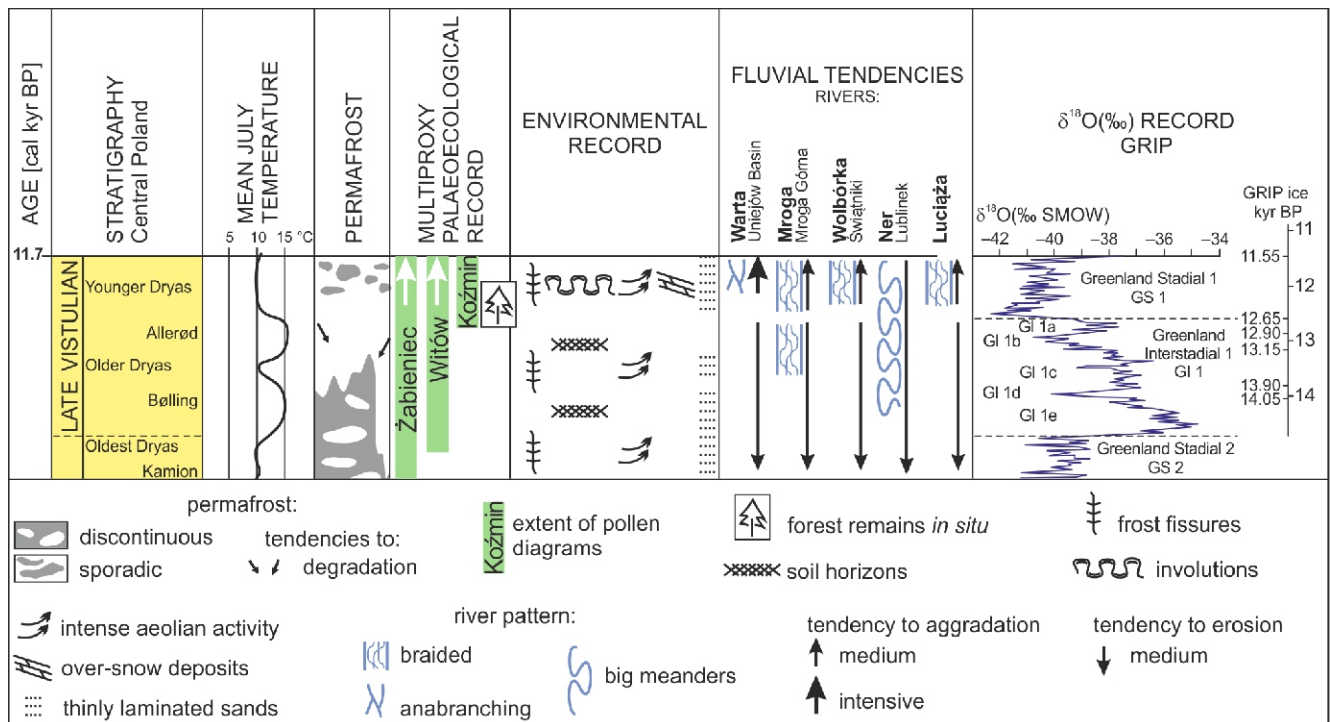


Fig. 2. Correlation of stratigraphic division and environmental processes in central Poland during the Warta Stadial – Eemian Inter-glacial – Vistulian cycle (compiled after Jastrzębska-Mamełka, 1985; Martinson et al., 1987; Turkowska, 1988, 2006; Klatkova, 1996; Stuiver and Grootes, 2000; Petera, 2002; Wachecka-Kotkowska, 2004; Forsytek, 2005; Roman and Balwier, 2010; Roman et al., 2014; Majecka et al., 2018)



**Fig. 3.** Features of the environment in central Poland during the Late Vistulian (compiled after Dylikowa, 1967; Turkowska, 1988, 2006; Manikowska, 1995a; Klatkova, 1996; Björck et al., 1998; Petera, 2002; Wachecka-Kotkowska, 2004; Dzieduszyńska, 2011; Dzieduszyńska et al., 2014a; Roman et al., 2014)

1993). The Upper Plenivistulian (MIS 2) included extreme cooling and dryness coupled with the maximum extent of the last SIS in Poland. The Late Vistulian started with a gradual temperature rise after the retreat of the ice sheet (first symptoms of climate amelioration in the study area being at ~15 ka <sup>14</sup>C BP, that is ~18 ka cal BP, the termination of MIS 2). The interval between 14.2 ka cal BP and the beginning of the Holocene – 11.7 ka cal BP was characterized by a progressive warming, but with alternating warm and moderate climatic periods (Bølling, Allerød – GI 1), as well as coolings with near-glacial conditions, especially the significant cooling of the Younger Dryas – GS 1 (Fig. 3; Lowe et al., 1994; Rasmussen et al., 2014).

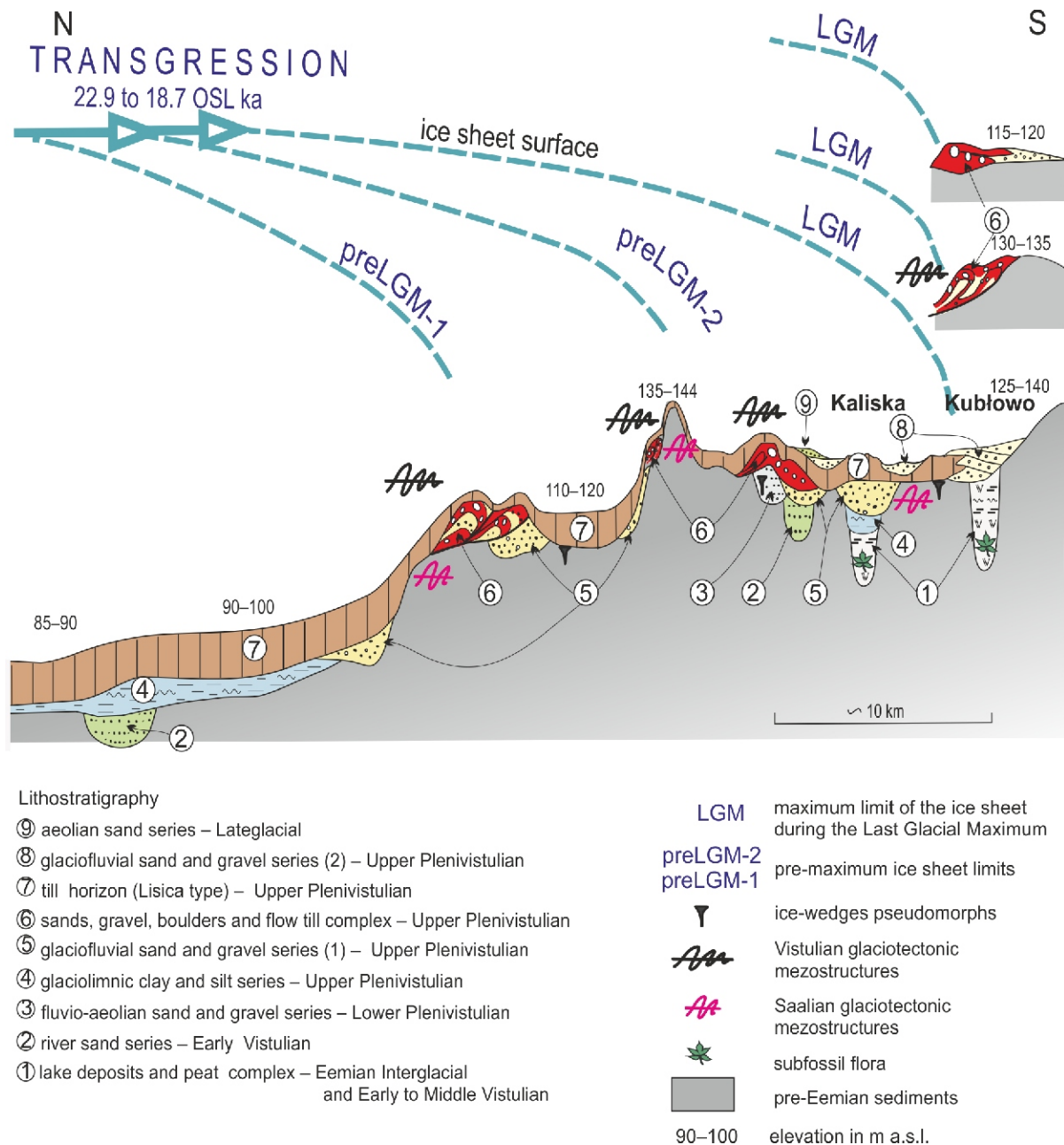
## SEDIMENTARY ENVIRONMENTS WITH RELIABLE EXPRESSION OF THE VISTULIAN ENVIRONMENTAL CHANGE

### GLACIAL ENVIRONMENT

The northern part of central Poland is of special interest for Pleistocene stratigraphy in Poland, and also for palaeogeography, with regard to the expansion of the last SIS in the Central European Lowland (Mojski, 2005; Wysota et al., 2009; Roman, 2010, 2019; Marks, 2012). The area is located in the terminal zone of the SIS and its northernmost part was affected by the Plock ice lobe, which refers to the glacier that invaded the territory of Poland moving southwards along the Vistula valley, occupying the Plock Basin and the surrounding morainic plateaux, and finally, reached its maximum extent during the last glacial stage in Poland (Figs. 1, 2 and 4). The ice sheet left a single till, the stratigraphic setting of which was determined by referring to the subfossil flora site at Kaliska (Domosławska-Baraniecka, 1965; Janczyk-Kopikowa, 1965)

where the till overlies Eemian lake deposits (Figs. 1 and 4). The age of the Plock lobe advance has been more precisely constrained by luminescence dating, and supposed to have occurred between 22.9 and 18.7 ka OSL (Roman, 2010; Table 1). This revealed that the glacial event is younger than the Greenland Stadial 3, identified with the Last Glacial Maximum defined to span between 27.54 and 23.34 ka (Hughes and Gibbard, 2015). The Kubłowo site, presumed to be located barely 1 km from the last ice-sheet margin, and its Eemian–Vistulian pollen and Cladocera records (Roman and Balwierz, 2010; Niska and Roman, 2014; Mirosław-Grabowska et al., 2018), would have revealed any possible ice sheet advance during earlier Vistulian cold stages, e.g., MIS 5d, MIS 5b or MIS 4.

The succession of glacial deposits in the northern part of central Poland is well established (Skompski, 1969; Baraniecka and Skompski, 1978; Baraniecka, 1979) and subsequent research has improved the understanding of the Vistulian facies that occur beneath the till unit (Roman and Lisicki, 2000; Roman, 2004, 2010, 2011). Glacial sedimentary (sub)environments have been clearly recognized in a number of exposures (Roman, 2010). In addition, hundreds of archive drilling logs have been useful to establish lithostratigraphy. Nine lithological units, expressed in different sedimentary types and landforms, have been distinguished (Fig. 4). Glaciotectionic mesostructures have been studied in disturbed sediment sequences, to deduce the movement direction of the ice which caused the deformation structures, and to use it as a stratigraphic indicator. Kinetostratigraphic units have also been distinguished, the youngest of which, the Vistulian unit, is expressed as a progressive sequence indicating a single deformative transgression cycle (Roman, 2010, 2013, 2019). This progressive sequence also applies to the transverse ranges allocated in the hinterland of the maximum extent of the Plock ice lobe, demonstrating these as overridden end moraines. Thus earlier findings, based mainly on morphostratigraphic criteria, discussing the oscillatory-recessive nature of



**Fig. 4. Lithostratigraphic units and ice sheet margin position during the Vistulian Glaciation in the northern part of central Poland (after Roman, 2010)**

these landforms (e.g., Galon and Roszkówna, 1967; Niewiarowski, 1983; Mojski, 2005) should be reinterpreted.

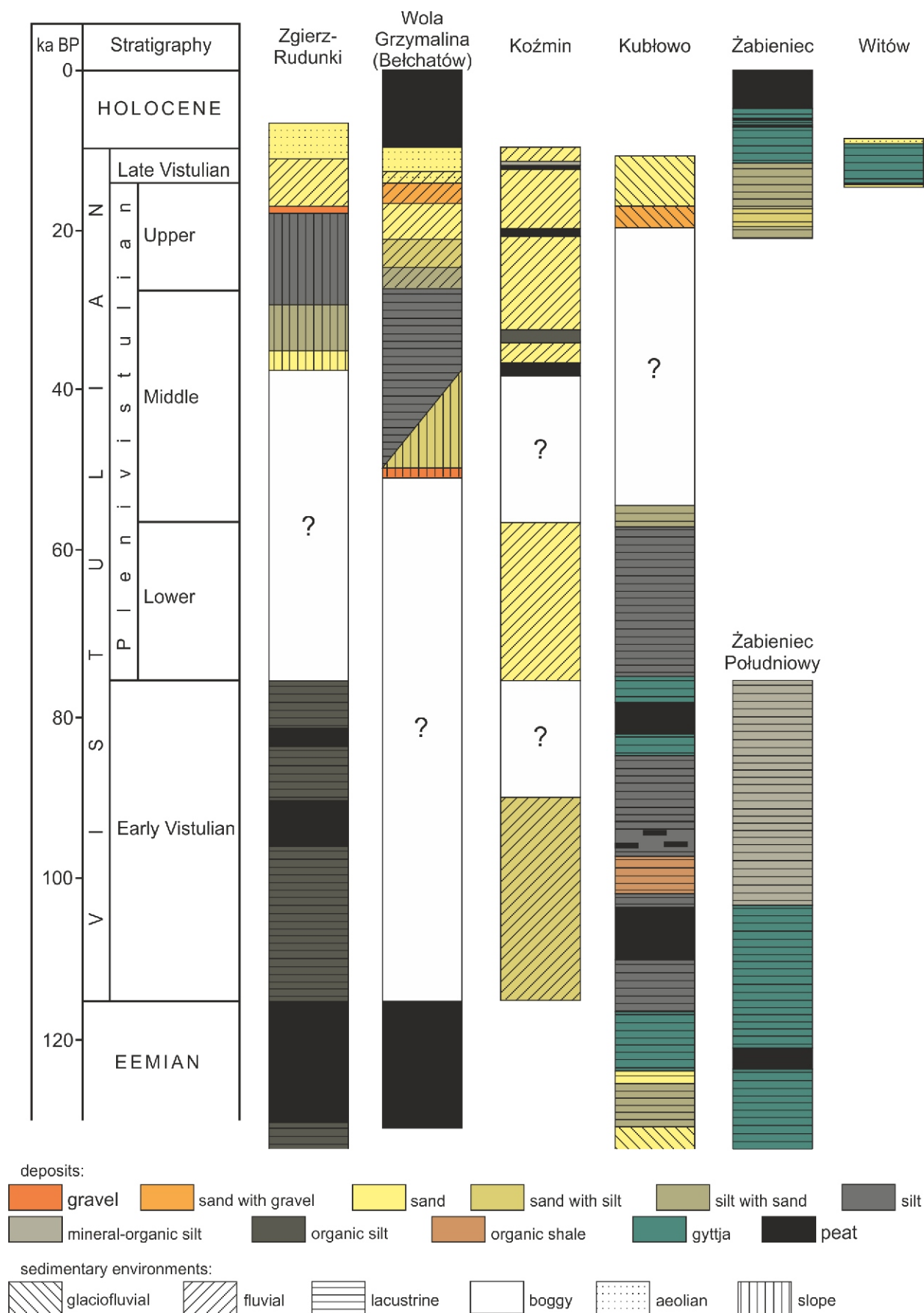
There remain unexplained issues regarding the range and stages of development of a widespread proglacial lake, the “Warsaw ice-dammed lake” (Różycki, 1972; Baraniecka and Konecka-Betley, 1987; Marks, 2002), formed in the foreland of the transgressive Vistulian ice sheet and reaching north up to the Płock Basin (Skompski, 1969; Baraniecka, 1979; Roman, 2010). In this context, the water outflow towards the west and the relation to the formation of terraces in the Warsaw-Berlin ice marginal valley (cf. Fig. 1) are significant. The origin and age of the terraces are still debated and need further research.

#### LAKE-BOG ENVIRONMENT

The Late Pleistocene subfossil lacustrine and bog deposits, palynologically studied, are known from many boreholes in central Poland (Klatkova, 1990; Bruj and Roman, 2007; Roman,

2016; Majecka et al., 2018) but only a few have been documented in the exposures at brown coal mines (Goździk and Jastrzębska-Mamełka, 1982; Goździk and Balwierz, 1994; Forsytek et al., 1999; Petera, 2002; Goździk and Skórzak, 2011; Wachecka-Kotkowska et al., 2018) or in geoenvironmental excavations. Predominantly, the sediments filled melt-out depressions within the Late Saalian till plain. Most of them are mineral and organic lacustrine or bog deposits, accumulated from the decline of the Late Saalian until the end of the Eemian. Long successions which include also the Early Vistulian, e.g. Zgierz-Rudunki (Jastrzębska-Mamełka, 1985) and Żabieniec Południowy (Majecka et al., 2018), or even reaching up to the second stadial of the Plenivistulian, as described at Kubiowo (Roman and Balwierz, 2010; Mirosław-Grabowska et al., 2018; Fig. 5), are quite rare. The post-Eemian succession at the Kubiowo site has been subdivided into seven units. In the Early Vistulian, two warm (Brørup and Odderade) and two cool (Herning and Rederstall) intervals have been distinguished.





**Fig. 5.** Lithostratigraphy and depositional environments in selected Eemian and Vistulian key sites in central Poland (for location see Fig. 1) after Wasylićkowska (1964), Krzyszkowski (1990), Klatkowska (1997), Petera (2002, modified), Roman and Balwierz (2010) and Majecka et al. (2018)

The next three climatic oscillations correspond with the Shalkholtz and Ebersdorf stadials and with the Oerel Interstadial (Figs. 2, 5 and 6).

There is some regular pattern to the content of organic matter in the lake deposits. Organic-rich lacustrine deposits correspond to warm climate oscillations, while deposits related to cold events are more organic-poor due to a growing supply of clastic particles from the adjacent area of reduced vegetation. However, cool intervals are also recorded in peat and mineral lacustrine deposits. A higher content of mineral grains could indicate sparser vegetation (pollen spectra indicating shrub tundra with birch), connected with enhanced slope processes or deepening/reactivation of a lake in a wetter climate, possibly due to decreased evaporation at lower temperatures (Klatkova, 1997). The peat layer at the top of the lake-bog succession, seen in some exposures, is disturbed by cryostructures, giving evidence of periglacial conditions during the Upper Plenivistulian.

No evidence of continuous organic succession has been found for the period between the second part of the Middle Plenivistulian and the late Upper Plenivistulian, excluding short phases of organic deposition dated at ~30 ka <sup>14</sup>C BP, 26 ka <sup>14</sup>C BP and 18.5 ka <sup>14</sup>C BP (Table 1), registered in superposition within the extraglacial Vistulian fluvial deposits in the Warta River valley (Forysiak et al., 1999; Petera, 2002; Figs. 2, 5 and 7). In turn, the record at the Żabieniec site is the sole documented example of a biogenic lake-bog succession from the last glaciation onwards (Majecka et al., 2018) in central Poland (Figs. 2, 3 and 5). However, for the extraglacial area of central Poland, the record from Witów has been taken as a key profile since the 1960s (Wasylikowa, 1964). It displays a pattern of environmental changes based on variation in vegetation from the Oldest Dryas to the beginning of the Holocene, recorded in an intra-dune peat bog (Fig. 8). Extensive peat bog research, currently being carried out in central Poland, is providing an increasingly accurate and complex picture of changes in the Late Vistulian environment, especially of the Plenivistulian/Late Vistulian transition and Late Vistulian/Holocene boundary (Dzieduszyńska and Forysiak, 2015; Forysiak, 2018). The environment of the Allerød and the Younger Dryas has been recognized within a high resolution study at the Koźmin Las site (Fig. 3), where a unique discovery of an *in situ* riparian forest accompanied by organic-rich sediments led to the reconstruction of a series of short-term events taking place on the floodplain (Dzieduszyńska et al., 2014a).

Profiles with long records of palaeoenvironmental changes – Kubłowo and Zgierz-Rudunki – should undergo re-examination due to the possibility of using a wider range of methods. The potential results would be valuable in relation to regional correlations, and the Vistulian climate reconstruction in a mid-European context. Investigations into many closed depressions are promising too, as regards obtaining a full Vistulian profile.

#### FLUVIAL ENVIRONMENT

Investigations carried out into the Vistulian fluvial environment have been focused on depositional changes, tendencies to erosion or aggradation, and shifts of channel pattern (Figs. 2 and 3). The processes registered in the sedimentary successions were concordant with climatic changes, but were also modified by local non-climatic factors such as catchment size, topography, lithology and vegetation.

Processes of intense river erosion took place in the Lower Plenivistulian and are correlated with the cataglacial Schalkholz phase (Turkowska, 1988, 2006). Deposits of this age are missing in most of the river valley sections studied. This erosional tendency continued in some valleys also throughout the Middle Plenivistulian (MIS 3); these include the Moszczenica River where organic silt dated at 32.8 ka <sup>14</sup>C BP, 28.9 ka <sup>14</sup>C BP (Table 1) rests directly on Eemian or glacial deposits (Kamiński, 1993).

Sedimentation of 10–30 m of fluvial deposits occurred between ~40 ka and 22 ka <sup>14</sup>C BP (Turkowska, 1988; Goździk, 1995; Goździk and Zieliński, 1996). The depositional succession of the Middle Plenivistulian is characterized by rhythmically bedded overbank silts and sands correlated with a low-energy fluvial environment. In the bottoms of river valleys, shallow extensive pools or peatbogs were established (Turkowska, 1988). Under conditions of rapid aggradation, a series of deposits consisting of organic or mineral-organic horizons separated by clastic fluvial material were formed. In the Warta River valley, dating of peat intercalations yielded ages of ~36.3 ka <sup>14</sup>C BP and 24.2 ka <sup>14</sup>C BP (Fig. 7 and Table 1; Forysiak et al., 1999; Petera, 2002; Forysiak, 2005). The aggradation of fluvial sediments operated in conjunction with mass-wasting processes. Middle Plenivistulian alluvia containing organic horizons intercalated with slope deposits constitute the major, older fill of the high terrace (4–12 m), commonly present in the valleys of the area studied. The younger, Upper Plenivistulian member of this terrace developed under the coldest climatic conditions of MIS 2. A significant change in the style of sedimentation occurred. The fluvial succession consists of coarse sandy-gravelly material indicative of the high-energy environment of a braided river system. Also, a high frequency of aeolian-abraded quartz grains points to aggradation forced by aeolian sand supply (Fig. 2), forming the fluvioaeolian series (Goździk, 2007). The two members of the Plenivistulian terrace are separated by a clearly expressed surface representing a weak erosional tendency, which according to the radiocarbon-dated Plenivistulian overbank deposits, took place not earlier than ~21–20 ka <sup>14</sup>C BP (Turkowska, 1997). The geological record in the Plenivistulian fluvial deposits contains evidence of the formation of ice wedges, the apogee of this being in the Upper Plenivistulian (Figs. 2, 7 and 9A, B; e.g., Klatkova, 1996; Petera-Zganiacz, 2011).

Starting from the first signals of warming at ~15 ka <sup>14</sup>C BP (~18 ka cal BP), a transformation of the size and type of river channels occurred. Chronology is provided from the middle Vistula River valley, where organic material from the infilling of the Upper Plenivistulian braided channel dated at ~14.6 ka <sup>14</sup>C BP (Table 1) is overlain by dune sands (Manikowska, 1985). Erosion in the river valleys resulted in their deep incision, up to 20 m, and the morphological emergence of the Plenivistulian terrace. Evolution of the river valleys was controlled by a reduction in sediment load, and led to a shift in the channel pattern from braided into meandering with large meanders. Turkowska (1997, 2006) noted that the time of this transformation varied, depending on local conditions such as catchment topography and lithology (also Turkowska and Dzieduszyńska, 2011). In central Poland, there are valleys in which this change occurred at ~14 ka <sup>14</sup>C BP and ones in which the tendency to braiding lasted up to the Holocene.

The cooling of the Younger Dryas brought about an intensification of fluvial activity and a return of aggradation in some

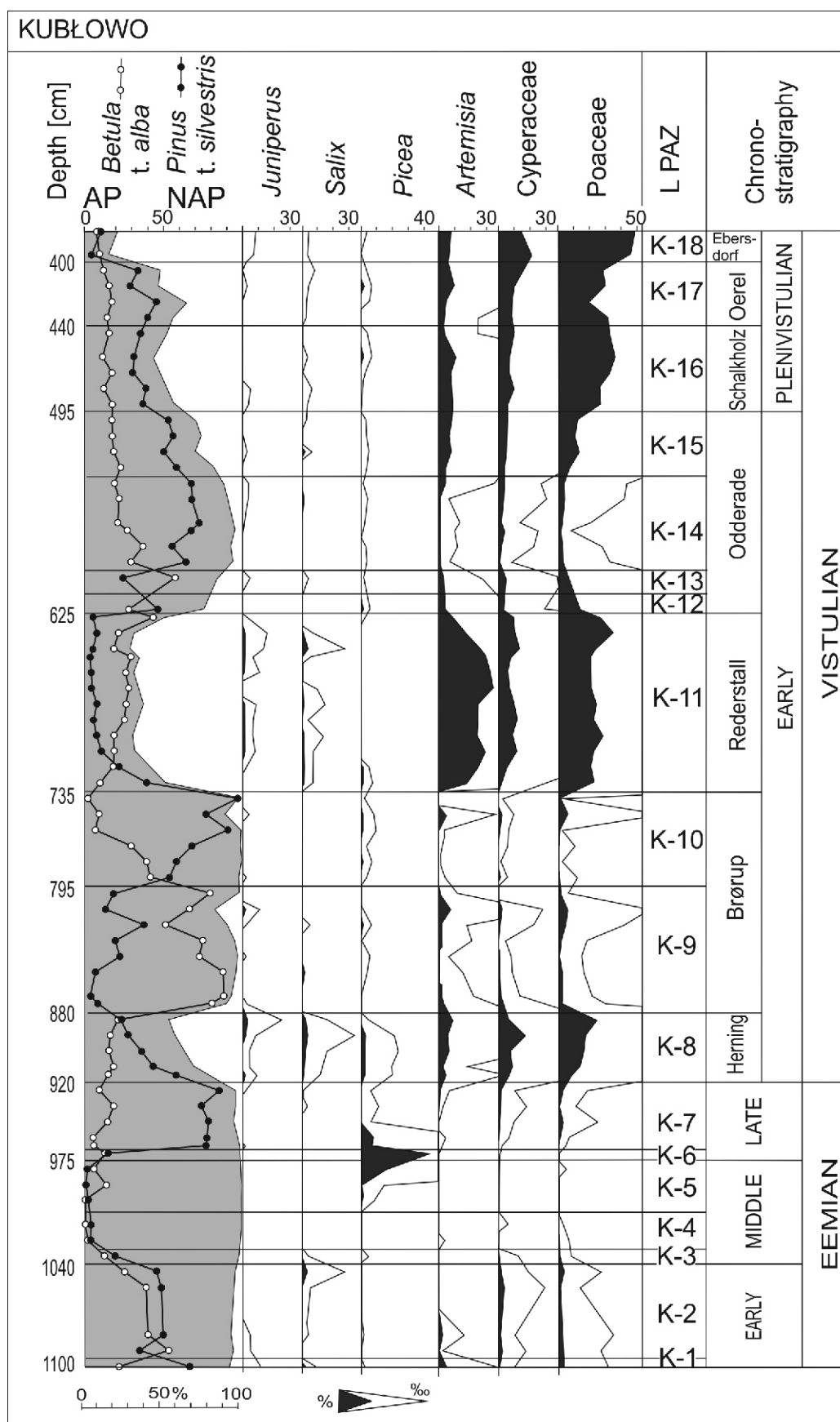


Fig. 6. Simplified pollen diagram of the Kubłowo Eemian–Vistulian succession (after Roman and Balwierz, 2010)

Only selected taxa significant for post-Eemian vegetation development characteristics are shown

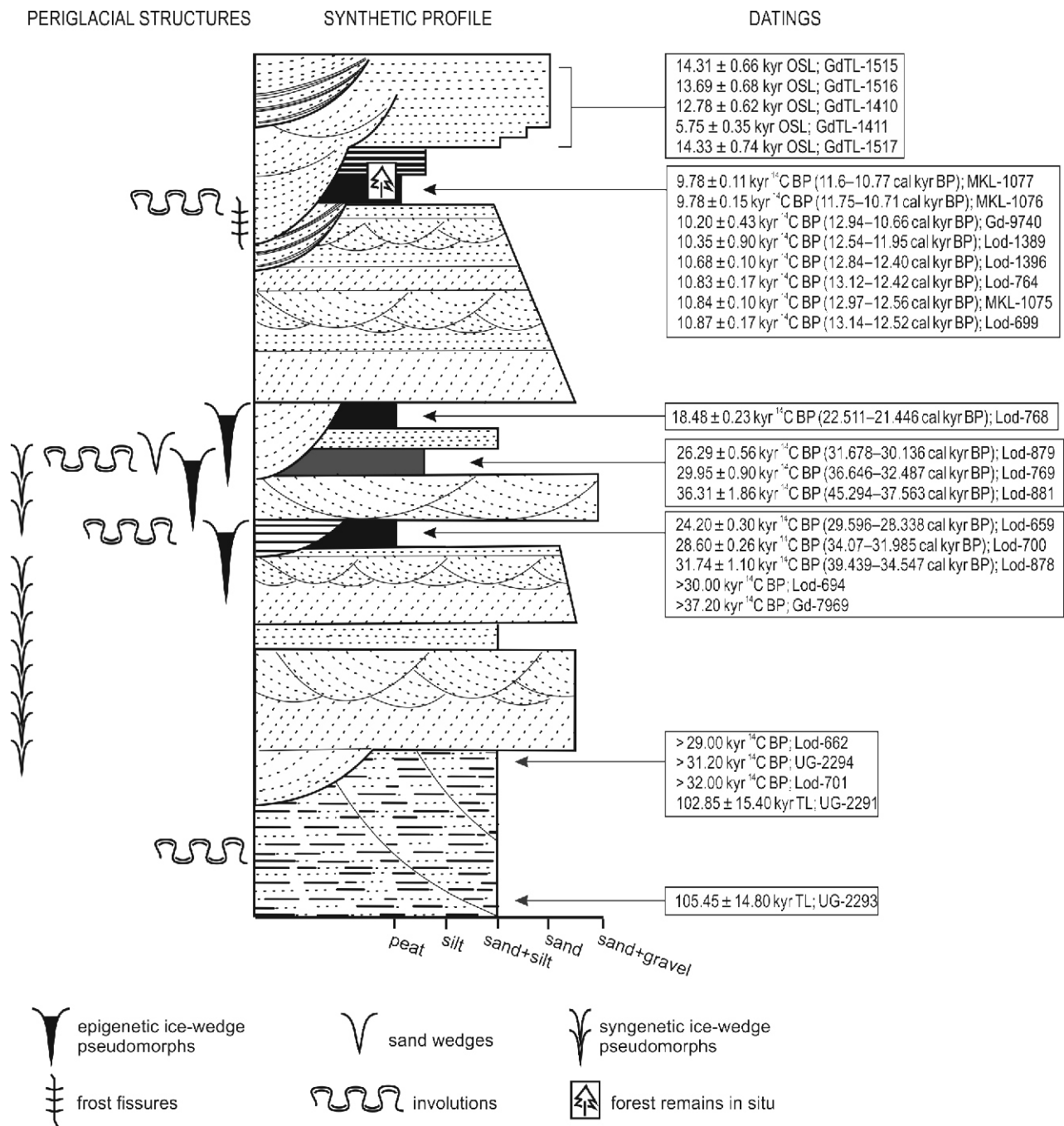


Fig. 7. Synthetic profile of Vistulian alluvia in the Warta River valley at the Koźmin site

valleys (Fig. 3). In the middle section of the Warta valley, the evolution of the river system was deduced from the role of large discharges during heavy floods, registered via characteristics of overbank deposits. The river runoff that occurred there, over the entire wide surface of the floodplain, favoured the division of stream flow and finally the initiation of a multichannel system (Peters, 2002; Turkowska et al., 2004; Forsytek, 2005; Peters-Zganiacz et al., 2015). Intensification of hydrological conditions over the floodplain during the Younger Dryas in the study area has been reported also from the Grabia River

(Pawłowski et al., 2015). The determination of scale of the floods of this age is thus a challenge for further studies.

The geological evidence from the study area raises questions about causes of different Vistulian fluvial successions in different valleys, and thus about the scale and nature of local modifications of a general environmental tendency. A clearer image of the fluvial sedimentary environment may be given from absolute age determinations of rhythmically bedded clastic overbank successions. Furthermore, greater attention should be paid to the mutual relations between the intensifica-

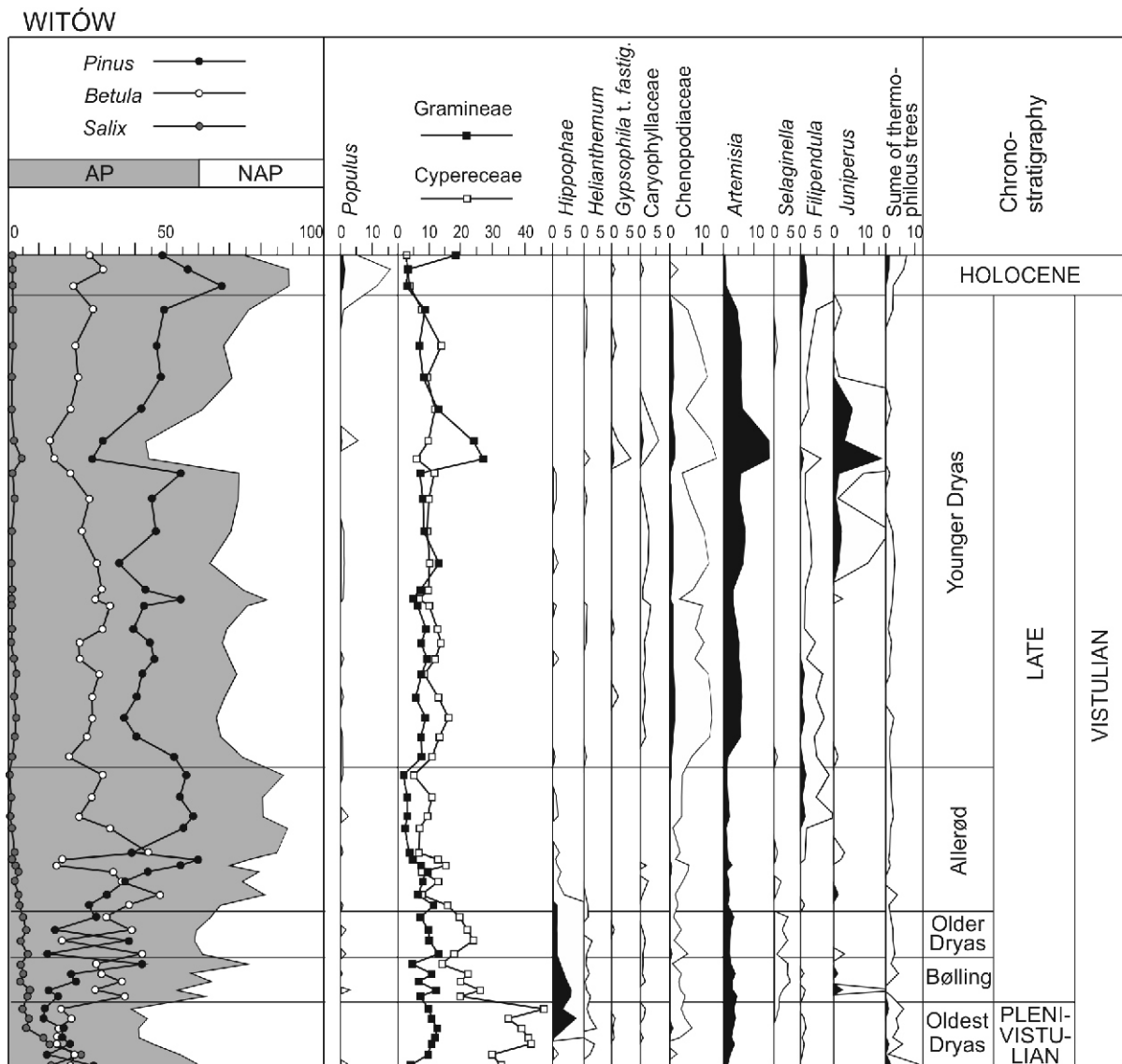


Fig. 8. Simplified pollen diagram from Witów showing the development of vegetation during the period from the Oldest Dryas to the beginning of the Holocene (after Wasylukowa, 1964)

Only selected taxa significant for the Vistulian vegetational decline are shown

tion of slope and aeolian processes, and the transformation of the fluvial system in central Poland.

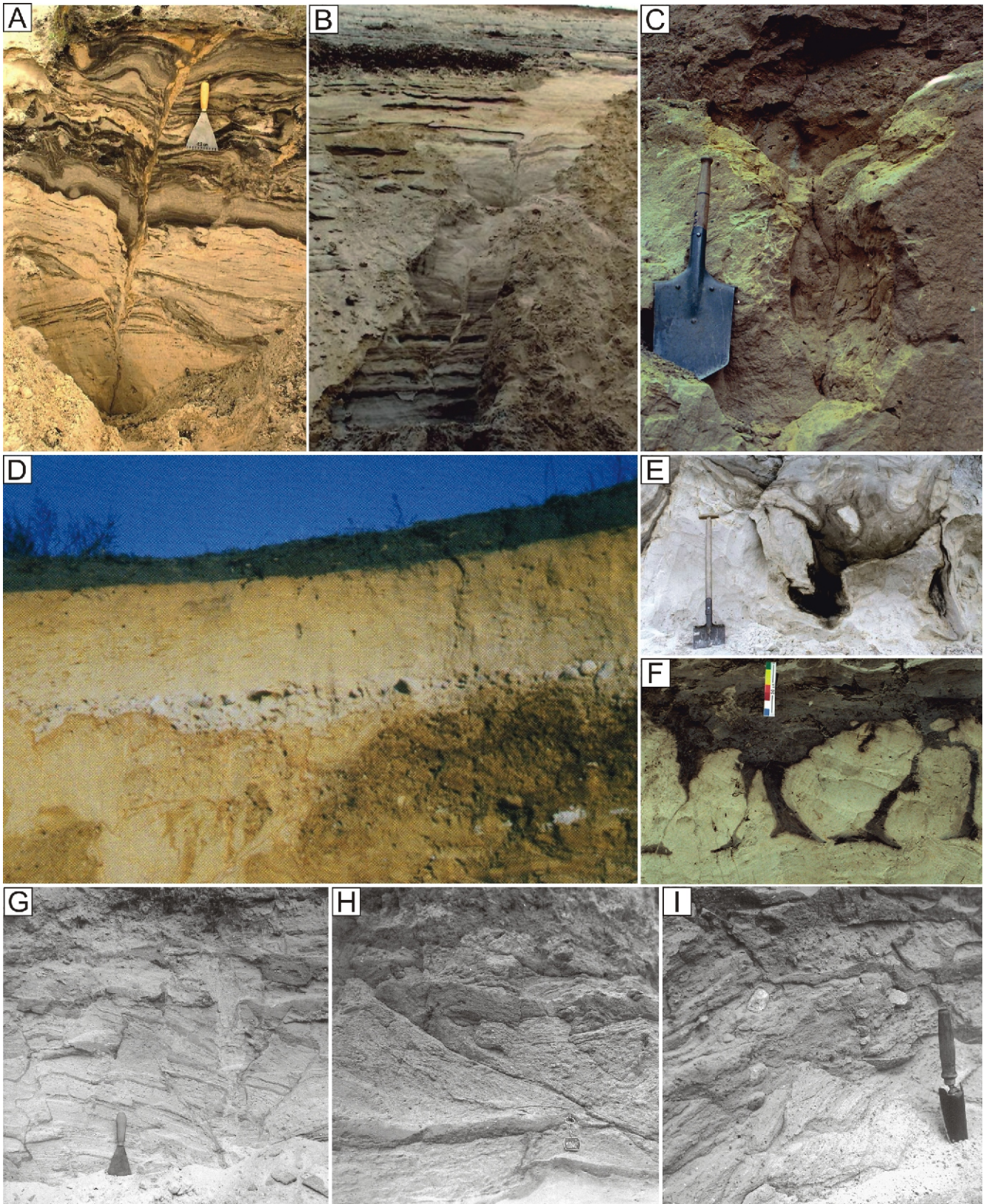
#### SLOPE ENVIRONMENT

In the Vistulian slope environment the characteristics of most slope-waste deposits, widespread and well recognized in the study area, indicates their formation over an impermeable frozen substrate. The processes of most significant diagnostic value are slopewash and solifluction (Dyliik, 1967, 1972; Figs. 2 and 3).

Rhythmically stratified slopewash sediments, known as "sandy-silty series" in the study area, developed in alternating aerial and gleyey sedimentary conditions, predominantly in the Lower and Middle Plenivistulian (MIS 4, MIS 3). The rate of this sedimentation increased due to water saturation of surficial layers during the climate wetting that occurred in response to the Denekamp and presumably in the Hengelo warmings

(Klatkova, 1997). Concentrated slopewash over the frozen ground largely contributed to the formation of a system of periglacial dry valleys and dells, landforms characteristic of the area studied (Klatkova, 1965). Slopewash was also active in the Vistulian decline when sedimentation of thinly laminated sandy deposits occurred. These formed subaerially and are occasionally cut with fine frost fissures.

The slope sedimentary environment during the cold apogee of the Upper Plenivistulian (MIS 2) was affected primarily by solifluction under arctic desert conditions on glacial and glaciofluvial plains. Freeze-thaw conditions activated mudflows. Unstratified and heterogeneous deposits with lobe-like structures commonly cover the slopes of the study area (Dyliik, 1967; Klatkova, 1965; Turkowska, 1975). Solifluction, together with frost heave and deflation, was involved in the formation of a gravelly stone pavement situated below very large, well-developed epigenetic ice-wedges (Fig. 9D). The upper sections of these periglacial structures often contain loaded material moved by solifluction. The stratigraphical position of most pave-



**Fig. 9. Selected features of the Vistulian deposits in central Poland**

**A** – epigenetic ice-wedge pseudomorph, Koźmin site (photo by J. Petera, 1998); **B** – syngenetic ice-wedge pseudomorph, Koźmin site (photo by H. Klatkova, 1996); **C** – sand wedge structure with primary infill beneath Vistulian till, Lisica site (photo by M. Roman, 1999); **D** – gravel lag with sand wedge, overlain by aeolian sand (photo by B. Manikowska, 1991); **E** – Upper Plenivistulian involutions, Janiszew Poduchowny site (photo by J. Petera, 2005); **F** – Younger Dryas flat-bottomed involutions, Koźmin site (photo by H. Klatkova, 1996); **G, H, I** – oversnow deposits, Zgierz-Rudunki site (photo by D. Dzieduszyńska, 1982)

ment horizons from the study area was indirectly established by TL dating of the underlying deposits at ~17.5 ka (Table 1).

Peculiar sedimentary conditions registered in the study area for the Younger Dryas are related to the “oversnow deposition” (Klatkova, 1997; Dzieduszyńska, 2011; Dzieduszyńska and Petera-Zganiacz, 2018). The deposit consists of poorly sorted material with an admixture of chaotically spaced large pebbles, with lamination disturbed by small faults and folds (Fig. 9G–I). Its origin was connected with deposition on snow by wash, mudflow or wind. Thawing of the snow resulted in the development of collapse structures. The succession was dated by TL at ~12.8 ka (Table 1).

#### AEOLIAN ENVIRONMENT

The activation of aeolian processes during the Vistulian was closely connected with periods of marked climate cooling and the development of a periglacial domain. The main promoting factors were an increase of dryness (precipitation mostly as snow, ~200 mm per year), increase in the wind speed and low ground moisture (Klatkova, 1996; Huizer and Vandenberghe, 1998; Helmens, 2014). The high efficiency of aeolian processes loosened the plant cover and consequently exposed the ground to deflation.

Evidence of an aeolian environment is expressed in central Poland in two different ways: as textural features of Vistulian deposits and as landforms: aeolian coversands and dunes. The intensification of aeolian processes in the coldest periods of the Vistulian was marked by changes in the characteristics of quartz grain surfaces and gradually increasing amounts of wind-abraded, round and matt grains (RM), and moderately rounded grains (M) bearing traces of modification in the aeolian environment. Quartz grains were long abraded in the aeolian environment, but in most cases have been found in fluvial deposits and contributed to fluvio-aeolian deposits (Goździk, 2007; Zieliński, 2007).

Textural features of thick Vistulian fluvial deposits indicate the occurrence of levels with an increased percentage of wind-abraded grains (Fig. 2). The first of these is connected with the considerable Vistulian cooling during the Lower Plenivistulian (MIS 4). In the fluvial deposits of the Warta River, the percentage of wind-abraded grains rose by ~5% in comparison with the average value of the Vistulian substrate or Early Vistulian deposits and reached ~35% (Petera, 2002). During the Middle Plenivistulian (MIS 3), a systematic but slow increase of wind-abraded grains in the Vistulian alluvia was recorded, and at the end of that period the amount of round and matt grains rose rapidly and remained very high during the whole Upper Plenivistulian (MIS 2), reaching usually >50% (Manikowska, 1992, 1993; Goździk, 1995, 2007; Petera, 2002; Forsytek, 2005). Markers of more significant aeolian processes in the Vistulian environment are present in the textural properties of clastic deposits overlying the organic infills of the closed depressions as well as in the slope deposits (Manikowska, 1985, 1992, 1993; Goździk, 1991, 2007; Forsytek et al., 2010).

Intensive deflation, during the coldest period of the Upper Plenivistulian on plains or in dry valleys, led to a progressive concentration of the gravel and stony fraction and to the formation of a gravelly stone pavement (Fig. 9D), which protected the underlying deposits from wind action. The large clasts reveal traces of wind abrasion and some of them were transformed into ventifacts. The scale and intensity of the aeolian processes may be inferred from the properties of the material trapped in thermal contraction structures. The infills of the sand wedges are characterized by the highest amount of RM grains (up to >60%; Goździk, 1973, 1991; Manikowska, 1992, 1993; Roman

and Lisicki, 2000; Petera-Zganiacz, 2013). Above the gravelly stone pavement, during the transition between the Upper Plenivistulian and the Late Vistulian, the cover sands were deposited under favourable terrain conditions (Manikowska, 1992; Goździk, 2007).

Although aeolian processes were involved in the overall Vistulian palaeogeographical development, the timing of dune building was restricted to the period from the Oldest Dryas to the Younger Dryas. Manikowska (1994, 1995a) proposed three stages of dune formation separated by two periods of landscape stabilization (Fig. 3): the development of initial forms during the Oldest Dryas, soil development during the Bølling, the main phase during the Older Dryas when the dunes achieved mature forms, finished by the development of the Allerød soil horizon, and the transformation stage during the Younger Dryas. The results of geomorphological and sedimentological analyses showed the dominant past wind directions as W and SW and the velocities as 3–6 m/s, in gusts to 9 m/s (Krajewski, 1977).

Although central Poland is rich in aeolian landforms, some of the dunes post-date the Late Vistulian. Instances of classically fashioned dunes belonging to the Holocene stage of formation were reported by Twardy (2008). Therefore the statement about the abundance of dunes needs to be verified by reanalysis of aeolian successions with fossil soils and implementation of age determination by the OSL method.

#### PERIGLACIAL EVIDENCE

Periglacial phenomena dominated during a large part of the Vistulian in central Poland, approximately from the beginning of the Plenivistulian to the Late Vistulian (e.g., Goździk, 1995; Klatkova, 1996). Evidence of the occurrence of continuous and discontinuous permafrost and periglacial processes was present in each sedimentary environment where morphogenetic processes were intensified, which bound them into a coherent system.

The first symptoms of a periglacial environment were recorded in deposits of Early Vistulian age. The cryogenic structures as syngenetic ice-wedges, epigenetic ice-wedges and pingos were associated with cold stages of the Early Vistulian, under discontinuous or sporadic permafrost (Dylik, 1967; Klatkova, 1996).

Periglacial structures are common in Plenivistulian deposits, and most of them developed during the Middle and Upper Plenivistulian (Fig. 2). These structures are represented by all kinds of ice-wedges and/or sand wedges, often associated with involutions (Fig. 9A–C, E; e.g., Goździk, 1973; Krzyszkowski, 1990; Klatkova, 1996; Petera, 2002; Petera-Zganiacz, 2011, 2013). Most sand wedges were formed in the Upper Plenivistulian (MIS 2); however, OSL dates of the sand influx into the ice wedges correspond also to the middle part of MIS 3 (~41–43 ka; Roman, 2010). In areas of rapid accumulation, a few horizons with ice-wedges and permafrost-related involutions were documented, e.g. within fluvial deposits of the brown coal open pits of Bełchatów, Koźmin and Adamów (Krzyszkowski, 1990; Petera, 2002; Forsytek, 2005). The thick clastic fluvial deposits locally alternate with thin radiocarbon-dated organic deposits which provided the basis for determinations of the relative age of the periglacial structures (Fig. 7).

Permafrost behaviour throughout the Late Vistulian may be inferred from the lake-bog environment of the Żabieniec profile, where the geochemical record points to its rapid degradation at the start of the Oldest Dryas (Forsytek et al., 2010; Dzieduszyńska and Forsytek, 2015). The disappearance of the permafrost in central Poland took place in the Allerød (Goździk,

1996; Klatkova, 1996). In some areas, for example when not even a thick peat layer was present in the substrate, a reaggradation of frozen ground conditions might have occurred in response to the Younger Dryas cooling, resulting in the development of periglacial involutions (Figs. 3 and 9F; Petera-Zganiacz and Dzieduszyńska, 2017).

## ENVIRONMENTAL CHANGES THROUGHOUT THE VISTULIAN

Patterns of the Vistulian palaeogeographical development of central Poland, reflected in the properties of sedimentary environments, are inferred based on a critical review of the published and archival data. Insight into their nature allows highlighting of events considered crucial and unique for the area studied (Figs. 2, 3 and 5).

### EARLY VISTULIAN

Early Vistulian environmental development took place under unstable climate conditions with mean July temperatures fluctuating between 5 and 15°C (Fig. 2). Transition from forest to shrub tundra is recorded in long continuous lake-bog successions especially at the Kubłowo and Zgierz-Rudunki sites (Figs. 2, 5 and 6). The palaeobotanical content from these sites indicates that central Poland during cold stadials of the Early Vistulian (VS<sub>1</sub>, VS<sub>2</sub> in Fig. 2) found itself at the far forefront of the ice cover (cf. Tobolski, 1991; Stankowski et al., 1999; Roman, 2010; Roman and Balwierz, 2010; Roman et al., 2014; Marks et al., 2016). The abiotic sphere contains some traces of frost activity, such as frost cracks and unique pingo ruins linked to VS<sub>2</sub>, which are the earliest display of periglacial or permafrost conditions. Influence of progressive climate cooling featured in the lithology of palaeolake infills by an increase in the amount of clastic sediment, ranging to transition from organic to clastic deposition. The slope processes did not interrupt biogenic sedimentation, but in alternating with clastic input might have been crucial in the smoothing of glacial and interglacial relief (see Majecka et al., 2018). The resultant of the variably recognized Early Vistulian fluvial processes is considered to be a weak tendency to aggradation limited to a floodplain zone.

### PLENIVISTULIAN

The Plenivistulian as recorded in the sedimentary environments discussed comprises three distinct units. Significant coolings occurred during the Lower Plenivistulian and the Upper Plenivistulian. Mean July temperature estimated at below 5°C (Fig. 2) paused vegetation growth. Middle Plenivistulian warming with July temperatures of ~10°C allowed relatively rich vegetation development. The most significant aggradation phase in the valleys of the region is generally connected with the whole Plenivistulian.

Increasing climate aridity and a clear trend to severe permafrost conditions influenced environmental evolution in the Lower Plenivistulian (Marks et al., 2016). The only pollen profile which provides a continuous record of vegetation and palaeoecological conditions of that period is from Kubłowo (Roman and Balwierz, 2010; Niska and Roman, 2014). The beginning of the Lower Plenivistulian brought intense fluvial erosion. However, locally, as in the middle section of the Warta valley, aggradation took place in a depositional environment interpreted as a sand-bed braided river (Figs. 2 and 7). In other river valleys of central Poland, accumulation of sandy-silty

sediments started with interfingering of slope processes under loosened vegetation cover and fluvial activity. The climate aridity and presence of material exposed to wind action resulted in an increase in wind-abraded grains in the fluvial deposits (Petera, 2002).

The Middle Plenivistulian was dominated by intensive morphogenetic processes under humid climatic conditions (Van Huisteden, 1990; Manikowska, 1995b), associated with still-extant permafrost. Because the active layer was thicker, effective slope processes were activated, which afterwards influenced efficient aggradation in the river valleys (Fig. 2). During the Middle Plenivistulian the main phase of deposition of the sandy-silty series, a characteristic sedimentary unit of Vistulian profiles at many sites in central Poland, took place (e.g., Klatkova, 1965; Turkowska, 1975, 1988; Krzyszkowski, 1990). In the area discussed, dry periglacial valleys and dells formed through concentrated sloopwash over frozen subsoil (Klatkova, 1965). Efficient slope processes terminated biogenic sedimentation, as at the Kubłowo site, where the pollen record terminates in the Ebersdorf Stadial (Fig. 6). Information about vegetation during younger parts of the Middle Plenivistulian comes from organic deposits in these river valleys which were wide enough for the existence of shallow reservoirs of organic-clastic sedimentation in distal parts of floodplains. The pollen record available for short sections of the profiles shows open vegetation typical of a cold climate, but it does not provide a basis for stratigraphic correlation (Balwierz, 2007). Dating is possible only if a deposit's age is within the limit of the radiocarbon method. Such instances have been recorded in some sections of the Warta River valley within the study area (Figs. 2 and 7). The presence of organic deposits in the river valleys is therefore associated with the nature of their functioning rather than with climate changes (van Huisteden, 1990). The organic deposits are cut by ice-wedge casts and deformed due to loading or cryohydrostatic pressure in the active layer of permafrost (e.g., van Huissteden et al., 1986; Van Huissteden, 1990; Petera, 2002; Kasse et al., 2003; Fig. 9A, B, E).

The apogee of cold occurred during the Upper Plenivistulian. The beginning of this period brought significant environmental changes. During the transition from the Middle to Upper Plenivistulian the style of deposition in river valleys changed – the sandy-silty series was replaced by coarser deposits accumulated in more dynamic sedimentary environment (Turkowska, 1988; Krzyszkowski, 1990; Petera, 2002; Forsyjak, 2005). The fluvial deposits record an intensification of aeolian processes expressed as the largest amount of wind-abraded grains (Fig. 2). On the uplands, severe and dry climate conditions resulted in the development of thermal contraction polygons, including sand wedges filled with aeolian sand. The extremely cold thermal conditions of the Upper Plenivistulian correlate with the most pronounced cryohorizons. One symptom of intensive aeolian processes was the formation of a gravelly stone pavement – autochthonous on uplands (Fig. 9D) and allochthonous in dry valleys (Klatkova, 1965). The northern part of the study area during the apogee of cold was occupied by the ice sheet, which left glacial-related deposits dated at ~22.9–18.7 ka OSL (Roman, 2010; Fig. 4). In favourable localities of the extraglacial zone biogenic sedimentation took place, e.g. in the Warta River valley with organic deposits dated at 22.51–21.45 ka cal BP (Petera, 2002; Figs. 2 and 7).

### LATE VISTULIAN

The transition from the Upper Plenivistulian cold to the Late Vistulian was marked by strong erosion associated with beginning of changes in river patterns from braided to meandering (Turkowska, 1988) and formation of the high terrace. Intensified



aeolian processes have a morphological expression as sand covers. In closed depressions of different origin, biogenic sedimentation started.

The environmental changes of the Late Vistulian are known from many profiles with continuous pollen and palaeozoological records, especially from the Witów (Fig. 8) and Żabieniec sites (Wasylikowa, 1964; Dzieduszyńska and Forsyjak, 2015; Forsyjak, 2018; Majecka et al., 2018; Fig. 5). Mean summer temperatures, as inferred from biotic proxies, ranged from 10 to 17°C (Fig. 3). Climate warmings in the Bølling and the Allerød were preceded by long-lasting cold of the Oldest Dryas and divided by short, but clearly marked the Older Dryas cooling (Dzieduszyńska, 2019). The main phase of dune formation in central Poland is located during this shortest part (~250 calendar years) of the Late Vistulian. The Younger Dryas cooling brought significant changes to almost all sedimentary environments (Dzieduszyńska, 2011). The formation of meandering systems stopped and the river pattern in some valleys returned to braided or multichannel systems, as in some parts of the Warta River (Forsyjak, 2005; Petera-Zganiacz et al., 2015; Fig. 3). Intense floods and aggradation dominated river valleys, dunes became remodelled, and activated slope processes led to the formation of finely laminated sands and over-snow deposits (Fig. 9G–I) which are the most extensive sedimentary successions in the dry periglacial valleys of the study area. Features characteristic of a cold environment, such as frost fissures and different types of involutions (Fig. 9F), developed under conditions of permafrost which regraded locally in favourable places, e.g. under peatbogs (Petera-Zganiacz and Dzieduszyńska, 2017).

## CONCLUSIONS

1. Most Vistulian deposits in various sedimentary environments in central Poland are those from cold periods related to periglacial or permafrost conditions. Moreover, in the northernmost part of the area discussed, the Vistulian sedimentary succession is dominated by glacial-related deposits correlated, on the basis of litho- and kinetostratigraphy, with a single ice-sheet (the Płock ice lobe) advance ~22.9–18.7 ka OSL.

2. If data collected from different localities and sedimentary environments is considered, there is a distinctive increase in periglacial activity throughout the Plenivistulian with its apogee

during the Upper Plenivistulian; interstadial warmings did not influence significantly this general trend.

3. Based on the integrated sedimentological record, the continuous permafrost was established with the onset of the Plenivistulian (MIS 4, 3, 2) and lasted with short breaks up to the Late Vistulian. However, evidence of frozen ground conditions is present also in stadials of the Early Vistulian (MIS 5d, b), and reflects increasing cooling, and also in the Late Vistulian when permafrost regraded in response to the Younger Dryas.

4. A reaction of every sedimentary environment to the climatic changes during the Upper Plenivistulian (MIS 2) is significantly expressed. Prior to that period, the environmental response was less dynamic, and the record of changes depends also on local factors. During the rapid climatic fluctuations of the Pleistocene–Holocene transition, permafrost disappearance, hydrological instability and changes of vegetation cover took place; the dynamics and efficiency of these processes, especially in slope, fluvial and aeolian environments, was high.

5. Of the various processes operating under periglacial conditions, none of them should be taken as outstanding. Only the integration of the abundant data from major sedimentary sub-environments provides a mostly comprehensive picture of Vistulian changes, including those that are subtle and barely registered in the deposits.

6. Poorly recognized so far are glaciolacustrine sediments of vast proglacial lakes in the northern part of the study area. They would show a continuous record of increasing cold, an apogee during MIS 2, and subsequent warming of the Pleistocene–Holocene transition.

Although the sedimentary environments of the discussed area are well recognized, the synthesis of existing data indicates deficiencies and shows possible directions of further studies. To take part in the current discussion on global palaeoenvironmental evolution, it is necessary to: (1) unify research methods; (2) emphasize the distinction between regional palaeoclimatic conditions and global ones; (3) create models (palaeoclimatic, palaeohydrological), therefore converting from qualitative into quantitative analysis of sediments and processes.

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