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Quaternary stratigraphy of Poland – current status

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ABSTRACT:

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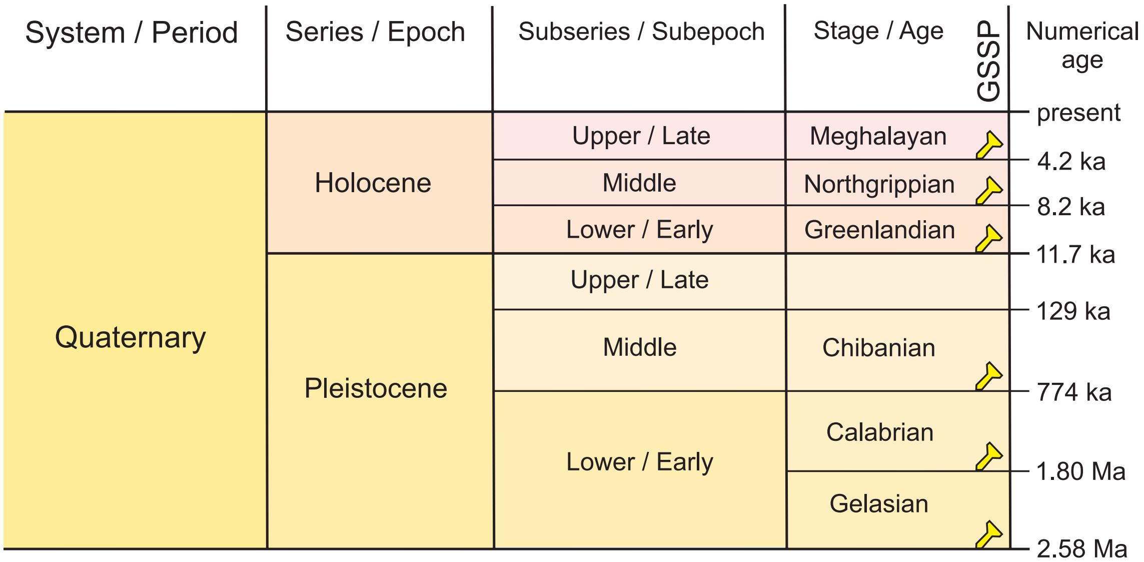
A critical verification of the previous stratigraphic Quaternary subdivisions has updated the setting of the stratigraphic units in Poland. Inconsequently applied classification and terminology in the Polish Quaternary stratigraphy has been accompanied by arbitrary correlation with marine isotope stages. This has resulted in the creation of several stratigraphic units, occasionally with ambiguous stratigraphic setting and chronology, and usually devoid of the type sections. A record of most of the Early and Middle Pleistocene is full of sedimentary hiatuses. The detailed stratigraphic setting of 5 glaciations (Nidanian, Sanian 1, Sanian 2, Odranian and Vistulian) and 4 interglacials (Podlasian, Ferdynandovian, Mazovian and Eemian) has been established in the Pleistocene of Poland. The palaeomagnetic Brunhes/Matuyama boundary was determined within the Podlasian Interglacial and therefore, the oldest glaciation (Nidanian) has no equivalent anywhere in Europe. The stratigraphic units distinguished are correlated with those in Western Europe and with the marine isotope stages. The Quaternary stratigraphy in Poland is faced with the necessity of how to define regional stratotypes of the main stratigraphic units and boundaries. A crucial issue is to change the approach from a qualitative description of the stratigraphic units to one based also on selected quantitative criteria.

Key words: Pleistocene; Holocene; Climatostratigraphy; Chronostratigraphy; Glaciations; Interglacials; Central Europe.

INTRODUCTION

A reliable and updated stratigraphic subdivision of the Quaternary is commonly needed, not only due to the outstanding significance of its deposits in geological investigations, geological mapping included, but also to its leading role for human societies. In Europe, where the Quaternary was defined for the first time, its sediments and processes modelled both subsurface geology and landscape. The enormous spatial differentiation and varied accuracy of investigations support the traditional and commonly accepted subdivision of the Quaternary into the Pleistocene and the Holocene. A profound discussion carried on in the last 20 years has resulted in the establishment of the almost complete formal subdivision of the Quaternary on a global scale (Text-fig. 1; cf. Gibbard *et al.* 2010; Cita *et al.* 2012; Walker *et al.* 2018; Head *et al.* 2021; Suganuma *et al.* 2021). Based on the same stratigraphic standards (cf. Marks *et al.* 2014a), the Polish Quaternary stratigraphic units should be verified and correlated both with the global stratigraphic units and the European subdivisions.

All stratigraphic subdivisions of the Quaternary are of regional origin and were created, not only for particular continents, but also for individual countries or even their fragments (cf. http://quaternary.stratigraphy.org/regional-divisions). Formal definition of the chronostratigraphic stages, supported by geochronologic and magnetostratigraphic dating, and correlated with marine isotope stages (MIS), formed the background for a global stratigraphy of the Quaternary. A subdivision of the Quaternary, based on climatostratigraphic units distinguished mainly in



System / Period	Series / Epoch	Subseries / Subepoch	Stage / Age	GSSP	Numerical age
Quaternary	Holocene	Upper / Late	Meghalayan	⚑	present 4.2 ka
		Middle	Northgrippian	⚑	8.2 ka
		Lower / Early	Greenlandian	⚑	11.7 ka
	Pleistocene	Upper / Late			129 ka
		Middle	Chibanian	⚑	774 ka
		Lower / Early	Calabrian	⚑	1.80 Ma
			Gelasian	⚑	2.58 Ma

Text-fig. 1. Formal chronostratigraphic/geochronologic subdivision of the Quaternary (International Chronostratigraphic Chart of the International Commission on Stratigraphy); 'golden spikes' indicate Global Stratotype Section and Point (GSSP) boundaries and the stratigraphic units are presented with CMYK colour codes, introduced by the Commission for the Geological Map of the World in September 2020; after Head *et al.* (2021), modified.

the Netherlands, Germany and the United Kingdom (Zagwijn 1985; Gibbard *et al.* 2005; Litt *et al.* 2007), is considered for one which is relevant in Europe.

The duration of the Pleistocene and the Holocene is drastically divergent from each other, much more than that of the Quaternary and the preceding geological periods. The Pleistocene started at 2.58 Ma and the Holocene at 11.7 ka, so it was over 220 times shorter than the Pleistocene. Studies of the Quaternary were mainly based on more easily accessible terrestrial deposits and a decisive role in their formation was played by climate change. A modern climatostratigraphic approach is supported by examination of continuously deposited marine deposits that contain environmental proxies and are calibrated to the insolation curve, making a much more detailed and reliable subdivision of the Quaternary possible. The aim of this paper is to present a current state of the stratigraphic research of the Quaternary, based on recent achievements in Poland and adapted to the internationally acceptable stratigraphic classification and terminology (http://quaternary.stratigraphy.org/stratigraphic-guide).

METHODS

In studies of the Quaternary in Poland several categories of stratigraphic classification are applied (Marks *et al.* 2014a). The most common are: lithostratigraphy (including pedostratigraphy and cryostratigraphy), morphostratigraphy, biostratigraphy (including palynostratigraphy, malacostratigraphy, teriostratigraphy and anthropostratigraphy), magnetostratigraphy, chronostratigraphy (combined strictly with geochronology) and climatostratigraphy (combined with isotope stratigraphy). Units of a single category may be diachronous to the ones of the other categories.

Lithostratigraphy and morphostratigraphy

Lithostratigraphy of tills has only a limited significance due to their regional diversity, and its indiscriminate application has resulted in the irrational multiplication of the stratigraphic units (cf. Lisicki 2003). A principal task in the lithostratigraphy of sand and gravel series in Poland is the separation of fluvial and glaciofluvial deposits, based on grain size and heavy minerals' analyses (Marks 2004a). The relation of fluvial deposits to a base of erosion is of primary importance as many a time, several dozen metres thick sandy-gravel series in drilling cores, located several dozen metres below a sea level, were considered to be fluvial ones. Morphostratigraphy is complementary to lithostratigraphy, because the Quaternary deposits in Poland are mostly of terrestrial origin with enormous lateral variability and if connected with landforms, in which they occur, their univocal stratigraphic classification is possible.

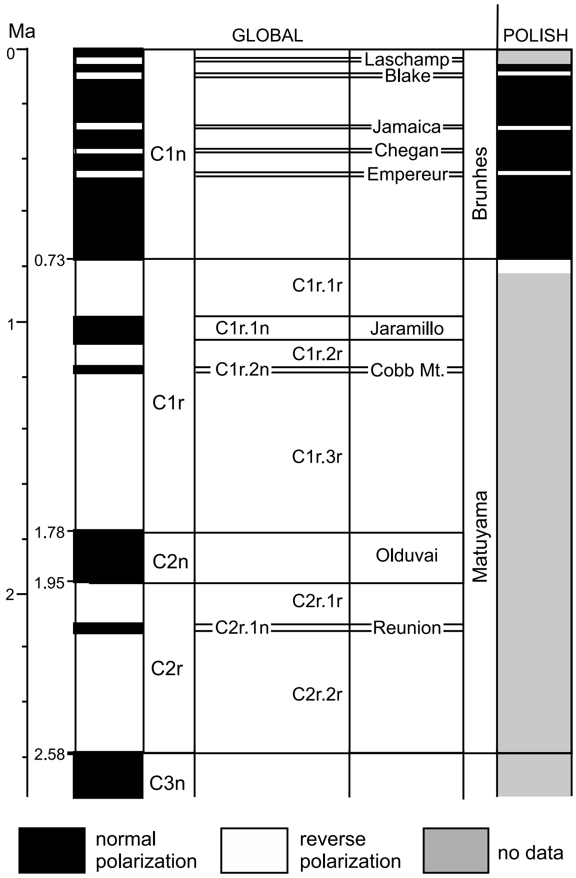
Biostratigraphy

Biostratigraphy is mainly based on ranges of indicator taxa, typical of definite environments and climate. The Quaternary is characteristic for its gradual decreasing temperatures and at the same time, varied range of summer and winter temperatures during successive warm and cold phases. In the Lower Pleistocene, it resulted in the decreasing participation and decline of floristic and faunistic taxa, inherited after the Neogene (cf. Lindner 1992). A typical interglacial pollen succession starts with the protocratic stage and terminates with the telocratic one, both represented by boreal vegetation of a temperate climate, and separated by the mesocratic stage with mixed and deciduous forest (Iversen 1964). In spite of this general similarity of all interglacials, each of them is characterised by specific pollen taxa (Środoń 1960) and a characteristic pollen succession (cf. Lindner *et al.* 2013).

A significant role in biostratigraphy is played by the so-called long pollen sequences that comprise several interglacial pollen succesions (e.g., van der Hammen *et al.* 1971; Reille and de Beaulieu 1995). Their order and characteristics enable correlation of distinguished climatostratigraphic units with $\delta^{18}O$ curves in deep-sea sediments (Tzedakis *et al.* 2004; Martrat *et al.* 2007). In the Polish stratigraphy, the most important long pollen sequences comprise a full interglacial pollen succession and fragments of the preceding and the following glaciations or coolings (e.g., Granoszewski 2003; Bińka and Nitychoruk 2003; Pidek 2015). The older interglacials in Poland (Podlasian and Ferdynandovian) were longer and had 2–3 thermal optima each, separated by distinct coolings. The younger interglacials (Mazovian, Eemian and Holocene) were shorter and had only a single thermal optimum (Lindner *et al.* 2013). Such a change resulted probably from significant transformation of the Earth's climatic system during the so-called Mid-Pleistocene revolution (Maslin and Ridgwell 2005) when the orbital oblique cycle (41 ka), predominant in the Early Pleistocene, was gradually replaced by the eccentric cycle (100 ka). It is reflected in the Polish stratigraphy by change of length in time and the passing from poly- to monocyclic interglacials (Lindner *et al.* 2013).

Magnetostratigraphy and chronostratigraphy

The Quaternary chronostratigraphy in Poland is strictly referred to the global one (cf. Text-fig. 1) and is consistent with the global subdivision, supported by the results of scarce palaeomagnetic investigations (Text-fig. 2). The chronostratigraphy of the Upper Pleistocene and the Holocene is generally based on radiocarbon, OSL and cosmogenic isotope dating, and in speleothems – on U/Th dating.



Text-fig. 2. Global magnetostratigraphy after Heller and Evans (1995): C – Cainozoic and Cretaceous magnetozones (younger than the lower Aptian), n – normal polarization, r – reverse polarization; Polish magnetostratigraphy; after Głazek *et al.* (1977a, b), Nawrocki and Wójcik (1995), Nawrocki and Siennicka-Chmielewska (1996).

Climatostratigraphy

It is an integrated stratigraphy (holostratigraphy) that combines all categories of stratigraphic classification to achieve the highest age resolution and the best stratigraphic correlation in local to global scale (cf. Marks *et al.* 2014a). Cyclothems are treated in climatostratigraphy as isochronic units, formed by the acting of different processes that result in cyclic sedimentation and are connected with cyclic climate changes, reflected by glacial-interglacial and loess-palaeosol cycles (Kukla 1978; Lindner *et al.* 2002). A theoretical background for the establishment of climatic cycles was given by the Earth's orbital parameters, expressed by the Milankovič's cycles that are considered to be the driving force of the climatic cycles.

The lithological and palaeontological variability of deposits is mainly determined by rhythmic climatic changes. The limited range of applied dating methods makes chronology to be a difficult task in the Quaternary climatostratigraphy and to overcome this, a reference to isotope stratigraphy is commonly applied, based on the record of variations in the oxygen isotope ratio $^{18}O/^{16}O$ ($\delta^{18}O$) in deep-sea sediments and ice cores. This has enabled the distinguishing of a sequence of oxygen isotope stages (Emiliani 1955), named marine isotope stages (MIS) if defined in deep-sea cores.

The rhythm of Quaternary climate change has been considerably modified in different areas, therefore climatostratigraphic units are principally of regional or local character. They are recorded by varied glacier extents, translocation of vegetation zones, migration of animals and humans. The boundaries of climatostratigraphic units are synchronous only in limited areas, and their straightforward correlation with chronostratigraphic units is usually not possible. On the other hand, the sedimentation rate of marine deposits is relatively constant and, considering the delay of oceanic reaction to climate change (Parrenin *et al.* 2007), cores of deep-sea sediments make the dating of the boundaries of climatostratigraphic units possible and MISes are commonly used in stratigraphic correlation (cf. Cohen and Gibbard 2019).

Chrono- and climatostratigraphic terminology is commonly mixed with each other, but it results in low accuracy of interregional correlation, the more so that most climatostratigraphic units have no stratotypes. The essence of modern climatostratigraphy is based on the synchronization of local terrestrial and offshore records (usually fragmentary, but with high resolution), with continuous deep-sea sequences (with lower resolution) and ice cores. The application of the theory of Milankovič's cycles to calculate the age of each MIS (cf. Imbrie *et al.* 1984) and the dating of ice cores (cf. Orombelli *et al.* 2010) has enabled the correlation of climato- and chronostratigraphic units, in spite of the diachronicity of climate changes and the delayed reaction of the environment.

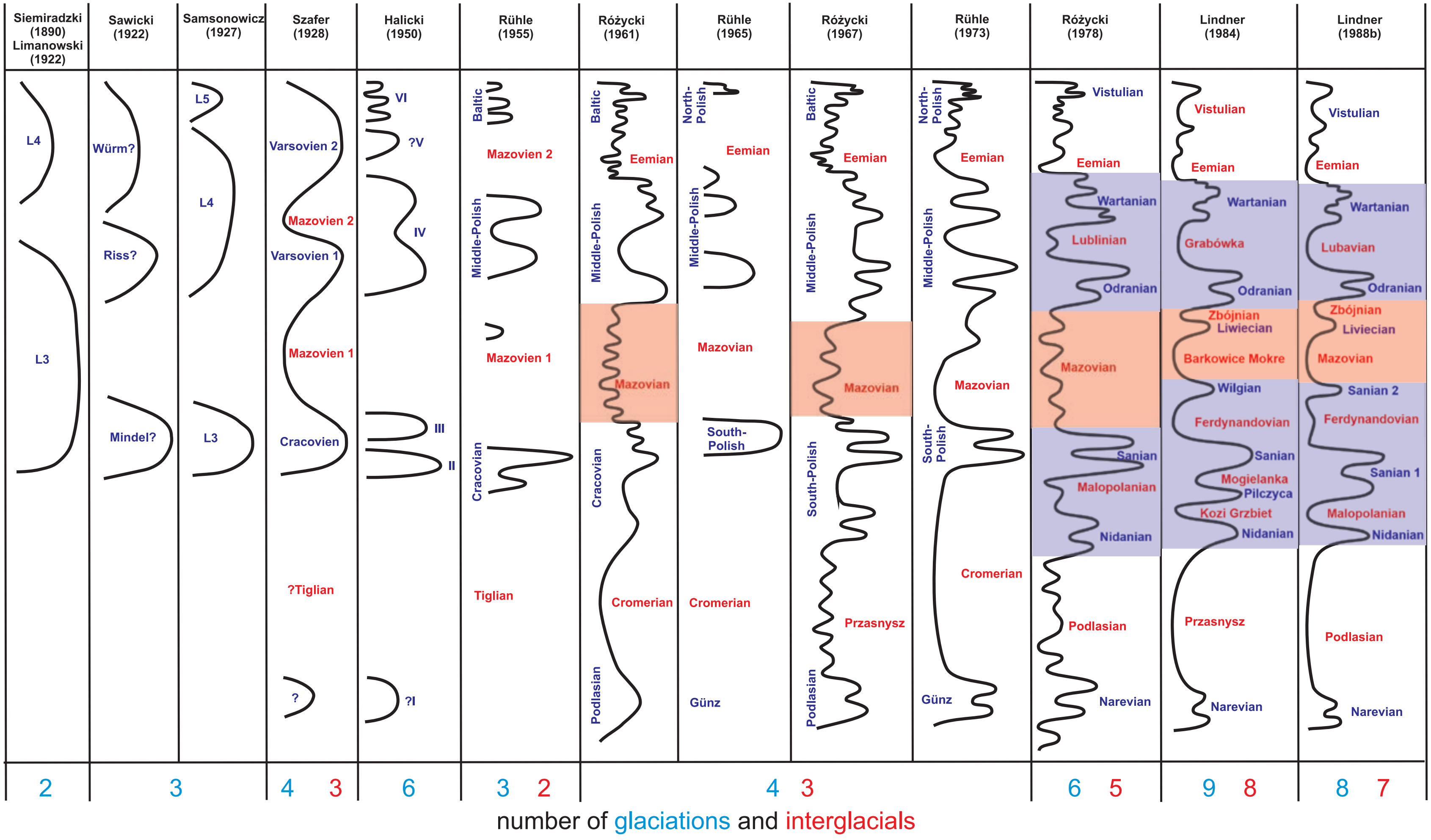
In the traditional subdivision of the Quaternary in Poland, glaciations (coolings) and interglacials (warmings) were considered as climatostratigraphic stages, based on arbitrary recognized type sections (cf. Ber and Marks 2004). Such stages were supposed to represent the first-rank climatic oscillations (e.g., Mojski 1985, 1995, 2005), but based on biostratigraphic and lithostratigraphic evidence, some of them were found to be more complex units. At present, such primary climatostratigraphic units are considered to be of a lower rank. The glacial part of the Pleistocene was composed of glacial-interglacial cycles with subordinary stadial-interstadial cycles (cf. Lindner *et al.* 2002). The main climatic cycles that occur in continuous sequences of the interglacial–glacial–interglacial type, represent climatostratigraphic stages, named complexes (e.g., Cromerian Complex, South-Polish Complex). In the Polish climatostratigraphy, polycyclic interglacials are occasionally also defined as complexes (cf. Lindner *et al.* 2013).

Stratotypes

A stratigraphic unit can be defined, based on its diagnostic features and boundaries. The diagnostic features enable the recognition of the unit when its boundaries are out of sight. The lower and upper boundaries are the most important, because they reflect diagnostic features that are changing in time. The Global Stratotype Section and Point (GSSP) is a geological section (outcrop or drilling) that comprises a standard succession of beds of a defined stratigraphic unit or boundary (cf. Marks *et al.* 2014a). Complex stratotypes are composed of several partial stratotypes, each with a fragment of the defined stratigraphic unit. In the stratotype area of a stratigraphic unit or a boundary, the stratotype is located or this stratigraphic distinction was made for the first time. Auxiliary stratotypes extend the knowledge of a given GSSP between different regions (Head *et al.* 2022), being always subordinate to GSSPs.

CURRENT STRATIGRAPHY OF POLAND

The first studies of the stratigraphy of Poland were initiated by Siemiradzki (1890), who distinguished 2 glaciations in the Polish Lowland. This proposal was supplemented with a third, youngest glaciation by Sawicki (1922) whereas Szafer (1928) named 2 separating interglacials and suggested a possible occurrence of a fourth, oldest glaciation. During the last several dozen years, intensive geological mapping in Poland has supplied an immense amount of new geological data. It has resulted in the development and frequent modifications of the stratigraphic subdivision. Many new stratigraphic units were intro-



Text-fig. 3. Historical subdivisions of the Polish Pleistocene, after Różycki (1980), modified and supplemented; glaciations in blue and interglacials in red, megaglaciations and megainterglacials are highlighted in colour.

duced, up to 9 glaciations and 8 interglacials, partly clustered into so-called megaglaciations and megainterglacials, each of them composed of several minor glaciations and interglacials (Text-fig. 3). To stop this trend and to introduce a more reliable subdivision, 4 complexes (Preglacial, South-Polish, Middle-Polish and North-Polish) were proposed, each of them composed of a set of several warm and cold stratigraphic units (Ber *et al.* 2007a, b).

All Quaternary stratigraphic units in Poland are informal (cf. Murphy and Salvador 1999). At the very beginning they were correlated with stratigraphic units in the Alps, then with subdivisions used in Western Europe (e.g., Lindner 1988b; Mojski 1993) and isotope stratigraphy. Polish traditional stratigraphic subdivisions commonly contained the unit named Preglacial, Prepleistocene or Protopleistocene, representing the climatostratigraphic units that preceded this part of the Pleistocene, in which glaciations occurred in Poland (cf. Różycki 1967, 1969, 1980). Elsewhere in northern continental Europe, located inside the extent of the Scandinavian glaciations, but non-glaciated in the Lower Pleistocene, this interval was informally named the preglacial Pleistocene (e.g., Litt *et al.* 2007). Lately, the term ‘Preglacial Complex was proposed in Poland (Ber *et al.* 2007a, b). Based on the erratic material found in deep-sea cores from the North Atlantic, the Scandinavian glaciations were already initiated in the Miocene (Thierens *et al.* 2012), therefore a use of the terms ‘Preglacial’ and ‘Preglacial Pleistocene’ does not seem reasonable.

LOWER PLEISTOCENE

The Lower Pleistocene in Poland is represented mostly by fluvial and lake sediments. The Scandinavian material appears in the upper part of the sequence, indicating the first advance of the Scandinavian ice sheet in continental Europe.

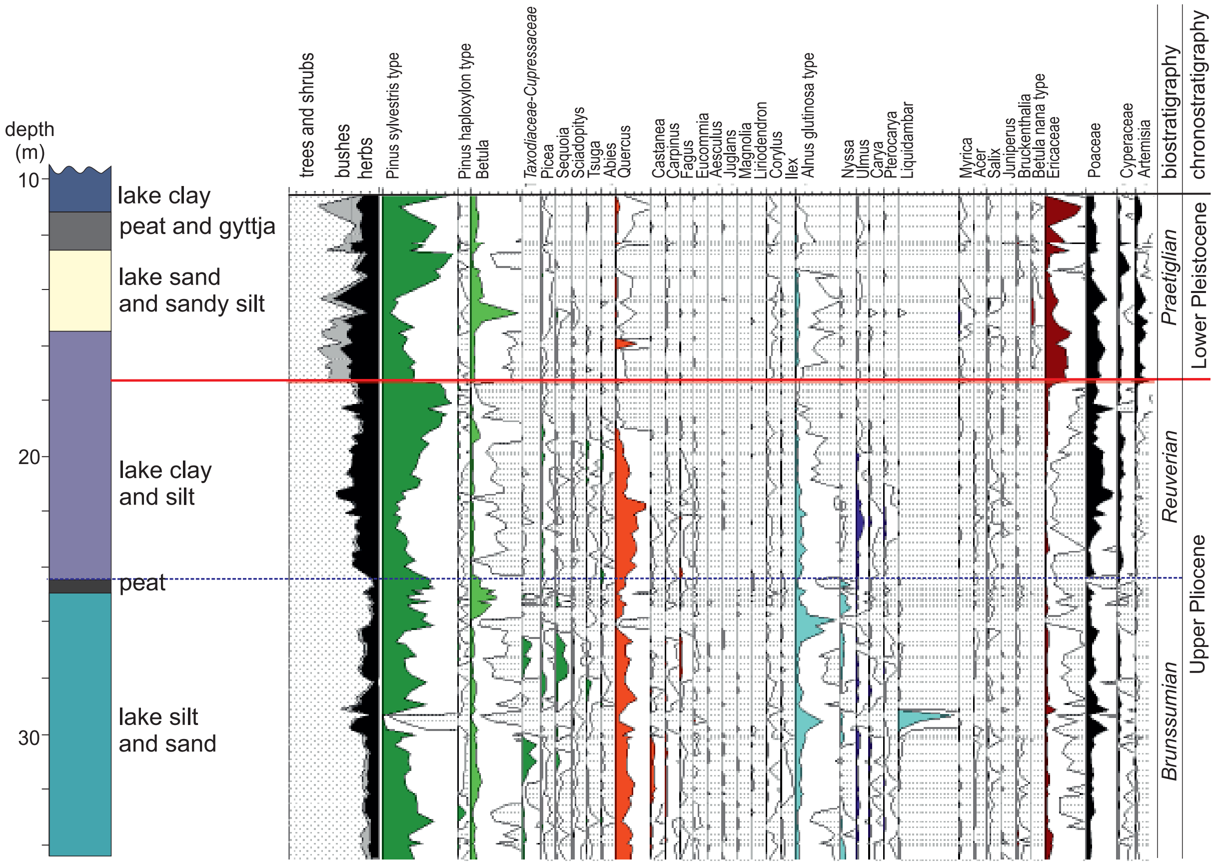
Preglacial issue

The stratigraphy of this part of the Pleistocene was established at the sites Ponurzyca (Baraniecka 1975; Stuchlik 1975) and Rożce vel Różce (Baraniecka 1991; Stuchlik 1994) in central Poland (cf. Table 1). The preglacial sequence at Ponurzyca is composed of an alluvial sedimentary series, interbedded with lake sand and silt. It is overlain by glaciofluvial deposits and a till (Baraniecka 1975). Based on pollen analysis at Ponurzyca and Rożce, 2 warmings (Ponurzyca and Celestynów) and 2 coolings (Rożce and Otwock) were distinguished, correlated respectively with Praetiglian, Tiglian, Eburonian and Waalian in the Lower Pleistocene of Western Europe (Baraniecka 1975, 1991; Stuchlik 1975). In the preglacial pollen succession, a gradual decrease in Neogene-type taxa is noted and the pollen spectrum of the youngest warming (Celestynów) is similar to the ones in the Pleistocene interglacials (Stuchlik 1975). In spite of a lack of satisfactory dating, Baraniecka (1991) considered that these warm and cold intervals are the climatostratigraphic stages of the Preglacial Superstage, correlated them with the Krasnystaw Series of Mojski (1985). Referred to the informal, although commonly accepted location of the Quaternary/Pliocene boundary (cf. Zagwijn 1979), all these stages were found to represent the Lower Pleistocene.

Preglacial deposits were recognized also at Wólka Ligęzowska, Wysokin, Sacin and Ceteń in the Lower Pilica region (Makowska 2015). They are represented by fluvial sand, silt and clay with organic matter and inserts of peat and gyttja. The pollen succession at Wólka Ligęzowska indicates a drastic climate change, resulting in deforestation, documented by a rising content of the pollen of herbaceous plants and Ericaceae (Text-fig. 4). A cooling trend in the Pliocene was expressed by the gradual decline of thermophilous taxa and the development of boreal communities with pine and birch (Winter 2015). It was accompanied by lower winter temperatures and annual precipi-

Chronostratigraphy	Western Europe	Poland			
	Climatostratigraphy (Zagwijn 1989)	Vegetation-climatic periods (Stuchlik 1995)	Climatostratigraphy (Baraniecka 1991)	Climatostratigraphy (Winter 2015)	Drilling sections (Winter 2015)
Lower Pleistocene	Waalian	V	Celestynów	Ceteń	Ceteń
	Eburonian	IV	Otwock	Otwock	
	Tiglian	III	Ponurzyca	Ponurzyca	Wysokin
	Praetiglian	II	Różce	Wólka Ligęzowska	Wólka Ligęzowska
Pliocene	Reuverian	I	Reuverian	Reuverian	
	Brunssumian			Brunssumian	

Table 1. Climatostratigraphic warm (red) and cold (blue) stages of the Lower Pleistocene in Poland, based on palynostratigraphy; after Winter (2015), modified.



Text-fig. 4. Lithology and pollen spectrum of the Wólka Ligęzowska 4 section; after Makowska (2015), Winter (2015), and Granoszewski and Winter (2016), simplified and modified.

tation, characteristic of a more continental climate. The Pleistocene started with a cool interval at Wólka Ligęzowska, correlated with the Praetiglian and indicated by forest-steppe-tundra and steppe-tundra developed in a boreal and subarctic climate (Popescu *et al.* 2010; Winter 2015; Granoszewski and Winter 2016). Warmer oscillations were expressed by loose birch-pine or pine forest. Such changes were in agreement with long-lasting global climatic trends and enabled correlation with other sites in Europe. In spite of the lack of reliable dating, it was argued that this should determine the Pliocene/Pleistocene boundary (cf. Popescu *et al.* 2010).

The palynostratigraphic record of the younger climatostratigraphic stages in the preglacial part of the Pleistocene is fragmentary at many sites in the Lower Pilica Valley region, but it indicates alternate warm and cold stages (Winter 2015). Based on the thermal demands of plant assemblages in warm stages, the mean summer temperature was >19.5°C and the winter one slightly <0°C (Pross and Klotz 2002), which suggests a weak climate seasonality. In cold stages the mean summer temperature reached 10°C and the winter one dropped to -20°C (cf. Granoszewski and Winter 2016).

The palynologic record of the youngest stage (Ceteń warming) is uninterrupted, with a climatic optimum with numerous trees of high thermic demands (*Castanea*, *Eucommia* and *Ostrya*), much *Quercus*, *Betula* and herbs (Winter 2015). The following rapid rise of Poaceae and a decline of *Eucommia*, *Ostrya*, *Carpinus* and *Corylus* indicate a cooling and continental climate. A renewed occurrence of *Quercus*, *Ostrya*, *Carpinus* and the newcomer *Castanea* proves that a warm climate recurred.

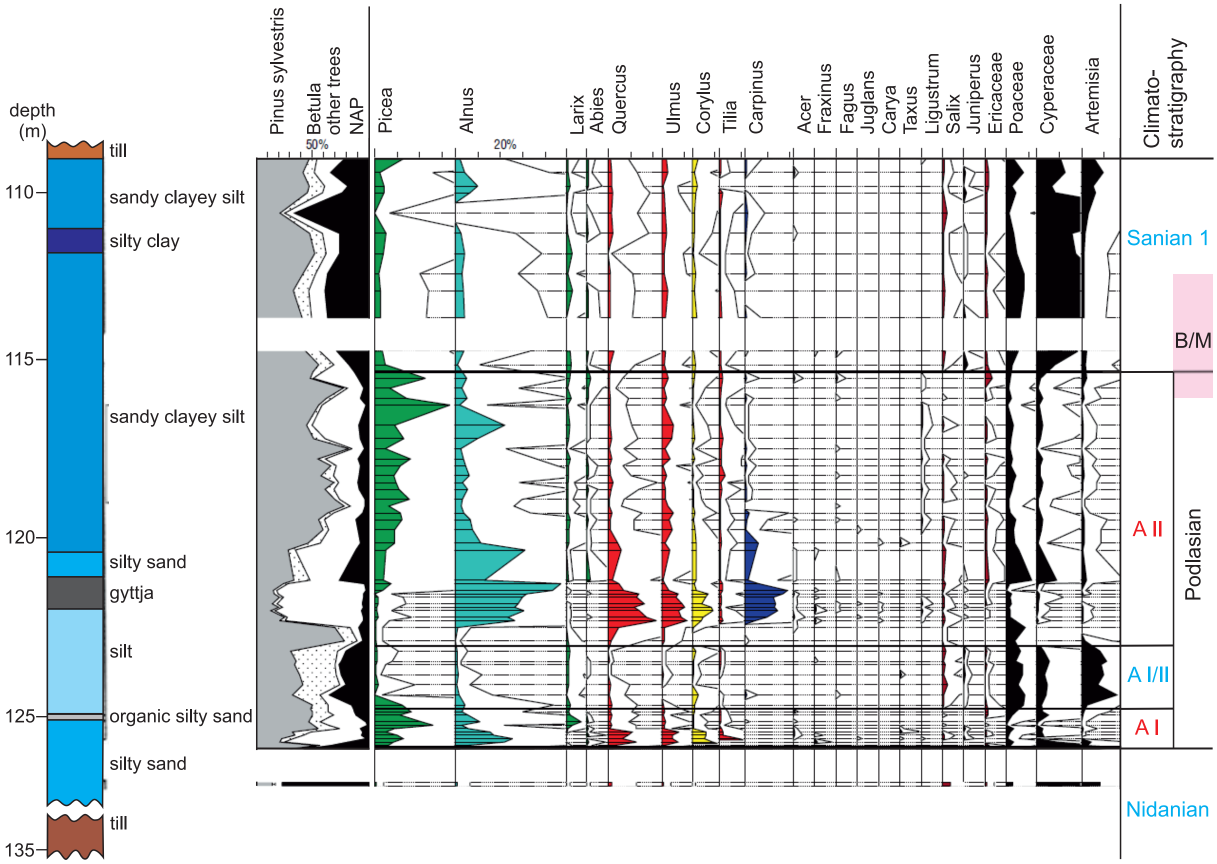
A new drilling at Rożce enabled verification of the stratigraphy in the south-eastern part of the Mazovian Lowland (Bujak *et al.* 2016). The pollen analysis proved that the ‘preglacial’ deposits at this site are of Lower Pliocene age, suggested by palaeomagnetic investigations to be 4.62–5.23 Ma, i.e. in a middle part of the Gilbert magnetochrone. Above, there was glaciofluvial sand and gravel, and till, presumably of the Nidanian Glaciation (cf. Bujak *et al.* 2016). This new section proved the existence of a stratigraphic hiatus of ~3.5 myrs, with therefore a lack of the preglacial series described by Baraniecka (1991).

Glacial issue

The youngest part of the Lower Pleistocene which is the beginning of the South-Polish Complex and the Lower/Middle Pleistocene boundary has been described in Poland mainly at 5 sites: Kozi Grzbiet, Szczebra, Kalejty, Kończyce and Czarnucha.

At Kozi Grzbiet in the Holy Cross Mts, cave breccias and clays were examined, overlain by glaciofluvial sand. The clay contained numerous feldspars, amphiboles and pyroxenes of Scandinavian derivation (Głazek *et al.* 1976, 1977a, b), whereas mollusc shells (Stworzewicz 1981) and bones of amphibians (Młynarski 1977), reptiles (Szyndlar 1981) and mammals (Nadachowski 1985) indicated the occurrence of a wet deciduous forest (Głazek *et al.* 1977a, b), although some mammal bones suggested also a cool climate. The collagen content of the bones confirmed that they represented the late Biharian fauna with 2 warm periods separated by a cold phase (Nadachowski 1985; cf. Palombo 2014). The age of the cave deposits was determined by FCl/P and collagen methods at 700–550 ka (Wysoczański-Minkowicz 1969) and in the lower part of the sequence, the Brunhes/Matuyama boundary was detected (Głazek *et al.* 1977a). Therefore, the cave deposits were correlated with the older part of the Cromerian Complex (cf. Cohen and Gibbard 2019) and based on this, the Malopolanian Interglacial was distinguished in the Polish stratigraphy (Lindner 1978; Różycki 1978), named also the Kozi Grzbiet Interglacial (Lindner 1988a) and at present considered as an older part of the Podlasian Interglacial (cf. Lindner *et al.* 2013).

At the site Szczebra in north-eastern Poland, lake gyttja, silt and peat, were underlain by a till (Ber 1996, 2000; Ber *et al.* 1998). A pollen spectrum in this lake and marsh sequence represented 2 interglacial-like warmings, separated by a significant cooling. The older warming was less warm, as expressed



Text-fig. 5. Lithology and pollen spectrum of the Augustovian succession from Kalejty; after Krzywicki (2002), Ber (2006), and Winter (2006), modified; B/M – Brunhes/Matuyama boundary.

by boreal vegetation typical of a temperate climate (Janczyk-Kopikowa 1996). The following cooling was represented by boreal and subarctic taxa and the younger warming was more complete and typical of a deciduous forest. The pollen succession at Szczebra was named the Augustovian succession (Janczyk-Kopikowa 1996) of the Augustovian Interglacial (Ber 1996). Similar pollen successions were found also at several other sites in north eastern Poland, among others at Kalejty (Text-fig. 5; Lisicki and Winter 2004; Winter 2001, 2006, 2008) and Czarnucha (Ber 2009; Nawrocki 2009), in which the Brunhes/Matuyama boundary was determined in the final part or after the second warming (Ber 2000, 2005, 2006).

At the site Kończyce in southern Poland, fluvial sand and gravel without Scandinavian material are overlain by glaciofluvial sand and gravel with a till bed inside (Wójcik *et al.* 2004). These sediments are overlain by organic silt, in which a fragment of an interglacial succession was detected with a high content of pollen of *Quercus*, *Alnus*, *Tilia* and *Corylus* and a lower participation of *Ulmus*, *Carpinus* and *Abies* deciduous trees (Marks in press). These deposits are located below the Brunhes/Matuyama boundary, and therefore can represent the Augustovian succession and any dissimilarities in vegetation communities may result from the regional and altitudinal locations (cf. Lindner *et al.* 2013).

The presence of the Brunhes/Matuyama boundary at Kalejty and Kończyce suggests that their pollen successions represent the older part of the Podlasian Interglacial (cf. Lindner *et al.* 2013), which corresponds with the Cromerian I in Western Europe (Gibbard *et al.* 2005) and MIS 21-19 in deep-sea sediments. A till under the Augustovian succession represents the oldest glaciation in Poland, presumably the same which was confirmed, based on presence of Scandinavian material below the Brunhes/Matuyama boundary at Kozi Grzbiet (Głazek *et al.* 1976, 1977a). This glaciation is named at present the Nidanian Glaciation and corresponds with the Narevian Glaciation in Belarus and the Dorst Substage of the Bavel Stage in Western Europe (cf. Lindner *et al.* 2013).

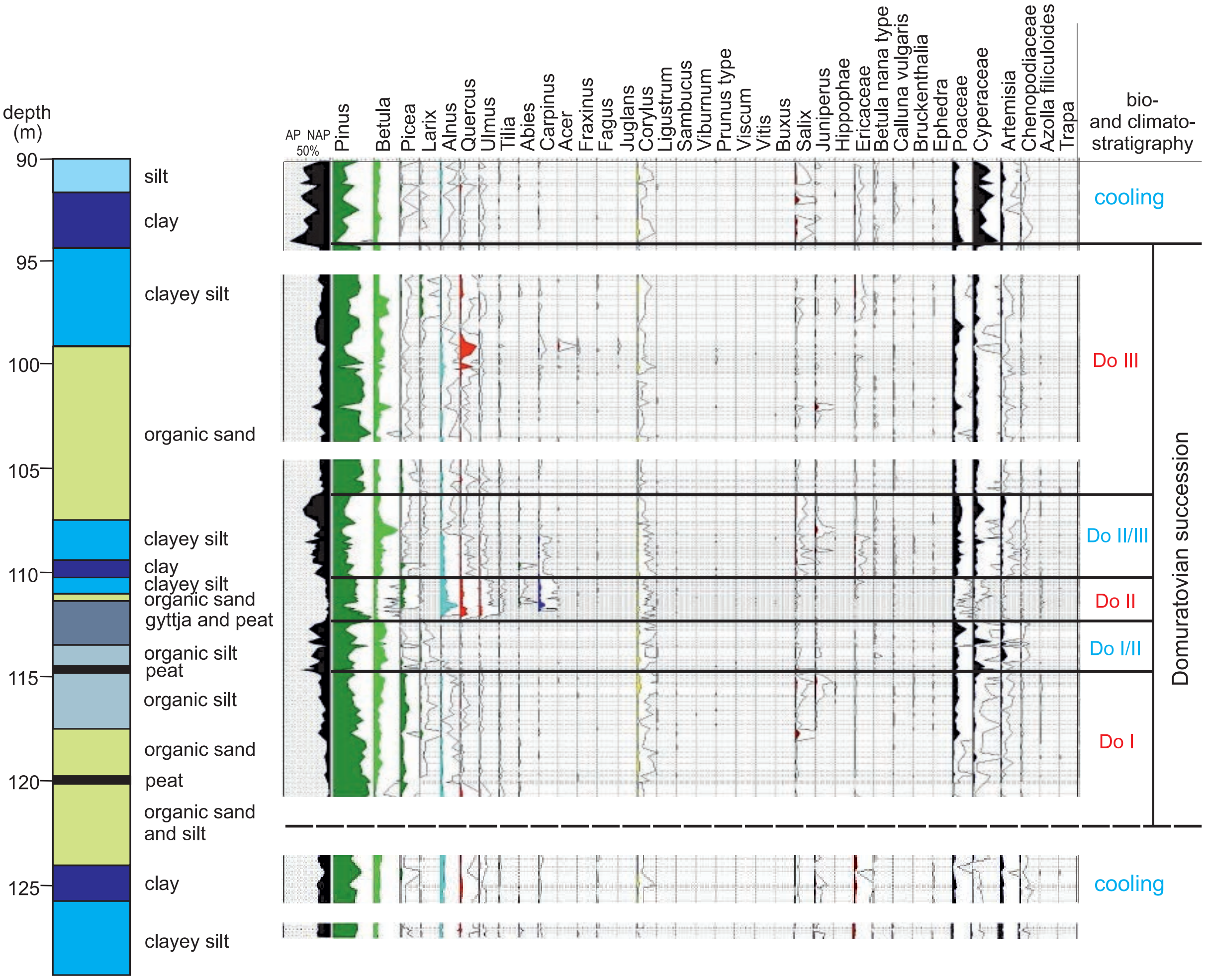
MIDDLE PLEISTOCENE

A beginning of the Middle Pleistocene was documented at the sites Domuraty, Leszczany and Gawrych Ruda in northeastern Poland and is represented by the younger part of the Podlasian Interglacial (cf. Lindner *et al.* 2013). At Domuraty, there are fluvial-lake sediments with plant fossils, diatoms and mollusc shells (Lisicki and Winter 2004; Winter and Lisicki 2005; Winter *et al.* 2008), underlain by a till of the Nidanian Glaciation. In these sediments the Domuratovian succession was examined (Text-fig. 6), composed of 3 warmings (Do I–III) and separated by 2 coolings (Winter *et al.* 2008; Winter 2011, 2017). This tripartite succession reflects mostly the dynamics and large-scale climatic transformation at the beginning of the Middle Pleistocene, probably with regional and local environmental influence. The succession has many hiatuses at Domuraty (cf. Winter and Lisicki 2005) whereas at other sites preservation is fragmentary (Winter 2017), presumably due to their setting within a fluvial series, in which organic deposition is usually episodical. Warm intervals are represented by a mixed forest, typical for a temperate continental climate (Granoszewski and Winter 2016) and was correlated with 3 warm substages MIS 17.5, 17.3 and 17.1 (Winter 2015).

In spite of its having a similar geologic setting, the Domuratovian succession is distinctly different from the Augustovian one while its unique character is indicated, among others by occurrence of hornbeam and fir in Do III (cf. Lindner *et al.* 2013), and by its occurrence within the Brunhes magnetozone (Winter, 2017). Both these successions seem to represent different parts of the same interglacial complex that corresponds to MIS 21–17 and it is named the Podlasian Interglacial (Lindner *et al.* 2013).

An advance of the first Scandinavian ice sheet in the Sub-Carpathian region is indicated by the appearance of the so-called mixed gravels which are fluvial deposits with admixture of Scandinavian material (Lindner and Marks 2013, 2015). The geological setting and pollen succession of the interglacial series at Jasionka, Łowisko and Bukowina in the Sandomierz Basin prove that this area was occupied by the Sanian 1 Glaciation only (Text-fig. 7; Marks 2022, 2023).

The site Ferdynandów in the Southern Podlasie Lowland plays an important role in the Middle Pleistocene stratigraphy of Central Europe (cf. Text-fig. 8). The interglacial pollen succession was preliminarily examined at this site by Janczyk-Kopikowa (1963) but, in spite of crucial differences (2 climatic optima and more thermophilous trees), it was considered as a representative of the Mazovian Interglacial (Janczyk-Kopikowa 1975) which, according to the stratigraphic subdivisions used at that time, contained several successive warmings of the so-called Great Interglacial (Różycki 1964). The name Ferdynandovian Interglacial was introduced by Janczyk-Kopikowa *et al.* (1991) and its stratigraphic

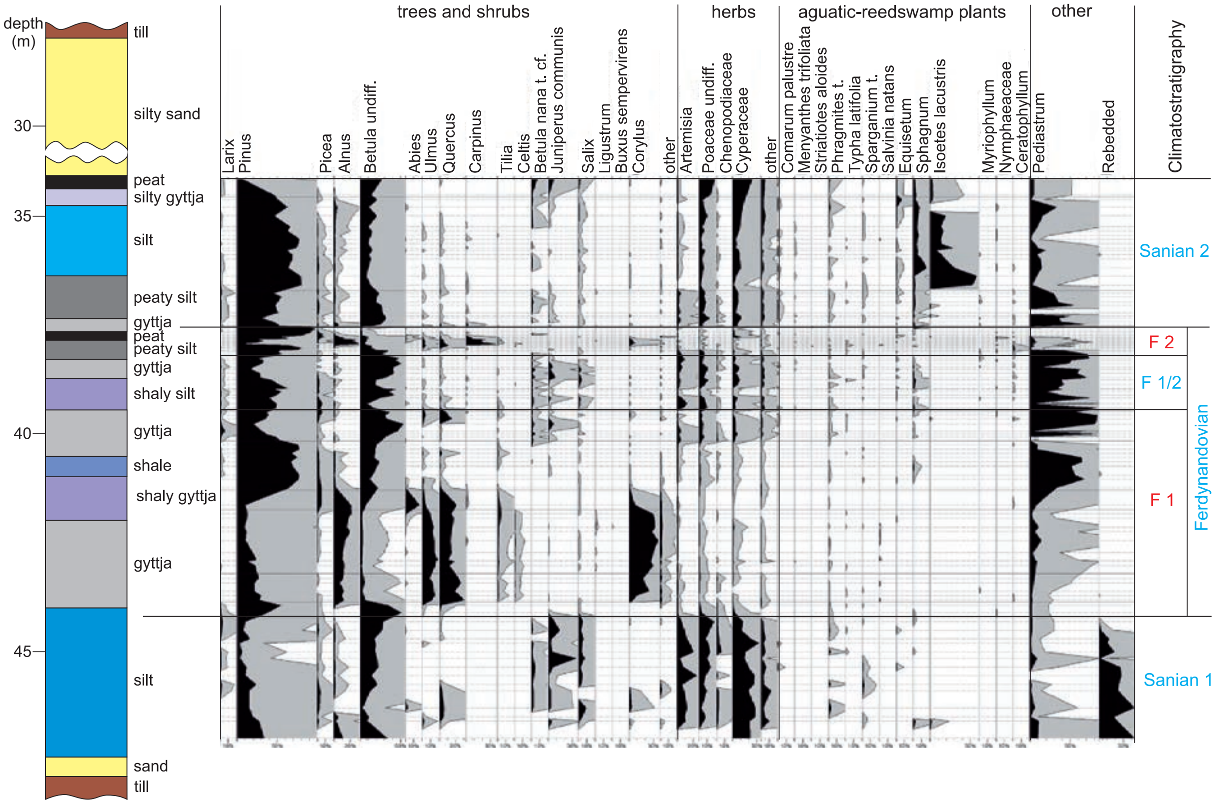


Text-fig. 6. Lithology and pollen spectrum of the Domuratovian succession from Domuraty 2; after Winter (2011, 2017), modified.

setting was determined by Rzechowski (1996a, b). The presence of a till above the interglacial deposits was used to create the Wilga Glaciation (Mojski 1985), at first correlated with the Sanian Glaciation in southern Poland (Lindner 1978; Różycki 1978) and then, after bipartition of the latter – with the Sanian 2 Glaciation (Lindner *et al.* 2013). The Ferdynandovian succession or a part of it was identified in many interglacial sites in Central and Eastern Poland, but also in Belarus, Russia (Rylova and Savchenko 2005; Molodkov and Bolikhovskaya 2010), Denmark (Andersen 1965), Germany and the Netherlands (Zagwijn 1996).

The pollen spectrum at Ferdynandów started in the late glacial of the Sanian 1 Glaciation (Text-fig. 8), with steppe-like and shrub tundra communities (Pidek 2015). Mixed and then deciduous forest was characteristic of the older interglacial warming F 1 (Lindner

Text-fig. 7. Extent of Scandinavian glaciations in Poland: N – Nidanian, O – Odranian, S1 – Sanian 1, S2 – Sanian 2, W – Vistulian.



Text-fig. 8. Lithology and pollen spectrum of the Ferdynandovian succession from the site Ferdynandów 2011, after Pidek *et al.* (2015), modified.

et al. 2013), with cold winters and maritime influence (Winter 2017). During the optimum, mean temperatures were -3°C in winter and 18°C in summer (Pidek and Poska 2013). A cool climatic oscillation in F 1 was indicated by a decline of oak and hazel, and a rise of birch and pine (among others Janczyk-Kopikowa 1975; Pidek and Małek 2010; Pidek 2015; Granoszewski and Winter 2016). In the cold phase F 1/2, there were numerous climatic oscillations, with open communities and birch-pine forest in a continental, cool temperate climate (Pidek 2015; Winter 2017). The younger warming F 2 was represented by deciduous forest with abundant hornbeam (Pidek 2015), indicating a stable climate, but colder and more continental than in F 1, and with colder winters (Winter 2017). The early glacial of the Sanian 2 Glaciation was indicated by a pine-birch forest and open communities (Pidek 2015). The Ferdynandovian Interglacial has been commonly correlated with MIS 15–13, although if this is the case it is striking why the F 2 warming is represented by a considerably thinner series than the F 1 warming. At Ferdynandów, this fact was explained by the presence of more compressed sediments, composed of shaly gyttja, silt and peat (cf. Pidek *et al.* 2015). However, a comparison of the thermal demands of the different communities distinguished in the Ferdynandovian succession at Łuków (Pidek and Poska 2013) with the sea surface temperature in the Atlantic at that time suggests that F 1 corresponds to MIS 15 whereas F 2 represents a short warming at the beginning of MIS 14 (Bińka and Marks 2018).

In the western part of the Southern Podlasie Lowland, deposits of the Ferdynandovian Interglacial are usually overlain by a till of the Sanian 2 Glaciation, whereas sediments of the Mazovian Interglacial have no till cover in the same area. A lack of the Sanian 2 till cover in some of the Ferdynandovian sites (Żarski *et al.* 2009) suggests that the Scandinavian ice sheet was much less extensive than postulated previously (e.g., Lindner 2005). A deglaciation after the Sanian 2 Glaciation is recorded by a thick glaciolacustrine series in Podlasie, Mazovia, Warmia and western Mazury Lakeland (Marks 1994, 1995a, b; Marks and Pavlovskaya 2003). In northern Warmia, the stratigraphic setting of these deposits is determined by the overlying fluvial series, correlated with deposits of the Holstein sea in the Kaliningrad District of Russia (Kondratiene and Gudelis 1983; cf. Marks 1994, 1995a, b). These glaciolacustrine deposits in Poland correspond with similar ones in the Netherlands and the Lower Elbe valley in Germany, where they are undoubtedly overlain by marine deposits of the Holstein sea (cf. Marks 1995a, b).

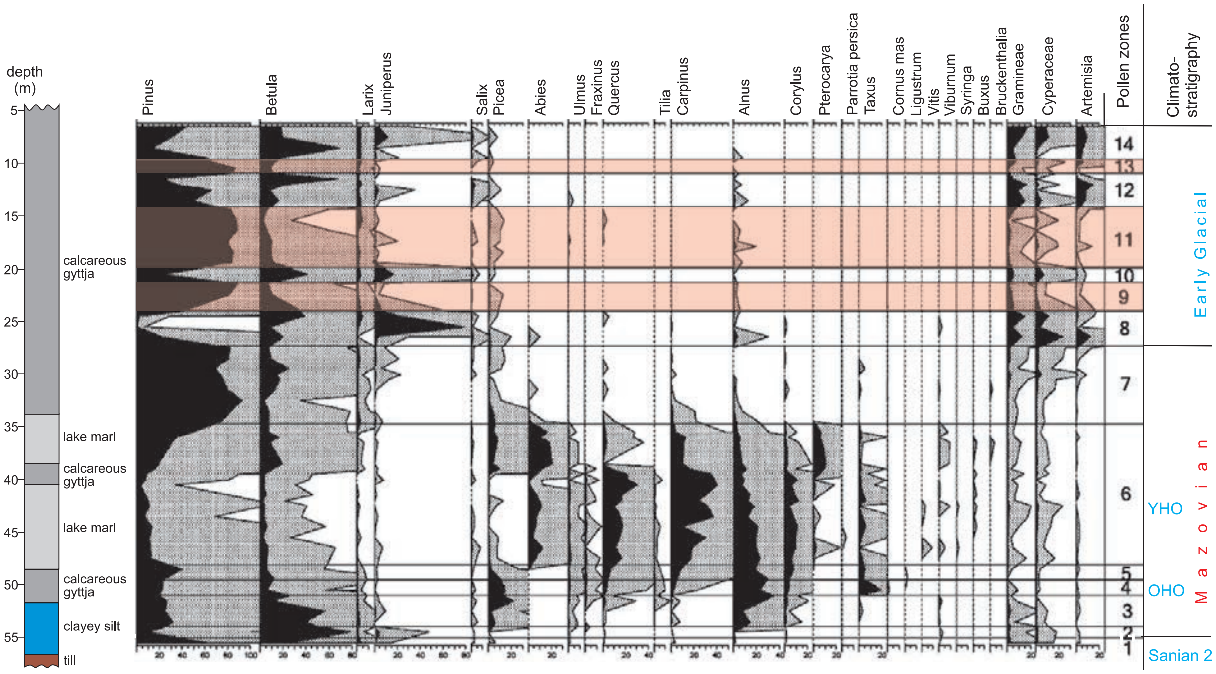
The stratigraphy of the late Middle Pleistocene (MIS 11–6) in Europe is far from being clarified, but it is roughly correlated with stratigraphic units from the Holsteinian Interglacial to the Saalian Glaciation. The stratigraphic subdivisions of the northern, glaciated part of Europe contain hiatuses or units with incredible settings and this makes interregional correlation difficult. In Poland, this part of the Middle Pleistocene is named the Middle-Polish Complex which is subdivided into 3 interglacials and 3 glaciations, some of which seem mostly incredible. In south-eastern Poland, there are well recognized loessy-palaeosoil complexes and fluvial sediments of this stratigraphic interval. The geological settings of the Mazovian Interglacial and the Odranian Glaciation are well defined and are supported by a reliable correlation with marine isotope stages (cf. Nitychoruk *et al.* 2005, 2006; Bińka and Marks 2018; Marks *et al.* 2019b). However, the principal problem for a considerable part of the Middle-Polish Complex was the arbitrary correlation of poorly defined stratigraphic units with the definite marine isotope stages (cf. Ber *et al*. 2007a, b).

The Mazovian Interglacial (Holsteinian) is commonly correlated with MIS 11 which was the warmest one (Hughes *et al.* 2020) and lasted ~31 kyrs (Desprat *et al.* 2007). The name and first sites of this interglacial in Poland were proposed by Szafer (1928) and the Mazovian succession was established at the site Barkowice Mokre (Sobolewska 1952). Since that time, many sites with the Mazovian succession have been examined in Poland, but only some of them were analysed in detail, making palaeoclimatic and regional interpretation possible. Such sites are exceptionally numerous in Podlasie (Krupiński 1984–1985, 1988a, b, 1993, 1995a–c, 1996a, b, 1997, 2000; Krupiński and Lindner 1991; Krupiński and Nitychoruk 1991; Krupiński *et al.* 1986, 1988; Bińka and Nitychoruk 1995, 1996; Bińka *et al.* 1996, 1997; Marks and Karabanov 2017; Marks *et al.* 2018). Abundant yew is the most characteristic component of forest communities in the younger part of the climatic optimum (Granoszewski and Winter 2016) whereas the occurrence of exotic taxa and other thermophilous plants further to the east indicates a considerably warmer and wetter climate than the modern one (Text-fig. 9). The Mazovian succession indicates an unstable climate, with 2 distinct but short coolings, named the Older and Younger Holsteinian Oscillations (Bińka and Nitychoruk 1995, 1996; Krupiński 1995c; Nita 1999; Winter and Urbański 2007; Koutsodendris *et al.* 2012, 2014; Nitychoruk *et al.* 2018; Marks *et al.* 2019b).

The interglacial succession is followed by a post-interglacial one at some sites in Poland (cf. Dyakowska 1952; Środoń 1960; Bińka *et al.* 1987; Winter 1991; Krupiński 1995a, 2000; Bińka and Nitychoruk 1996; Janczyk-Kopikowa 1996; Mamakowa 1998; Nita 1999; Pidek 2003). In a climatostratigraphic sense, the longest post-interglacial succession was recorded at Ossówka, composed of 4 stadials with steppe vegetation and 3 interstadials with pine forest, typical of a continental climate (cf. Krupiński 1995a). A similar pollen succession with 3 interstadials was identified at Łuków (Pidek and Poska 2013) and at other sites in Central and Western Europe (e.g., Reille *et al.* 2000; Urban *et al.* 2011). A comparison of the thermal demands of vegetation communities in the Mazovian succession at Ossówka with sea-surface temperatures in the Atlantic at the same time suggests that 2 older stadials and 2 older interstadials occurred still within MIS 11 (Bińka and Marks 2018).

The interglacial pollen successions ascribed to MIS 9 and MIS 7 were distinguished only at the sites Zbójno and Losy (cf. Lindner *et al.* 2013). Their stratigraphic setting is contested, the same as those of the Liwiecian (MIS 10) and Krznanian (MIS 8) glaciations (cf. Bińka 2010; Marks 2004b, 2011; Marks *et al.* 2016a). Oxygen isotope curves from deep-sea sediments suggest that MIS 9 was a very warm interglacial whereas MIS 10 was almost as cold as MIS 6 (Rodrigues *et al.* 2011; Hughes *et al.* 2020). The most enigmatic was MIS 7: cooler than a typical interglacial, but with several warm and cold lower-rank units (cf. Railsback *et al.* 2015).

A maximum extent of the Odranian Glaciation in Eastern Poland was demarcated along the northern slope of the Małopolska and Lublin Uplands, rising to >300 m a.s.l., and a distinct glacial lobe was distinguished in the northern Sandomierz Basin (Text-fig. 7; cf. Muchowski 1992). Most sites of the Mazovian Interglacial in southern Podlasie and the southern part of the neighbouring Brest Polesie in Belarus are not covered by a till of the Odranian Glaciation (cf. Velichkevich *et al.* 1993; Albrycht *et al.* 1995; Marks and Karabanov 2017; Marks *et al.* 2018; Pochocka-Szwarc *et al.* 2021). Therefore, the ice sheet extent of the Odranian Glaciation in this part of Poland is located further north and corresponds with the younger Warta Stadial (cf. Marks 2004c; Marks and Pavlovskaya 2006; Marks *et al.* 2018).



Text-fig. 9. Lithology and pollen spectrum of the Mazovian succession from the site Ossówka; after Nitychoruk *et al.* (2005), modified and supplemented; indicated are: Older Holsteinian Oscillation (OHO), Younger Holsteinian Oscillation (YHO) and interstadials in the post-interglacial period (pollen zones 9, 11 and 13).

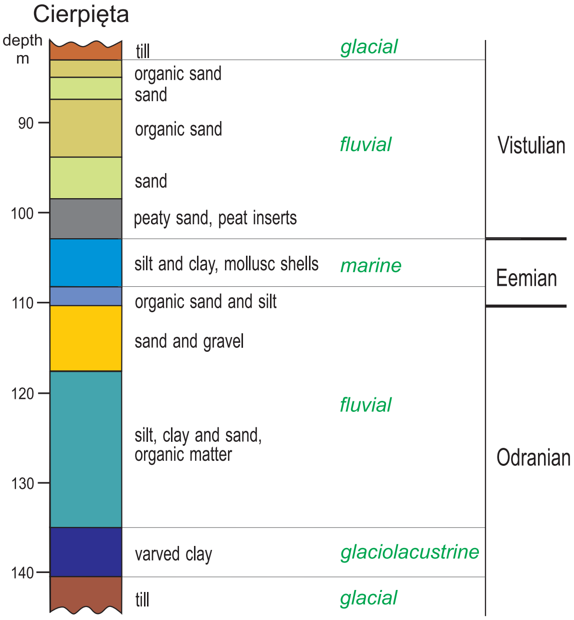
In the extraglacial part of Poland, a gradual cooling during MIS 6 favoured agradation of permafrost and intensive aeolian accumulation, recorded in fluvial sediments (cf. Zieliński 2007; Woronko 2012; Woronko and Bujak 2018) and by accumulation of the so-called upper older loess (Maruszczak 1985, 1991; Lindner and Marks 2008). At the sites Załubińcze in the Carpathians and Odonów in the Holy Cross Mts, the palaeomagnetic event Jamaica-Biwa I dated at 180–200 ka (cf. Laj and Channel 2007) was detected in these loesses (Nawrocki and Wójcik 1995; Nawrocki and Siennicka-Chmielewska 1996). In the anaglacial part of the Odranian Glaciation, the climate was very dry, presumably due to a limited atmospheric circulation in a narrow periglacial corridor between the Scandinavian ice sheet and the Carpathians and the Sudetes, but it became wetter during deglaciation (Marks *et al.* 2018, 2019b).

At many sites, the late glacial pollen succession passes without any break into the one of the Eemian Interglacial (cf. Marks *et al.* 2016a). The pollen successions at the sites Imbramowice (Mamakowa 1989), Szwajcaria (Borówko-Dłużakowa and Halicki 1957) and Warszawa-Wawrzyszew (Krupiński and Morawski 1993) indicate that the Odranian Glaciation terminated with 2 stadials of open vegetation, these separated by an interstadial, at first with shrubs and then a boreal forest (Bińka and Nitychoruk 2003; cf. Marks *et al.* 2016a).

UPPER PLEISTOCENE

This is represented by the North-Polish Complex in Poland and starts with the Eemian Interglacial (MIS 5e), the palynostratigraphy and palaeoecology of which are very well recognized (Granoszewski and Winter 2016; Marks *et al.* 2016a) at almost 300 sites (Bruj and Roman 2007; Żarski *et al.* 2015). The Eemian succession is composed of 7 regional pollen zones (RPAZ), represented by 4 local pollen zones (LPAZ) E1–E4 at the site Imbramowice (Mamakowa 1989) and by E5–E7 at the site Zgierz-Rudunki (Jastrzębska-Mamełka 1985).

The Eemian Interglacial in Poland is unique for its marine sediments noted for the first time by Berendt (1865, 1866) and Jentzsch (1895), then confirmed in many drillings and outcrops in the Lower Vistula region and the Elbląg Upland (e.g., Makowska 1979, 1986, 2009). These sediments are composed of offshore brackish and marine facies with plant and fauna fossils (Pożaryski 1951; Brodniewicz 1960,



Text-fig.10. Lithology and stratigraphy of the section Cierpięta in the Lower Vistula region; after Marks *et al.* (2014b), modified.

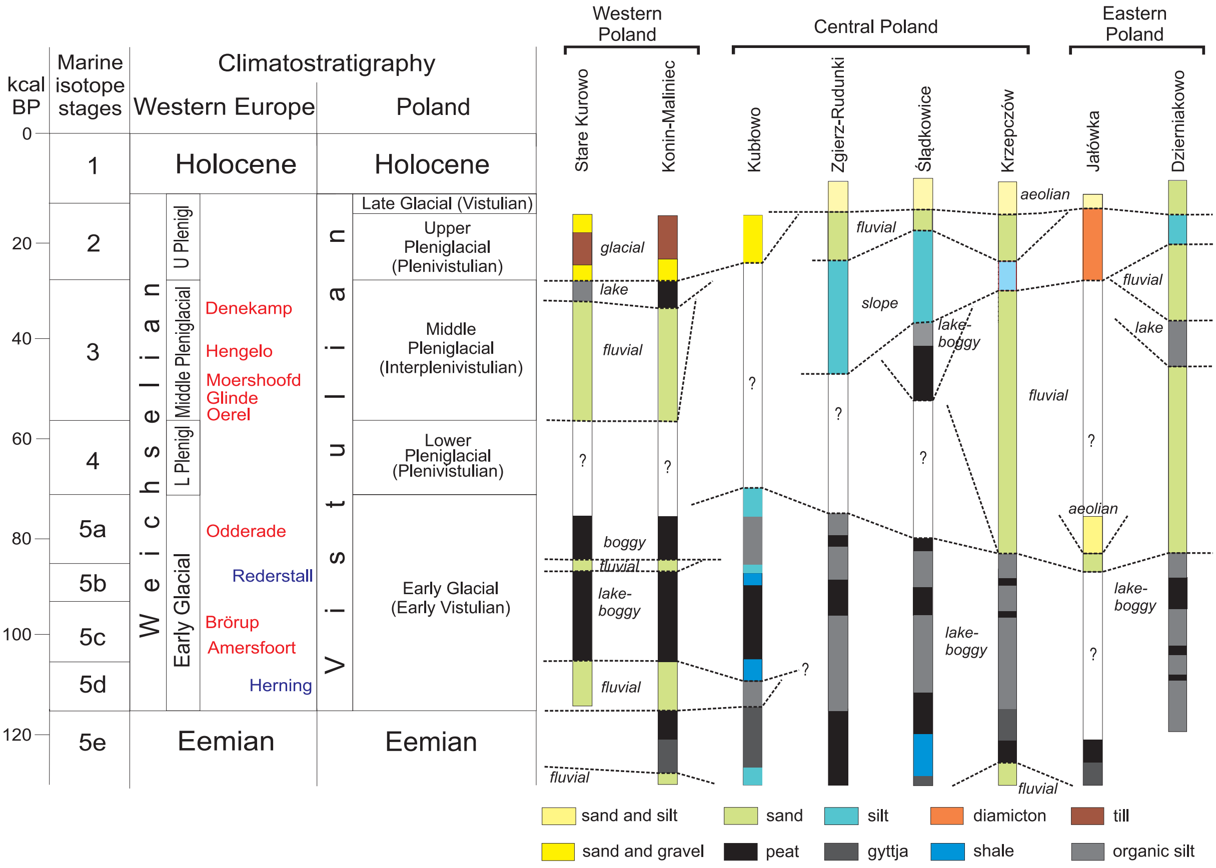
1965a, b, 1969a, b, 1972; Nowak 1965; Head *et al.* 2005; Knudsen *et al.* 2012; Marks *et al.* 2014b). In north-western Poland, near Śliwin and Rewal, redeposited sand and sandy silt with shell debris presumably represent marine beach and lagoonal facies of the Eemian Interglacial (Krzyszkowski *et al.* 1999b).

A sequence of sediments of the Eemian sea in Poland is the most complete in the Lower Vistula region, and its stratigraphic setting is unquestionable, because it is underlain and overlain by tills, respectively of the Odranian and the Vistulian glaciations (cf. Makowska 1979, 1986, 1994). On the other hand, the number and chronology of the marine transgressions have been discussed for many years, because 2 interglacial marine series were occasionally identified (Keilhack 1904; Makowska 1979, 1986, 1989, 1990, 2004a, b, 2009; Nowak and Rabek 1987; Rabek 1990), but this was completely exceptional in the Baltic Basin (cf. Miettinen *et al.* 2002; Andrén 2008).

The stratigraphy of the Eemian sea deposits in Poland is based on detailed investigations at the sites Licze, Obrzynowo and Cierpięta (Text-fig. 10), in which only a single marine series was recorded (Makowska *et al.* 2001; Head *et al.* 2005; Knudsen *et al.* 2012; Marks *et al.* 2014b). The site Cierpięta can be treated as a type section of the Eemian sea in Poland. The late glacial of the Odranian Glaciation starts with varved clay, overlain by fluvial deposits that continue at the beginning of the Eemian Interglacial and are replaced by sediments of a shallow sea with marine fossils, located presumably close to a river mouth as indicated by a significant admixture of terrestrial plant macrofossils (Marks *et al.* 2014b). The early glacial of the Vistulian Glaciation is represented by fluvial sediments, deposited in a temperate climate.

The environment of the Eemian sea is reflected at many sites, as shown by by analyses of diatoms, dinoflagellata, molluscs, ostracods, foraminifers and sea-urchins (Makowska 2001; Head *et al.* 2005; Krzymińska *et al.* 2007; Marks *et al.* 2014b). Fragments of sea-urchins at the sites Elbląg, Licze, Obrzynowo and Cierpięta prove a salinity to 28 psu, which is much higher than suggested by the diatom analysis at Licze and Obrzynowo (Knudsen *et al.* 2011, 2012). During the maximum transgression, the Eemian sea had wider straits with the North Sea and was connected with the White Sea through the Karelian isthmus. A sea bay in the Lower Vistula region extended as far south as Kwidzyn and Prabuty (Makowska 2009). Based on correlation of RPAZ from northern Poland (Mamakowa 1989), Bispingen in northern Germany (Müller 1974; Field *et al.* 1994) and Denmark (Andersen 1961, 1965, 1975), the marine transgression was found to reach the southern Baltic region during the first 300 years of the Eemian Interglacial. Then, diatom analysis suggests that the first transgression maximum occurred at 800–3500 years, the second at 6200–6600 years and a final regression in northern Poland at ~7500 years after the beginning of the Eemian Interglacial (cf. Knudsen *et al.* 2012).

In the Lower Vistula region, i.e. the stratotype area of the Vistulian Glaciation, above the Eemian marine sediments there are at least 5 tills, the stratigraphic setting of which was interpreted in many ways (e.g., Makowska 1979, 1986; Drozdowski 1979, 1986; Mojski 1999; Wysota 2002; Marks 2011; Woźniak *et al.* 2018). The identified climatic episodes during the Vistulian Glaciation provide a more reliable chronology, occasionally correlated with oxygen isotope curves of Greenland ice cores (Marks *et al.* 2016b; Starkel *et al.* 2017; cf. Rasmussen *et al.* 2014; Cohen and Gibbard 2019). The stratigraphy of the Vistulian Glaciation in Poland is generally based on environmental and climatic transformations, notified at many sites (e.g., Kozarski 1991; Klatkowa 1997; Starkel *et al.* 2007; Jary 2009; Roman *et al.* 2014), but the record is particularly fragmentary for the Middle Pleniglacial (Text-fig. 11; cf. Klatkowa 1997). The stratigraphy of the Upper Pleniglacial is strictly connected with advances of the Scandinavian ice sheet in northern and central Poland (Marks *et al.* 2016b), when the climate was extremely cold and dry (Marks



Text-fig. 11. Vistulian climatostratigraphy; after Marks *et al.* (2016a), modified.

et al. 2019a). Long pollen sequences from the Eemian Interglacial to the Middle Pleniglacial were examined at several sites (Granoszewski 2003; Roman and Balwierz 2010), among which the site Horoszki Duże has presumably a continuous pollen record, but multiproxy analyses and precise dating are lacking.

The climate was more continental in eastern Poland during the Amersfoort, Brørup and Odderade interstadials whereas in western Poland it was so during the Rederstall and Herning stadials, and the cold episode between Amersfoort and Brørup (Marks *et al.* 2016a). A full pollen succession of the Early Glacial has been examined at many sites of lake sediments, among others Zgierz-Rudunki (Jastrzębska-Mamełka 1985), Władysławów (Tobolski 1991), Horoszki (Granoszewski 2003), Łomżyca (Niklewski and Krupiński 1992) and Machacz (Kupryjanowicz 1994). Considerable climatic amelioration during interstadials favoured replacement of steppe-tundra and the development of a boreal forest (Granoszewski and Winter 2016). At the site Wildno in Dobrzyń Lakeland, lake clay and silt contain mollusc shells (Dzierżek and Szymanek 2013) whereas at the site Zwierzyniec in Central Poland, Eemian peat is overlain by fluvial deposits with abundant aeolian material, typical of accumulation in a periglacial zone (Kalińska-Nartiša *et al.* 2016).

In the Lower Pleniglacial in Poland, a steppe-tundra with rare boreal trees was common (Granoszewski 2003). Northern Europe, together with the Baltic Basin, was partly occupied by the Scandinavian ice sheet (e.g., Andersen and Mangerud 1989; Petersen and Kronborg 1991; Houmark-Nielsen 1994, 2010) and possible glacial deposits were identified also at many sites in north-eastern Poland (e.g., Drozdowski 1979, 1986; Makowska 1979, 1986; Marks 1988; Wysota 2002; Weckwerth *et al.* 2011; Woźniak *et al.* 2018; Marks et al. 2022c). It was occasionally postulated that the ice sheet was more extensive than during the Upper Pleniglacial (e.g., Marks 1988; Lisicki 1997, 1998; Ber 2000; Krzywicki 2002; Banaszuk and Banaszuk 2010), although this was questioned as not being supported by a reliable method of dating (e.g., Wysota 2002; Mojski 2005; Marks 2011; Marks *et al.* 2016a). There are no glacial landforms of this age at the land surface and single cosmogenic isotope datings, suggesting the pre-Upper Pleniglacial age of ice sheet advance, seem to reflect rather a complicated history of exposition and burial of erratics than a deglaciation itself (cf. Rinterknecht *et al.* 2005, 2010; Tylmann *et al.* 2019).

In the Middle Pleniglacial stratigraphy many warm and cold episodes were distinguished (Kozarski 1991; Jary 2007; Starkel *et al.* 2007; Kupryjanowicz 2008; Jary and Ciszek 2013; Roman *et al.* 2014; etc.), but their sedimentary record is generally short at particular sites, usually with low resolution and inadequate dating, and containing numerous hiatuses. Most climatic episodes were identified in fluvial deposits, therefore records are isolated and not synchronic with one another. A limited ice sheet advance in northern Poland cannot be excluded at 37–33 ka and 28.5–27.0 ka BP (Weckwerth *et al.* 2011; Marks 2012). Rapid and short temperature rises did not allow for the development of more thermophilous plants, but vegetation typical of the preceding cold phases disappeared. Slope, aeolian and fluvial processes prevailed (Rotnicki 1987; Starkel 1988; Krzyszkowski *et al.* 1995, 1999a, 2001; Dzierżek and Stańczuk 2006; Krzyszkowski and Kuszell 2007; Wachecka-Kotkowska *et al.* 2014, 2018; Gębica *et al.* 2015; Starkel *et al.* 2017; Ludwikowska-Kędzia 2018). In the eastern part of the Warsaw Basin, the upper part of the Eemian peat was eroded and replaced by aeolian sand (Marks *et al.* 2016a), OSL dated at 43–39 ka BP and 31–25 ka BP (Kalińska-Nartiša and Nartiš 2016), and >48–32 ka BP at the sites Kubłowo and Wildno (Roman and Balwierz 2010; Dzierżek and Szymanek 2013). The Middle Pleniglacial terminates with accumulation of the lower younger loess in the South Polish Uplands and the foreland of the Carpathians and the Sudetes (Maruszczak 1991).

In the Upper Pleniglacial, the Scandinavian ice sheet advanced in northern Central Europe, reaching southernmost in south-western Poland (Marks *et al.* 2022c). Organic deposits under a till of this ice sheet advance were radiocarbon dated at 26.6–25.3 cal ka BP (Stankowska and Stankowski 1988; Gogołek and Mańkowska 1989; Rotnicki and Borówka 1995; Kramarska 1998; Krzyszkowski *et al.* 1999a), and consequently the ice sheet must have occupied northern Poland after 25 cal ka BP. The maximum extent of this ice sheet is commonly correlated with the Last Glacial Maximum (LGM), although these two events are asynchronic. The LGM should be referred to a climatic minimum during the last Pleistocene glaciation and is reflected by the lowest global sea level, synchronic with the largest volume of the ice bodies in the world (cf. Clark and Mix 2002; Clark *et al.* 2009). There are two main marginal standstills of the ice sheet connected with LGM in Poland. The older, Leszno Phase dated at 25–24 cal ka BP (Niewiarowski *et al.* 1995; Stankowski *et al.* 1999; Gamrat *et al.* 2017; Tylmann *et al.* 2019), represents the maximum ice sheet limit in Germany and western Poland (Marks *et al.* 2022c). The younger, Poznań Phase, dated at 21–19 cal ka BP (Stankowski *et al.* 1999; Wysota *et al.* 2009; Marks 2012; Roman 2017) is reflected by the maximum ice sheet limit in central and eastern Poland, Lithuania, Belarus and Russia (Marks 2015; Marks *et al.* 2022c). A synchronous maximum ice sheet extent of roughly 5 ka can be explained by the varied activity of different ice streams, activated during successive ice sheet advances to the south of the Baltic Basin (Punkari 1997; Boulton *et al.* 2004; Marks 2002; Marks *et al.* 2016a) and in central Poland it is reflected by the transgressive Płock Lobe in the Middle Vistula valley (Marks 2012). The Leszno and Poznań tills were recognized and dated at Konin-Mikorzyn (Stankowska and Stankowski 1988) and Wapienno (Sokołowski 2002; Sokołowski and Bluszcz 2004; Sokołowski and Woronko 2007; Wysota *et al.* 2009). A bipartite sequence of varved clays of the Warsaw ice-dammed lake (cf. Różycki 1972), among others at Plecewice, is also the evidence for 2 ice sheet advances during the LGM (Marks *et al.* 2016a).

After the Poznań Phase, the ice sheet retreat was interrupted by local and regional advances during successive phases: Chodzież (Kujawy), Pomeranian and Gardno (Roszko 1968; Kozarski 1995; Mojski 2005; Marks 2012; Marks *et al.* 2023a). The Chodzież Phase is indicated by a separate till, glaciotectonic deformations and vast outwash plains (Uniejewska *et al.* 1979; Kozarski and Nowaczyk 1985; Kozarski and Kasprzak 1987; Böse and Górska 1995; Kozarski 1995; Pettersson 2002) and its age is estimated at 17.7 ka BP (Kozarski 1986, 1995). The most outstanding ice-marginal zone during the Vistulian Glaciation was formed during the Pomeranian Phase (Mojski 2005). Its till is generally separated from the Poznań till by glaciofluvial and glaciolacustrine deposits (Marks *et al.* 2023a). A retreat of the ice sheet after the Pomeranian Phase was dated with cosmogenic isotopes at ~16.7 ka BP (Tylmann *et al.* 2019). The ice sheet retreat in Poland was terminated by a local advance during the Gardno Phase (15.5–16.0 ka BP), indicated by a separate till and end moraines with large-scale glaciotectonic deformations (Petelski

<table>
<tr><th>Stratigraphy</th><th colspan="2">Germany</th><th>Age [cal ka]</th><th colspan="3">Poland</th></tr>
<tr><td>Holocene</td><td colspan="2">Holocene</td><td>11.7</td><td colspan="3">Holocene</td></tr>
<tr><td rowspan="8">Late Glacial</td><td>Younger Dryas</td><td></td><td>12.68</td><td rowspan="9">Late Glacial</td><td colspan="2">Younger Dryas</td></tr>
<tr><td rowspan="3">Allerød</td><td>Allerød B</td><td>13.08</td><td rowspan="5">Bølling- Allerød Interstadial</td><td rowspan="3">Allerød</td></tr>
<tr><td>Gerzensee oscillation *LST* (12.88 cal ka BP)</td><td>13.15</td></tr>
<tr><td>Allerød A</td><td>13.35</td></tr>
<tr><td colspan="2">Older Dryas</td><td>13.54</td><td>Older Dryas</td></tr>
<tr><td colspan="2">Bølling</td><td>13.67</td><td>Bølling</td></tr>
<tr><td colspan="2">Oldest Dryas</td><td>13.80</td><td colspan="2" rowspan="3">Oldest Dryas</td></tr>
<tr><td colspan="2">Meiendorf</td><td>14.45</td></tr>
<tr><td rowspan="2">Upper Pleniglacial</td><td colspan="2" rowspan="2">Pomeranian Phase</td><td>14.90</td></tr>
<tr><td></td><td>Upper Pleniglacial</td><td colspan="2">Pomeranian Phase</td></tr>
</table>

Table 2. Climatostratigraphy of the Late Glacial, *LST* – Laacher See Tephra; after Marks *et al.* (2023b), modified and supplemented.

1977; Rotnicki 1995; Rotnicki and Borówka 1995; Jasiewicz 1999). The following stabilisation of the ice sheet margin in the southern Baltic Basin occurred during the Słupsk Bank Phase, OSL dated at 15.2 ka and the Southern Middle Bank (Uścinowicz 1996, 1999; Uścinowicz *et al.* 2019).

Intensive aeolian activity was not continuous but resulted in the formation of aeolian sandy covers and dunes, mainly on outwash plains and higher terraces in the ice-marginal spillways. In the Warsaw Basin, aeolian sands on the Błonie and Radzymin terraces were deposited in several phases, dated at 16–15 ka BP and 14 ka BP (cf. Dzierżek *et al.* 2015; Kalińska-Nartiša *et al.* 2016). A break in aeolian deposition is indicated by a buried soil in sediments of the highest (Otwock) terrace in the Middle Vistula valley at Kamion, dated at 15.8 cal BP (Manikowska 1982), that is during the Pomeranian Phase (Marks *et al.* 2016a). Loess accumulated in southern Poland, particularly within the so-called European Loess Belt (Badura *et al.* 2013; Lehmkuhl *et al.* 2021).

The Late Glacial is composed of several alternate warmings and coolings, stimulated by changes in oceanic and atmospheric circulation in the northern Atlantic region (Table 2). It starts with ice sheet retreat after the Pomeranian Phase, with 3 cold phases of the Oldest, Older and Younger Dryas and 2 intervening warm interphases of the Bølling and Allerød (cf. Dzieduszyńska 2019). In more recent publications the Late Glacial starts with the ice sheet retreat from Central Europe at ~14,9 cal ka BP (cf. Marks *et al.* 2023a). A small temperature rise in the Oldest Dryas (14.90–13.67 cal ka BP) resulted in the spreading of a tundra-steppe with herbs and bushes. Poland was still within a periglacial zone with a discontinuous permafrost (Kozarski 1993; Mojski 2005; Marks *et al.* 2023b), but its progressive degradation favoured melting of buried dead ice, activation of mass movements and the gradual decline of meltwater runoff (Błaszkiewicz 2005, 2011). In Germany, a slightly warmer episode of the Meiendorf Interstadial with shrub-steppe tundra vegetation was noted at 14.45–13.80 cal ka BP (Table 2; Litt and Stebich 1999; Brauer *et al.* 2001)

In the Bølling Interphase (13.67–13.54 cal ka BP) lake deposition was initiated and a more dense shrub vegetation with single trees appeared (Madeyska 1995). No continuous plant sequences are known as only isolated and thin organic inserts were found within mineral deposits (e.g., Błaszkiewicz and Krzymińska 1992; Niewiarowski 2003; Błaszkiewicz 2005; Nalepka 2005). The cooling of the Older Dryas (13.54–13.35 cal ka BP) was identified at rare sites in Poland (e.g., Ralska-Jasiewiczowa 1966; Nalepka 2005), therefore it is treated commonly as a part of the Bølling-Allerød Interstadial (Tobolski 1998). Climate deterioration is reflected by a loose shrub and bush vegetation (Marks *et al.* 2023b) and it favoured mass movements and lateral erosion in river valleys. Aeolian processes and dune formation were intensive in western Poland (Nowaczyk 1986).

In the Allerød Interphase (13.35–12.68 cal ka BP), melting of buried dead ice continued and sedimentation was intensive in lakes (e.g., Więckowski 1966; Nowaczyk 1994; Niewiarowski 2003; Błaszkiewicz 2005, 2011, Błaszkiewicz *et al.* 2015, Słowiński *et al.* 2015). The vegetation cover was predominately birch-pine forest but in Germany, an intra-Allerød cold event of the Gerzensee Oscillation was recorded in the middle part of the Allerød Interphase (Andresen *et al.* 2000; Litt *et al.* 2003). It is correlated with the eruption of the Laacher See volcano, dated at 12.88 cal ka BP (Litt and Stebich 1999) and resulted in a wider spreading of herbs (Marks *et al.* 2023b). A lower mean summer temperature (1–2°C) and higher precipitation induced a rise of the lake water levels.

The Lacher See Tephra is a key horizon in peatbogs in north-western Poland (Błaszkiewicz 2007).

The Bolling-Allerød Interstadial (14.9–12.68v cal ka BP), with its abrupt climate change in Europe, is among the main climatostratigraphic periods of the Last Deglaciation. However, the limits of this warm and humid climate were not clearly determined, the period was thermally unstable and the precipitation distribution was regionally and temporary varied (Palacios *et al.* 2023). Consequently, the vegetation changes associated with the Bolling-Allerød Interstadial did not occur synchronously everywhere (cf. Naughton 2023).

A rapid cooling in the Younger Dryas (12.68–11.7 cal ka BP) was accompanied by a renewed agradation of permafrost and the activation of periglacial processes with intensive solifluction and aeolian accumulation, also dune formation (Marks *et al.* 2023c). Open vegetation of park tundra predominated, but steppe-tundra predominated to the east. The site Lake Gościąż in the Płock Basin is a regional stratotype of the Younger Dryas (Goslar *et al.* 1998; Litt *et al.* 2001). Its lower boundary is dated at 12 620+133/-231 cal BP and the upper one (Pleistocene/Holocene boundary) at 11 470+126/-206 cal BP (Müller *et al.* 2021; Bonk *et al.* 2021). A good malacological record for the Late Glacial/Holocene transition was examined at numerous sites (cf. Marks *et al.* 2016a).

HOLOCENE

A huge environmental development started at the onset of the Holocene and continued up to modern times, expressed by plant and faunal migration, lake evolution and soil formation. The summer temperature increased distinctly in Central Poland from >14.6°C to 18.3°C in few decades at the beginning of the Holocene, but the winter temperature, from -19.1 to -12.8°C, was similar to that occurring during the late Younger Dryas, and annual precipitation was equal to 400–500 mm (Müller *et al.* 2021; Płóciennik *et al.* 2022). The Middle Holocene had a warm and stable climate with the air temperature 1.0–3.5°C higher than the modern one (Płóciennik *et al.* 2011; Renssen *et al.* 2012; Luoto *et al.* 2019; Kaufman *et al.* 2020; Kotrys *et al.* 2020).

The cold Bond events 11.3 and 8.2 cal ka BP were recognised at several sites in Poland (Starkel *et al.* 1998; Lauterbach *et al.* 2011; Fiłoc *et al.* 2016) whereas the 4.2 cal ka BP event is weakly detected (Pleskot *et al.* 2020). Several humid (9.5–8.5, 7.6–8.0, 6.4–6.2; 5.6–4.8 and 3.5–3.2 ka BP) and dry episodes (4.2 ka BP and 2.8 ka BP) were distinguished in Poland, based on peat and lake records (Michczyńska *et al.* 2013). Decreasing temperatures and increased climatic instability are characteristic of the last five thousand years. During the last two millennia, transformation of the natural environment was affected both by climate changes and human impact (Marcisz *et al.* 2015; Lamentowicz *et al.* 2019; Łuców *et al.* 2020; Mroczkowska *et al.* 2021).

The water-level of the southern Baltic Sea was rising with a varying rate, but continuously from ~50 m below the present sea level at the beginning of the Holocene (Uścinowicz 2003). The catastrophic draining of the Baltic Ice Lake (cf. Björck 1995; Jakobsson *et al.* 2007) enabled inflow of the Yoldia Sea (Uścinowicz 2003). The following uplift of the Danish-Swedish area cut off the connection with the North Sea at ~10.3 cal ka BP and resulted in the development of the freshwater Ancylus Lake. It terminated with a sudden regression at 8.5–8.4 cal ka BP and the transgression of the Mastogloia Sea (Uścinowicz 2003), followed by the Littorina transgression at ~8.3 cal ka BP. Since that time, the Baltic basin has become permanently connected with the North Sea. The sea level rise resulted in shoreline changes and extensive erosion of a previous terrestrial landscape and the development of the Łeba, Hel and Vistulian spits (Łabuz 2015).

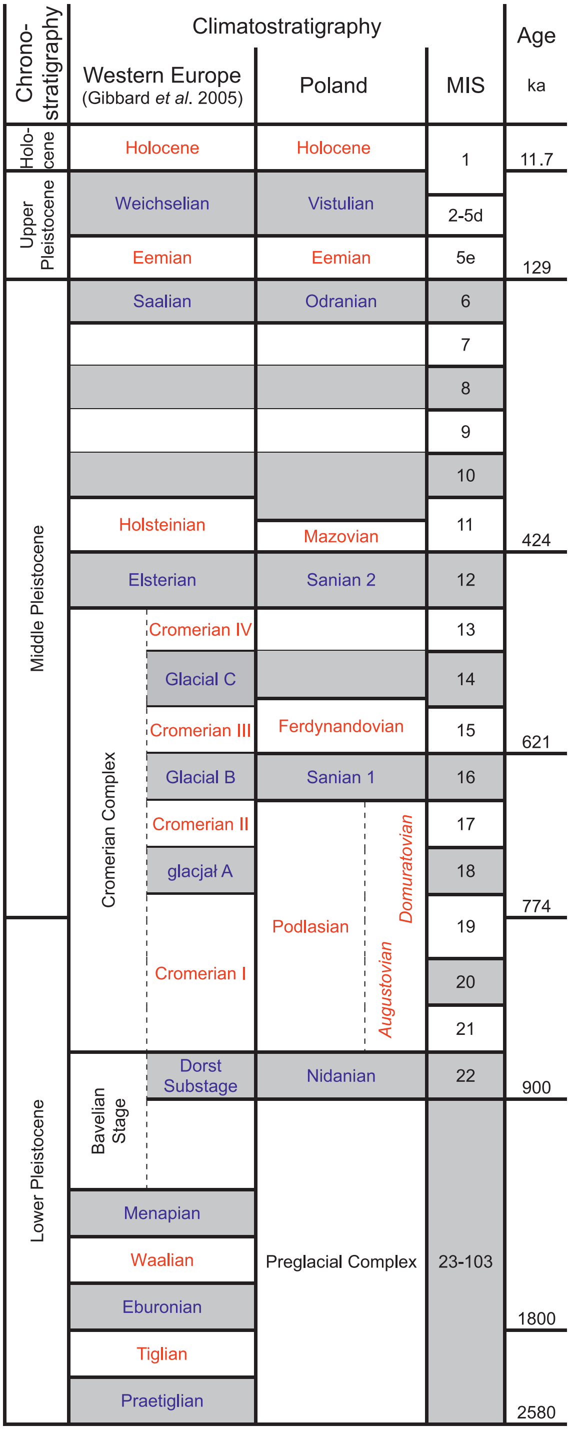
Progressive degradation of permafrost (cf. Szewczyk 2017) and final melting of buried dead-ice transformed glacial landscapes during the Early Holocene, producing the youngest lakes and the modern hydrographic network (Błaszkiewicz 2011; Kordowski 2013; Błaszkiewicz *et al.* 2015; Słowiński *et al.* 2015; Dietze *et al.* 2016; Dobrowolski *et al.* 2019). Aeolian processes continued during the Middle Holocene until 3.0 ka BP (Kalińska-Nartiša *et al.* 2016), with dune formation on the Baltic Sea spits as well as along marine and lagoonal shores (Fedorowicz *et al.* 2012).

The first forest communities were composed mainly of birch and pine, and open grasslands were common, especially on sandy soils. During the mid- and late Early Holocene, elm and oak spread, then the forest was enriched in deciduous trees (Ralska-Jasiewiczowa 2004). The climax forest became partly transformed by the Neolithic people during the late Middle Holocene (Kaczanowski and Kozłowski 1998), to provide areas for settlements, cultivated land, meadows and pastures. The environmental transformations in the Late Holocene were dependent both on climate and increasing human activity (Makohonienko 2004; Ralska-Jasiewiczowa 2004).

DISCUSSION

The Polish Quaternary stratigraphy needs to be based on principles that have been determined and accepted by the international community (http://quaternary.stratigraphy.org/stratigraphic-guide). Inconsequently applied classification and terminology, connected with arbitrary correlation with marine isotope stages (MIS) and without reliable dating, has resulted in the creation of several stratigraphic units devoid of type sections and with ambiguous stratigraphic settings. For these reasons, correlation of the stratigraphic subdivisions in Poland with the ones in the neighbouring countries was difficult if not impossible, although some progress was done by geological mapping of the border areas (e.g., Schultz *et al.* 2000; Marks and Karabanov 2011, 2017).

A verified scheme of the Polish Quaternary stratigraphy (Text-fig. 12) contains the stratigraphic units with a reliable setting, although not all of them are univocally dated. The so-called preglacial deposits, that is the ones, the deposition of which preceded the first advance of the Scandinavian ice sheet in the territory of Poland, started already in the Lower Pliocene (Brunssumian and Reuverian) and terminated in the late Early Pleistocene, but with a huge hiatus (~3 Ma) of the sedimentary record in southern Mazowsze (cf. Bujak *et al.* 2016). The Neogene/Quaternary boundary is reflected by a replacement of forest by forest-steppe and steppe tundra communities, characteristic of a subarctic climate (Winter 2015) but its location is not supported by reliable dating. The upper boundary of the Preglacial Complex (cf. Lindner *et al.* 2013) is expressed by the admixture of Scandinavian material in sediments, indicating the first advance of the ice sheet into the territory of Poland around 900 ka BP that is, much earlier than in other countries of continental Europe. Both lower and upper boundaries of the Preglacial Complex have only either a lithological or a palynological record in Poland, therefore the studies should be continued, particularly at the sites Ponurzyca and Wólka Ligęzowska that seem to be the key ones for the stratigraphic subdivision of the Lower Pleistocene in Poland (cf. Baraniecka 1991; Winter 2015). They should be followed by a revision of the stratigraphic setting of the 'preglacial' Kozienice and Krasnystaw series (cf. Mojski 1984). The gravels of these fluvial series of the Lower Pleistocene are resistant to physical weathering and they reflect deposition during episodic or seasonal floods in a very dry and probably also cold climate when the vegetation cover was scarce (cf. Popescu *et al.* 2010).



Chronostratigraphy	Climatostratigraphy: Western Europe (Gibbard *et al.* 2005)		Climatostratigraphy: Poland		MIS	Age ka
Holocene	Holocene		Holocene		1	11.7
Upper Pleistocene	Weichselian		Vistulian		2-5d	
	Eemian		Eemian		5e	129
Middle Pleistocene	Saalian		Odranian		6	
					7	
					8	
					9	
					10	
	Holsteinian		Mazovian		11	424
	Elsterian		Sanian 2		12	
	Cromerian Complex	Cromerian IV			13	
		Glacial C			14	
		Cromerian III	Ferdynandovian		15	621
		Glacial B	Sanian 1		16	
		Cromerian II	Podlasian	Domuratovian	17	
		glacjał A			18	
		Cromerian I			19	774
Lower Pleistocene				Augustovian	20	
					21	
	Bavelian Stage	Dorst Substage	Nidanian		22	900
			Preglacial Complex		23-103	
	Menapian					
	Waalian					
	Eburonian					1800
	Tiglian					
	Praetiglian					2580

Text-fig. 12. Quaternary stratigraphy of Poland, their correlation with Western Europe and marine isotope stages.

The chronology of the stratigraphic units of the 'glacial' Pleistocene, especially the ones of the late Early Pleistocene and the early Middle Pleistocene (Text-fig. 12), are determined based on the general geological setting and regional correlation (Sanian 1), relation to the Brunhes/Matuyama boundary (Nidanian, Podlasian) and correlation of terrestrial and marine temperature curves (Ferdynandovian, Mazovian). The most ambiguous is the Sanian 2 Glaciation, the extent of which may be similar to that of the Odranian Glaciation. Older interglacials have three (Podlasian) or two (Ferdynandovian) climatic optima separated by distinct coolings, whereas the younger ones (Mazovian, Eemian and Holocene) – have only a single one (Lindner *et al.* 2013). A critical verification of the previous subdivisions of the Quaternary in Poland has resulted in a revised correlation the main stratigraphic units, both with the ones in Western Europe and with the marine isotope stages (Text-fig. 12). It is the first step to select the regional stratotypes of the distinguished stratigraphic units and boundaries, making a reliable correlation with the international chronostratigraphic chart possible (cf. Text-fig. 1).

CONCLUSIONS

The verified stratigraphy of the Quaternary in the glaciated part of Poland presents only these stratigraphic units, the setting of which is supported by internationally accepted principles. However, corrections are possible if new sites, records and datings are available. The stratigraphic schemes of the extraglacial area, based on sites with fluvial, lake and loess sequences, are much more convincing and complete, at least for the Middle and Late Pleistocene. Combining the schemes from the glacial and extraglacial areas still remains a challenging field in Polish stratigraphy. Among the main limitations, there is a lack of good dating methods that could be applied to deposits of this part of the Middle Pleistocene whereas correlation of the terrestrial sequences with high-resolution oxygen isotope deep-sea curves can solve only partly the dating problems.

Definition of the regional stratotypes of the main climatostratigraphic units and boundaries is the main principle in Polish Quaternary stratigraphy. There are still lacking regional stratotypes for the main order boundaries as Pliocene/Pleistocene, Early/Middle Pleistocene and Middle/Late Pleistocene. The boundary Late Pleistocene/Holocene is the only that is close to having a stratotype section. Among the other goals in the Quaternary stratigraphy of Poland is a filling of gaps in the preglacial part of the Early Pleistocene and in the late Middle Pleistocene.

A longer-distant task in Quaternary stratigraphy is the transition from a qualitative description of the stratigraphic units to one based also on selected quantitative criteria. Such an approach would enable direct correlation with marine isotope curves, so far the best correlation tool in Quaternary stratigraphy.

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