

Quaternary stratigraphy and palaeogeography of Poland

LESZEK MARKS, JAN DZIERŻEK, ROBERT JANISZEWSKI, JAROSŁAW KACZOROWSKI, LESZEK LINDNER, ALEKSANDRA MAJECKA, MICHAŁ MAKOS, MARCIN SZYMANEK, ANNA TOŁOCZKO-PASEK and BARBARA WORONKO

Faculty of Geology, University of Warsaw, Al. Żwirki i Wigury 93, PL-02-089 Warszawa, Poland
E-mails: leszek.marks@uw.edu.pl, j.dzierzek@uw.edu.pl, r.janiszewski@uw.edu.pl, j.kaczorowski@student.uw.edu.pl, l.lindner@uw.edu.pl, a.majecka@uw.edu.pl, michalmakos@uw.edu.pl, m.szymanek@uw.edu.pl, atoloczko@student.uw.edu.pl, b.woronko@uw.edu.pl

ABSTRACT:

Marks, L., Dzierżek, J., Janiszewski, R., Kaczorowski, J., Lindner, L., Majecka, A., Makos, M., Szymanek, M., Tołoczko-Pasek, A. and Woronko, B. 0000. Quaternary stratigraphy and palaeogeography of Poland. *Acta Geologica Polonica*, **66** (3), 403–427. Warszawa.

Though the stratigraphical and palaeogeographical framework of the Quaternary in Poland is still to be completed, several crucial points have been confirmed recently. The preglacial series, accepted for years as belonging to the Lower Pleistocene, is undoubtedly of Early Pliocene age, with a huge hiatus above almost until the uppermost Lower Pleistocene. The earliest glaciation in Poland (Nidanian) occurred at about 900 ka BP when the ice sheet reached the mid-southern part of the country. The following Podlasiian Interglacial embraced the Brunhes/Matuyama boundary in the middle, in a similar fashion to the corresponding Cromerian Complex in Western Europe. The late Early and early Middle Pleistocene interglacials in Poland comprised 2-3 optima each, whereas every one of the younger interglacials was characterised by a single optimum only. The Late Vistulian ice sheet was most extensive in the western part of Poland (Leszno Phase) whereas the younger Poznań Phase was more extensive in the central and eastern part of the country. This was due to the varied distance from the glaciation center in Scandinavia, making the ice sheet margin reach a terminal position in different times. Palaeoclimatological research in the Tatra Mountains has provided new evidence for the atmospheric circulation over Europe. During cold phases of the Pleistocene in Poland a continental climate extended further westwards, quite the opposite that occurring during warmer intervals.

Key words: Pleistocene; Preglacial; Palaeoclimate; Molluscs; Pollen analysis; Mountain glaciers; Tatra Mts.

INTRODUCTION

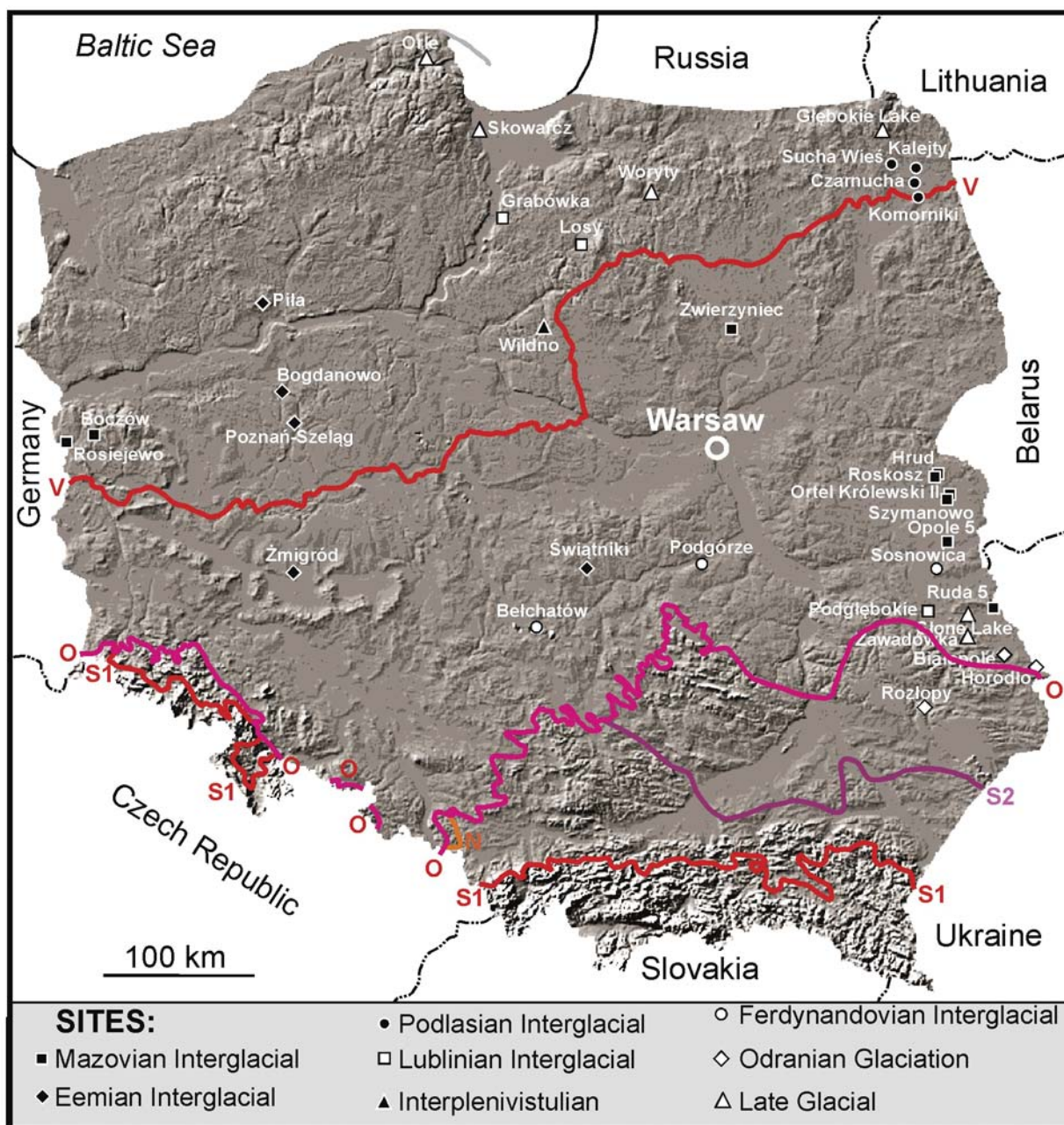
The aim of this paper is the presentation of the Quaternary stratigraphy and palaeogeography of the Polish Lowland. It has been enriched by recent achievements in palaeoclimate reconstruction and modelling of the Tatra Mountains during the last cold period of the Pleistocene.

Studies of the stratigraphy and palaeogeography of the Quaternary in the glaciated part of Poland (Text-fig. 1) have been initiated mostly in the central part of the country (cf. Dylik 1953; Różycki 1967, 1972). This is the area where the Quaternary sequence is the most diversified and numerous key sites are located (Dzierżek and Stańczuk 2006; Dzierżek *et al.* 2015). The Department of Climate Geology of the Faculty of

Geology of the University of Warsaw keeps continuing the achievements in understanding of the Quaternary geology of Poland and results of these most recent investigations are presented in this contribution. Central Poland has been for years the principal area for researches in Quaternary studies in this country. This was firstly due to a growing number of data collected during geological work connected with urban development in the Warsaw area and to the establishment of several actively operating research teams. A profound understanding of the Quaternary geology of central

Poland has been supplemented with the results of investigations carried through in other areas, especially in the Podlasie Lowland and the southern Mazury Lakeland (cf. Marks 1988; Nitychoruk 2000; Dzierżek 2009); and also in the adjacent areas of neighboring countries (Lindner *et al.* 2001, 2004, 2006; Marks and Pavlovskaya 2003, 2007).

Investigations in the Tatra Mountains have made a significant input to the palaeoclimatic modelling of northern continental Europe during the glacial episodes of the Late Pleistocene.



Text-fig. 1. Location sketch of selected sites with Pleistocene mollusc-bearing lake sediments and surface ice sheet limits of Pleistocene glaciations in Poland (cf. Text-fig. 2). N – Nidanian, S1 – Sanian 1, S2 – Sanian 2, O – Odranian, V – Vistulian

HISTORY OF INVESTIGATIONS

The first investigations of the Quaternary of Poland were published in the 19th century and they focused mainly on the occurrences and derivation of erratics, and on the buried fauna and flora, as well as the number and age of glaciations. In the 1920s, the concept of the so-called Warsaw ice-dam lake and of the Żolibórz Interglacial appeared (Różycki 1929), the latter correlated at present with the Eemian Interglacial. The achievements of this pioneer research in central Poland were recapitulated by Różycki (1967, 1972). The second half of the 20th century was the time of intensive geological mapping, connected with the elaboration of the Detailed Geological Map of Poland in a scale of 1:50,000. Examination of numerous key sites took place laying the foundation for a profound discussion on the number and extent of Scandinavian glaciations (cf. Lindner *et al.* 2001, 2006; Marks 2004b, 2011; Gozhik *et al.* 2012), and on the palaeoclimate (Lindner *et al.* 2004), evolution of fluvial network (cf. Lindner *et al.* 1982; Marks 2004a) and on marine interglacial transgressions (cf. Makowska 1986; Marks *et al.* 2014). A major contribution towards our understanding of the chronology of the Late Glacial and Holocene was played by the exploration and detailed examination of laminated sediments of the Gościąż Lake (Ralska-Jasiewiczowa *et al.* 1998). In spite of almost a hundred years of research, including numerous research drillings and analysis of geological samples, there are still intervals of the Quaternary and regions in Poland that are not adequately known.

Still the least known is the preglacial part of the Lower Pleistocene (cf. Popescu *et al.* 2010; Bujak *et al.* 2016), defined in the Polish literature as the Preglacial or the Eopleistocene (e.g. Lewiński 1928; Kosmowska-Ceranowicz 1987; Mojski 2005). This lack of knowledge is due to different reasons, the most important of which is the extremely rare content of organic matter and the resulting limited dating possibilities. The traditional definition of this part of the Pleistocene, proposed by Lewiński (1928) and still applied, was based on lithological criteria, with the setting of preglacial deposits directly above the Neogene variegated clays in Mazovia and overlain in turn by the oldest Pleistocene glacial deposits. Such preglacial deposits are completely devoid of Scandinavian material.

In central and southern Poland a development of the Pleistocene fluvial network has been investigated, describing its relation to interglacial seas in the Baltic Basin (Makowska 1986; Marks 2005; Marks and Pavlovskaya 2003; Marks *et al.* 2014). The Middle and Late Pleistocene stratigraphy and palaeogeography

have been well recognized in the Mazovia Lowland and especially in its central part, named the Warsaw Basin. Geological setting of the Eemian sites, as well as origin and age of the Warsaw ice-dam lake have been recognized. The latter lake was a large proglacial reservoir in a forefront of the ice sheet of the so-called Wkra Stade (Różycki 1972).

Our understanding of the glacial history of the Tatra Mountains has been primarily based on geomorphological evidence (Klimaszewski 1988 and reference therein). Analysis of glaciofluvial levels in the northern foreland of these mountains allowed eight glacial episodes to be distinguished, the timing of which was constrained with thermoluminescence (TL) dating (Lindner *et al.* 2003). Based on them, the last glaciation in the Tatra Mountains could be subdivided into three stadials (Sucha Woda, Bystra, Białka) and their glaciofluvial deposits were TL dated at 89–81, 69–57 and 32–25 ka BP, respectively (Butrym *et al.* 1990; Lindner 1994). The maximum extent of the youngest Białka Stadial occurred during the subordinate Hurkotne Phase and the following recessional phases (Łysa Polana, Włosienica I–III and Pięć Stawów Polskich I–IV) took place at about 23, 16 and 14 ka BP, respectively (Lindner *et al.* 1990). In the High Tatra Mountains up to ten recessional phases were distinguished (Baumgart-Kotarba and Kotarba 1997, 2001). All phases were recorded by recessional terminal moraines and were correlated with the Alpine stadials. Such correlation was partly confirmed by optically stimulated luminescence (OSL) and single-aliquot regeneration (SAR) dating of the maximum end moraine in the Sucha Woda Valley and by radiocarbon dating of sediments in the Czarny Staw Gąsienicowy Lake (Baumgart-Kotarba and Kotarba 1993). A few groups of cosmogenic ages of erratic boulders in the Tatra Mountains have been distinguished (Dzierżek 2009). Among them, two older groups were ascribed to 90–85 and 43–32 ka BP whereas the others were clearly younger, representing 26–23, 22–20, 18–16 and 14–10 ka BP.

METHODS

Numerous and varied methods have been used in the source publications that form the basis for the present contribution. The following is a selection, with rough description, of the most important methods applied.

Geological mapping

Most of the geological and geomorphological source material came from the Detailed Geological Map of Poland in a scale of 1:50,000, finally com-

pleted in 2009. Some of the authors of the present contribution took part in the elaboration of several sheets of this map. The collected geological data were critically verified in the present contribution.

DTM analysis

Digital Terrain Model analysis was very useful in the recognition of specific landforms, the pattern of their occurrence and the spatial mutual relations. This analysis was especially helpful in the demarcation of glacial marginal zones as well as eskers and glaciofluvial trains. DTM analysis was also commonly applied to detect contemporaneous processes, especially mass movements that blurred the primary landscape and made stratigraphic investigations more difficult.

Structural and textural analysis

Results of standard lithological analyses from the Detailed Geological Map of Poland on a scale of 1:50,000 were available and could be used in the preparation of the present contribution. Detailed lithological examination of deposits in key sites enabled the determination of the general characteristics of the sediments, sedimentary environments and post-sedimentary changes. The analysis was focused on recognition of sedimentary structures, and on the measurement of grain size, heavy mineral composition of the sand fraction, petrographic composition of the gravel fraction, roundness and surface micromorphology of quartz grains. Rounding and frosting of quartz grains was particularly important for the detailed description of palaeoclimatic conditions, especially in the Pleistocene periglacial zone. The heavy mineral composition reflected sediment derivation, transport conditions and environmental characteristics.

Geochemical analysis

This has been used to supplement lithological analysis. Among other things, the content of CaCO_3 can be useful in the reconstruction of past weathering horizons, especially in a periglacial environment (Woronko *et al.* 2013). Determination of the content of C (total contents of organic C included), P, N and carbonates, and the ratios of heavy to light isotopes of oxygen and carbon, mainly for interglacial deposits with authigenic calcium carbonate, were also very important. The ratios of stable isotopes of O and C, compared with the results of other analyses, enabled their mutual verification and elaboration of full characteristics of the environmental conditions. Geochemical examination of mollusc shells

provided significant variations in Fe, Mn and Sr content and stable isotopes (Szymanek *et al.* 2016). Fe/Mn ratio in shells reflected changes in redox conditions, with low values characteristic of reduction, climate aridity and lower water level.

Palynological analysis

This has been applied commonly for reconstruction of vegetation history and climate change and for stratigraphic correlation. Hundreds of palynological sections covering different interglacials have been examined in Poland, several of them being of stratotype significance (among others Janczyk-Kopikowa *et al.* 1981; Mamakowa 1989; Krupiński 1995, 2000). Both organic (peat, gyttja) and non-organic deposits (lake silt and clay) constituted excellent archives for spores, especially in an anoxic environment. The pollen spectra from every site were grouped into local pollen assemblage zones (L PAZs) that were in turn correlated with the ones from other localities. Taxa of particular importance were represented by indicator plants with narrow tolerances in respect to particular environmental factors, providing detailed information, mainly on precipitation and temperature ranges of the coldest and the warmest months during deposition.

Malacological analysis

Fossil mollusc shells provided an excellent proxy for stratigraphical and palaeoecological reconstructions. The mollusc constituted the most common faunal remains in Pleistocene deposits in Poland and represented various terrestrial and aquatic environments. Subfossil thanatocoenoses were common in lacustrine marl, gyttjas and limy sand, silt and clay, whereas they were hardly preserved in most organic deposits. The mollusc shell assemblages reflected depositional conditions and enabled climate and environmental reconstructions for interglacial and glacial periods. Just a few Pleistocene mollusc species were regarded as biostratigraphical indicators (Alexandrowicz and Alexandrowicz 2011). Their stratigraphical significance was usually based on their first or last appearances (Text-fig. 2). Reconstruction of palaeoenvironmental conditions based on malacological record was strongly connected with structure of mollusc assemblages and relations between the main ecological groups typical of temporary and permanent stagnant water bodies and of rivers. Most species were wide climatic tolerant, therefore climate inferences were again based on fauna composition and appearance of diagnostic warmth-demanding and cold-tolerant species.

Palaeoclimate modelling

Environmental and palaeoclimate reconstructions are best based on multiproxy examination of past sedimentary environments, landforms, periglacial structures and palaeontological data. Such an approach has several advantages compared with a use of single indicators, including a range of climatic parameters, consistency of results based on different individual indicators and determination of the uncertainty margin in interpretation (Rychel *et al.* 2014). A multi-proxy approach enables testing of different methods against one another, finding that a climate pattern could be significantly different during warmer and colder intervals in the Pleistocene (cf. Marks *et al.* 2016a).

Palaeoclimate investigations were also focused on behavior of mountain glaciers, the latter being sensitive indicators of climate fluctuations. In the Tatra Mountains, the same as elsewhere in Europe, existence and dynamics of glacial systems were strongly dependent on atmospheric circulation patterns controlled

mainly by the North Atlantic Oscillation (cf. Kuhlemann *et al.* 2008). In order to calculate climate parameters (mean annual temperature, mean summer temperature and annual precipitation) that determined the existence of glaciers in steady state conditions, two independent models, previously used in the Alps (Ivy-Ochs *et al.* 2008), were applied (cf. Makos *et al.* 2013a, b, 2016).

Stratigraphical scheme

A new stratigraphic subdivision of the Pleistocene in Poland (Ber *et al.* 2007) presents 4 complexes: Preglacial, South Polish, Middle Polish and North Polish ones (Text-fig. 3). Each complex comprises the units that are glaciations (coolings) and interglacials (warmings) in a climatostratigraphic sense (Lindner *et al.* 2013).

The Preglacial Complex represents most of the Quaternary, including almost the whole Lower Pleistocene. Deposits of this complex do not indicate any

MIS		Stratigraphy	Gastropods	Bivalves
2-5d	Upper Pleistocene	Vistulian Glaciation	<i>Gyraulus laevis</i> <i>Gyraulus acronicus</i>	<i>Pisidium obtusale lapponicum</i> <i>Pisidium lilljeborgii</i> <i>Pisidium stewarti</i>
5e		Eemian Interglacial	<i>Belgrandia marginata</i>	
6	Middle Pleistocene	Odranian Glaciation	<i>Gyraulus laevis</i>	<i>Pisidium obtusale lapponicum</i> <i>Pisidium lilljeborgii</i>
7		Lublinian Interglacial		<i>Pisidium clessini</i>
8		Krznanian Glaciation		
9		Zbójnian Interglacial		
10		Liwiecian Glaciation		
11		Mazovian Interglacial	<i>Viviparus diluvianus</i> <i>Lithoglyphus jahni</i> <i>Theodoxus danubialis</i>	<i>Pisidium clessini</i>
12		Sanian 2 Glaciation		
13-15		Ferdynandovian Interglacial		
16		Sanian 1 Glaciation		
17-21		Lower Pleistocene	Podlasian Interglacial	<i>Fagotia wuesti</i> <i>Parafossarulus crassitesta</i> <i>Lithoglyphus jahni</i> <i>Viviparus diluvianus?</i>
22	Nidanian Glaciation			

Text-fig. 2. Characteristic mollusc species in Pleistocene lake sediments in Poland; MIS – marine isotope stages

symptom of glaciation in the Polish Lowland. The South Polish Complex comprises the 3 oldest glaciations (Nidanian, Sanian 1 and Sanian 2), with 2 interglacials (Podlasian and Ferdynandovian). In the Middle Polish Complex there are 3 glaciations (Liwiecian, Krznanian and Odranian) and 3 interglacials (Mazovian, Zbójnian and Lublinian). The North Polish Complex is composed of the Eemian Interglacial and the Vistulian Glaciation (Text-fig. 3).

Age control

When necessary the original radiocarbon ages were recalculated into calendar years using the radiocarbon age calibration curves of Reimer *et al.* (2013) and are presented as 'cal kyrs BP'. The timing of the glacial episodes of the last glaciation is based mostly on cosmogenic ^{36}Cl and ^{10}Be exposure age dating, both in the area occupied by Scandinavian glaciations (Rinterknecht *et al.* 2005, 2006a, b; Dzierżek and Zreda 2007; Marks 2012) and in the Tatra Mountains (Dzierżek *et al.* 1999; Dzierżek 2009; Makos *et al.* 2013a, b, 2014, 2016). OSL and TL dates have been used occasionally for establishing the chronology. Cosmogenic and luminescence ages are presented as 'ka BP'.

ORIGIN AND AGE OF PREGLACIAL DEPOSITS

Preglacial sediments are known from numerous drillings and rare outcrops in the Polish Lowlands, Sandomierz Basin, Lublin Upland, Carpathian and Sudetes forelands (cf. Bujak *et al.* 2016 and reference therein). They were deposited by rivers flowing from the west, south and south-east that aggraded large alluvial fans in the southern Mazovian Lowland, and were dissected by the rivers. The northernmost sites with preglacial deposits were examined in the Płock Basin (Roman 2010) and in the Kurpie Plain (Bałuk 1987). Several Early Pleistocene valleys were distinguished in the southern Mazovian Lowland with the westernmost river located probably along the present Vistula valley. Preglacial deposits occurred inside deep river valleys in the Lublin Upland and in the Carpathian Foreland. Lack of preglacial deposits in many areas has been presumably due to post-depositional erosion (Bujak *et al.* 2016).

The preglacial deposits are up to 30 m thick but never more than 60 m. They are composed of deltaic-floody (marshy-floody) and fluvial facies (Makowska 1976). The first facies was composed of rhythmically laminated gravel-sandy-silty deposits of the alluvial

fans. Silt and clay were deposited in small lakes located on the fans and organic sediments were deposited at fan peripheries. The fluvial facies were composed of gravel-sandy deposits.

Cyclic bedding is the most typical feature of the preglacial deposits. Each cyclothem started with gravel and terminated with silty sand, silt and occasionally clay (e.g. Lewiński 1928; Baraniecka 1975). The preglacial series contained no Scandinavian material, the lithologies being dominated by quartz and poorly rounded sandy grains of varied size, and the sediments were completely decalcified. Minerals resistant to physical and chemical weathering prevailed, accompanied by cherts and lydites, and there was a small admixture of dark minerals (cf. Woronko and Bujak 2010; Bujak *et al.* 2016).

The age of these preglacial deposits is a problem that cannot be solved definitely at present due to a lack of reliable dating methods. The conceptual proposal of Lewiński (1928) was clear enough and no other precise definition was needed. However, later investigation proved that the presence of underlying variegated clays to be discussed below was not necessary to define the overlying deposit as the preglacial one (Mojski 1984; Roman 2010; Makowska 2015). Thus, the preglacial series was directly underlain by Cretaceous rocks in the Lublin Upland (Mojski 1984; Maruszczak 2001) and it was suggested to be correlated with the Pliocene in the Polish Lowlands (Kosmowska-Ceranowicz 1987).

A stratigraphy of the preglacial series is based on palynological analysis of deposits from two key sites in the Mazovian Lowland, namely Ponurzyca near Otwock (Stuchlik 1975; Baraniecka 1975) and Różce near Grójec (Stuchlik 1994; Baraniecka 1991). Based on results of a palynological analysis, Stuchlik (1975) distinguished four climate phases in the preglacial series: two warm (Celestynów and Ponurzyca) and two cold (Otwock and Różce), and connected them in turn with Praetiglian, Tiglian, Eburonian and Waalian in the Lower Pleistocene of western Europe (cf. Text-fig. 3). Baraniecka (1991) regarded them as stages and combined them into the Preglacial Superstage (Text-fig. 4), although such an approach has not been supported by any dating. This proposed stratigraphic setting of the preglacial series became doubtful when the variegated clays were moved down in from the Pliocene to the Upper Miocene (Piwocki *et al.* 2004). This extended the time of deposition of the preglacial series to over 4 mln years (from 5.2 to 0.9 mln years ago).

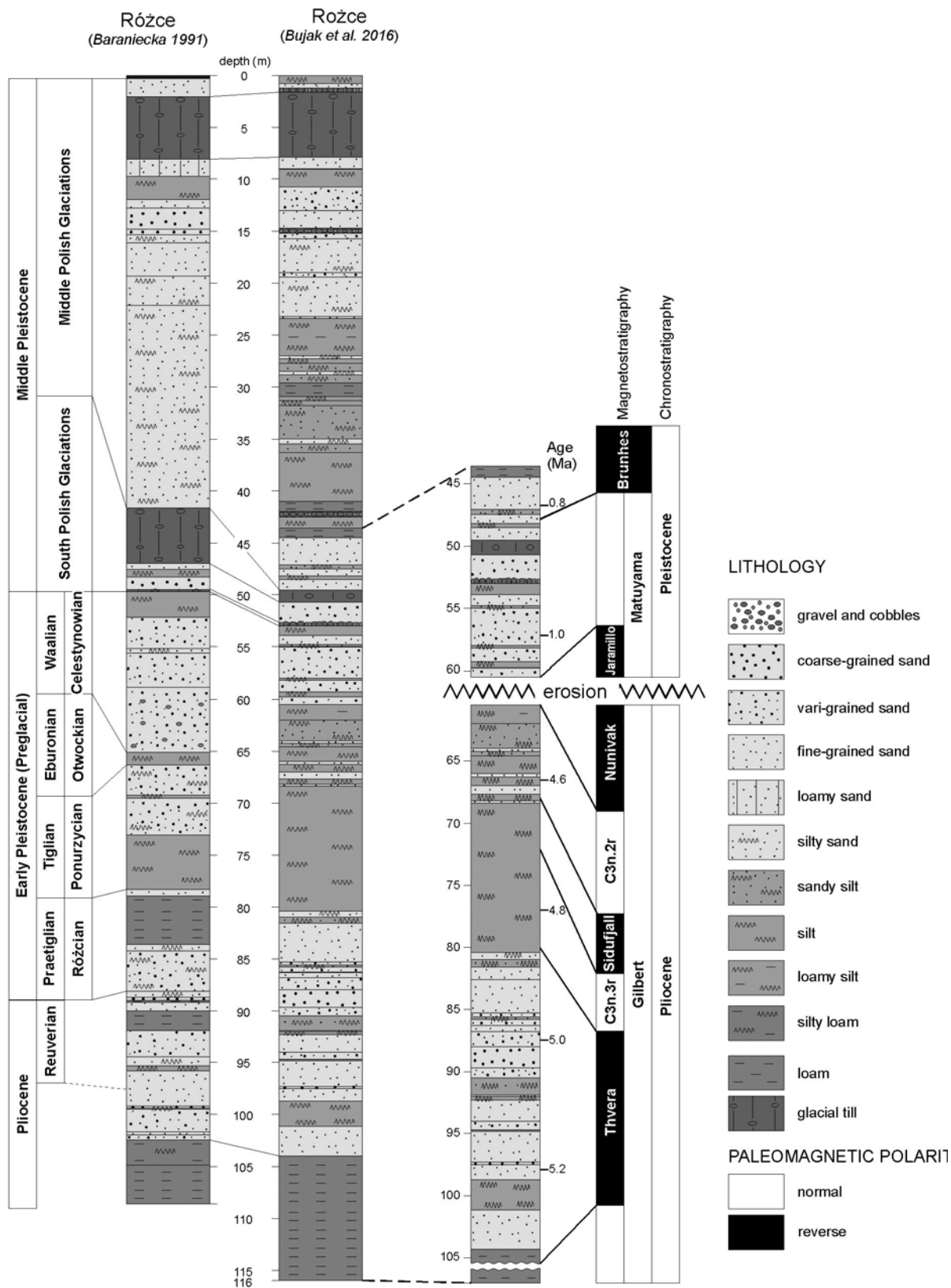
The preglacial series was re-examined in repeated drillings at Różce (spelling: Różce after Baraniecka 1991; cf. Bujak *et al.* 2016). Based on the new results

of Makowska (2015) and Winter (2015), new palynological data proved that the deposits correlated previously with the Preglacial are of the Early Pliocene age (Bujak *et al.* 2016). They were deposited 4.62–5.23 mln years ago, corresponding therefore to the middle part of the Gilbert palaeomagnetic epoch, comprising in turn the episodes of normal C3n.4n (Threva), reverse C3n.3r, normal

C3n.3n (Sidufjall) and reverse C3n.2r (Text-fig. 4) polarity. The interval connected with deposition of the preglacial series by Baraniecka (1991), comprised a stratigraphic hiatus of about 3 mln years (Bujak *et al.* 2016). However, at Ponurzyca, which was the key site for the Lower Pleistocene (Baraniecka 1991), the stratigraphic setting of the deposits remains open.

AGE ka BP	PALEO- MAGNETISM	STRATI- GRAPHY	WESTERN EUROPE	P O L A N D			MIS							
				complexes	GLACIATIONS INTERGLACIALS	LOESS (L) PALEOSOL (G)								
11.7		Holocene	Holocene	Holocene		modern	1							
130		Upper Pleistocene	Weichselian	North Polish	Vistulian	LM	2-5d							
			Eemian		Eemian	GJ1	5e							
420		Middle Pleistocene	Saalian	Middle Polish	Odranian	LSg	6							
			Schöningen		Lublinian	GJ2	7							
			Wacken		Krznanian	LSd	8							
			Fuhne		Zbójnian	GJ3a	9							
			Holsteinian		Liwiecian	LN1	10							
			Elsterian		Mazovian	GJ3b	11							
			780			Middle Pleistocene	Cromerian IV	Sanian 2	LN2	12				
								Ferdynandovian	GJ4(a+b)	13				
										14				
								Glacial C	Sanian 1	LN3	15			
16														
990		Lower Pleistocene	Cromerian III	Podlasian	GJ5(a+b)	17								
						18								
						19								
						20								
						21								
						22								
						23								
1070			Glacial A	South Polish	Nidanian	LN4	23-103							
1220			Cromerian I											
1240			Dorst											
1770		Lower Pleistocene	Waalian					Preglacial	Krasnystaw and Kozenice series	23-103				
											1990			
											2588			Praetiglian

Text-fig. 3. Stratigraphic subdivision of Poland and its correlation with Western Europe



Text-fig. 4. Log and age of preglacial deposits at Różce after Bujak *et al.* (2016), modified

STRATIGRAPHY AND PALAEOGEOGRAPHY OF LATE EARLY AND MIDDLE PLEISTOCENE

The Nidanian Glaciation is the oldest one in Poland (Text-fig. 3). A till of this glacial advance was found in northeastern and southern Poland beneath the Brunhes/Matuyama boundary, therefore it must be older than ca 780 ka BP (Lindner *et al.* 2013). The ice sheet occupied northern and central Poland, reaching the Moravian Gate and western foreland of the Carpathians (Text-fig. 5). It dammed the rivers flowing to the north and several proglacial lakes were developed at the southern margin of the Małopolska and Lublin Uplands. The oldest loess (LN4) was deposited in the anaglacial part of this glaciation in the western part of the Holy Cross region (Lindner 1991) and in the eastern part of the Lublin Upland (Dolecki 1995).

Two younger floristic successions (Augustovian and Domuratovian) in Poland comprised three warmings and two separating coolings of the Podlasiian Interglacial (cf. Lindner *et al.* 2013). The Augustovian succession (Text-figs 3, 6) was examined primarily at Szczebra (Janczyk-Kopikowa 1996) and Kalejty (Winter 2001) in northeastern Poland and comprised two warmings separated by a cooling. The older warming started with boreal vegetation (pine-birch forest with spruce), with thermophilous trees (*Quercus*, *Ulmus*, *Tilia* and *Corylus*) during the mesocratic stage, followed by *Picea* and *Larix*, and terminated with pine-birch forest and herbs. The younger warming started with rapid development of birch and then, of pine forest. Interglacial optimum was predominated by deciduous trees (*Carpinus*, *Quercus*, *Ulmus* and *Alnus*, accompanied by *Tilia*, *Fraxinus* and *Acer*) and other thermophilous taxa (*Carya*, *Juglans*, *Celtis*, *Eucommia*, *Azolla*, *Salvinia* and *Trapa*). This optimum was followed by drastic transformation to a forest, composed mainly of pine and spruce. Coolings between these warmings and after the younger warming were represented by boreal and subarctic taxa.

The Domuratovian succession was examined in northeastern Poland and it is represented by two warmings, the older one correlated with the younger warming in the Augustovian succession, and the younger one characterized by the presence of *Pinus*, *Quercus*, *Carpinus*, *Ulmus*, *Tilia*, *Alnus* and *Abies*, accompanied by *Acer* and *Ligustrum*. The second warming has been assumed to occur also in cave deposits at Kozi Grzbiot in the Holy Cross Mts (Głazek *et al.* 1976). This stratigraphic setting of the Podlasiian Interglacial was supported by a presence of the palaeomagnetic Brunhes-Matuyama boundary in the uppermost part of the second warming (Lindner *et al.* 2013).

The most characteristic mollusc assemblages from lake deposits of the Podlasiian Interglacial were examined at Komorniki in northeastern Poland (Text-fig. 1). The snails *Fagotia wuesti* Meijer and *Parafossarulus crassitesta* (Brömmle) were noted in deposits of a flow-through lake for the first time in the Pleistocene of Poland (Khursevich *et al.* 2005). Noteworthy was the appearance of the biostratigraphical indicator *Litoglyphus jahni* Urbański that, accompanied by *Viviparus diluvianus* (Kunth) and *Pisidium clessini* Neumayr, found also at Sucha Wieś and Czarnucha (Text-fig. 1). Both these sequences were dated as not younger than the Mazovian Interglacial (Skompski 2009), but geological setting and palynological data, supported by palaeomagnetic investigation, suggested correlation with the Podlasiian Interglacial (cf. Ber 2009). This interglacial was represented by the oldest pedocomplex GI5 (a+b) in the eastern part of the Lublin Upland (Dolecki 1995).

During the Sanian 1 Glaciation (Text-fig. 3) the ice sheet occupied the largest part of Poland. It reached the Sudetes and the Carpathians (Text-fig. 5) and its huge marginal tongues entered river valleys in the mountains that were open to the north. The ice sheet flowed around several elevations (main crests of the Holy Cross Mountains, Polish Jura and Sobótka Mt.), favouring development of smaller or more extensive nunataks. The loess LN3 was deposited in the eastern part of the Lublin Upland (Dolecki 1995) during the anaglacial part of this glaciation.

The younger interglacial was represented by the bi-optimal Ferdynandovian floristic succession (Text-figs 3, 6), with the stratotype site at Ferdynandów in central Poland (Janczyk-Kopikowa *et al.* 1981). According to Zagwijn (1996), both warmings of the Ferdynandovian Interglacial should be correlated with interglacials II and III of the Cromerian Complex. The older warming of the Ferdynandovian succession was expressed by a thermophilous deciduous forest with oak (*Quercus*), elm (*Ulmus*) and hazel (*Corylus*), followed by a fir-spruce forest. The separating cooling was represented by a coniferous forest (taiga) with pine, spruce and birch characteristic for a subarctic tundra. The younger warming comprised a deciduous forest with *Quercus*, *Tilia*, *Ulmus*, *Alnus* and *Corylus* and characteristic abundant hornbeam (*Carpinus*) (cf. Lindner *et al.* 2013). A mid-loess soil complex GI4 (a+b) developed in the eastern part of the Lublin Upland (Dolecki 1995). The Ferdynandovian Interglacial mollusc remains were noted at single sites (Text-fig. 1), including lake deposits at Sosnowica in Polesie Lubelskie (Skompski 1996), the Bełchatów open mine (Krzyszczkowski and Kuszell 1987) and Podgórze in

central Poland (Skompski 2004). The fauna from Sosnowica was represented by shell fragments of 15 mollusc species, typical of stagnant waters and temperate climate (Skompski 1996), whereas at Podgórze a single opercula of *Bithynia tentaculata* (Linnaeus) and probable occurrence of *Bithynia leachii* (Sheppard) were reported. These provided restricted palaeoecological data only, but the palynological record, plus ostracods and fish remains pointed out to their accumulation in a cool phase of the interglacial (Skompski 2004).

The Sanian 2 Glaciation was the youngest climatostratigraphical unit of the South Polish Complex (Text-fig. 3). The Scandinavian ice sheet moved around the Holy Cross Mountains and occupied the Lublin Upland, entered the Sandomierz Basin reaching the northern foreland of the Carpathians and in the west, the northern foreland of the Sudetes (Text-fig. 5). Similarly, as during the earlier glaciation, the highest crest of the Holy Cross Mountains and some depressions between them were the nunataks. At the edge of the Carpathians a meridional marginal valley was formed with proglacial and extraglacial discharge to the Dnistr valley (cf. Lindner and Marks 2013, 2015). In the Holy Cross region the maximum extent of the ice sheet was preceded by deposition of loess (Lindner 1991), including the loess LN2 in the eastern part of the Lublin Upland (Dolecki 1995).

The Mazovian Interglacial was the oldest climatostratigraphic unit of the Middle Polish Complex (Text-figs 3, 6). It was represented in about 70 sites, located mostly in central and eastern Poland, and was particularly common in the Podlasie Lowland (Krupiński 2000). The Mazovian succession indicated local and regional differences dependent on the geographical setting. The main theme that allowed correlation with the neighbouring areas in western and eastern Europe was primarily the characteristic spruce-alder and hornbeam-fir pollen zone during the optimum (Text-fig. 6). The interglacial succession started with a boreal forest with birch (*Betula*) and still large open areas. A transition from boreal into temperate conditions was recorded by a spruce forest with admixture of pine and trees with higher thermic requirements (*Ulmus*, *Quercus*, *Fraxinus*, *Corylus*, *Tilia*), wetland habitats dominated by alder (*Alnus*) and subsequently, an emergence of yew (*Taxus*). The latter was extremely high in the southern Podlasie Lowland (Krupiński 1995, 2000), indicating an influence of the marine atmospheric circulation. A younger part of the interglacial was predominated by a mixed forest with hornbeam and fir, accompanied by oak (*Quercus*), linden (*Tilia*), elm

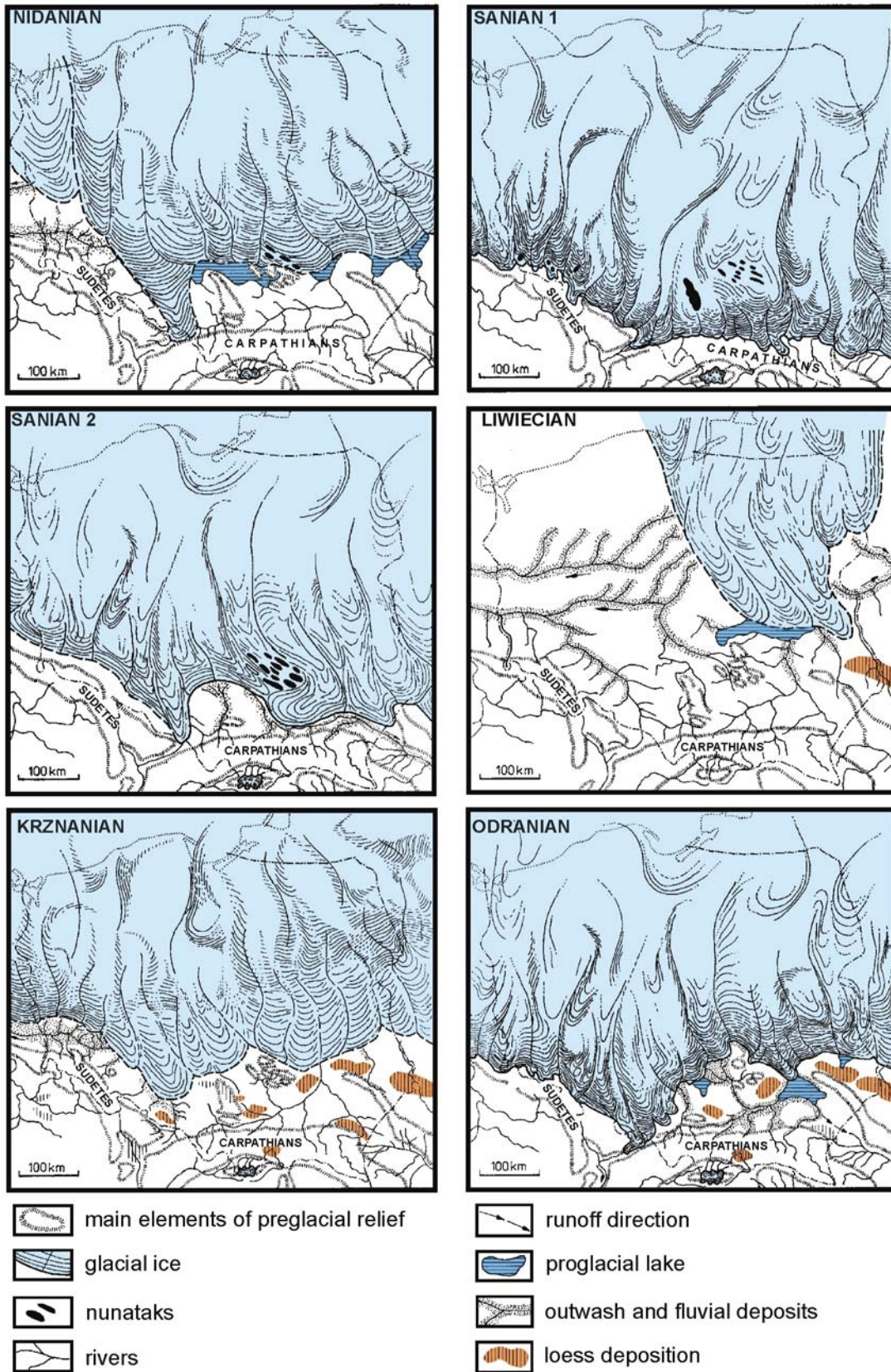
(*Ulmus*), maple (*Acer*) and ash (*Fraxinus*). At the end of the interglacial, a pine-birch forest expanded. The lake sediments of the Mazovian Interglacial comprised a characteristic mollusc assemblage with shells of *Viviparus diluvianus*, *Lithoglyphus jahni* and *Pisidium clessini* (e.g. Skompski 1989, 1996; Bałuk et al. 1991; Lindner et al. 1991; Albrycht et al. 1995; Szymanek 2012, 2013, 2014; Text-fig. 2). Noteworthy was a significant contribution of *Valvata piscinalis* (Müller) and *Bithynia tentaculata*. Quantitative relations between these species were indicative of water level changes, as *V. piscinalis* typical of a deeper lake appeared, while abundant *Bithynia tentaculata* indicated a drop of water level. This interglacial was recorded by the palaeosol GI3b in the Lublin Upland (Dolecki 2002).

The Liwiecian Glaciation (Text-fig. 3) was represented by a till that indicated the ice sheet limit in northeastern and mid-eastern Poland (Text-fig. 5). A vast proglacial lake occurred in a proglacial area, formed by damming of the Vistula valley and the valleys of its tributaries to the south of Warsaw. The meltwaters were drained both westwards across Wielkopolska Region to the Elbe valley in Germany and eastwards to the Pripyat valley in Belarus. Deposition of loess LN1 occurred in the Lublin Upland in the anaglacial period (Dolecki 2002).

Organic deposits of the Zbójnian Interglacial were correlated with a younger climatostratigraphic unit of the Middle Polish Complex (Text-fig. 3). The pollen succession of this interglacial was expressed by a high content (to 48%) of linden (*Tilia*), with significant participation of hornbeam (*Carpinus*), alder (*Alnus*) and hazel (*Corylus*) in the climatic optimum. The pollen succession of this interglacial has been suggested recently to be similar to the Eemian one as developed in western Europe (Bińska 2010). In loess sections of the Lublin Upland this interglacial was recorded by a buried soil GI3a (Dolecki 2002).

During the Krznanian Glaciation (Text-fig. 3) the ice sheet reached the northern forelands of the Małopolska and Lublin uplands and elevations in the foreland of the Sudetes (Text-fig. 5; cf. Lindner and Marks 1999). Several loess patches were deposited in southeastern Poland in the anaglacial part of this glaciation. This loess was named the older lower one LSd by Maruszczak (1991).

The Lublinian Interglacial (Text-fig. 3) is represented by organic deposits, with incomplete pollen succession, but characterized by earlier appearance of linden (*Tilia*) than hazel (*Corylus*), which made this succession different from a similar succession of the Eemian Interglacial (Lindner 2008). In loess sections



Text-fig. 5. Palaeogeography of Early and Middle Pleistocene glaciations in Poland after Lindner and Marks (1995), modified

AUGUSTOVIAN POLLEN SUCCESSION Szczębra Section (according to Janczyk-Kopikowa 1996)		FERDYNANDOVIAN POLLEN SUCCESSION Ferdynandów Stratotype Section (according to Janczyk-Kopikowa 1996)		MAZOVIAN POLLEN SUCCESSION Southern Podlasie Lowland (according to Krupiński 2000)		EEMIAN POLLEN SUCCESSION Imbramowice Stratotype Section (according to Mamakowa 1989)	
LOCAL POLLEN ASSEMBLAGE ZONE L PAZ		REGIONAL POLLEN ASSEMBLAGE ZONE R PAZ		REGIONAL POLLEN ASSEMBLAGE ZONE R PAZ		REGIONAL POLLEN ASSEMBLAGE ZONE R PAZ	
Sz 13	<i>Pinus-Juniperus-NAP</i>	11	<i>NAP-Pinus-Betula</i>	M 9	<i>Pinus</i>	E 7	<i>Pinus</i>
Sz 12	<i>Pinus-Betula-Alnus</i>	10	<i>Pinus-Betula-NAP</i>	M 8	<i>Carpinus-Quercus-Abies</i>	E 6	<i>Picea-Abies-Alnus</i>
Sz 11	<i>Pinus-NAP</i>	9		<i>Pinus-Betula-NAP</i>	M 7	<i>Abies-Carpinus-Quercus- (Corylus)</i>	E 5
Sz 10	<i>Pinus-Alnus- Picea (Azolla- Salvinia)</i>	8	<i>Alnus- Carpinus</i>		M 6	<i>Pinus-Picea-Alnus</i>	E 4
Sz 9	<i>Quercus-Ulmus- Carpinus</i>	7	<i>Betula-Pinus-NAP</i>	M 5	<i>Taxus-Picea-Alnus</i>	E 3	<i>Quercus-Fraxinus-Ulmus</i>
Sz 8	<i>Pinus-Betula-Artemisia</i>	6	<i>Pinus-Betula</i>	M 4	<i>Picea-Alnus-(Taxus)</i>		
Sz 7	<i>Pinus-Picea- Azolla</i>	5	<i>Abies-Picea</i>	M 3	<i>Picea-Alnus-(Pinus)</i>	E 2	<i>Pinus-Betula-Ulmus</i>
Sz 6	<i>Betula-Pinus- Azolla</i>	4	<i>Quercus- Ulmus-Corylus</i>	M 2	<i>Betula-Pinus-(Picea-Alnus)</i>		
Sz 5	<i>Pinus-Picea</i>	3	<i>Pinus-Betula-Quercus</i>				
Sz 4	<i>Betula-Larix</i>	2	<i>Betula-NAP-Pinus</i>	M 1	<i>Betula-NAP</i>	E 1	<i>Pinus- Betula</i>
Sz 3	<i>Pinus</i>	1	<i>Betula-NAP-Pinus</i>				<i>Betula</i> <i>a Pinus</i>

Text-fig. 6. Typical floristic successions of the Augustovian, Ferdynandovian, Mazovian and Eemian in Poland

this interglacial was represented by a soil complex of the 'Tomaszów' type, defined as the soil GI2 (Maruszczak 1991). An occurrence of *Pisidium clessini* in lake deposits, generally typical of older interglacials, was also noteworthy (Makowska 1969).

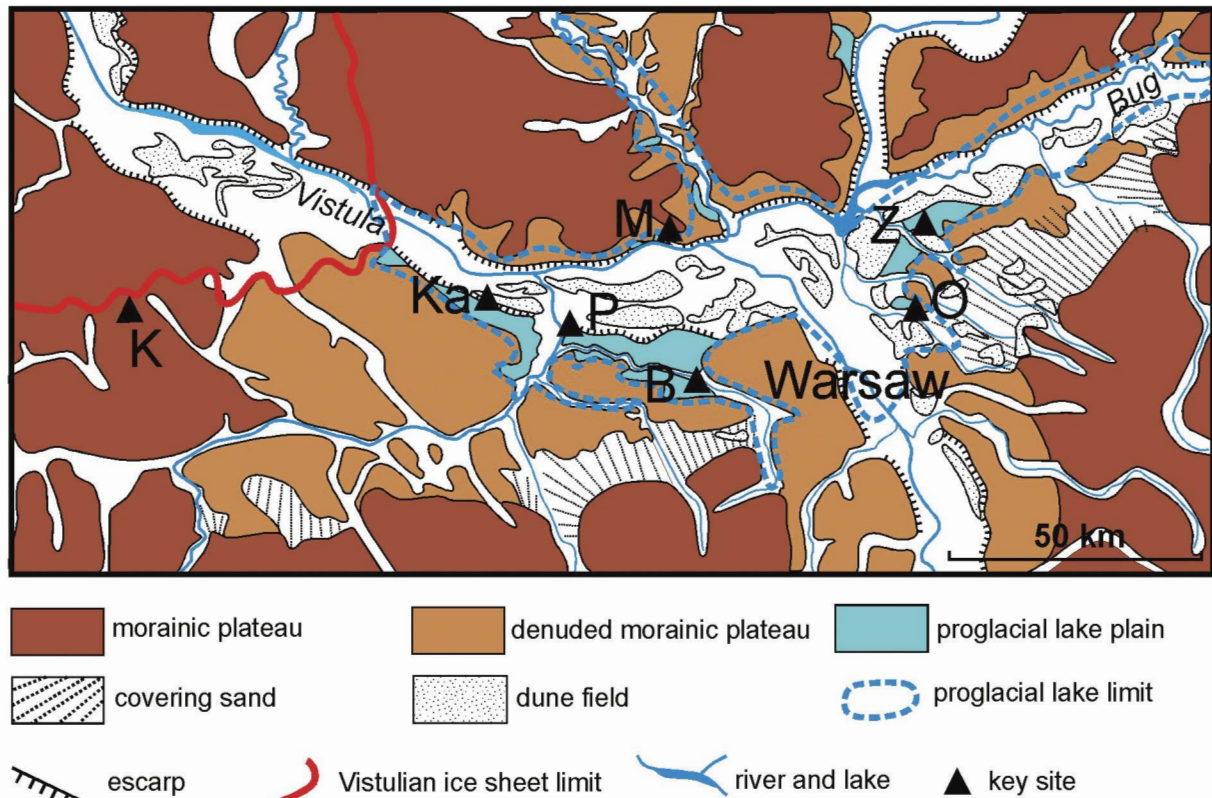
During the Odranian Glaciation (Text-fig. 3) the Scandinavian ice sheet reached the Sudetes, Polish Jura, Holy Cross Mountains and Lublin Upland, entered the Moravian Gate and occupied also the northern Sandomierz Basin (Lindner and Grzybowski 1982; Text-fig. 5). Recent studies carried through in eastern Poland and western Belarus indicated a more limited ice sheet extent of the Odranian Glaciation in this region (cf. Marks *et al.* 2016b). Several ice-dam lakes developed in Upper Pilica, Middle Vistula and Upper Wieprz river valleys. Well expressed morainal zones were formed by the retreating ice sheet of the Warta Stadial (Lindner 2005). The older upper loess LSg was deposited during this glaciation in the Lublin Upland (Maruszczak 1991). Molluscs appeared in small water bodies in the loess area. However, due to a small number of species and specimens they were usually of minor palaeoecological significance. The most important site of the Warta Stadial age was at Horodło in eastern Poland, with a mollusc assemblage typical of a cool climate, indicated by *Pisidium lilljeborgii* Esmark and Hoyer, *Pisidium obtusale lapponicum* Clessin and subarctic loess species. Some taxa of higher thermal demands (e.g. *B. leachii*) could point to interphase-rank climate amelioration (Skompski 1996). A malacofauna of such cold, periglacial lakes (e.g. Białopole near Chełm, Rozłopy near Zamość) contained freshwater species accompanied by cold-loving land snails *Valtonia tenuilabris* (Braun) and *Pupilla muscorum* (Linnaeus) or *Gyraulus laevis* (Alder) (Skompski 1996). The late glacial pollen succession was recognized at several sites and was continued until the Eemian Interglacial. Long pollen sequences from Imbramowice (Mamakowa 1989), Szwajcaria (Borówko-Dłużakowa and Halicki 1957) and Warsaw (Krupiński and Morawski 1993) indicated varied vegetation succession. Two stadials in the Late Glacial were represented by varied herbaceous assemblages (usually exceeding 30%) with abundant index plants (among others *Helianthemum*, *Armeria*, *Pleurospermum austriacum*, *Selaginella selaginoides*), accompanied by juniper (*Juniperus*) and sea buckthorn (*Hippophaë*). There were shrubs with sea buckthorn during the separating interstadial, followed by a boreal forest. A birch-pine forest with spruce (*Picea*) occurred at the end of the late glacial of the penultimate glaciation in northeastern Poland.

LATE PLEISTOCENE PALAEOCLIMATE AND PALAEOGEOGRAPHY

There are about 260 sites with Eemian Interglacial lake deposits in Poland (cf. Bruj and Roman 2007). A full interglacial succession was represented by 7 regional pollen assemblage zones (R PAZ), with typical setting of L PAZs E1-E4 at Imbramowice (Mamakowa 1989) and R PAZs E5-E7 at Zgierz-Rudunki (Jastrzębska-Mamelka 1985). The interglacial pollen succession started with expansion of a pine-birch forest (Text-fig. 6) and was followed by the appearance of elm (*Ulmus*). Rising temperature affected a development of oak (*Quercus*) and then of hazel (*Corylus*), with a large participation of elm (*Ulmus*) and linden (*Tilia*); the latter reached its maximum after the hazel (Mamakowa 1989). Abundance of hornbeam (*Carpinus*) occurred in a younger part of the mesocratic stage and was an essential component of a deciduous forest. The end of the interglacial was recorded by development of a spruce-fir forest, alder (*Alnus*) on wetlands and followed by a pine forest with admixture of birch (*Betula*) in an unstable climate (Kupryjanowicz *et al.* 2016). In the Lower Vistula region a transgression of the Eemian sea occurred (Makowska 1986; Head *et al.* 2005; Knudsen *et al.* 2012; Marks *et al.* 2014). In loess sections this interglacial was recorded by the palaeosol GI1 (Maruszczak 1991).

The freshwater snails and bivalves of the Eemian Interglacial were represented by 60 species, including *Belgrandia marginata* (Michaud), indicative of the warmest phase (cf. Skompski 1996). Similarly to the Mazovian Interglacial, variable relations were observed in many Eemian sequences between *Valvata piscinalis* and *Bithynia tentaculata*, with predominance of the former in the early stage and the latter in the middle and the upper part of the interglacial (Alexandrowicz and Alexandrowicz 2010). Contrary to the situation in the Mazovian-age sections, a considerable admixture of land snails redeposited by flowing waters has been noted at many sites.

The cooling of the Early Vistulian was recorded in fluvio-periglacial deposits that covered a peat of the Eemian Interglacial. These deposits contained numerous crushed grains and quartz grains with distinctive aeolian surface micromorphology. Periglacial processes (cf. Dzierżek and Stańczuk 2006) transformed morainic highlands in central Poland. A separate peat bed, the pollen spectrum of which indicated pine forest and forest steppe vegetation with birch and larch (Kalińska-Nartiša *et al.* 2016), marked each warming during the Early Vistulian. At Wildno in the Dobrzyń Lakeland, clay and sandy silt from under a till



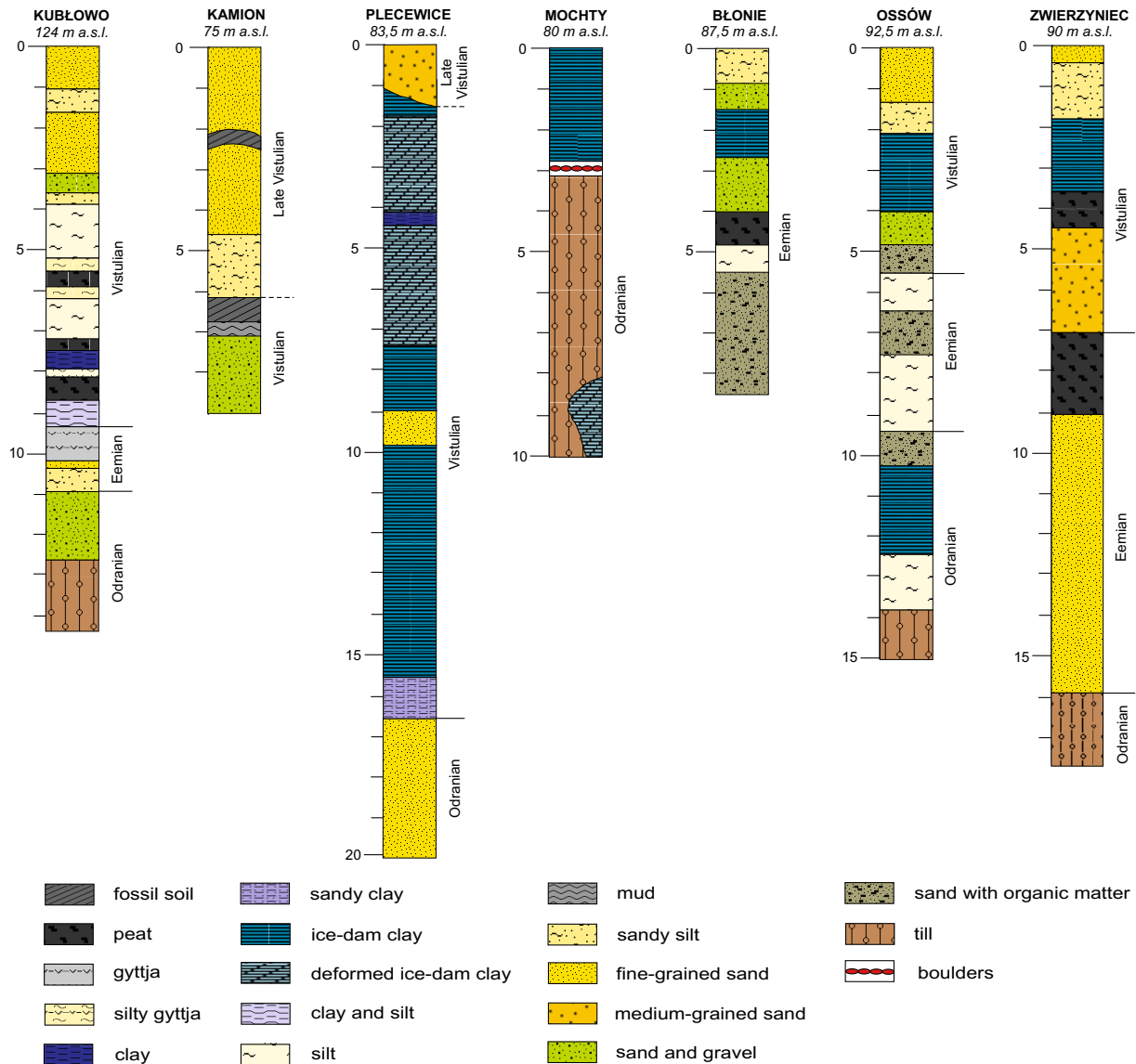
Text-fig. 7. Geological-palaeomorphological sketch of central Mazovia after Marks *et al.* (2006), modified; key sites: B – Błonie, K – Kubłowo, Ka – Kamion, M – Mochty, O – Ossów, P – Plecewice, Z – Zwierzyniec; for logs see Text-fig. 8

of the Late Vistulian Glaciation (Dzierżek and Szymanek 2013; Text-fig. 5) contained shell remains of *Bithynia tentaculata*, *Valvata piscinalis*, *Theodoxus cf. fluviatilis* (Linnaeus), *Valvata sp.*, *Viviparus sp.*, *Pisidium cf. amnicum* (Müller) and *Sphaerium sp.*

During the anaglacial part of the Vistulian Glaciation four beds of the younger loess LM were deposited in the South-Polish Uplands and in the forelands of the Sudetes and the Carpathians (Maruszczak 1991). The varved clay of the Warsaw ice-dam lake was found not to have been deposited at the same time (Text-fig. 7). Two thin beds of such a clay near Radzymin (Kowalczyk *et al.* 2014; Kalińska-Nartiša *et al.* 2016) were underlain by two layers of peat and gyttja, separated by a fine-grained sand and underlain by a till of the Odranian Glaciation (Text-fig. 8). Peat in the upper part of the Eemian geological sections in the eastern part of the Warsaw Basin was locally partly or completely eroded and covered with a thin series of fine-grained sand from the Vistula Glaciation. Such sand was dated at Kubłowo (Roman and Balwierz 2010) and Wildno (Dzierżek and Szymanek 2013) at >48–32 ka BP and this age indicated the interval just before the maximum ice sheet extent during the Leszno Phase of the Vistulian Glaciation (cf. Marks 2012), named the Inter-

plenivistulian. Therefore, the overlying varved clays were deposited induring the younger part of the Vistulian Glaciation and their two beds situated above organic deposits of Eemian Interglacial and Brørup Interstadial can indicate development of a proglacial lake in the two glacial episodes that were the Leszno Phase and the Poznań Phase. During the latter, the ice sheet reached its maximum limit in the northwestern part of the Warsaw Basin (Marks 2012). The highest terrace of the Vistula (Otwock terrace) was formed after the maximum advance of the ice sheet. A palaeosol on the topmost deposits of this terrace at Kamion (western part of the Warsaw Basin), dated at 15.8 cal kyrs (Manikowska 1982), indicated development of the terrace during the Pomeranian Phase (cf. Marks 2012). The lower terraces of the Vistula were formed in variable climatic-hydrological conditions at the end of the Pleistocene and at the beginning of the Holocene.

The origin and age of the covering sands on the Vistulian ice-dam lake clays at Błonie and Radzymin terraces in the Warsaw Basin (cf. Dzierżek *et al.* 2015; Kalińska-Nartiša *et al.* 2016) or directly on the Eemian deposits have been primarily connected with deposition by streams that flowed northwards, cutting the



Text-fig. 8. Logs of selected key sites of Middle and Late Pleistocene age in Mazovia, central Poland: Błonie (Janczyk-Kopikowa 1974), Kublowo (Roman and Balwierz 2010), Kamion (Cichosz-Kostecka *et al.* 1991), Mochty and Plecewice (Dzierżek *et al.* 2015), Ossów (Sarnacka 1982), Zwierzyniec (Kalińska-Nartiša *et al.* 2016); for location see Text-fig. 7

morainic plateau slope. Deposition by these rivers formed alluvial fans that came into contact laterally, resulting in sandy apron-like covers at the foot of the northern slope of the morainic plateau. Detailed examination of these deposits indicated grain size indices typical of aeolian deposits (Kalińska-Nartiša and Nartiš 2016). Total contents of well-rounded mat (RM type) and partly rounded grains (EM/RM) in the covering deposits were more characteristic of aeolian than fluvial deposits. The covering deposits were OSL dated, just above a till at 43–39 ka BP and upwards in turn at 31–25 ka, 16–15 ka and 14 ka BP (Kalińska-Nartiša and Nartiš 2016).

The climate of the Early Vistulian indicated distinctly high continentality in the eastern part of Poland, but exclusively during the warm interstadials of Amersfoort, Brørup and Odderade (Marks *et al.* 2016a). Continentality was considerably smaller during the intervening cooler stadials (Herning, cold phase between Amersfoort and Brørup, Rederstall). These warm interstadials seemed to have most continental climate during the Brørup (similar to the present one), but less during the Amersfoort and least during the Odderade. A full floristic succession, together with the upper boundary of the early Vistulian was recorded in several sites in Poland, including Zgierz-Rudunki

(Jastrzębska-Mamełka 1985), Władysławów (Tobolski 1991), Horoszki (Granoszewski 2003), Łomżyca 1 (Niklewski and Krupiński 1992) and Machacz (Kupryjanowicz 1994). In Europe, an eastward decreasing trend of continentality during the Early Vistulian cold stadials might have resulted from a remarkably less dynamic Gulf Stream in the North Atlantic, rebuilding atmospheric circulation in the southeastern sector of the Scandinavian ice sheet (cf. Marks *et al.* 2016a).

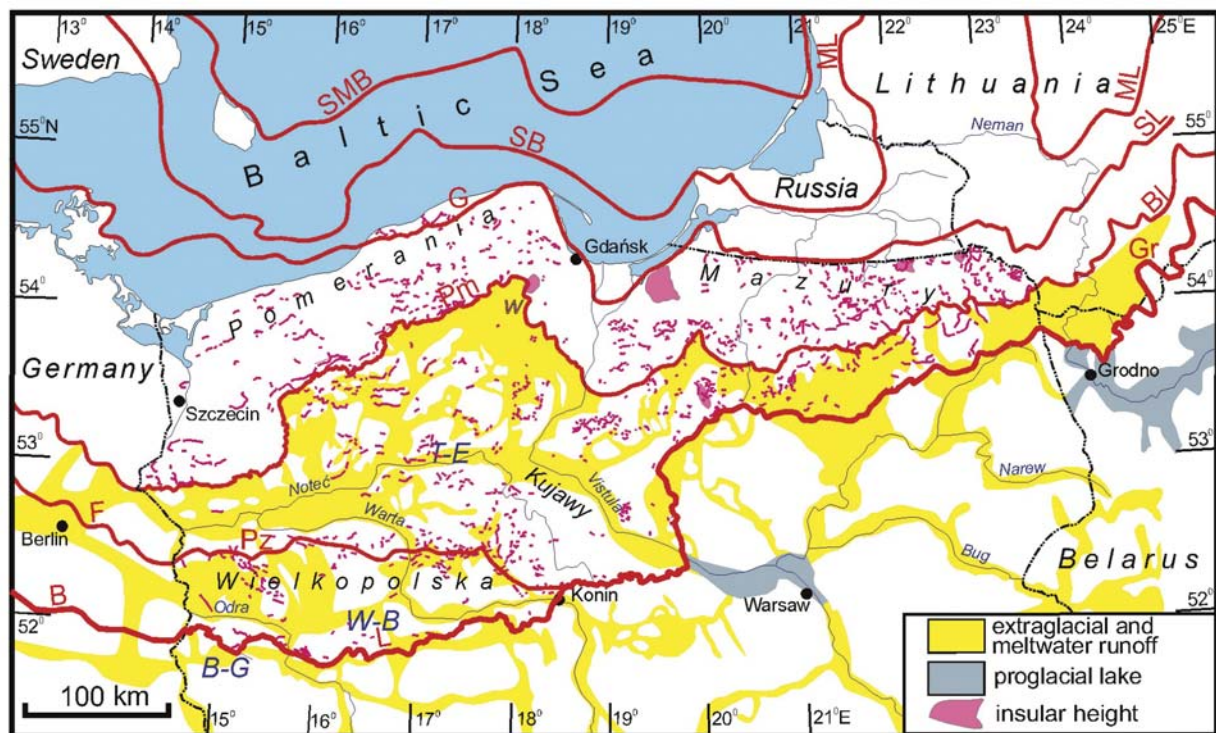
LAST GLACIAL MAXIMUM IN POLAND

During the Late Vistulian Glaciation (Text-figs 3, 9) the ice sheet occupied most of northern Poland (Marks 2012) and the Warsaw ice-dam lake was formed in the Vistula valley (cf. Różycki 1972). The Late Vistulian ice sheet limits in Poland were indicated by ice-marginal formations, generally with small end moraines, ice-marginal fans and outwash plains (Marks 2015). The southernmost extent of the ice sheet occurred during the Leszno Phase at 24 cal kyrs BP in western Poland (Text-fig. 9). The next was the Poznań Phase (20–19 ka BP), indicated by the ice margin standstill, after 50–70 km retreat, in western Poland. This was undoubtedly a transgressive glacial episode

and indicated the maximum ice sheet limit in central and eastern Poland, with the Płock lobe in the Middle Vistula valley (cf. Marks 2012). The Poznań Phase was followed by ice sheet retreat and then readvance during the Pomeranian Phase (17–16 ka BP) when several glacial lobes at the ice margin were formed. Cosmogenic isotope ages, supplemented with calibrated radiocarbon data, indicated up to 5 kyrs difference along the Late Vistulian maximum ice sheet limit in Poland (from 24 to 19 ka BP). This means that several secondary palaeo-ice streams presumably could be active to the south of the Baltic depression during successive phases of the Late Vistulian Glaciation (cf. Punkari 1997; Boulton *et al.* 2004).

Erratic assemblages in tills, till fabric and stream-lined glacial landforms indicated that the Late Vistulian ice sheet limits in Poland were probably formed by the postulated main palaeo-ice streams that expanded from the Baltic Basin that acted as the main discharge track of the Baltic Palaeo-ice Stream. The ice sheet advanced through the Pomeranian Bay, Gulf of Gdańsk and Gulf of Riga (cf. Marks 2002) but not reaching the Polish territory at the same time.

The Gardno Phase was a younger transgressive event, expressed by prominent push moraines in the central part of the Polish seashore (Text-fig. 9) and it



Text-fig. 9. Limits of the major glacial phases during the Late Vistulian in Poland and neighbouring areas after Marks (2012), modified. L – Leszno Phase, Pz – Poznań Phase, Pm – Pomeranian Phase, G – Gardno Phase, SB – Stupsk Bank Phase, SMB – Southern Middle Bank Phase, B – Brandenburg Phase, F – Frankfurt Phase, Gr – Grüda Phase, BL – Baltija Phase, SL – South Lithuanian Phase, ML – Middle Lithuanian Phase; indicated are subordinate end moraines, main ice-marginal streamways (B-G – Baruth-Głogów, W-B – Warsaw-Berlin, T-E – Toruń-Eberswalde), interlobal heights, proglacial and extraglacial runoff zones

was dated at 16.8–16.6 ka BP (Marks 2002). Two younger ice sheet limits were distinguished in the southern Baltic Sea Basin to the north of the present Polish coastline (Text-fig. 9). They were in turn the Słupsk Bank Phase, dated at 16.2–15.8 cal kyrs BP and the Southern Middle Bank Phase, dated at 15.4–15.0 cal kyrs BP (Uścińowicz 1999).

There are dozens of sites with a good malacological record for the Late Glacial/Holocene transition. The changes of the Late Pleistocene freshwater malacofauna reflected considerable environmental transformation connected with deglaciation of northern Poland. Poor mollusc assemblages with arctic or subarctic species occurred in many initial lakes. Among them, the most important were *Pisidium obtusale lapponicum* and *Gyraulus laevis*, essential for malacostatigraphic subdivision into two zones: *Pisidium obtusale lapponicum* (>13.8 ka BP) and *Gyraulus laevis* (13.8–10.5 ka BP) ones (Alexandrowicz 2009). Molluscs of the first zone inhabited small and shallow water bodies, developed under severe climatic conditions.

LAST GLACIATION IN THE TATRA MOUNTAINS

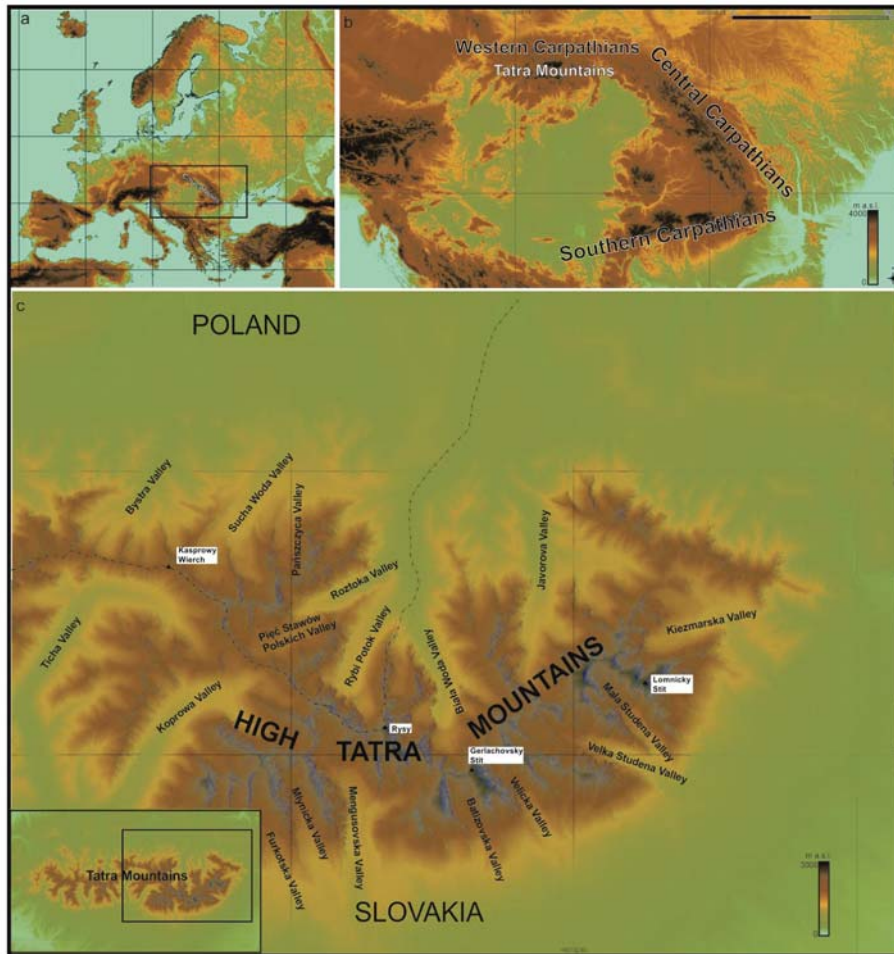
Most of the formerly glaciated European mountain ranges were located in the Mediterranean region and their usefulness for palaeoclimate reconstruction of the continent interior was mostly elusive. The Tatra Mountains formed the northernmost Alpine mountain belt (Text-fig. 10) to be glaciated during the Pleistocene. Due to its geographical location, the Tatra range could serve as the major palaeoclimatic link between the southern mountain ranges and northern Europe occupied by the Scandinavian ice sheet in the Pleistocene. For this purpose, a timing of former glaciations in the Tatra Mts, in particular of the last one, and a magnitude of its cooling, could help in understanding a climatic pattern of central Europe during the Late Glacial/Early Holocene transition.

Recent exposure ages for moraines and glacially abraded bedrock in the High Tatra Mountains made their deglaciation chronology more precise (Makos *et al.* 2013a, b, 2014; Makos 2015). Dating of glacially moulded bedrock along valley and cirque walls enabled to follow a down-wasting of glaciers in the past. An exposure age of moraines indicated several cold episodes during the last deglaciation.

According to the exposure age of a moulded bedrock below the uppermost trimlines, the last maximum advance of glaciers occurred well before 21.5 ka BP. This age confirmed also the first pulse of ice melting, which lasted at least until 18 ka BP. The second

warmer period occurred between 15.5 and 13 ka BP (Makos *et al.* 2013b), which was additionally confirmed by the lake sediment record in the High Tatra Mountains (Krupiński 1984). These findings were supported by ^{36}Cl and ^{10}Be exposure ages of moraines in the Tatra Mountains that suggested stabilization of the maximum moraines at 22–26.5 ka BP (Makos *et al.* 2014), thus during the global LGM (Clark *et al.* 2009). The maximum advance was defined in the Tatra Mountains as LGM I and the subsequent re-advance of glaciers occurred probably at around 18 ka BP and was defined as LGM II (Text-fig. 11; Makos *et al.* 2014). However, recent studies of the deglaciation chronology based on ^{10}Be dating suggested that the first post-maximum re-advance might have occurred as early as 20.5 ka BP. Subsequent significant cold events occurred around 17 ka and 13 ka BP according to the Greenland Ice Core chronology (Rasmussen *et al.* 2014). They were expressed by development of terminal and lateral moraines, stabilization of which took place at around 16.5, 15.5, 14 and 12.5 ka BP (Makos *et al.* 2014, 2016). The two older stages reflected a cooling of the Greenland Stadial GS 2.1a, which was an equivalent of the Oldest Dryas in continental Europe. A short cooling during the Greenland Interstadial (GI), which was defined as GI-1 d and correlated with the Older Dryas, represented the 14 ka BP phase. The youngest phase reflected the last Pleistocene significant cold episode named the Younger Dryas that was the equivalent to GS-1 (Rasmussen *et al.* 2014). Comparable timing of the last deglaciation was also determined in the European Alps (Ivy-Ochs *et al.* 2008), Pyrenees (Palacios *et al.* 2015), Scottish Highlands (Small *et al.* 2012), Southern Carpathians (Ruszkiczay-Rüdiger *et al.* 2014), Rila Mountains (Kuhlemann *et al.* 2013) and Anatolian Peninsula (Sarıkaya *et al.* 2014).

Furthermore, a geomorphological record of the last glacial cycle coupled with the exposure age chronology, allowed to reconstruct the geometry of glaciers in the Tatra catchments during successive phases (Makos and Nitychoruk 2011; Makos *et al.* 2013a, b, 2014; Zasadni and Kłapyta 2014). The LGM glaciers in the Tatra Mountains had different shapes, from single basins to dendritic systems, sometimes with expanded piedmont fronts (Makos *et al.* 2014). The glaciers retreated into separate valleys during the subsequent phases, and existed there as valley and cirque glaciers in the Late Glacial and Early Holocene (Makos *et al.* 2013a, b; Makos 2015). The accurate geometry of glaciers allowed a calculation of their key parameters. They were: equilibrium line altitude (ELA), mean surface slope, ice thickness, basal shear stress and mass balance. The mass balance was then



Text-fig. 10. Location of the Tatra Mountains in Europe (a) and in the Carpathians (b); (c) indicates the eastern part of the Tatra Mountains, where most chronological and palaeoclimatic studies have been carried out

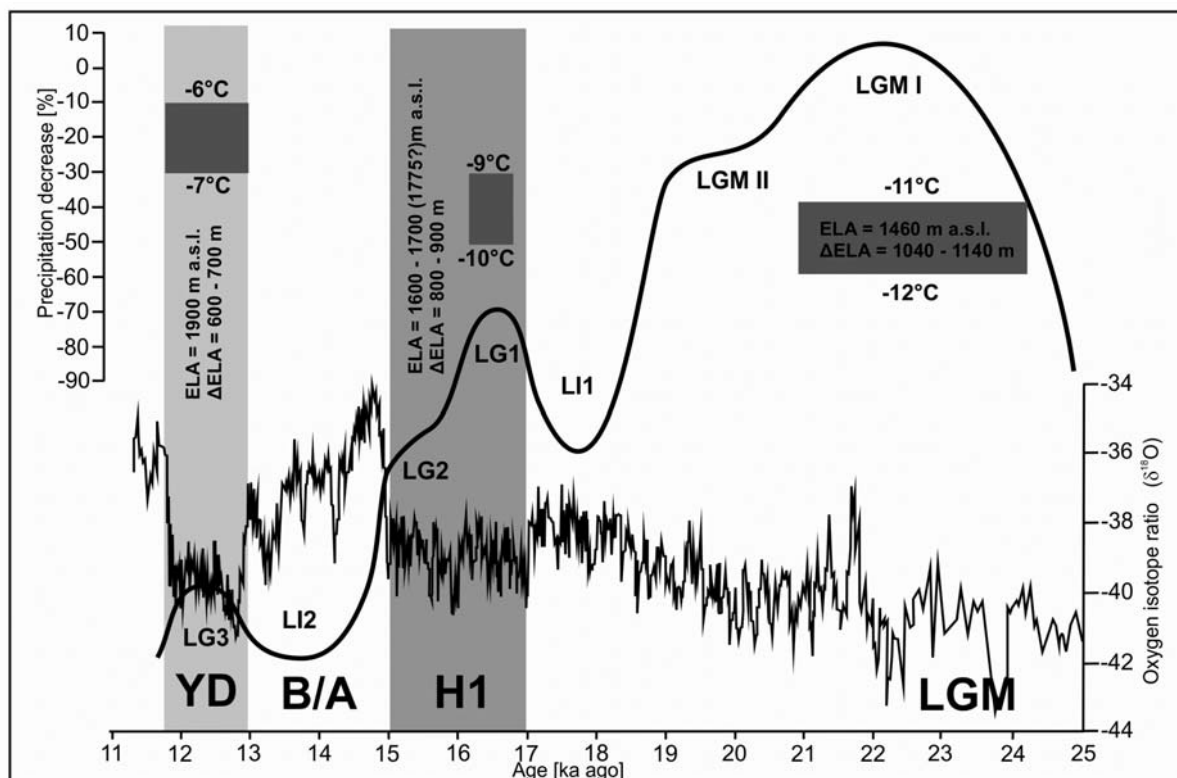
used as a proxy for the modelling of temperature and precipitation at the ELA of a glacier.

Glacier-climate modelling in the Polish and Slovakian Tatra Mountains has yielded very promising results (Makos and Nitychoruk 2011; Makos *et al.* 2013a, b, 2014). During the LGM, the equilibrium line of the north-facing glaciers was located at 1460 m a.s.l. (Text-fig. 11). The ELA of glaciers of southern exposition was located about 150–200 m higher. These glaciers were stable when mean annual temperature was lower by about 10–12°C and precipitation was 40–60% lower in relation to modern values (Makos *et al.* 2014). At the first Late Glacial recessional stage at around 16.5 ka BP, the glaciers in the High Tatra Mountains existed in steady-state conditions when the mean annual temperature decreased by 9–10°C and precipitation was equal 30–50% of modern values (Makos *et al.* 2013a). The ELA rose up to 1600–1700 m a.s.l. In the western part

of the massif, the annual precipitation was probably 10–30% higher and the ELA was located about 100 m lower than in the High Tatra Mountains. The last significant advance of glaciers around 12.5 ka BP occurred when the mean summer temperature lowering reached 5°C and precipitation was reduced by 30% in relation to modern conditions (Text-fig. 11). The ELA was located at around 1900–1990 m a.s.l. at that time (Makos *et al.* 2013b).

CONCLUSIONS

The stratigraphical and palaeogeographical framework of the Quaternary in Poland presented here is still to be completed. However, there are several distinct points that are crucial for further research. Starting from the bottom of the stratigraphical chart of Poland,



Text-fig. 11. Summary of palaeoclimatic reconstructions in the Tatra Mountains (Makos *et al.* 2013a, b; 2014); time ranges of the H1 event (Hemming 2004), the Bølling/Allerød and the Younger Dryas (Rasmussen *et al.* 2014) are indicated; GRIP ice-core record after Rasmussen *et al.* (2014); solid black line shows changes of relative glacier extent during subsequent advances in the study area LGM – Last Glacial Maximum, LG 1-3 – Late Glacial stadials 1-3; LI 1-2 – Late Glacial interstadials 1 and 2, B/A – Bølling/Allerød Interstadial, ELA – equilibrium line altitude of glaciers

it looks obvious that a completely different approach is needed in relation to the so-called preglacial series. The preglacial series that has been accepted for years is undoubtedly of the Early Pliocene age and there is a huge hiatus spanning the Upper Pliocene and most of the Lower Pleistocene.

Geological data suggest that the earliest glaciation in Poland with the Scandinavian ice sheet reaching the southern part of the country, occurred about 900 ka BP i.e. at the end of the Matuyama palaeomagnetic epoch. A setting of the following Podlasian Interglacial is confirmed by the Brunhes/Matuyama boundary in the middle and it corresponds therefore to the classical Cromerian Complex in western Europe. The late Early and early Middle Pleistocene interglacials in Poland comprised 2-3 optima each, whereas each of the younger interglacials was characterised by a single climatic optimum only.

There is already quite a consistent chronological picture of the Late Vistulian glacial phases in Poland. The maximum ice sheet limit was the most extensive in the western part of Poland (Leszno phase) but in central and eastern Poland the younger Poznań phase was

more widespread. This was partly due to the varied distance from the glaciation centre in Scandinavia, making the ice sheet margin to reach its terminal position at different times. Both during the maximum and the most deglacial phases the glacial limits indicated lobate patterns of marginal formations, reflecting outlets of the postulated palaeo-ice streams within the Scandinavian ice sheet to the south of the Baltic Sea basin.

Palaeoclimatological research in the Tatra Mountains supplied with valuable input into the construction of Late Pleistocene and Holocene glacier-climate models (cf. IPCC 2014). As the Scandinavian ice sheet has affected the northern part of Europe during the last glacial cycle, reconstruction of the climate in glaciated mountains in the central and southern parts of the continent has helped to understand the interactions between the ice sheet and the mountain glaciers. It provided new evidence to the atmospheric circulation pattern over Europe during glacial times, which created in consequence, a very useful tool to predict further climatic oscillations dependent on changes in air mass movement directions and moisture inflow in Europe. On the other hand, palaeoclimate research in the low-

land part of Poland suggested that during cold phases of the Pleistocene the climate continentality was weaker eastwards, quite the opposite of that during the warm intervals.

Acknowledgements

The research was funded partly by the Ministry of Science and Higher Education in projects N307 020 32/0544 (MM), 1349/B/P01/2009/37 (LM) and 497/N-BI-AŁORUŚ/2009/0 (LM) and by the National Science Centre in projects DEC-2011/03/B/ST10/06188 (MM), DEC-2011/03/B/ST10/06329 (MS), DEC-2013/09/B/ST10/02118 (BW) and DEC-2013/09/B/ST10/02040 (LM). Fieldwork in the Tatra Mountains were undertaken with permission of the Tatra National Park. Valuable remarks and comments of two anonymous reviewers are greatly appreciated.

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Manuscript submitted: 13th January 2016

Revised version accepted: 30th August 2016