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CHRONOSTRATIGRAPHY OF THE LATE VISTULIAN IN CENTRAL POLAND AND THE CORRELATION WITH VISTULIAN GLACIAL PHASES

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Abstract

The Vistulian decline was a period of rapid environmental events. The authors correlated ages of the last Scandinavian Ice Sheet limits in northern Poland with ages of prominent events adapting the conditions of periglacial environment of Central Poland in response to the Late Vistulian climate warming. Ages from previous thematic geological and palaeogeographical studies were collected. The approach used indicates that despite methodological uncertainties and sometimes inconsistency of ages, it is especially helpful in timing of first warming signals (ca. 19–18 cal ka BP) and establishing of environmentally bipartite 3 millennia of the Oldest Dryas in the extraglacial zone. Abrupt warming at the onset of the Bølling-Allerød is well registered in biotic and abiotic archives available from Central Poland and remains in agreement with the large recession of the southern ice sheet margin.

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Key words: radiometric methods, ^{14}C probability density function, extraglacial environment, last glacial phases, Late Pleistocene

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INTRODUCTION

The cataglacial phase of the last glacial period is clearly manifested in palaeoenvironment. Rapid changes concerned both the glaciated areas, where huge surfaces were successively released from the ice cover, and also an ice-free extraglacial zone. Transition from a glacial to interglacial domain in the non-glaciated areas actually concerned changes of environment which throughout the Vistulian experienced a wide range of periglacial conditions, either permafrost or cold-climate. Dynamic transformation towards moderate Holocene climate followed there global changes expressed in a regional scale in the rate and pattern of the Scandinavian Ice Sheet (SIS) retreat and driven by the same Atlantic air-masses circulation (Marks, 2012; Hughes *et al*., 2015; Moreno *et al*., 2014).

The present study discusses the issue of synchronicity of environmental responses inferred from different archives coming from different realms – glacial and periglacial – and investigated using various approaches, including different dating methods. It is based on the reconstructed palaeoenvironmental events which took place in the old morainic part of Central Poland, in the range regionally named the Łódź Region (Turkowska, 2006), and on the timing of glacial episodes distinguished from the chronology of the Late Vistulian ice sheet readvances and standstills in northern Poland. The age and extents of the Vistulian ice sheet phases in the Polish Lowland have been presented in numerous source publications (eg. Kozarski, 1995; Roman, 2010; Wysota and Molewski, 2011; Marks, 2012).

Also, it was made an attempt to refer to mountain areas of the Carpathians and the Alps. The palaeoecological and geomorphological studies carried out there, supported by reliably dated deposits, served as examples of records of cold or warm phases taking place synchronously to the events observed in Central Poland and in the area of the last glaciation. The general dependence of the evolution of the area of Łódź Region on global factors conditioned by atmospheric circulation in Central Europe and referring to the Greenland cores, has been identified in the multiproxy studies (Dzieduszyńska *et al*., 2014; Dzieduszyńska, 2019), and justifies correlation with these European sites, where similar reactions to global tendencies are also observed at the end of the Vistulian (Rasmussen *et al*., 2014). Being aware of differences between mountain and lowland areas, the authors of the article do not look for direct environmental relations between them.

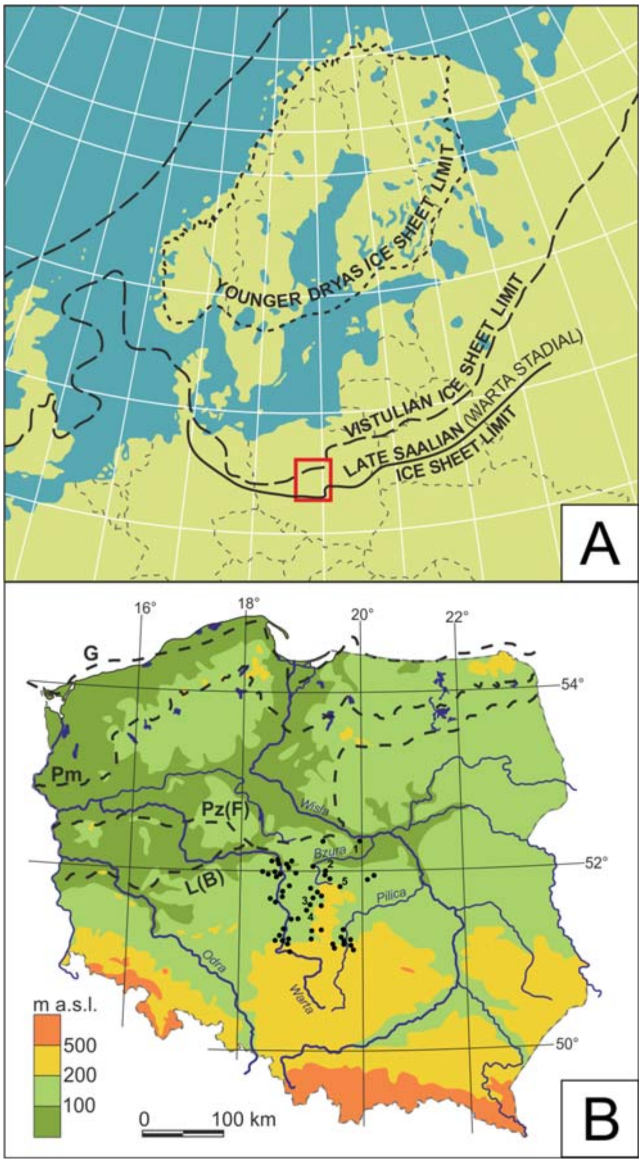

Fig. 1. A. Selected glacial limits with the location of study area (compiled from different authors, see text for references); B. Limits of phases of the last SIS in Poland: L (B) – Leszno (Brandenburg) Phase; Pz (F) – Poznań (Frankfurt) Phase, Pm – Pomeranian Phase, G – Gardno Phase (compiled from different authors, see text for references). Black spots mark sites with radiocarbon data (after Dzieduszyńska, 2019); the localities mentioned in the text have been assigned to the digits: 1 – Kamion, 2 – Witów, 3 – Dobroń, 4 – Aleksandrówek, 5 – Żabieniec.

In the presented contribution the authors aim to compare the stratigraphic boundaries and correlate temporarily prominent events that finally modelled the Pleistocene landscape. Timing correlation of regional periglacial morphogenesis with glacial phases, occurring within neighboring geographically areas, is possible due to recent progress in reliability of dating methods. In previous approaches from the Łódź Region, very general opinion was only presented that the Late Vistulian warming is synchronous with the SIS retreat from the Pomeranian Phase line and no attempts to make chronological comparisons between glacial and extraglacial environments were made (see synthesis of the Vistulian evolution in the study by Turkowska, 2006).

STUDY AREA

The study area is limited from the south by the maximum extent of the late Saalian ice sheet (Warta Stadial) whereas in the north it reaches the LGM ice margin of the Poznań Phase (Fig. 1A, B). The longitudinal boundaries of the Łódź Region are delimited by morphological criteria – in the west the area is bounded by the Warta River valley and in the east by the Pilica and Bzura River valleys (Fig. 1). Most of this area has a typical flat or slightly undulating lowland landscape, with heights between 80 up to 250 m a.s.l. The relief is more diversified, especially in the northern part where the terrain descends through a series of broad flat levels separated by zones of steeper slopes (Fig. 1). The study area remained under periglacial conditions during the Vistulian cold period, which largely remodeled the glacial relief (Turkowska, 2006).

Deglaciation of this area is indirectly determined for the Płock Basin in the Vistula ice lobe using optically stimulated luminescence (OSL) technique at around 18.7 ka (Roman, 2010). At the course of the Late Vistulian progressive warming, the ice sheet retreated northward up from the territory of Poland, and at the very end of the Vistulian (ca. 11.7 cal ka BP) it moved from the standstill position of the Salpausselkä moraines zone in southern Finland (Fig. 1) (eg. Lunkka *et al.*, 2001; Donner, 2010; Hughes *et al.*, 2015). These two dates define our time frame for interpretation in the present study.

The choice of the Łódź Region for discussing the presented issue is supported by reliable geological and geomorphological evidence existing there, in many cases including the geochronological control approximated predominately from radiocarbon dates, gathered during decades of comprehensive palaeogeographical investigations (among others: Wasylikowa, 1964; Manikowska, 1991, 1985; Turkowska, 1988, 2006; Dzieduszyńska, 2011; Forysiak, 2012; Dzieduszyńska *et al.*, 2014; Petera-Zganiacz *et al.*, 2015).

MATERIALS AND METHODS

The source material used in the presented compilation comes from the previously published regional geochronological data. The ages achieved from different radiometric methods were compared and interpreted together which allowed to combine temporarily the discussed events.

Ages of extraglacial deposits

The basic research materials of chronostratigraphy of the Late Vistulian of the Łódź Region is the set of 175 radiocarbon datings obtained there for geological samples (organic mud, peat, gyttja, wood, fossil soil, plant remains, charcoal) derived from all sedimentary environments (Dzieduszyńska, 2019). They come from 55 localities, spaced quite evenly over the study area (Fig. 1B). Source materials: conventional dates (both bulk-sample and AMS ages), after converting into a calendar time scale and using software available (https://c14.arch.ox.ac.uk/oxcal/Oxcal.html), gave finally the updated chronology, with the values of the time boundaries. Description and details of the applied procedure are in the above cited study. In palaeogeographical studies, the idea of interpretation is that for a sufficiently large set of radiocarbon dates, the frequency of their occurrence, reflected by its high or low values, are the result of the presence or absence of phenomena, i.e. depend on environmental conditions.

Ages of glacial episodes

Ages relevant to the SIS advances and retreats during the Late Vistulian in Poland are derived from different dating methods. Age determination of the ice sheet limits by Kozarski (1995) was based on radiocarbon datings of biogenic deposits underlying or overlying glacial series, and on thermoluminescence (TL) dating of aeolian material. The difficulty in using data from that study for correlation purposes are uncalibrated radiocarbon ages, which affected incorrect reference of warmings (interphases) to coolings with ice advances. Dating of ice advances in the Vistula lobe performed by Roman (2010) and Wysota and Molewski (2011) was established on optical luminescence technique (OSL) from fluvial, fluvioperiglacial and glaciofluvial sand. Valuable source of ages of glacial episodes in the Polish territory is the compilation by Marks (2012) with collected radiocarbon ages of organic remains deposited in lake and glaciolacustrine deposits and cosmogenic isotope dates (^{36}Cl and ^{10}Be) obtained for Scandinavian erratic boulders (Rinterknecht *et al*., 2005; Dzierżek and Zreda, 2007).

CHRONOSTRATIGRAPHICAL AND PALAEOGEOGRAPHICAL FRAMEWORK OF THE LATE VISTULIAN IN THE ŁÓDŹ REGION

As demonstrated in the preceding section, a collection of geochronological data was used for estimation of the regional boundaries of particular periods in the Late Vistulian (Dzieduszyńska, 2019), reflected in the course of the probability density function (PDF) (Fig. 2). Its shape also informs about the nature of environmental conditions: peaks reflect warmings, deflections illustrate coolings and steep slopes coincide with changes occurring rapidly (after Michczyński and Michczyńska, 2006).

Discussing the Late Vistulian history of the Łódź Region, it should be kept in mind that on the over-regional scale, geological and environmental processes were certainly influenced by the behavior of the last Scandinavian Ice Sheet. On the global scale, variable climatic conditions of the last glacial period decline which comprise alternating warmer and cooler periods ranging in duration from millennia to decades (according to Greenland ice core chronology, Rasmussen *et al*., 2014) played a role. At the regional level, palaeogeographical evolution was controlled by geological heritage and local morphological conditions which either fostered global changes or remained indifferent (Turkowska, 2006; Turkowska and Dzieduszyńska, 2011).

First signals of a climatic amelioration were registered as early as ca. 18–17 ka cal BP (Fig. 2A). In the palaeogeography of the Łódź Region the age around 18 ka cal BP coincides with stabilization in a fluvial environment followed by a strong erosion (Turkowska, 1988, 2006; Petera-Zganiacz *et al*., 2015). At that time, organic sediments on the terrace of the Middle Vistula River valley at the Kamion site near Wyszogród were laid down (Manikowska, 1985). The radiocarbon results yielded for this horizon are as follow: 14.3±0.3 ka ^{14}C BP (18.1–16.5 ka cal BP) for the bottom, 13.5±0.29 ka ^{14}C BP (17.1–15.4 ka cal BP) for the top, while the resulting date of the sample taken from the whole unit was 14.59±0.27 ka ^{14}C BP (18.4–17.1 ka cal BP) (Fig. 3). Hence the proposal by the cited author to name this period the Kamion Phase, named also Epe in Denmark after Kolstrup (1980). A picture of warming at around that time is provided by a change in cladoceran, chironomid and diatom subfossils recorded in peat archives of the study area (*cf.* Dzieduszyńska and Forysiak, 2015) as well as supported by palaeoenvironmental reconstruction based on radiocarbon data set from the Bełchatów opencast mine (Wieczorek *et al*., 2017).

At about 17.2–14.2 ka cal BP the deflection of the PDF curve dates the Oldest Dryas cooling (Fig. 2A). Its stratigraphic position as the cold period preceding the onset of distinct late glacial warming is in the regional context well established in the palaeogeographical literature, although the timing has not been strictly determined so far (Manikowska, 1985, 1991; Goździk, 1995).

The chronostratigraphical boundaries for the Bølling-Allerød period in the Łódź Region are established at 14.2 ka cal BP and 12.6 ka cal BP (Fig. 2A). It is characterized by climatic instability and abrupt changes of environmental conditions, registered in mineral and biogenic geoarchives of the region (e.g. Wasylikowa, 1964; Manikowska, 1985; Goździk, 1995; Forysiak, 2012). The Bølling (14.2–13.5 ka cal BP) warming was a time of an initial soil development under loose forest vegetation. A short subsequent cooling correlated with the Older Dryas (13.5–13.25 ka cal BP) was recognized as a main phase of inland dunes' formation (Manikowska, 1985, 1991). The Allerød warming occurred between 13.25 and 12.6 ka cal BP and was a time of pedogenesis. The shape of the PDF curve (Fig. 2A) points that the period was tripartite, subdivided by the inter-Allerød cold oscillation between 13.05 and 12.85 ka cal BP. So far, there is no convincing evidence for the reaction of abiotic components of the environment in the study area. The premise of loosening vegetation and ac-

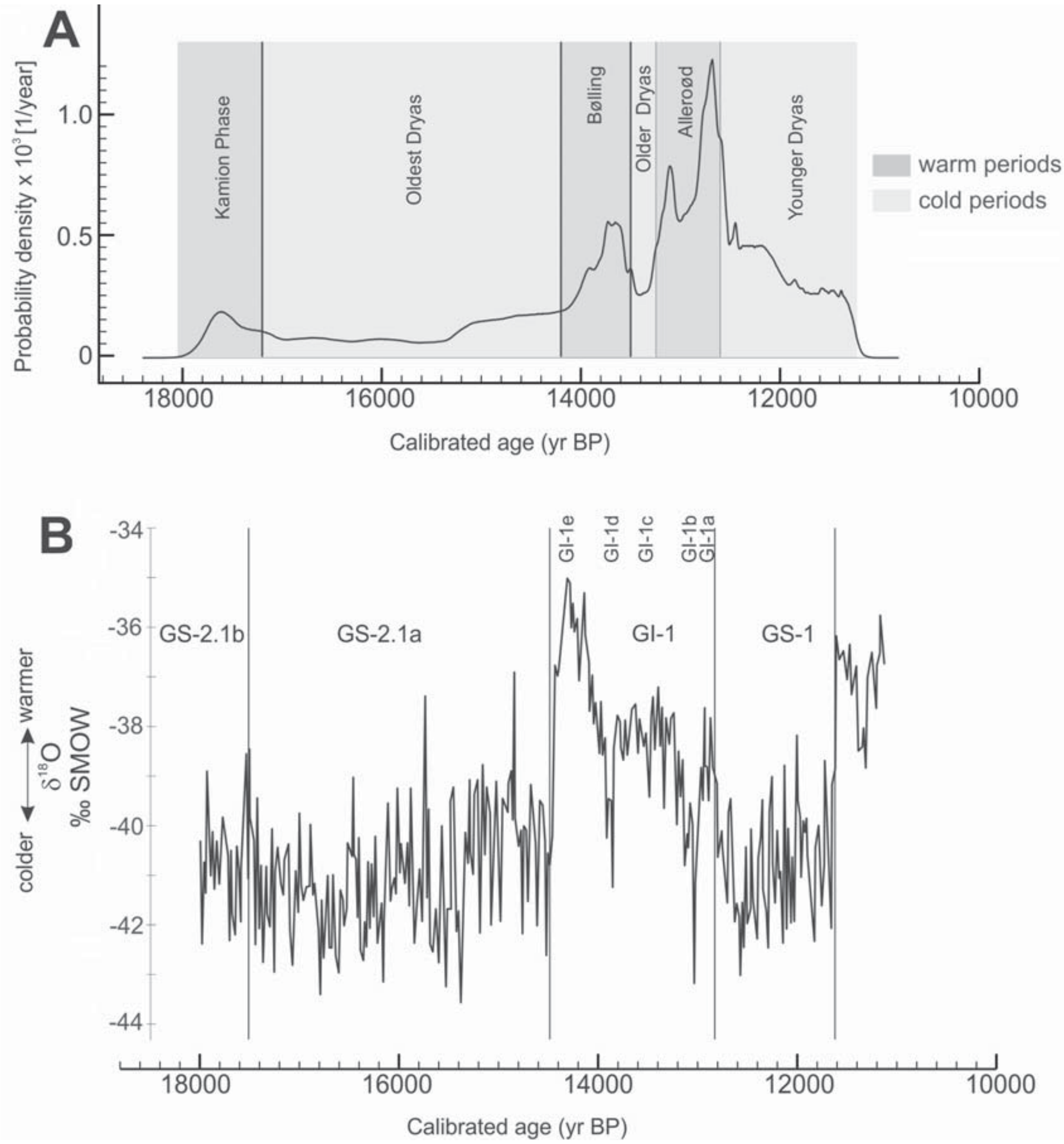

Fig. 2. Probability density function for the radiocarbon dataset from the Łódź Region (after Dzieduszyńska, 2019) (A); oxygen isotope record of the NGRIP core (after Rasmussen *et al*., 2014) (B).

tivation of aeolian processes may be the presence of thin sandy interbeddings reported by Manikowska (1985) for the Allerød pedolith at some localities of the study area (e.g. Aleksandrówek, Dobroń). Some hints for this cold episode come from a chironomid record in the Żabieniec peatbog profile (Płóciennik *et al*., 2011).

The last climatic oscillation of the Late Vistulian is a significant and abrupt cooling of the Younger Dryas (12.6–11.65 ka cal BP). Cooling and accompanying vegetational changes towards a decrease in the forest cover facilitated activation of high energy efficient morphogenetic processes in slope, fluvial and aeolian environments (Dzieduszyńska, 2011). Among environmental changes, a return to aggradation and transformation of a river channel pattern (Petera-Zganiacz *et al*., 2015) are especially well documented.

Chronostratigraphy of the Łódź Region in an over-regional context

Climate oscillations of the Late Vistulian recorded in geoarchives of the study area may be correlated with other independent environmental data. Updated chronostratigraphy of the Łódź Region based on the PDF curve shape (Dzieduszyńska, 2019) was correlated with stratigraphy based on high resolution isotopic dataset in the Greenland ice cores (Rasmussen *et al*., 2014) (Fig. 2B) and multiproxy record from lake sediments of the Meerfelder Maar in the Eifel Region (Litt *et al*., 2001) and the Gerzensee Lake in Swiss Plateau (Ammann *et al*., 2013; van Raden *et al*., 2013).

The initial section of the analyzed time span (up to the Lateglacial warming of Bølling-Allerød) is not strictly defined in the Greenland ice-core isotopic record, but the

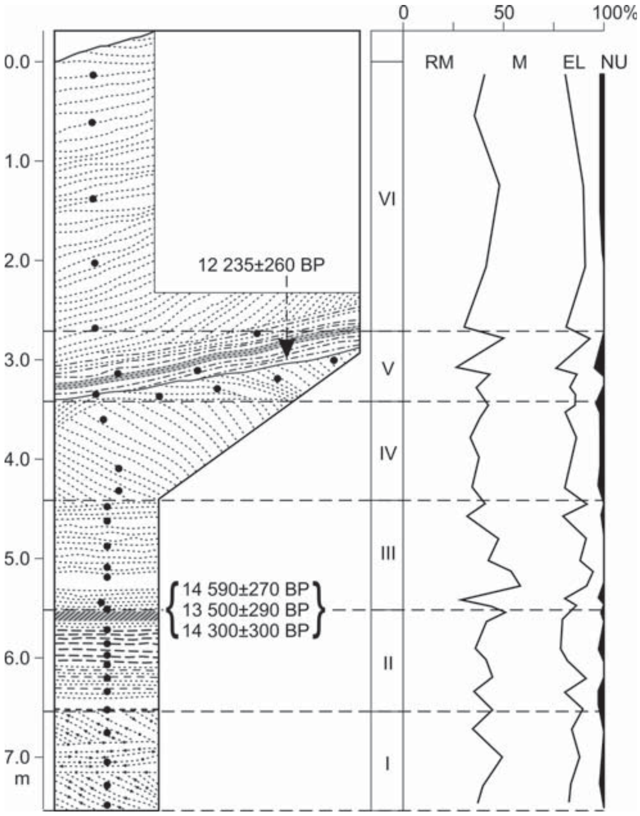

Fig. 3. Kamion sedimentary section and quartz grain abrasion characteristics (after Cichosz-Kostecka *et.al*., 1991). RM – round mat grains, M – intermediate grains, EL – shiny grains, NU – unabraded grains. Calibrated radiocarbon data are given in text.

boundary between GS-2.1b and GS-2.1a cold sub-events is placed at ca. 17.5 ka cal BP, thus similarly to the proposed stratigraphic boundary between the first warming and the cold of the Oldest Dryas in the study area (Fig. 2). Long duration of this cooling is also postulated from the isotopic high resolution record and vegetation succession pattern from the Gerzensee section in Switzerland (Ammann *et al*., 2013; van Raden *et al*., 2013). A different approach is introduced by Litt *et al.* (2001) for annually laminated sediments of the Eifel Region in northern Germany, placing the Oldest Dryas in the Lateglacial between 13.8 and 13.67 ka cal BP. It is because this stratigraphic scheme identifies a preceding early warming (14.45–13.8 cal ka BP) with the Meiendorf phase.

Ages within the Bølling-Allerød chronozone are clearly defined, though there is a shift at its onset – in relation to the Greenland stratigraphy in the Łódź Region it started about 350 years later (respectively 14.55 and 14.2 ka cal BP). Climatic oscillations of the Lateglacial in the record of the study area have equivalents in the 5-fold subdivision of GI-1 period. Similar duration of them was registered in Gerzensee and Eifelmaar. Nevertheless, the main difference concerns chronostratigraphy by Litt *et al.* (2001), where the Bølling was determined as short as 130 years and started ca. 530 years later than in the Łódź Region (see Dzieduszyńska, 2019). There is no doubt about the onset of the Younger Dryas (GS-1), and the difference at the time of its beginning reaches 250 years (12.85 ka cal BP in Greenland vs. 12.6 ka cal BP in the study area – Fig. 2).

It is apparent that the recorded discrepancies in the length of individual intervals and ages of their boundaries differ, which results from lags in climatic shifts of still unknown genesis, from possible terminological and interpretative inaccuracies, and evidently from quality of used data (see Brauer *et al*., 2014). Nevertheless, a quasi simultaneous occurrence of major changes gives ground for claiming about globally deriving mechanism of the Lateglacial environmental events in the study area and therefore for correlation with glacial events, also driven by global causes.

THE LAST VISTULIAN ICE SHEET LIMITS IN THE POLISH TERRITORY

Repeated glacial cycles within the last Vistulian Glaciation are commonly accepted for the area of the Central European Lowland (e.g. Makowska, 1976; Mojski, 1993; Matveyev, 1995; Ehlers *et al*., 2004; Marks 2015). Recognizing of several-phase pattern of the ice sheet advance driven primarily by temperature drop and precipitation increase makes it necessary to accept the existence of periods of milder climatic conditions separating them, which entail ice recession. The oldest and southernmost phase of the ice sheet in Poland was the Leszno (Brandenburg in Germany) Phase (Fig. 1B) which occurred at 24 ka (Marks, 2012).

The younger was the Poznań (Frankfurt in Germany) Phase. Kozarski (1995) estimates the age of the maximum ice sheet extent at 18.8 ka. Following Wysota (2002) and Wysota and Molewski (2011), the ice sheet occurred in Kujawy Region and the northeastern part of Wielkoposka Region between 19.0 and 18.0 ka. The age of the Vistula ice lobe advance (Płock Basin) based on OSL dating is approximated between 22.9 and 18.7 ka (Roman, 2010). Geochronological data, including the cosmogenic isotope ages published by Marks (2012), indicate the interval of 20.0–19.0 ka.

Between the Poznań Phase and the subsequent Pomeranian Phase, some minor glacial oscillations (subphases) occurred, limits of which are expressed by end moraines, most clear in the landscape of Wielkopolska, Kujawy and Dobrzyn lakelands. In the chronology of ice sheet advances by Kozarski (1995) the Chodzież Subphase dated at 17.7 ka was the most prominent.

The ice sheet readvance during the Pomeranian Phase was definitely more important for the relief of northern Poland (Fig. 1B). Studies by Kozarski (1995) show its age at ca. 16.2 ka. Marks (2012) suggests the interval 16–17 ka, but indicates that same cosmogenic results date this phase later. Wysota (2002) gives the age of the maximum extent at ca. 16.5 ka.

The last of the Late Vistulian phases – the Gardno Phase – is not as exactly placed in the chronology as the previous ones. According to Kozarski (1995) it occurred at 14.5 ka. Mojski (1993) claims that it could have been part of recession of the Pomeranian Phase. Also Marks (2012) indicates the lack of clear chronological position of this event, as radiocarbon-dated samples of biogenic deposits from the Gardno Lowland and the southern Baltic Sea Basin gave ages between 16.2 and 15.0 ka. In the study by Marks *et al.* (2016) a date 16.6–16.8 ka for this period is defined.

In the Tatra Mountains glacial events are well correlated with the Late Vistulian ice sheet limits in northern Poland. Marks *et al.* (2016) determine the maximum advance of glaciers in LGM-I and LGM-II phases, for which provide a total time interval of 25–18.5 ka. The following episode LI1 (Late Glacial interstadial) was a warming phase dated between 18.5 and 17 ka. The succeeding period of mountain glaciers expansion occurred at 17–15 ka (LG1 and LG2 – Last Glacial stadials), followed by warming (LI2) between 15 and 13 ka. The last advance of the glaciers in the Tatra Mountains took place at 13–11.8 ka.

DISCUSSION

The Leszno Phase can be only tentatively correlated with the events in the Łódź Region. It is mostly because of lack of sufficient reference in the investigated biogenic deposits either in the material containing organic admixture. In the most complete profile of biogenic sediments at Żabieniec, precise correlation is not possible at the current state of studies, because the age estimates of the sediments do not provide clear results and are roughly dated at ca. 22 ka cal BP, thus the Upper Plenivistulian (Forysiak *et al.*, 2010, Płóciennik *et al.*, 2011).

The geological record in many localities of the Łódź Region contains evidence for the formation of ice wedges, indicative of permafrost conditions. The apogee of the development of such structures is associated with the Upper Plenivistulian, when sand wedges developed. Very cold conditions of an arctic desert promoted formation of autochthonic stone pavements with ventifacts on the plains. Intensive slope processes contributed to development of the allochthonic stone pavement on slopes and in the dry valleys (eg. Klatkowa, 1965, 1996; Dylik, 1967; Goździk, 1995).

The onset of climatic changes at ca. 19 ka terminated the LGM stand of the SIS and the ice margin receded from the Poznań Phase position, possibly followed by subphases as postulated by Kozarski (1995). In spite of the deglaciation, the river network in the Polish Lowland was considerably transformed. Unblocking of fluvial discharge of the pre-Vistula and the pre-Oder systems westwards, activated strong erosional tendencies in river valleys in Central Poland (Wiśniewski, 1987; Turkowska, 1988) and resulted in the morphological development of high terraces. Their surfaces could have been occupied by shallow marshes and early soils, as it was a case at the Kamion site (Cichosz-Kostecka *et al.*, 1991; Manikowska, 1991). Radiocarbon ages obtained there create basis for indication of a warm phase at around 18–17 ka cal BP. An attempt to analyze the pollen composition in the Kamion profile indicated presence of *Betula* and single grains of *Pinus* to be confirmed only (Balwierz, unpubl.), which, however, indicates existence of a plant community, whereas according to Manikowska (1985, 1991) the soil horizons developed. Similar suggestions as to the warming were reported from lake deposits in the Alps (Ammann *et al.*, 2013) and the Carpathians (Magyari *et al.*, 2018), documented as the herb tundra development (Vescovi *et al.*, 2007; Orban *et al.*, 2018). This indicates that warming was recorded not only in the Greenland ice cores, terrestrial sediments and soils of the Polish Lowlands, but also in the mountain lakes in Europe, so it was of global significance.

Subsequent slow cooling caused the Oldest Dryas interval which lasted for about 3 millennia. It is associated with the Heinrich event 1 (Hemming, 2004) in a global context and correlated with the Pomeranian glacial episode and development of mountain glaciers (Marks *et al.* 2016). The periglacial area in the ice sheet foreland experienced intense aeolian processes, as reported from several sites of Central Poland (e.g. Wasylikowa, 1964; Manikowska, 1985; Goździk, 1995; Turkowska, 2006). The palaeosoil in the Kamion section is covered by overbank sands, however dominated by material which was subjected to mechanical abrasion under condition of strong aeolization (Cichosz-Kostecka *et al.*, 1991), expressed in a high content of aeolian (RM) grains (Fig. 3). The overlying series originated in the aeolian environment and according to Manikowska (1991) proves the formation of initial dunes, but the deposited material properties indicate conditions favouring strong mechanical weathering and deflation processes. Thus, in the Kamion section, the Oldest Dryas was bipartite in deposition and likely in climatic conditions. The bipartition of the Oldest Dryas was suggested also by Wasylikowa (1964) from a pollen record of the Witów site in Central Poland. The Oldest Dryas floristic succession is well documented in the Alpine lake archives (Ammann *et al.*, 2013). The vegetation in its older part was characterized by shrub tundra with tree stands, in the younger it was open forest (Vescovi *et al.*, 2007), and both phases were divided by the development of *Pinus cembra*, dated at around 16 ka BP. Similarly, a study of pollen assemblages preserved in lake sediments in the Southern Carpathians shows herb-dominated vegetation between 17.0 and 15.5 BP, followed by establishment of shrubs with increasing amounts of *Pinus* and then *Picea* (Magyari *et al.*, 2018). The examples cited prove that the Older Dryas could have been climatically changing and long-term period, with two advances of the ice sheet and mountain glaciers. Therefore, it is difficult to accept the Oldest Dryas as a 130-year cold at around 13.8 cal ka BP in the record from northern and northeastern Germany (Litt *et al.* 2001). In the records of different areas of the North Atlantic region this episode is an equivalent of Aegelsee Oscillation or Older Dryas (Lotter *et al.*, 1992; Ammann *et al.*, 2013; van Raden *et al.*, 2013).

The rapid climatic warming at the onset of the Bølling coincided with the quick retreat of the Scandinavian Ice Sheet beyond the southern Baltic Sea Basin (Marks, 2012) and the recession of the mountain glaciers (Marks *et al.*, 2016); it was also a time of a northward shift of the Atlantic sea-ice margin, leading to a northward relocation of the Atlantic storm tracks (Moreno *et al*., 2014). The warming is clearly interpreted as the establishment of forest in the European Lowland and in mountain areas (eg. Wasylikowa, 1964; Lotter *et al*., 1992; Ammann *et al*., 1994; Vescovi *et al*., 2007), and the soil development, also on poor dune habitats (Manikowska, 1985, 1991).

There is no agreement as to chronology of further standstills or readvances of the ice sheet margin over the Baltic Sea during deglaciation (*cf.* Marks, 2012), until the area of ice-marginal landforms in southern Scandinavia was reached. End moraines firmly date and create base for reconstruction of the SIS extent in the Younger Dryas (13–12 ka after study by Hughes *et al*., 2015). The Salpausselkä I, II, III moraine chains positions in southern Finland are considered to be the morphostratigraphic determinant of that period and are attributed to the ice sheet readvance. This three moraine lines indicate climatic complexity of the Younger Dryas (Andersen *et al*., 1995), which is credibly registered also in the response of biotic and abiotic components of the environment in Central Poland, including permafrost re-aggradation (see Dzieduszyńska, 2011; Forysiak, 2012; Petera-Zganiacz *et al*., 2015; Petera-Zganiacz and Dzieduszyńska, 2017).

From 19 ka onwards the presence of any evidence of cold is associated with seasonal and perennial frost (Klatkowa, 1996). Cold returns were then not conducive for the formation of mature diagnostic periglacial features, mainly because the atmospheric circulation pattern generated an increasing amount of snowfalls eastwards, which protected the ground from frost penetration (Kozarski, 1993; Isarin *et al*., 1998). Only small-scale features (periglacial involutions, frost fissures, denivation structures, sharp-edged blocks, fragipan layers) developed in the localities favourable to frozen ground re-aggradation, such as beneath peatbogs (Dzieduszyńska and Petera-Zganiacz, 2018).

Summarizing, the available current data are insufficient to make correlation with the environmental events accompanying abrupt climate oscillations of the Vistulian termination. Moreover, it should be kept in mind that still updating chronostratigraphic scheme of the last glacial to interglacial transition based on independent environmental data (ice cores, lacustrine profiles) provides more and more accurate dating and explanation of driving mechanisms of climatic changes. The coupling of high-resolution records obtained for terrestrial environment with less precise glacial phases' timing is not always possible, especially since the ice sheet may remained inactive in response to minor climatic oscillations of decades in duration or perhaps cooling state prevented the ice sheet from readvancing.

CONCLUSIONS

The following conclusions can be drawn from the presented chronostratigraphical data and the critical review of published materials:

- Organic and mineral sediments in geoarchives of the Łódź Region contain a record of successive phases of the Late Vistulian: Kamion Phase, Oldest Dryas, Bølling, Older Dryas, Allerød, Younger Dryas.
- Radiocarbon age determination of these phases along with palaeobotanical characteristics of environmental changes in the Late Vistulian allow to refer to the climatostratigraphical scheme of the glacial phases (advances, standstills, recessions) in central Europe.
- The initial warming of the Kamion Phase (ca. 18–17 ka cal BP) is correlated with the interphase separating the Poznań Phase and the Pomeranian Phase in Poland, whereas in the Greenland event stratigraphy is located at the turn of GS-2.1b and GS-2.1a cold sub-events.
- About 3 millennia of the Oldest Dryas cold (ca. 17.2–14.2 ka cal BP) postulated for the Łódź Region on the basis of the PDF curve is in agreement with the record obtained for the Swiss Alp; it was a period of distinct environmental bipartition, during which the Late Vistulian SIS advanced twice, during the Pomeranian Phase and the Gardno Phase.
- The rapid change of thermal and humid properties of the environment at the turn of Oldest Dryas and Bølling is well registered in biotic and abiotic archives in the Łódź Region as a pronounced warming (Bølling) of a centuries duration (ca. 14.2–13.5 ka cal BP), and remains in agreement with the large ice sheet recession.
- Subsequent phases: Older Dryas, Allerød and Younger Dryas with a well-established chronostratigraphic setting in terrestrial profiles in Europe are also fully confirmed in the examined sites of Central Poland; because of lack of credible glacial data they cannot be correlated with the SIS episodes, until its front position during the Younger Dryas.

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