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Sub- and supra-moraine loesses in the Vistula catchment (Poland) with regard to the age and extent of the Scandinavian ice-sheets

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ABSTRACT:

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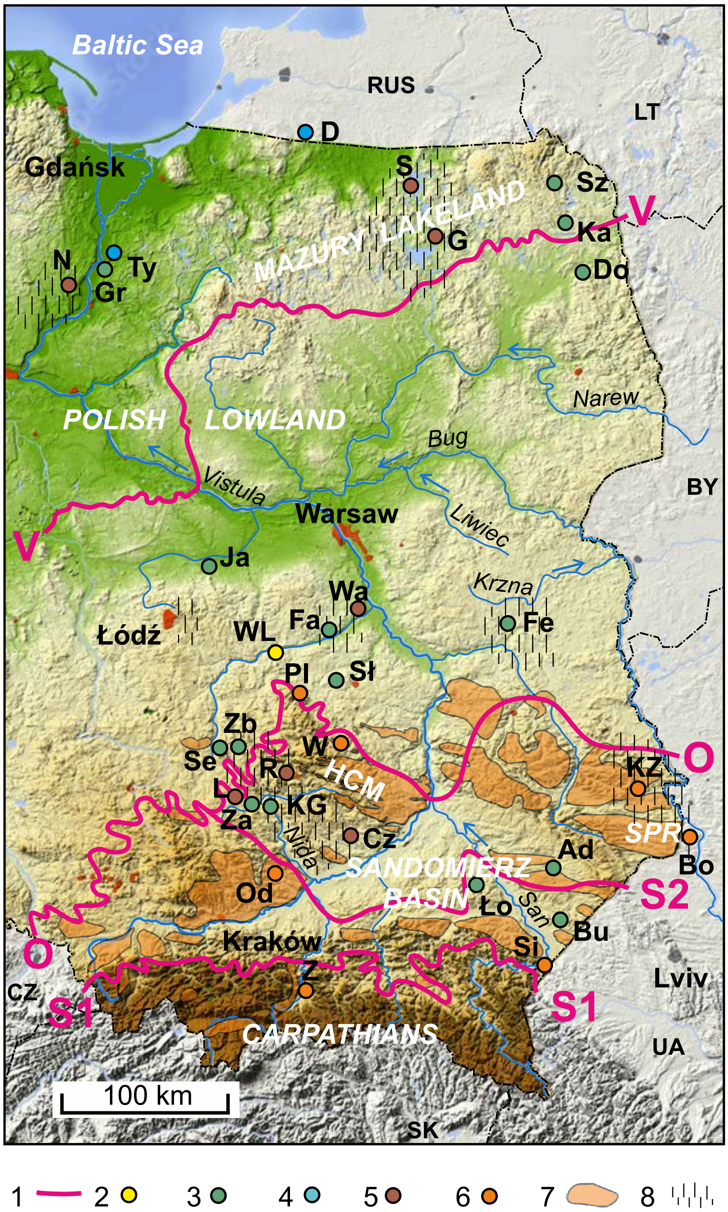
The study focuses on the geochronology and correlation between loesses and glacial tills in the Vistula catchment in Poland, in an area covered by all Scandinavian ice-sheets and characterized by thick loess successions. The basis for this correlation was a litostratigraphic analysis of selected loess sites in the uplands, which are well-documented in the literature, and the occurrences of loess and loess-like deposits under the cover of glacial deposits in the lowland part of the Vistula catchment, characterized by a much sparser documentation. The nomenclature of loess horizons follows Maruszczak (2001) and Kukla (1987), but sometimes is significantly changed, according to modern Quaternary stratigraphical schemes. According to the analysis, accumulation of almost all loess horizons distinguished so far has been documented in the Pleistocene succession of the Vistula catchment: the oldest – lower (LNd), middle (LNs), and upper (LNg); older: lower (LSd), middle (LSs), and upper (LSg); and younger: lowest (LMn), lower (LMd), middle (LMs), and upper (LMg). In most cases loess accumulation took place in steppe-tundra conditions preceding the maximum ice-sheet development during the succeeding Scandinavian glaciations. For selected sites, the loess occurrence is presented in superposition to glacial tills and interglacial deposits. The distinguished loesses and glacial tills are tied to the stratigraphic schemes of the Pleistocene in Poland (Marks *et al.* 2016, 2019) and correlated with Ukrainian loess horizons (Łanczont *et al.* 2019).

Key words: Pleistocene; Climatostratigraphy; Glacial tills; Loess successions.

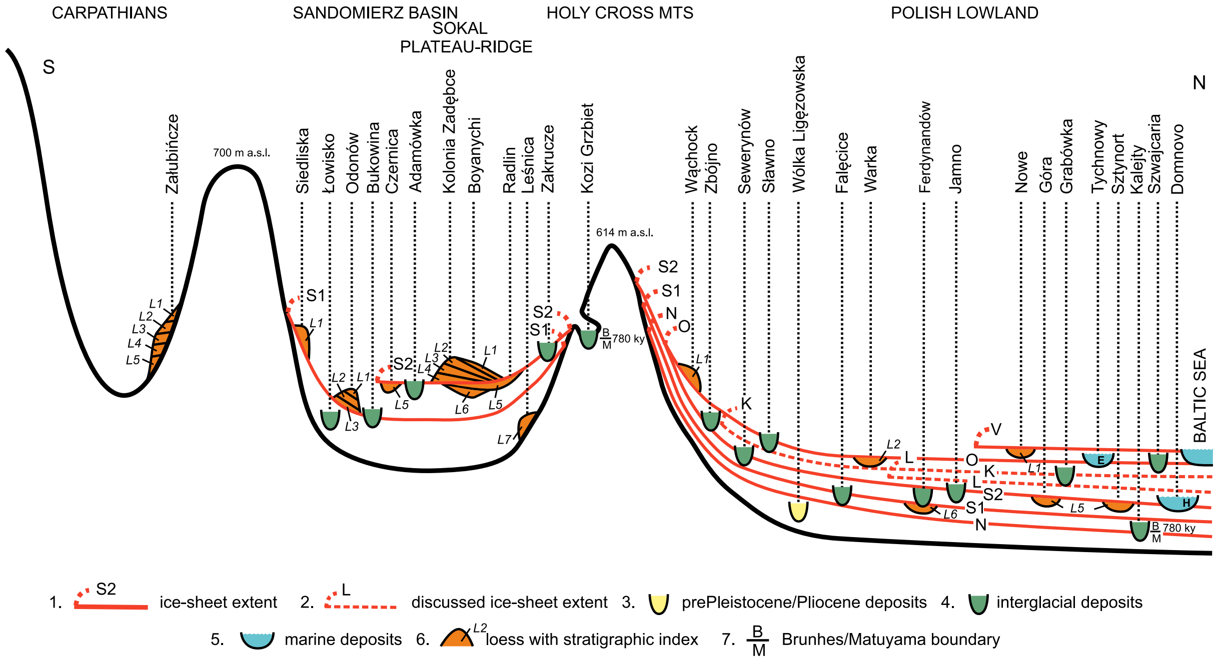
INTRODUCTION

The discussion on Pleistocene stratigraphy in Central-East Europe is dominated by concepts based mainly on the analysis of organogenic deposits separating glacial deposits in glaciated areas or on the analysis of loess successions with palaeosols. This article presents a novel approach to Pleistocene climatostratigraphy based on data from loess horizons coupled with analysis of the overlying or adjacent glacial tills. Taking into account the achievements of the loess research groups in Lublin (Malicki 1950; Maruszczak 1976, 2001; Dolecki 1993, 1995; Łanczont 1995; Łanczont *et al.* 2019, 2022a, b, 2023), Warsaw (Różycki S.Z. 1961, 1972; Straszewska 1961; Straszewska and Kopczyńska 1961; Krajcarz *et al.* 2016), Katowice (Jersak 1973, 1977; Jersak *et al.* 1992) and Wrocław (Jahn 1950; Cegła 1972; Jary 1996, 2007; Jary and Ciszek 2013; Badura *et al.* 2013) supplemented by our own studies (Lindner 1991, 1992; Lindner *et al.* 1998, 2004; Lindner and Bogucki 2002; Dzierżek and Lindner 2020; Chlebowski and Lindner 1992; Dzierżek *et al.* 2020), we would like to emphasize the marked significance of loesses in determining



Text-fig. 1. Location of selected study sites with regard to the main Scandinavian ice-sheet extents in the Vistula catchment (partly based on Dzierżek and Kulus 2023). 1 – ice-sheet extent during the: Sanian 1 (S1), Sanian 2 (S2), Odranian (O), and Vistulian (V) glaciations; 2 – sites with preglacial deposits: WL – Wólka Ligęzowska; 3 – interglacial sites Podlasian (Ło – Łowisko, KG – Kozi Grzbiet, Do – Domuraty, Ka – Kalejty); Ferdynandovian (Bu – Bukowina, Po – Podgórze, Fa – Falęcice, Fe – Ferdynandów); Mazovian (Ad – Adamówka, Za – Zakrucze, Se – Sewerynów, Ja – Jamno); Zbójnian (Zb – Zbójno); Lublinian (Gr – Grabówka); Eemian (Sł – Sławno, Sz – Szwajcaria); 4 – sites with marine interglacial deposits: Holstein (Mazovian) (D – Domnovo), Eemian (Ty – Tychnowy); 5 – sites with sub-moraine loess and loess-like deposits: Cz – Czernica, L – Leśnica, R – Radlin, W – Warka, N – Nowe, G – Góra, S – Sztynort; 6 – sites with supra-moraine loess: Z – Załubińcze, Si – Siedliska, O – Odonów, B – Boyanychi, KZ – Kolonia Zadębce, W – Wąchock, Pl – Politów; 7 – surface loess; 8 – sub-moraine loess and loess-like deposits. HCM – Holy Cross Mountains; SPR – Sokal Plateau Ridge.

the panregional stratigraphy and palaeogeography of areas subjected to the influence of Scandinavian ice-sheets. In general, over the last 800 ky, loess accumulation in central and eastern Europe has been conditioned by global climate changes. Repeated periods of prolonged cold climate allowed transgressions of the Scandinavian ice sheets recorded in glacial till. Each time, the development of the ice sheet was preceded by a period of prevailing periglacial conditions and loess accumulation. The cool periods alternated



Text-fig. 2. Location of selected sites with sub- and supra-moraine loess on the Quaternary climatostratigraphic scheme of the Vistula catchment (after Dzierżek and Kulus 2023, changed). For other explanations see Text-figs 1–3.

with shorter warming phases, during which a denser vegetation cover developed, enabling the formation of soils.

Therefore, beside glacial tills and interglacial organic deposits, loesses with palaeosols are extremely important climatostratigraphic members of the Pleistocene for Central and Eastern Europe (e.g., Kukla and Ložek 1961; Kukla 1975, 1987; Pécsi 1979; Veklich 1979; Lindner 1991, 1992; Mojski 2005; Jary 2007).

The fact that the Vistula catchment (Text-fig. 1) is located along one of the main currents of ice-sheet advance along the Baltic Sea trough (Marks 2005) allows for a mutual analysis of both glacial tills and loess horizons. This is not the case in areas of south-eastern Europe, where climate change in the Pleistocene is recorded “only” in long loess – palaeosol sequences (Marković *et al.* 2015; 2021).

Our analysis shows that loesses occur both below and above glacial tills, a fact that can be observed in drillcores and exposures, respectively (Text-fig. 2). Stratigraphic research of supra-moraine loesses (uncovered by glacial tills) has a long tradition (e.g., Różycki S.Z. 1961; Jersak 1965, 1973; Maruszczak 1972, 1976, 1986; Jersak *et al.* 1992; Łanczont 1995; Jary 2007; Jary and Ciszek 2013), whereas studies of sub-moraine losses are rather scant, despite reaching back to the 1920s (Czarnocki 1927) or 1950s (Karaszewski 1952; Różycki F. 1961). Sub-moraine loesses were mostly documented during intense drilling activities related to the mapping of the area of Poland at the scale of 1:50 000 (e.g., Filonowicz 1972; Walczowski 1972; Makowska 1973; Makowska *et al.* 1976).

The term sub-moraine loesses was first used by Karaszewski (1952) to refer the silty and silty-sandy deposits occurring beneath glacial till or ice-dammed clays in numerous exposures in the Pilica valley escarpment (50 km to the S of Warsaw, Text-fig. 1). Numerous shells of molluscs typical of subaerial loesses: *Succinea oblonga*, *Pupilla muscorum* and *Vallonia tenuilabris* were found in these sediments (Karaszewski 1952). The good state of preservation of shells in the sediments of the fine sandy fraction, in places with traces of layering, testifies, according to the author, to the genesis of the loess in an aquatic or periodically flooded environment. However, this species set of molluscs excludes the possibility of sediment binding to the aquatic environment (Alexandrowicz and Alexandrowicz 1995; Dzierżek *et al.* 2022). Therefore, the genesis of this sediment should be associated with slope loess or colluvial loess, according to Krajcarz *et al.* 2016). The presence of mollusc shells in silty sediments covered by glacial till was also documented in the western part of the Holy Cross Mountains by Poliński (1927). In turn, F. Różycki (1962) described numerous examples of the occurrence of sub-moraine loess in geological drillings in the Lódź region (Text-fig. 1). Further geological studies have led to the finding of further layers of sub-moraine loess in boreholes, up to several meters in thickness in the Lower Vistula and Mazurian regions (Makowska 1973, Makowska *et al.* 1976) and in the area of the Holy Cross Mountains (Łyczewska 1973; Lindner 1988a, b). These sediments were described both as typical subaerial loesses and as loess-like deposits. This motivated the authors to use this documentation for stratigraphic correlation of Pleistocene sediments, as is commonly done for loess profiles found at the land surface.

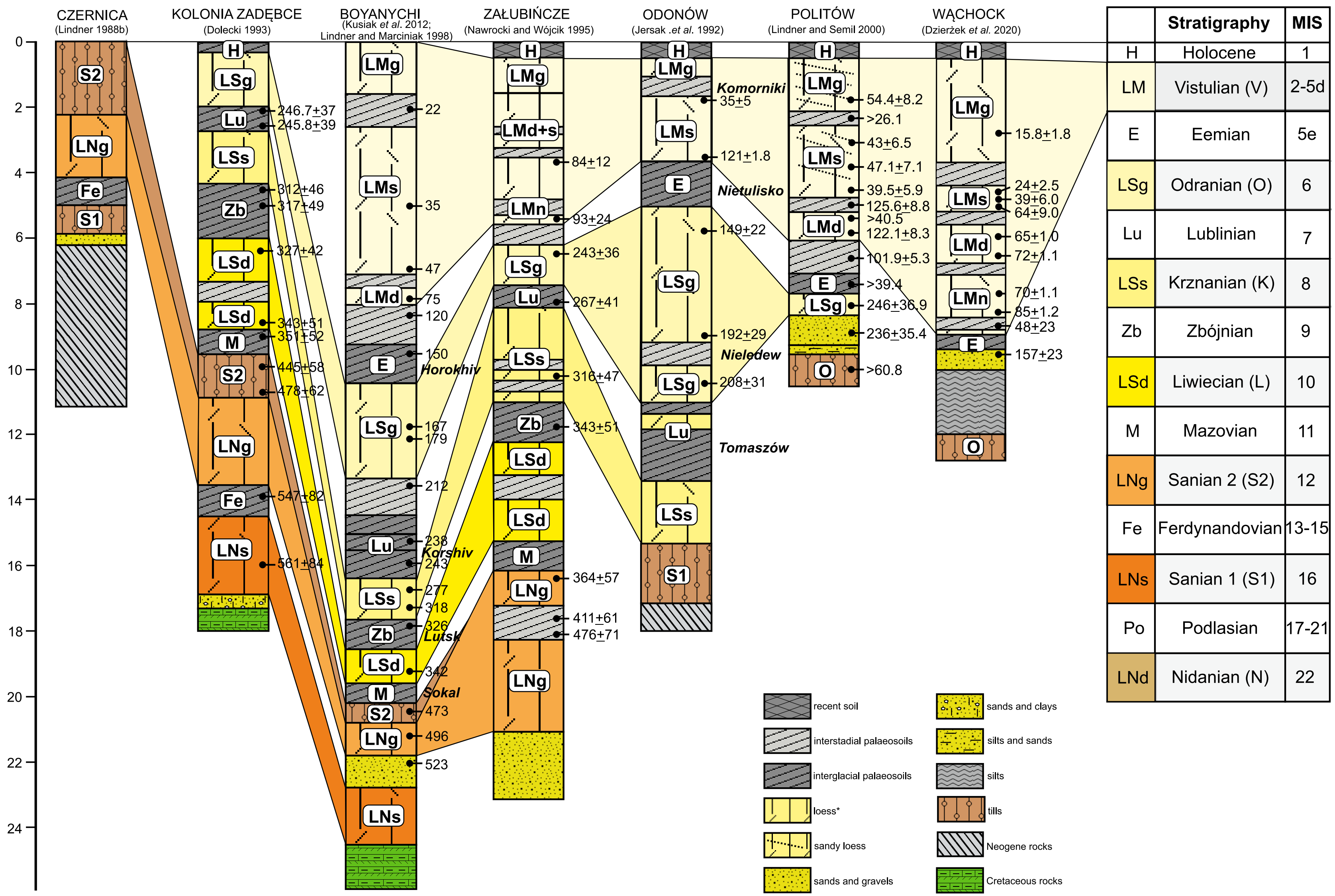
The aim of this study is an attempt to correlate selected loess successions with glacial tills in the Vistula catchment using a framework of the most recent stratigraphic schemes for the Pleistocene of Poland (Marks *et al.* 2016, 2019; Marks 2023) and the climatostratigraphic scheme of Ukrainian loesses (Łanczont *et al.* 2019, 2022a, b, 2023).

MATERIAL AND METHODS

The correlation is based on a lithostratigraphic analysis of the most important loess successions with palaeosols occurring in exposures located in the Polish part of the Vistula catchment, and selected drillcores with documented loess horizons and loess-like deposits (Text-fig. 2). The stratigraphic position of the important sites with documented interglacial flora has also been included. The analysed successions showing the mutual relationships between glacial tills and loesses include: Czernica (Lindner 1988b), Kolonia Zadębce (Dolecki 1993), Załubińcze (Nawrocki *et al.* 1988; Nawrocki and Wójcik 1995), Odonów (Jersak 1977; Jersak *et al.* 1992), Politów (Lindner and Semil 2000), and Wąchock (Dzierżek and Lindner 2020; Dzierżek *et al.* 2020). Data from the Boyanychi succession in Ukraine has also been taken into account (Maruszczak 1994; Bogucki *et al.* 1995) due to its high climatostratigraphic significance and close vicinity to the loesses of SE Poland (Text-fig. 3). The analysed loesses have been marked by the letter symbols proposed by Maruszczak (1976, 2001) and Dolecki (2001), commonly used in Polish loess literature (e.g., Łanczont 1995; Jary 2007), modifying it according to the modern Pleistocene stratigraphy schemes (Lindner *et al.* 2013; Marks *et al.* 2016; Marks 2023; Marks and Jary 2023). Therefore, the original correlation of loess in the analysed profiles with the Marine isotopic stages was also changed. This also resulted in a different correlation of some lithostratigraphic cells with marine isotopic stages compared to the source studies of the analysed profiles. Numerous thermoluminescence (TL) dates of loesses and palaeosols from earlier reports were also used. The datings were made in the 1980s and 1990s, and in most cases are archival (Text-fig. 3). The authors are aware of the debated quality of the TL dating technique used at the time and the limited reliability of the results presented. Methodological differences between the traditional TL method and the high-resolution technique of modern luminescence dating (post-infrared-IRSL method, Moska *et al.* 2015, 2017, 2019) cause limited efficiency in correlating results from the two research techniques. This is shown in the detailed dating of loess in Złota near Sandomierz (Moska *et al.* 2018) where the age of different units of this profile differs significantly in comparison with previous results. However, it was difficult to reject the published TL dates for the analysed loess profiles. Thus, despite the fact that the TL dates are cited in the text and in the figures, this does not mean that they were the basis for the age analysis of the sediments carried out.

The palaeogeographic scheme showing the documentation and stratigraphic position of particular loess horizons with regard to the ice-sheet ranges in the area between the Carpathians and the Baltic Sea (Text-fig. 2) was based on data from the lithological logs of exposures located in the southern part of the Vistula catchment coupled with data on the geological setting of loess-like deposits occurring in drillcores in the remaining area. The scheme combines data on the loess age, the number and age of palaeosols, and the most important sites with documentation of pre-glacial and interglacial deposits in Poland (Dzierżek and Kulus 2023). The distinguished loesses, palaeosols, and glacial tills were correlated with seven cold intervals (Nidanian, Sanian 1, Sanian 2, Liwiecian, Krznanian, Odranian, Vistulian), of which most are characterized by the development of Scandinavian ice-sheets. The presented stratigraphic context and the correlation of particular loess horizons with glacial intervals (Text-fig. 4) includes the numbering of loess horizons (from L7 for the oldest in the study area loesses to L1 for the younger loesses) proposed by Kukla (1987) and recently used in the study of loesses in south-east Europe (Łanczont *et al.* 2019; 2023; Marković *et al.* 2015; 2021).

The authors are aware that treating fossil (sub-moraine) loesses on a par with the well-developed profiles of supra-marine loess may be debatable. However, there are several arguments to support the validity of



Text-fig. 3. Correlation of the main sub- and supra-moraine loess sections in the Vistula catchment and TL ages of loess horizons (after different authors). *colour of loess depends on age; LNd – lower oldest loess, LNs – middle oldest loess, LNg – upper oldest loess, LSd – lower older loess, LSs – middle older loess, LSg – upper older loess, LMd – lower younger loess, LMs – middle younger loess, LMg – upper younger loess, LM – younger loess (undivided).

this concept. First, the geological documentation of the occurrence of sub-moraine loesses in boreholes (and in exposures) was carried out by experienced geologists (Czarnocki 1927, 1931; Karaszewski 1952; Łyczewska 1971; Makowska *et al.* 1976) including by the second author (Lindner 1998a, b). This gives validity to the accuracy of the lithological identification of the sediments in the drillings. These geologists distinguished in their descriptions between typical loesses – similar to the commonly available subaerial loesses – and stratified, clogged loesses, i.e. loess-like sediments accumulated in water bodies or on slopes. Another important argument is the presence in some profiles of a terrestrial snail fauna characteristic of sub-aerial loesses. Under such assumptions, the analysis below is an interesting attempt to use this under-explored documentation to expand the possibilities of regional lithostratigraphic correlation of Quaternary sediments giving a reasonably logical, coherent and reasonably complete view of the Pleistocene environmental changes. The links to long, well-studied profiles of supra-moraine loesses from southern Poland and Ukraine (Jary and Ciszek 2013; Łanczont *et al.* 2019; Moska *et al.* 2015; 2018) as well as the matching of the obtained climatostratigraphic model to oceanic curves, make our proposal worthy of attention in subsequent such analyses.

RESULTS

Oldest loesses (LN)

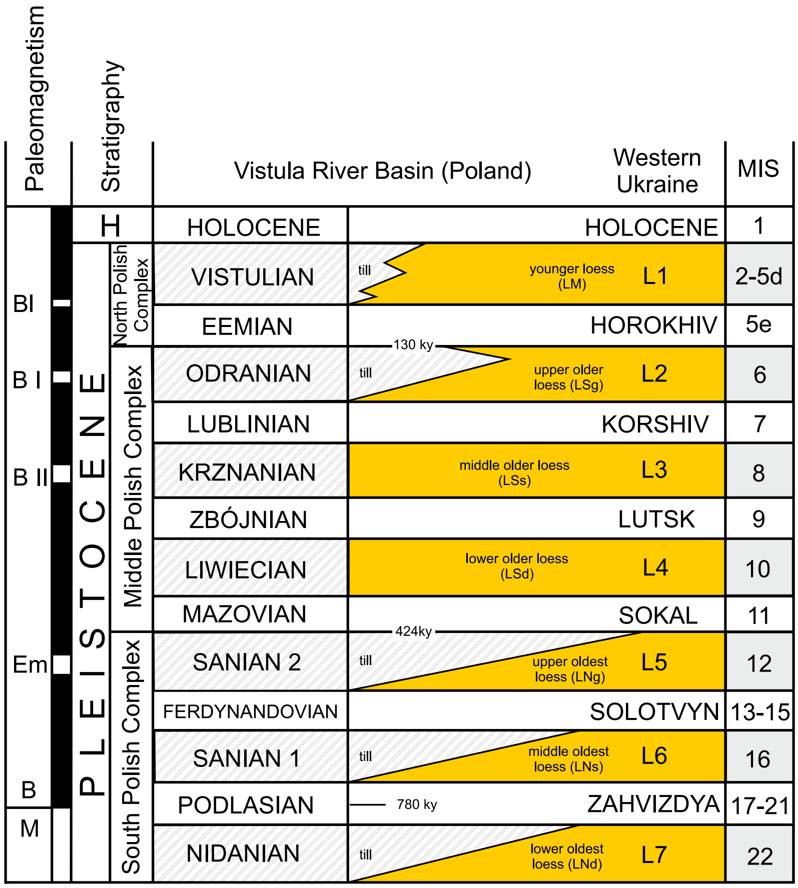
The potential occurrence of the oldest (sub-moraine) loesses in the Vistula catchment was first mentioned for the western part of the Holy Cross Mountains (Czarnocki 1927, 1931; Poliński 1927). These reports were based on analysis of drillcores cut through Pleistocene deposits, including a thick silty series with remains of malacofauna typical of sub-aerial loesses. Worth noting is the fact that they were identified for the first time by Czarnocki (1927), who wrote that "three intervals of loess formation correspond to three phases of glaciations in the central part of the Holy Cross Mountains". Dolecki (1995, 2001) and Maruszczak (2001) saw four levels of loess as the oldest in SE Poland, but their age assignment was in accordance with the Quaternary stratigraphic division of the time (Lindner and Wojtanowicz 1997) and in the light of current research has lost its relevance. Recently, the oldest loess was identified in the lower part of the Biśnik Cave succession in the Polish Jura Chain (Krajcarz 2023).

Lower oldest loess (LNd, L7) – Nidanian (MIS 22)

Following observations in the western part of the Holy Cross Mountains, the oldest loesses in the Pleistocene of Poland are represented by carbonate-free loams and loess loams preserved below silty sands and glacial till of the Nidanian Glaciation (Lindner *et al.* 2013) in the Wierna Rzeka catchment (Lindner 1977, 1980, 1991). In the younger sediments of the Podlasian Interglacial the Brunhes/Matuyama boundary (780 ky) was observed in the nearby site with a Cromerian fauna in Kozi Grzbiet Cave near Chęciny (Lindner *et al.* 2013). The loams, referred to here as lower oldest loess (LNd) reach 10 m in thickness in drillings located near Strawczyn and Ruda Strawczyńska (Lindner 1977), where they overlie older (pre-glacial?) alluvia, and in Leśnica (Text-fig. 2), occurring directly on a Mesozoic basement. Grey and greenish loess-type loams lying in the base of the Pleistocene in the Holy Cross Mountains were already mentioned by Czarnocki (1931, p. 83). In western Ukraine (Text-fig. 4), the equivalent of the lower oldest loess (LNd) is loess L7, older that the Zahvizdya soil complex which also records the Brunhes/Matuyama boundary (Łanczont *et al.* 2019).

Middle oldest loess (LNs, L6) – Sanian 1 (MIS 16)

The middle oldest (sub-moraine) loess (LNs) from the Sanian 1 Glaciation has been recognized in the western and middle part of the Holy Cross Mountains in numerous drillcores, i.e., in Szydłówek, Bodzentyn, Psary and Radoszyce (Czarnocki 1927, 1931; Łyczewska 1971; Lindner 1977). It reaches a thickness of 2–3 m and is described as yellow-brown, $CaCO_3$-free loess loams. The loess has also been registered in the deep river valleys of Wierna Rzeka, Sufraganiec and Silnica, where Czarnocki (1927) discovered and Poliński (1927) described remains of loess malacofauna: *Succinea oblonga* Drap., *Pupilla muscorum* L., *Vallonia tenuilabris* A.Br., *Columella columella* (Mts) Benz. and *Vertigo parcedentata* A.Br. In the southern part of the Holy Cross Mountains loess-like loams of this age are grey-green in colour and contain the above malacofauna (Filonowicz 1972). In the northern foothills of the Lublin Upland and the Mazury Lakeland (Text-fig. 1) loesses have been found under several horizons of glacial deposits at depths of several tens of meters (Makowska *et al.* 1976). In the first area it is represented by loess drilled in three profiles in Ferdynandów (Text-fig. 2), where it lies directly below glacial till presently assigned to the Sanian 1 Glaciation, overlain by an organic series presently associated with



Text-fig. 4. Correlation of the main horizons of glacial tills (grey) and loesses (yellow) of the Vistula catchment and western Ukraine (based on: Marks *et al.* 2016; Łanczont *et al.* 2019). Loess symbols after Maruszczak (2001) and Kukla (1987). Palaeomagnetic epochs: M – Matuyama, B – Brunhes; palaeomagnetic events: Em – Emperor, B II – Biwa II, B I – Biwa I, Bl – Blake.

the Ferdynandovian Interglacial (Janczyk-Kopikowa *et al.* 1981). The thickness of this loess varies from 5 to 10 m and has a high content of the 0.05–0.01 mm fraction (50–80%). Analysis of its clay mineral composition has indicated the dominance of illite (c. 53%) over kaolinite (21.5%) and montmorillonite (averagely 15%), as well as the presence of chlorites (Makowska *et al.* 1976). The cited authors emphasize that the loess contains a large amount of crushed quartz grains (over 50%), and among the heavy minerals – a large amount of ilmenite and the prevalence of garnets over amphiboles. The garnet-zircon-rutile assemblage, characteristic of Upper Cretaceous rocks, may point to the contribution of these deposits as the source of loess silt.

Studies of the Kolonia Zadębce site near Hrubieszów (Text-fig. 1) have indicated that here also occur loess-like loams, TL-dated at 561 ± 84 ky (Dolecki 1993), which in reference to the present state of knowledge of Pleistocene stratigraphy (Marks *et al.* 2016) should also represent the middle oldest loess (LNs). The upper part of this loess, TL-dated at 547 ± 82 ky, is subject to pedogenic processes, according to Dolecki (1993) representing the Ferdynandovian Interglacial (Text-fig. 3). A correlative of the middle oldest loess (LNs) in western Ukraine is loess L6 (Text-fig. 4), preserved mainly in the upper Dniester catchment (Łanczont *et al.* 2019). Another correlative is the oldest loess from Boyanychi (Text-fig. 3), preserved below a sand-gravel series TL-dated at 523 ky (Lindner and Marciniak 1998).

Upper oldest loess (LNg, L5) – Sanian 2 (MIS 12)

In Kolonia Zadębce, the Sanian 2 Glaciation is recorded by loess-like alluvial-slope sediments covered by glacial till (Text-fig. 3). These deposits reach over 4.5 m in thickness, are $CaCO_3$-free and contain 40% of the silt fraction, 35.4% of the clay fraction, and 3.5% of the sand fraction (Dolecki 1993). In the Holy Cross Mountains, $CaCO_3$-free loess of this age (LNg) was observed in road cuts near Radlin (Text-fig. 2) under the youngest glacial till in the area. The position and lithological features of this loess are identical with the sub-moraine loess from Mąchocice upon Lubrzanka, TL-dated at 580 ± 84 ky and correlated with the Sanian 2 Glaciation (Lindner 1988a).

Further to the south, the upper oldest loess (LNg) has been registered in 3 drillcores (Text-figs 1–3): Czernica, Wydymacz, and Kiełczyna, located in the middle part of the Czarna Staszowska catchment to the north of Staszów (Walczowski 1972). In Czernica, the thickness of this $CaCO_3$-free, yellow-brown loess varies from 1 to 10 m, and a palaeosol representing the Ferdynandovian Interglacial is preserved in its base (Lindner 1988b). The glacial till covering this loess (Text-fig. 1) stretches further to the south-east to the Sandomierz Basin (Wojtanowicz 1972; Kwapisz and Szajn 1987; Lindner 1988b).

The upper oldest loess (LNg) has also been recognized in the Masurian Lakeland (Text-fig. 1). Its sub-moraine setting at a depth of over 100 m is evidenced by several drillcores: Sztynort near Giżycko, Góra near Olsztyn, and Jeleń near Karwica (Makowska *et al.* 1976). The best recognized succession of this loess is in the Góra borehole (Text-fig. 2), in which loess loams were probably formed in the marginal part of an ice-dammed reservoir.

A discrete context of the upper oldest loess (LNg) is documented by the Załubińcze section, lying beyond the furthermost range of the Scandinavian ice-sheet (Text-fig. 1). In this section located within a brick pit in the northern part of the Sącz Basin (Butrym and Zuchiewicz 1985; Nawrocki *et al.* 1988; Nawrocki and Wójcik 1995), the loess (loess-like sediment), 6 m thick, covers fluvial deposits from the Sanian 1 Glaciation (Text-fig. 3). It contains an interstadial palaeosol, TL-dated at 411 ± 16 ky and 476 ± 71 ky. The Emperor palaeomagnetic event was noted within this loess (Nawrocki and Wójcik 1995), correlated with MIS 12 (Bleil and Gard 1989) and dated at 472–440 ky (Shackelton and Opdyke 1973).

In many sites, the upper oldest loess (LNg) and the overlying glacial till of the Sanian 2 Glaciation are covered by organogenic deposits representing the Mazovian Interglacial (Mamakowa 2003). In western Ukraine, its correlative is loess L5, underlying glacial till of the Sanian 2 Glaciation in Boyanychi (Text-fig. 3) in the eastern part of the Sokal Ridge (see Lindner 1992), where it is TL-dated at 496 ky (Lindner and Marciniak 1998). It has been also registered in the upper Dniester catchment (Łanczont *et al.* 2019).

Older loesses (LS)

This term refers to 3 main loess horizons occurring in the Vistula catchment and accessible mostly in exposures. The two older horizons have been attributed to eolian accumulation during the Liwiecian and Krznanian coolings (Lindner 1992, 2005; Lindner and Marks 1999, 2008; Marks *et al.* 2019; Marks 2023). In this paper they are referred to the lower older loess (LSd) and middle older loess (LSs). The succeeding supra-moraine loess is the upper older loess (LSg). Its accumulation took place during the Odranian Glaciation. The older loesses occur also in the lower part of deposits infilling the Biśnik and Nietoperzowa caves in the Polish Jura (Krajcarz 2023). The differences in the assignment of older loess horizons compared to the proposal of Maruszczak (2001) are due to the adoption by the authors of this paper of the stratigraphic scheme by Lindner *et al.* (2013) and partly by Marks (2023).

Lower older loess (LSd, L4) – Liwiecian Glaciation (?) (MIS 10)

In the Załubińcze site this loess (LSd) lies on palaeosol developed during the Mazovian Interglacial. It reaches 4 m in thickness and is distinctly bipartite as emphasized by an interstadial palaeosol (Text-fig. 3). A palaeosol TL-dated at 343 ± 51 ky and linked with the Zbójnian Interglacial is developed in its uppermost part (Nawrocki and Wójcik 1995). In Kolonia Zadębce (Text-fig. 3) this loess is also bipartite with an interstadial palaeosol. The lower part of the loess is composed of silt (35–42%), clay (19–26%) and sand (1%), and is TL-dated at 327 ± 42 ky (Dolecki 1993). The upper part of the section is characterized as a loess-like deposit, $CaCO_3$-free and TL-dated at 342 ± 51 ky (Dolecki 1993). In Nieledew near Kolonia Zadębce, the loess is at least 4.5 m thick and covered by palaeosol characterized by spots and traces of gleying processes, probably from the Zbójnian Interglacial (Lindner and Marciniak 1998). There may also be correlated with the Liwiecian interval loam accumulation within the lower Pilica ice-dammed basin. The vast extent of these deposits could have been linked with washing out of the contemporary subaerial loesses probably covering large areas of the Holy Cross Mountains and the Lublin Upland during the interval preceding the Zbójnian Interglacial warming (Lindner and Brykczyńska 1980; Lindner 1992).

The correlative of the lower older loess (LSd) in Ukraine is loess L4 (see Łanczont *et al.* 2019). In

Boyanychi setion (Text-fig. 3) this loess covers the Sokal palaeosol and is TL-dated at 342 ky (Lindner and Marciniak 1998).

Middle older loess (LSs, L3) – Krznanian Glaciation (?) (MIS 8)

In Załubińcze, the middle older loess (LSs) is over 5 m thick and corresponds to three stadials separated by two gley soils of interstadial character (Text-fig. 3). Based on TL-dates of this loess between 316 ± 47 ky and 267 ± 41 ky, Nawrocki and Wójcik (1995) linked its accumulation with MIS 8, at that time attributed to the Odranian Glaciation. The composite lithostratigraphic and palaeopedologic context of this loess, as well as the record of the Biwa II – Chagan palaeomagnetic event (298–290 ky) in its lower part, suggest that this loess should be attributed to the Krznanian Glaciation, according to a later stratigraphic correlation (Marks *et al.* 2016). However, at this stage of studies, an even more complex climatostratigraphic setting in this part of the Załubińcze section should not be excluded. It is characterized by a low content of carbonates (1–4%). The loess overlies palaeosol from the Zbójnian Interglacial, and a forest-steppe chernozem from the Lublinian Interglacial is developed in its top (Lindner 2008). TL dates at 245.8 ± 39 ky and 246.7 ± 37 ky for the chernozem seem to confirm loess accumulation during the Krznanian cooling (*cf.* Marks 2023). In the nearby Nieledew section, the middle older loess (LSs) reaches 1.7 m in thickness. According to Maruszczak (1976) it is less rich in carbonates, and its upper part is clearly modified by younger pedogenic processes linked with the Lublinian Interglacial. In earlier studies, the Krznanian cooling (Lindner 1977) was linked with the younger premaximal stadial (Końskie, Krzna) of the Odranian Glaciation, and even elevated to the rank of a separate glaciation (e.g., Lindner *et al.* 2004, 2013). In the Vistula catchment, deposits of the Odranian and Krznanian glaciations are separated by inter-till organogenic series in Grabówka, Losy and Podlesie (Lindner 2008), which are correlated with MIS 7 (Sejrup *et al.* 1999).

In the Odonów section near Kazimierza Wielka, the middle older loess (LSs) is the basement for palaeosol determined by Jersak (1973) as the Tomaszów-type palaeosol (Text-fig. 3). In the Holy Cross Mountains area this loess is preserved in the Opatów section, where it also underlies a Tomaszów-type palaeosol (Jersak 1973; Jersak *et al.* 1992).

In western Ukraine, in this stratigraphic position lies L3 loess with interglacial palaeosol of the Korshiv horizon in the topmost part, so far referred to the Dnieper Glaciation (see Łanczont *et al.* 2019). In Boyanychi (Text-fig. 3), the age of this loess is TL-dated at 318–277 ky (Kusiak *et al.* 2012).

Upper older loess (LSg, L2) – Odranian (MIS 6)

The upper older loess (LSg), corresponding to the Odranian Glaciation is preserved in a supra-moraine context in almost all exposures in the upland areas of the Vistula catchment and in the Carpathians. Maruszczak (1976) indicated that in Nieledew the loess originally had a thickness of at least 2.5 m and in an unweathered state is characterized by a larger content of carbonates (over 12%) than the lower loess horizons. It covers a Tomaszów-type palaeosol formed during the Lublinian Interglacial and is the basement for the younger Nietulisko I-type palaeosol developed during the Eemian Interglacial and the initial stadial and interstadial units of the Vistulian (Jersak 1973).

In Kolonia Zadębce, the upper older loess (LSg) is characterized by trace contents of $CaCO_3$ (0.5%), probably due to Holocene pedogenic processes. The loess contains 43.5% silt, 27% clay and over 1% sand. It is over 2 m thick and its topmost part is subject to Holocene erosion-denudation processes (Text-fig. 3). Loess covers a palaeosol developed as forest-steppe chernozem from the Lublinian Interglacial (Dolecki 1993; Lindner 2008). In Odonów (Text-fig. 3), the upper older loess (LSg) was subject to TL age determinations at the Silesian University of Technology (Bluszcz 1987), University of Marie Curie-Skłodowska (Butrym 1987), and the University of Warsaw (Prószyńska-Bordas *et al.* 1987), and the obtained dates at 208 ± 31 ky and 149 ± 22 ky allow its accumulation to be linked with the Maximal (Radomka) Stadial, separated by the Nieledew palaeosol from the Post-Maximal (Warta) Stadial within that glaciation (Lindner 2005; Marks 2023).

Probably of the same age is the sub-moraine loess discovered by Karaszewski (1952) near Warka upon Pilica (Text-figs 1 and 2), where it is over 2 m thick. It is characterized by a fawn colour, vertical cleavage, presence of carbonates and a 70% content of silt. The loess contains also a rich malacofauna: *Succinea oblonga*, *Pupilla muscorum* and *Vallonia tennilabris*. Loess probably of the same age, also in a sub-moraine context, is preserved in Brzeżniak ravine, 5 km to the south of Ostrowiec Świętokrzyski, where it lies on a sand series and an underlying glacial till (Kosmowska-Suffczyńska 1972). It should be considered that correlatives of this loess are two horizons of sub-moraine loess (lower and lowermost), described by F. Różycki (1961) in the Łódź Upland. Loess in a supra-moraine context but under a palaeosol from the Eemian Interglacial is preserved in Żurawica near Sandomierz (Straszewska and Kopczyńska 1961). It is also worth noting that the Jamaica (Biwa I) palaeomagnetic event, TL-dated at 180 ky (Bleil and Gard 1989), has been registered in Załubińcze (Nawrocki and Wójcik 1995) and Kolosy (Nawrocki and Siennicka-Chmielewska 1996). This confirms that the accumulation of the upper older loess (LSg) should be linked with the Odranian Glaciation, correlated with MIS 6 (Marks *et al.* 2016).

In central Ukraine, loess L2 determined as Tyasmin is placed in this stratigraphic position (Łanczont *et al.* 2019). In the Boyanychi section (Text-fig. 3) it is TL-dated at 179–167 ky. Moreover, it should be emphasized that based on earlier reports of the Polish-Ukrainian research team on the occurrence of glacial tills in sections containing the upper older loess (LSg) in Poland and central Ukraine (e.g., Stayky, Vyazivok) it can be concluded (Lindner *et al.* 2004) that the Dnieperian Glaciation in the Dnieper catchment is older than the Odranian Glaciation in the Vistula catchment, as evidenced by the most recent correlations of these glaciations with MIS 8 and MIS 6 (see Łanczont *et al.* 2019; Marks *et al.* 2019).

Younger loess (LM, L1) – Vistulian (MIS 2-5a-d)

The younger loess (LM) is characterized not only by its having the largest extent in the Vistula catchment (and beyond), but also a subdivision into maximally four stadial units, referred to as: lowest younger less (LMn), lower younger loess (LMd), middle younger loess (LMs), and upper younger loess (LMg), separated by four horizons of interstadial soils (e.g., Maruszczak 2001; Jary 2007; Moska *et al.* 2018, 2019; Dzierżek *et al.* 2020). In most sections, the younger loess covers the lowest horizon B of the Eemian palaeosol and the overlying chernozem from the Brørup Interstadial (*cf.* Jary and Ciszek 2013), but they do not always contain a complete record of Vistulian changes of climatic conditions, for example the profile Strzyżów (Moska *et al.* 2019). The mutual relations of particular horizons of the younger loess and palaeosols have been shown in Text-fig. 3. The loess reaches the largest thicknesses (exceeding 20 m) in the Lublin Upland in Kazimierz Dolny, Klementowice and Hulcze, as well as in the Carpathian Foreland near Przemyśl in Orzechowce and Jarosław (Maruszczak 1976). Recently, over 10 m of this loess were drilled at Korzecko in the Holy Cross Mountains (Dzierżek *et al.* 2023).

TL dates of the loess from Odonów (Text-fig. 3) indicate that its accumulation began at c. 121 ± 1.8 ky and ended after 35 ± 5 ky (Prószyńska-Bordas *et al.* 1987). It should be emphasized that the younger loess, particularly the upper younger loess (LMg), is characterized by the richest malacofaunal assemblage with *Succinella oblonga* (Drap.), *Pupilla muscolum* (L.) and *Vallonia tenuilabris* (A.Br.), recorded in numerous sites (Alexandrowicz S.W. 1995; Alexandrowicz W.P. 2014). The large content of loess silt in the atmosphere is evidenced by its accumulation close to the outlets of caves registering the presence of Palaeolithic humans in the Holy Cross Mountains (Madeyska 1974) and of most caves in the Polish Jura (Krajcarz *et al.* 2016; Krajcarz 2023). Loess accumulation was possible due to the domination of near-surface western winds at that time (Dzierżek *et al.* 2022).

In Załubińcze (Text-fig. 3), the younger loesses are TL-dated at 93 ± 24 ky (LMn) and at 84 ± 12 ky (LMd+s) (Nawrocki and Wójcik 1995). In the Holy Cross Mountains area, the younger loess occurs on a vast area and has been analysed in several sections, e.g., Podgórze (Straszewska 1961), Nietulisko and Komorniki (Jersak 1973), Polanów Samborzecki (Kusiak and Łanczont 2000; Jary 2007), Złota (Moska *et al.* 2015, 2018), Wąchock (Karaszewski *et al.* 1977; Lindner and Prószyński 1979; Dzierżek *et al.* 2020) and Politów (Lindner and Semil 2000). In the profile Złota with a thickness of 13 m OSL dates obtained on 45–63 µm quartz grains are in the range of 76.7+5.1–20.1+1.5 ky (Moska *et al.* 2015). The profile consists of a pedocomplex correlated with the Eemian and Early Vistulian (MIS 5), less a unit correlated with the Lower Plenivistulian (MIS4), a pedocomplex linked to the Middle Plenivistulian and an over six meters thick Upper Plenivistulian loess unit (Moska *et al.* 2015, 2018).

In the Wąchock section (Lindner and Madeyska 1980), similarly as in Żurawica near Sandomierz (Straszewska and Kopczyńska 1961), a thin layer of loess was observed between the Eemian soil and the upper horizon of gley palaeosol (Text-fig. 3). It may document the earliest Vistulian phase of loess accumulation (oldest younger loess, NLM, *cf.* Dzierżek *et al.* 2020; Dzierżek and Lindner 2020). The Blake palaeomagnetc episode (Tuchołka 1976) is recorded in Nieledew. Moreover, the Wąchock section is, compared to all others, located closest to the sites with sub-moraine younger loess, e.g., Nowe (Makowska 1973) in the range of the

Vistulian ice-sheet (Wysota 2002). This is very important for the correlation of particular horizons of the supra-moraine younger loess with horizons of the sub-moraine younger loess recorded in the lower Vistula valley with post-Eemian marine sediments (see Makowska 1973, 1986; Makowska *et al.* 1976). This correlation shows that the oldest younger loess (NLM) preserved in the Wąchock section can correspond to accumulation during the Herning cooling (Behre 1989) and may be correlated with the interval preceding the first (Toruń Stadial) advance of the Vistulian ice-sheet in the lower Vistula valley (Makowska 1986, 2009). The overlying complex of two interstadial palaeosols (Brørup and Odderade) separated by the lowest younger loess (LMn), TL-dated at 85 ± 12 ky, may correspond to the Gniew interstadial formation (see Makowska 1986), referred to MIS 5a–c. The lower younger loess (LMd), TL-dated at 65 ± 1.0–72±1.1 ky, occurring higher up in Wąchock (Text-fig. 3), may represent the Świecie Stadial (Makowska 1973, 1986) corresponding to MIS 4 (see Dzierżek and Szymanek 2013). In Wąchock, the lower younger loess (LMd) is overlain by two younger palaeosols (Orel and Glinde), middle younger loess (LMs), TL-dated at 39 ± 9 ky, and the Moershoofd + Hengelo + Denekamp palaeosol complex. This part of the section probably corresponds to the Grudziądz interstadial formation in the lower Vistula valley (Makowska 1986; Dzierżek and Szymanek 2013) corresponding to MIS 3. Most loess sections in the southern part of the Vistula catchment are capped by the upper younger loess (LMg) (Text-fig. 3), which developed in an interval preceding the development of the Vistula ice-sheet in the Main Stadial (MIS 2). In some described sections, this loess contains large amounts of sand or sandy interbeddings (Text-fig. 3; Dzierżek *et al.* 2023). The large proportion of coarser grains in younger loess is also documented in high-resolution studies of the Tyszowce, Złota and Strzyżów profiles (Moska et al. 2015; 2018; 2019) and is due to the increase in the rate of accumulation and the close source of material in extremely harsh conditions of climate and environment which dominated at this time. In the lower Vistula valley in Nowe (Makowska 1973), this loess is covered by the youngest glacial till.

In western Ukraine, the younger loess (L1) commonly covering palaeosol of the Horokhiv horizon (Bogucki and Łanczont 2002; Łanczont *et al.* 2019). In Boyanychi (Text-fig. 3), TL dates indicate its age within c. 75 ky (LMd) and 22 ky (LMg) (Kusiak *et al.* 2012).

DISCUSSION

Analysis of the presented data allows for the statement that in the Vistula catchment are preserved traces of accumulation of all loess horizons distinguished in the literature: oldest (lower – LNd, middle – LNs, and upper – LNg), older (lower – LSd, middle – LSs, and upper – LSg) and younger (lowest – LMn, lower – LMd, middle – LMs, and upper – LMg). The oldest loesses, encountered mainly in drillcores, are usually developed as $CaCO_3$-free loess loams, sometimes with loess malacofauna, that were formed from the washing out of subaerial loesses formed in the anaglacial parts of the Nidanian (MIS 22), Sanian 1 (MIS 16), and Sanian 2 (MIS 12) Scandinavian glaciations. Confirmation of mutual relationships between loess accumulation and ice-sheet advance recorded in the form of direct cover of the upper oldest loess (LNg) by glacial till of the Sanian 2 Glaciation has been found in Czernica, Kolonia Zadębce, and Boyanychi. Palaeosol corresponding to the Ferdynandovian Interglacial occurs below the upper oldest loess (LNg) in Kolonia Zadębce and Czernica, whereas an interstadial palaeosol is preserved within the thick horizon of this loess in Załubińcze (Text-fig. 3).

Older loesses (LSd, LSs and LSg) are accessible mainly in numerous exposures and are supra-moraine loesses (Text-figs 2 and 3). They are linked with climate coolings: Liwiecian (MIS 10) – LSd and Krznanian (MIS 8) – LSs, earlier considered as separate glaciations (see Lindner and Marks 1999, 2008; Marks *et al.* 2016), and with the Odranian Glaciation (MIS 6) – LSg (Text-fig. 4). In Kolonia Zadębce, Załubińcze and Odonów these loesses contain palaeosols from the Mazovian, Zbójnian and Lublinian interglacials (Tomaszów-type palaeosol), which correlate well with respective palaeosols recognized in Boyanychi: Sokal, Lutsk and Korshiv (Text-figs 3 and 4). Interstadial palaeosols developed also in middle older loesses (LSs) in Załubińcze and in upper older loesses (LSg) in Odonów.

A significant break in the Upper Pleistocene eolian accumulation is recorded as the Eemian Nietulisko palaeosol in Wąchock, Politów, Odonów and Horokhiv; in Boyanychi it is preserved between the older and younger loess horizons (Text-fig. 3). Pedocomplexes of this age are also well recognized in many other important loess profiles of southern Poland and Ukraine, including Tyszowce, Strzyżów, Złota, Biały Kościół (Jary 2007; Jary and Ciszek 2013; Moska 2017, 2018, 2019), Dubrivka (Łanczont *et al.* 2019) and many others (Maruszczak 2001).

Younger loesses (LM) are recorded in most sections as 3-5 stadial subaerial loesses separated by interstadial palaeosols. Most data on the record of climate change during the Vistulian are registered in the Wąchock section, where the oldest younger loess (NLM) is probably present (Dzierżek and Lindner 2020). Palaeosols and gleying horizons visible in the successions of younger loesses correlate well with the stadial-rank advances of the Vistulian ice-sheet (MIS 5d-a) in the lower Vistula valley and with interstadial horizons separating these advances (see Makowska 1973, 1986, 2009; Dzierżek and Szymanek 2013). The stratigraphic scheme proposed for the Vistula basin generally corresponds to a model based on the analysis of long soil-lesson sequences in extraglacial areas of SE Europe, although it does not record all minor climate changes, especially in the oldest part of the Pleistocene (Marković *et al.* 2015, 2021). In context of the focus of this paper, worth emphasizing is the fact that the remains of the Pleistocene ice-sheets, both those that have a well-determined stratigraphic position (Nidanian, Sanian 1, Sanian 2, Odranian, and Weichselian) and, as well those of a disputed age and range (Liwiecian, Krznanian), are recorded in the Vistula catchment (see Marks 2023). Glacial tills corresponding to these glaciations often occur directly on loesses, which suggests that loess accumulation took place in steppe-tundra conditions preceding the maximum ice-sheet advance during successive Scandinavian glaciations. Such a case in the Vistula catchment, where areas of loess accumulation largely overlap with the ice-sheet ranges of all Scandinavian glaciations is a unique case on a European scale. Moreover, palaeosols with a variable level of development occurring in loess sections in the southern part of the study area document climatic changes of lower rank, with a much higher resolution than in the ancient fluvial or lacustrine sediments. The result is that palaeogeographic correlation based on mutual relationships in the position of glacial tills, loesses and palaeosols, particularly in long successions, is much more effective compared to that based on the analysis of only glacial and interglacial sediments. Traces of palaeomagnetic episodes within the Brunhes Epoch, preserved in loess successions and with precise age assignment, fix this correlation on a geochronological scale. Numerous TL dates taken from the literature for particular loess sections largely confirm the general chronology of eolian accumulation, but due to the diverse methodological approach used in TL age determinations by different laboratories, they were not used directly in the correlation presented here.

We have used geological data acquired at different times and by different research teams, as well as our own results of studies on loesses and glacial deposits. This review paper is a continuation of earlier studies of the second author on the age correlation of loesses in Poland and Ukraine (Lindner *et al.* 2004; see Dzierżek and Kulus 2023). Knowledge on the geological context of many of the cited sections and sites with loesses and glacial tills has enhanced this palaeogeographic correlation. However, taking into account the quality of output data, the diverse research workshop studies of particular sections, the changing knowledge on Pleistocene stratigraphy, or lack of the possibility of modern studies in the most crucial sites with the application of one standard, it has to be emphasized that the presented analysis is only an attempt to combine partial data in a comprehensive history of the succession of eolian and glacial phenomena resulting from climate change in the Pleistocene. We hope that the presented tentative palaeogeography in the Vistula catchment will become a benchmark for further studies on this topic in other areas and serve for potential verification, appropriately to the augmentation of new data.

The presented data indicate that in the Vistula catchment, the distinguished sub- and supra-moraine loesses, and the palaeosols and glacial tills separating them, precisely document the Pleistocene rhythm of climate change, expressed in seven first-rank climatic coolings (see Różycki S.Z. 1972), separated by six interglacial rank warmings (Lindner *et al.* 2013; Dzierżek and Lindner 2019). The most recent publications focused on the Pleistocene of Poland (Marks 2023; Marks and Jary 2023) seem to show evidence that only the first three of these coolings (Nidanian, Sanian1 and Sanian 2) and the two last ones (Odranian and Vistulian) were characterized by the development of glaciations, whereas the middle coolings (Liwiecian and Krznanian) were probably deprived of this possibility. In such a case, when the record of climate change expressed by buried glacial sediments is ambiguous, the study of loesses proves more precise. This is the case especially, since modern high – resolution research methods allow for very detailed analysis of the loess – palaeosol sequences (cf. Marković *et al.* 2015, 2021; Moska *et al.* 2015, 2018, 2019; Łanczont *et al.* 2019, 2022a, b).

A general conclusion from the analysis is that in the study of the climatostratigraphy of Pleistocene sediments, new possibilities and high efficiency of regional correlations are provided by the study of long profiles of loess and the fossil soils separating them, especially when they are preserved in superposition with glacial till.

CONCLUSIONS

- All loess horizons, so far distinguished in the literature (Maruszczak 2001), i.e., oldest, older, and younger, are recorded in the Vistula catchment. Together with the palaeosols and glacial tills separating them, they record the rhythm of climate changes reflected in seven first-rank coolings separated by six interglacial intervals.
- The three oldest loesses: lower oldest loess (LNd, L7), middle oldest loess (LNs, L6), and upper oldest loess (LNg, L5) are preserved in a sub-moraine context. They were accumulated in steppe-tundra conditions preceding the maximum development of Scandinavian ice-sheets during the Nidanian, Sanian1 and Sanian 2 glaciations.
- The two older loesses are preserved both in sub- and supra-moraine settings. They are marked as the lower older loess (LSd, L4) and middle older loess (LSs, L3), and accumulated during the Liwiecian and Krznanian climate coolings. Accumulation of the upper older loess (LSg, L2) preserved in a sub- and supra-moraine context took place in the Odranian Glaciation.
- The younger loess (LM, L1) linked with the Vistulian Glaciation, is preserved in a sub-moraine context only in the lower Vistula valley. In the remaining area as a supra-moraine loess it is sub-divided into four horizons of stadial rank: lowest younger loess (LMn), lower younger loess (LMd), middle younger loess (LMs), and upper younger loess (LMg).
- Pleistocene loesses in the Vistula catchment record four episodes of the Brunhes palaeomagnetic epoch (Em – Emperor, BII – Biwa II, BI – Biwa I and Bl – Blake), allowing for correlation of the analysed loesses and palaeosols with the climatic coolings and warmings registered in deep-marine deposits (MIS 22-1).

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