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# Depositional conditions of the Upper Younger Loess during the Last Glacial Maximum in central and eastern Europe

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## ABSTRACT:

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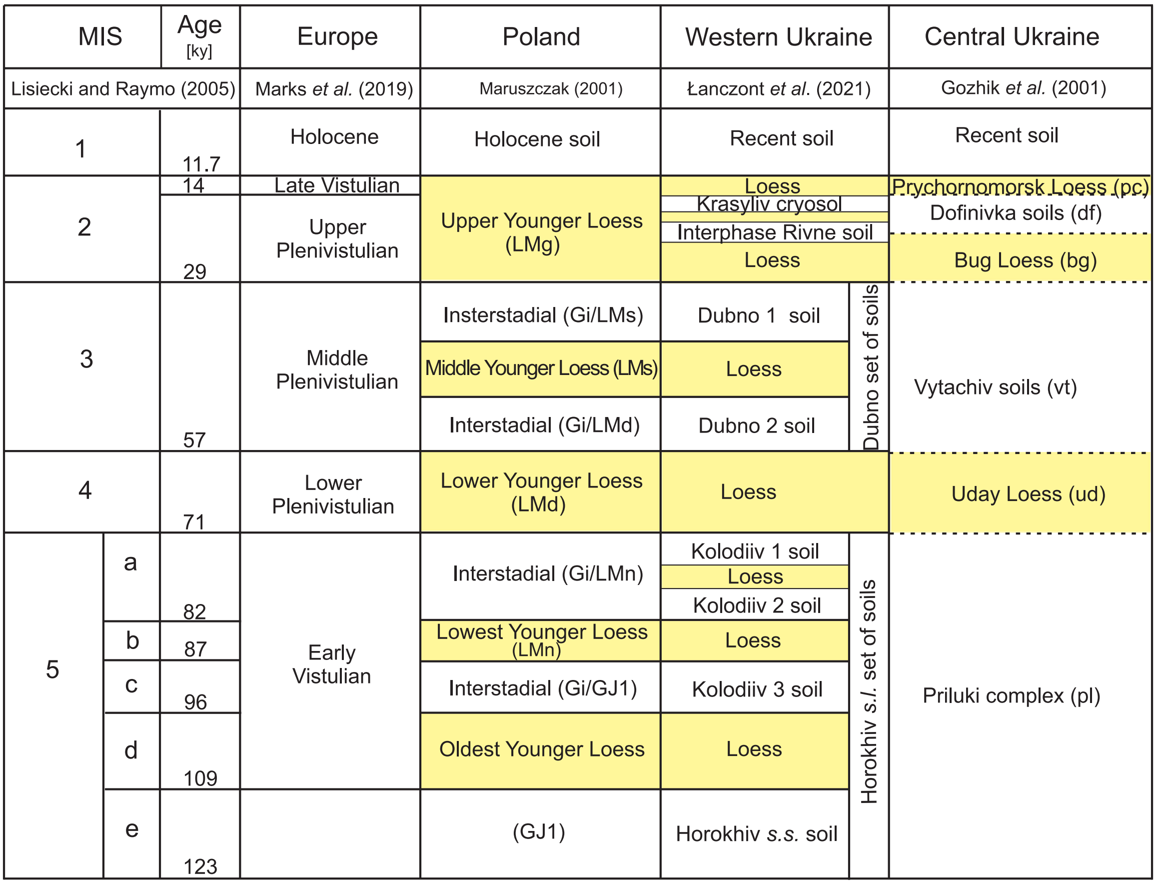
This paper is a summary of the results of research on the accumulation conditions of the Upper Younger Loess (LMg) in Poland and Bug loess (bg) in Ukraine from the maximum stage (MIS 2) of the Vistulian (Weichselian) Glaciation in central and eastern Europe. These studies included an analysis of the morphological (topographic) situation of the loess cover, its grain size and heavy mineral composition, the preserved structures of loess sedimentation as well as mollusc and pollen analyses of this loess. They revealed that the accumulation of Upper Younger Loess (UYL) might have been more dependent on the prevailing moisture conditions than previously thought. These conditions could have been caused by cold air masses from an ice sheet and warm air masses from the Mediterranean Sea and Atlantic coming together in the Carpathians and the Holy Cross Mountains and favouring the formation of dust storms and precipitation. In this process, a loading of loess dust (formed from local rocks weathering in periglacial conditions) by atmospheric moisture particles was especially significant. The moist substrate not only favoured the periodic development of vegetation and molluscs but also enabled the interception of dust and the accumulation of an increasingly thick loess cover. Westerly and south-westerly winds predominated in the UYL as indicated by the topographic position of loess patches and the mineral composition of the studied loess. Periodically an increased air circulation from the east and northeast occurred.

**Key words:** North European Loess Belt; Vistulian Glaciation; Aeolian processes; Palaeowind circulation; Heavy minerals.

## INTRODUCTION

The Upper Younger Loess (UYL), defined by Maruszczak (2001) as LMg in the main loess profiles in Poland, has a strictly defined stratigraphical position correlated with Marine Isotope Stage 2 (MIS 2) (Lindner *et al.* 2004) (Text-fig. 1). In the Ukrainian profiles its equivalent is Bug loess (bg) according to Bogutsky *et al.* (1980) and Szelkoplyas *et al.* (1985) and it is distinguished in the highest parts of prycharnomorsk loess, according to Gozhik *et al.* (2001a). Numerous luminescence dates (both TL and OSL methods) from this loess from the Polish and Ukrainian profiles are mostly in the range of 30–14 ka (Fedorowicz *et al.* 2018; Dzierżek and Lindner 2020; Valde-Nowak and Łanczont 2021; and others). The



| MIS | | Age [ky] | Europe | Poland | Western Ukraine | | Central Ukraine |
|---|---|---|---|---|---|---|---|
| Lisiecki and Raymo (2005) | | | Marks *et al.* (2019) | Maruszczak (2001) | Łanczont *et al.* (2021) | | Gozhik *et al.* (2001) |
| 1 | | 11.7 | Holocene | Holocene soil | Recent soil | | Recent soil |
| 2 | | 14 | Late Vistulian | Upper Younger Loess (LMg) | Loess | | Prychornomorsk Loess (pc) |
| | | | | | Krasyliv cryosol | | Dofinivka soils (df) |
| | | | | | | | |
| | | 29 | Upper Plenivistulian | | Interphase Rivne soil | | |
| | | | | | Loess | | Bug Loess (bg) |
| 3 | | | Middle Plenivistulian | Insterstadial (Gi/LMs) | Dubno 1 soil | Dubno set of soils | Vytachiv soils (vt) |
| | | | | Middle Younger Loess (LMs) | Loess | | |
| | | 57 | | Interstadial (Gi/LMd) | Dubno 2 soil | | |
| 4 | | 71 | Lower Plenivistulian | Lower Younger Loess (LMd) | Loess | | Uday Loess (ud) |
| 5 | a | 82 | Early Vistulian | Interstadial (Gi/LMn) | Kolodiiv 1 soil | Horokhiv *s.l.* set of soils | Priluki complex (pl) |
| | | | | | Loess | | |
| | | | | | Kolodiiv 2 soil | | |
| | b | 87 | | Lowest Younger Loess (LMn) | Loess | | |
| | c | 96 | | Interstadial (Gi/GJ1) | Kolodiiv 3 soil | | |
| | d | 109 | | Oldest Younger Loess | Loess | | |
| | e | 123 | | (GJ1) | Horokhiv *s.s.* soil | | |

Text-fig. 1. The position of the Upper Younger Loess (LMg) in Poland and Bug loess (bg) in Ukraine (after Maruszczak 2001; Gozhik *et al.* 2001a; Łanczont *et al.* 2021) on the stratigraphic scheme of the Vistulian in Europe (after Lisiecki and Raymo 2005; Marks *et al.* 2019).

UYL profiles often comprise thin gleyed soils, and permafrost structures (Łanczont and Bogutskyj 2007; Gozhik *et al.* 2001b; Łanczont *et al.* 2021). Those sediments are typical for periglacial steppe-tundra climatic conditions prevailing in the extraglacial zone during the Last Glacial Maximum (LGM). This period was characterised by favourable (but variable) conditions of loess accumulation in many regions of Europe and the world, among others in central Europe (e.g., Haase *et al.* 2007; Jary 2007; Badura *et al.* 2013; Sümegi *et al.* 2021), in western Europe (e.g., Antoine *et al.* 2009a, b, 2013; Moine *et al.* 2017), in southern Europe (e.g., Marković *et al.* 2009; Jipa 2014), as well as in China (e.g., Kukla 1987; Zhang *et al.* 1994; Xiong *et al.* 2001; Vasiljević *et al.* 2014; Stevens *et al.* 2016) and the North American Great Plains (e.g., Hayward and Lowell 1993; Muhs and Bettis III 2003; Bromwich *et al.* 2005). The LGM climate is characterised by frequent centennial to millennial-scale temporal changes and/or seasonal changes (Dietrich and Seelos 2009; Strandberg *et al.* 2011; Marković *et al.* 2015; Ludwig *et al.* 2016; Moine *et al.* 2017; Schaffernicht *et al.* 2020; Sümegi *et al.* 2021). This resulted in major environmental changes in the areas adjacent to the ice sheet and changes in vegetation further on its foreland (Granoszewski 2003; Mamakowa 2003; Gerasimenko and Rousseau 2008; Komar *et al.* 2009; Łanczont *et al.* 2021). The LGM climate variations are confirmed in the lake cores (Dzierżek and Szymanek 2013; Kalińska-Nartisa *et al.* 2016) and glacial sediments (Dzierżek and Stańczuk 2006; Marks *et al.* 2019) as well as in loess profiles (e.g., Jary 2007; Jary and Ciszek 2013; Jary *et al.* 2021; Łanczont and Boguckyj 2007; Antoine 2009b; Sima *et al.* 2009, 2013; Marković *et al.* 2009; Bokhorst et al. 2011; Lefort *et al.* 2021; Rousseau *et al.* 2021).

These variable conditions are widely discussed in the studies on the genesis and depositional environment of the UYL in central and eastern Europe. The main research problem centres on attempts to reconstruct the directions of loess-forming winds and the role of bedrock in determining the manner of accumulation of this loess. There are opinions on both westerly (e.g., Różycki 1976; Lindner 1976; Cegła 1972; Chlebowski and Lindner 1989, 1992; Chlebowski *et al.* 2007; Paruch-Kulczycka *et al.* 2003; Bokhorst *et al.* 2011; Dzierżek *et al.* 2020) and easterly (e.g., Maruszczak 1967; Jersak 1970; Jersak *et al.* 1992; Marks *et al.* 2019; Pańczyk *et al.* 2020) winds controlling UYL accumulation. However, since the glacial period was generally divided into an oceanic phase (enhanced ice sheet accumulation) connected with westerly winds and a continental phase (enhanced development of the periglacial zone) connected with easterly winds, the process of formation and deposition of loess material should register this bipartite character (e.g., Jahn 1950; Różycki 1976).

After studying for some years the loess in Poland, Belarus and Ukraine (Sanko *et al.* 1980; Chlebowski and Lindner 1992; Lindner 1976; Paruch-Kulczycka *et al.* 2003; Chlebowski *et al.* 2003a, b; 2007; Lindner *et al.* 2004; Dzierżek *et al.* 2020; Dzierżek and Lindner 2020) we tried to verify these issues. We aimed to determine the prevailing direction of loess-forming winds in central and eastern Europe and the relationship between the substrate and the UYL accumulation conditions. We also considered the influence of topographic conditions on the dynamics of aeolian processes.

## GEOLOGICAL SETTING

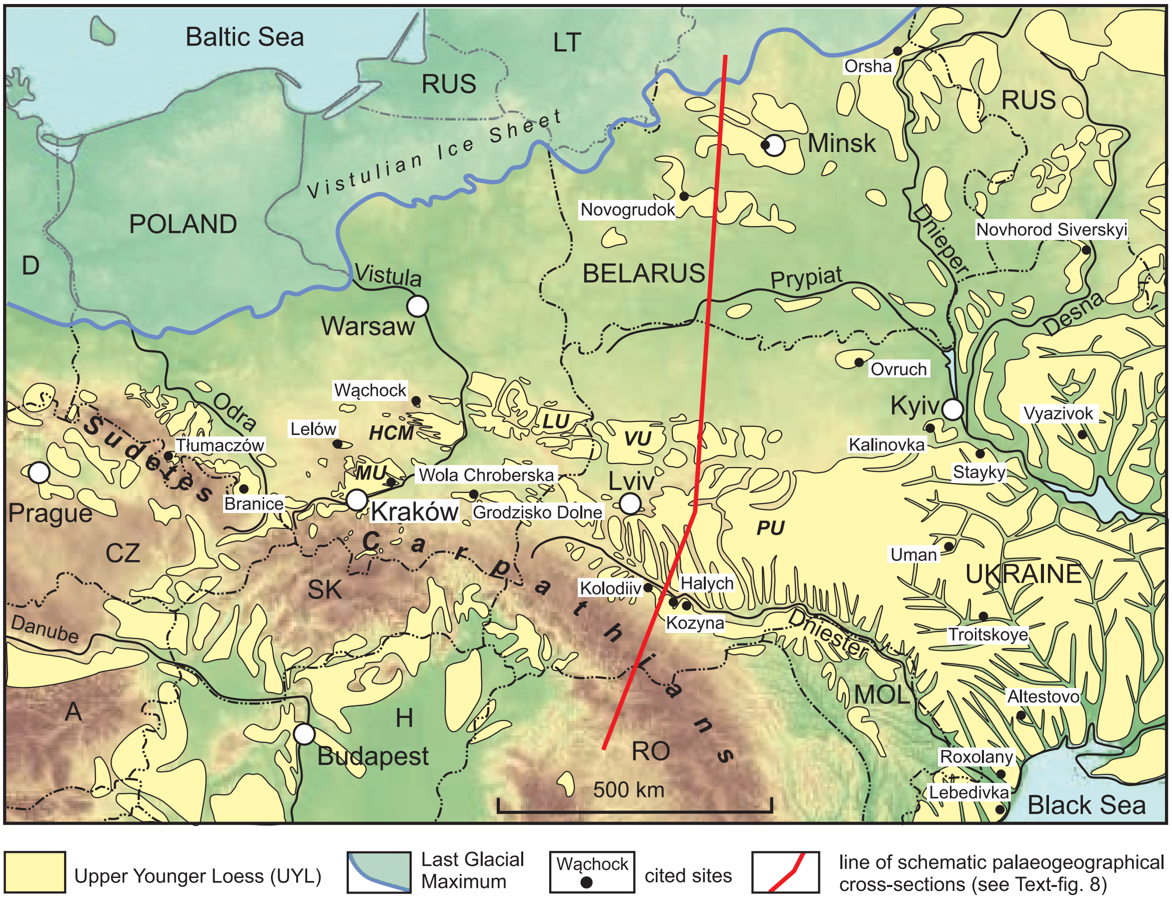
The study area covers a significant part of the northern European loess belt extending from southern Germany, through southern and eastern Poland, to western Ukraine and Belarus (Text-fig. 2). The Upper Younger Loess studied in this paper occurs north of the Carpathian arc (the most spectacular morphological element of the study area) and south of the line of the maximum extent of the Scandinavian ice sheet (SIS) during the last glaciation. Patches of this loess and loess-derived sediments also occur north of this line (Haase *et al.* 2007). Their formation corresponds with the recession of the ice sheet of the Vistulian Glaciation and the shift of the periglacial zone, thus, as younger, they are not included in this analysis.

The central and western parts are the highest of the Carpathians, with the highest peak Gerlach reaching 2655 m a.s.l. They are mainly built of Palaeozoic crystalline and metamorphic rocks, Mesozoic sedimentary rocks as well as the sandstones, shales and conglomerates which are the flysch formations of Cretaceous age. The Eastern Carpathians with the highest peak Hoverla (2.061 m a.s.l.), also made of flysch rocks, extend in a gentle curve from SE Poland and W Ukraine to the central part of Romania, where they turn into the Southern Carpathians.

The Upper Younger Loess forms a latitudinal belt, 50–200 km wide in the west and about 1000 km wide in the east of the study area (Text-fig. 2). In Poland, it forms more or less detached patches in the Małopolska Upland (MU), in the Holy Cross Mountains (HCM), in the Lublin Upland (LU) and also smaller patches in the Carpathian Foreland and the northern foreland of the Sudety Mountains. The Małopolska Upland is an area located on average 200–400 m a.s.l. The HCM with Łysica (612 m a.s.l.) are the highest part of MU and averagely located at 200–400 m a.s.l. In both regions loess contacts laterally with Mesozoic and, more rarely, Palaeozoic bedrock and with the Middle and Lower Pleistocene glacial tills, sands and gravels, as well as with younger fluvial sediments. The Upper Younger Loess covers significantly wider areas in the Lublin Upland. The gentle top surface of the LU rises 200–250 m a.s.l., rarely exceeding 300 m a.s.l. The bedrock of LU is mainly limestone, opoka, gaize, marl and chalk of Cretaceous age, often exposed on the ground surface. Glacial tills and sandy-gravel deposits of both Pleistocene and Neogene age are also present.

In western Ukraine, the Upper Younger Loess (Bug loess) (Text-fig. 1) forms large patches in the Volhynian Upland (VU) and the Podolian Upland (PU). It extends through the Dniester and Dnieper basins to the shore of the Black Sea covering an area of almost 500 000 km$^2$. In central and northern Ukraine a number of large, detached patches (islands) of loess occur in the Ovruch, Novhorod-Siverskyi, Kyiv and other regions (Text-fig. 2). The loess bedrock is built of crystalline rocks and Precambrian sandstones of the Ukrainian Shield. In some places, loess sediments are in lateral contact with Cretaceous rocks, Neogene clastic sediments as well as with glacial and fluvioglacial sediments of the Dnieperian (Odranian, Saalian) Glaciation (Haase *et al.* 2007). The Ovruch loess covers an area of over 4 000 km$^2$ in the western part of the middle Dnieper basin. Its maximum altitude reaches 315 m a.s.l. A smaller patch of loess occurs in the vicinity of Novhorod-Siverskyi in the Desna river basin (a left tributary of the Dnieper river), where its surface lies on average at 180–200 m a.s.l. Another extensive loess patch occupies the area south of Kyiv, where it builds a fragmented surface with an altitude of about 150–200 m a.s.l.

In the northernmost part of the European loess belt, the UYL also forms a fragmented cover with a complex of small detached patches in central and



Text-fig. 2. The occurrence of Upper Younger Loess in central and eastern Europe (after Krasnov *et al*. 1971, 1975; Haase *et al*. 2007) with the location of selected sites and the maximum extent of the Vistulian ice sheet (after Marks *et al*. 2016). *HCM* – Holy Cross Mountains, *MU* – Małopolska Upland, *LU* – Lublin Upland, *VU* – Volhynian Upland, *PU* – Podolian Upland.

eastern Belarus. In the vicinity of Novogrudok a narrow, 15-km-wide and 50-km-long loess island occurs. It is elevated about 200–290 m a.s.l. The loess patch in the Minsk area is much larger (50 km × 70 km). In both regions loess covers and/or contacts with glacial deposits of the Dnieperian Glaciation, including deposits of recessional moraines of that age (Krasnov *et al*. 1971, 1975). In the Orsha area, the studied loess forms a patch with a latitudinal extent of nearly 80 km and a width of up to 45 km, lying 200–250 m a.s.l. (Text-fig. 2).

## MATERIAL AND METHODS

There are over 100 important and well-developed loess profiles with different ages and lithological characteristics in the study area. In this paper we interpret again the previously published results of grain size analyses, heavy mineral composition, structural features and sedimentary structures of UYL, conducted by the authors, among others, in Wąchock, Lelów, Tłumaczów and Branice in Poland, Kolodiiv, Halych, Kozyna, Lebedivka, Roxolany, Altestovo, Troitskoye, Uman, Stayky, Kalinovka, Vyazivok, Ovruch and Novhorod-Siverskyi in Ukraine and Novogrudok, Orsha and Minsk in Belarus (Text-fig. 2). These data are supported by mollusc and palaeobotanical analyses of loess series of the studied area (e.g., Alexandrowicz 1995, 2009, 2011a, b, 2014; Gerasimenko 2006; Alexandrowicz and Dmytruk 2007; Gerasimenko and Rousseau 2008; Rousseau *et al*. 2011; Alexandrowicz *et al*. 2013).

They include, among others, profiles investigated by the authors in Wąchock, Lelów, Tłumaczów and Branice in Poland, Kolodiiv, Halych, Kozyna, Lebedivka, Roxolany, Altestovo, Troitskoye, Uman, Stayky, Kalinovka, Vyazivok, Ovruch and Novhorod-

Siverskyi in Ukraine and Novogrudok, Orsha and Minsk in Belarus (Text-fig. 2). In this paper, we focus on the upper sections of these profiles corresponding to UYL. We interpret again the previously published results of grain size analyses, heavy mineral composition, structural features and sedimentary structures, palaeobotanical analysis of loess series and mollusc analyses.

Archival granulometric analyses from selected profiles of the UYL were used to compare the percentages of the three main fractions: <0.01 mm, 0.01–0.05 mm and >0.05 mm (e.g., Chlebowski and Lindner 1992). The analysis of heavy mineral composition was carried out in the fraction 0.01–0.05 mm. In the optical microscope minerals or groups were indicated (Chlebowski and Lindner 1976). The mineralogical composition of some sandy deposits from the vicinity of loess profiles was also investigated.

The analysis of the topographic position of the loess in the study area included the size of loess patches, their altitude and location in relation to the morphological obstacles. These investigations also took into account the models of aeolian accumulation (Raffaele and Bruno 2019) and the results of studies on directions of aeolian deposition in natural (Lindner 1976; Lindner and Chlebowski 2001) and laboratory conditions (Cegła 1972). Consideration of the conditions of loess accumulation included the results of regional palaeoclimatic investigations for the Late Pleistocene in Europe (Sima *et al.* 2009, 2013; Bokhorst *et al.* 2011; Strandberg *et al.* 2011; Ludwig *et al.* 2016; Moine *et al.* 2017; Marks *et al.* 2019) and other regions (Hayward and Lowell 1993; Bromwich *et al.* 2005; Stevens *et al.* 2016).

Malacological analysis of the UYL loess focused on qualitative and quantitative studies of mollusc assemblages available for the studied region. The most representative and well-developed mollusc-bearing profiles were used to compile the regional malacological succession during the late Vistulian Glaciation (e.g., Alexandrowicz 1995, 2009, 2011a, b, 2014; Alexandrowicz *et al.* 2002, 2013, 2014, Alexandrowicz and Dmytruk 2007; Gerasimenko and Rousseau 2008; Krajcarz *et al.* 2016) . The structure of mollusc assemblages, the ecological tolerance of individual species (especially to temperature and humidity changes) and the occurrence of characteristic species typical of the specific conditions of loess accumulation were especially important. The occurrence of the so-called *Pupilla*-fauna typical of cold and dry conditions and intensive aeolian accumulation, the *Columella*-fauna representing cold and humid phases of moderate loess accumulation, the *Succinella*-fauna (= *Succinea* fauna) characteristic of somewhat warmer and more humid phases of the decadent part of glaciation, and the *Trochulus*-fauna (= *Trichia*-fauna) typical of interpleniglacial conditions (e.g., Ložek 1991, 2001; Alexandrowicz and Alexandrowicz 2011) were crucial for palaeoenvironmental interpretations. Sequences of these faunas from loess series of southern and eastern Poland and western Ukraine (e.g., Alexandrowicz 1995, 2011a, b, 2014; Alexandrowicz *et al.* 2002, 2013, 2014; Alexandrowicz and Dmytruk 2007; Gerasimenko and Rousseau 2008) were used in this paper in reconstructing the conditions of aeolian deposition in the region during MIS 2.

## REVIEW OF PROXY DATA

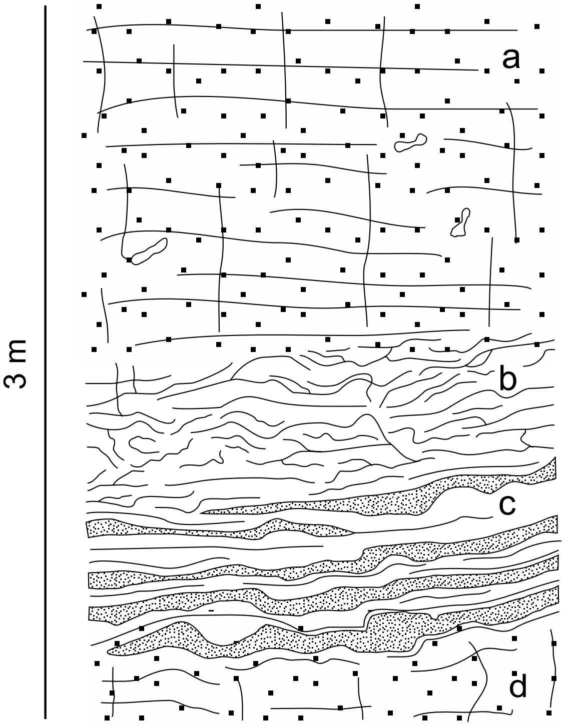
### ‘Loess structures’ and climatic conditions of loess accumulation

Several millimetres thick clay-iron streaks often occur in the subaerial loess. These are the traces of: 1) periodic snowfall melting (so-called “Limon à doublets”; Rousseau *et al.* 2007) or 2) rainfall accompanying the loess sedimentation. In the first case, they are evidence of the so-called niveo-aeolian accumulation of loess dust observed under natural conditions, e.g., in polar areas (Lindner and Chlebowski 2001). The role of soil moisture in loess deposition was also taken into account in the modelling of the LGM environment (Schaffernicht *et al.* 2020). In the second case, the manner of formation of such structures was obtained via a laboratory experiment (Cegła 1967, 1972). Artificial moistening of the surface of accumulated loess resulted in capillary moisture rising, which was essential for the trapping of the loess dust at the site of its deposition (Cegła 1969).

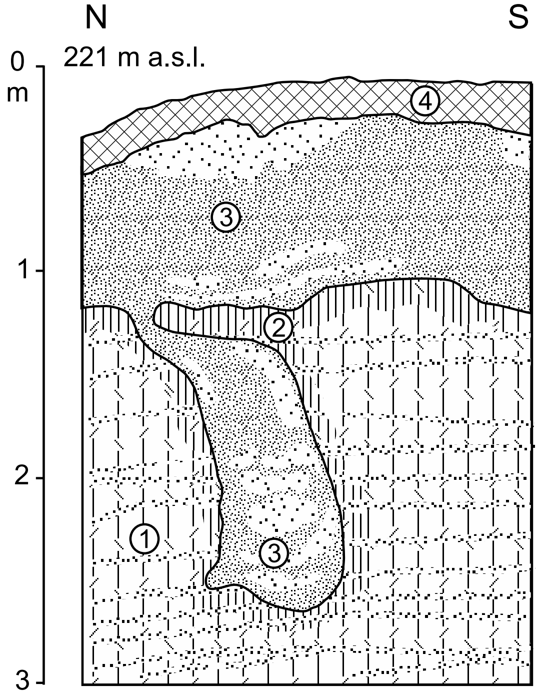
Other structures preserved in loess are traces of the ground ice expressed by short streaks or strongly flattened lenses (Text-fig. 3). They are slightly darker in colour and usually ‘gneissic in structure’ (Cegła 1972). Their formation is associated with winter ground freezing or with seasonal permafrost and indicates strong saturation of the loess with water during its accumulation.

Another type of ‘loess sedimentation’ structure observed in freshly exposed loess walls of the study area are rootcasts of herbaceous vegetation. This vegetation, typical of steppe-tundra conditions, favoured the trapping of loess dust on the accumulation surface. Such structures are often observed in the loess units with tundra palaeosol horizons (Dzierżek *et al.* 2020).

Within loess deposited on slopes and in the vi-



Text-fig. 3. Fragment of loess exposure at Błonie, Lublin Upland (after Cegła 1972). a – streaky loess; b – structures of iron streaks; c – solifluction structures; d – fine streaky loess.



Text-fig. 4. Fragment of loess exposure at Krakowa Góra near Borkowice, Małopolska Upland (after Lindner 1967, modified). 1 – calcareous loess with sand interbeddings; 2 – decalcified loess; 3 – sandy filling of an erosive cut within the periglacial structure; 4 – modern soil.

cinity of elevated areas built of sandstones or kame-type sand forms streaks and interbeddings of sandy material (Text-fig. 4) may often occur. They are up to several centimetres thick and are characterised by the same carbonate content as the parent loess. These interbeddings are observed within the loess patches in the western part of the HCM (Lindner 1967, 1976), in the eastern part of the Ovruch Massif in northern Ukraine and in the region of Novogrudok in Belarus (Chlebowski *et al*. 2007).

In the UYL profiles in both Poland and Ukraine there are also signs of deep freezing (permafrost) documented by 1- to 3-m-deep ice-wedges (Jersak *et al.* 1992; Lindner and Bogucki 2002; Fedorowicz *et al.* 2018). The development of ice-wedges preceded the accumulation of the UYL. They are often filled with this loess OSL and TL dated at 32.2 ± 4.7 ky to 14.7 ± 2.2 ky (Fedorowicz *et al*. 2018) and 24 ± 2.5 ky to 15.8 ± 1.8 ky (Dzierżek *et al.* 2020), which corresponds to MIS 2.

In the study area, the UYL often developed on the moist substratum of uplands and/or on impermeable weathered limestones covered by a residuum of glacial till. The moisture was provided by both periodic precipitation (snow and rain) (Hayward and Lowell 1993; Sima *et al.* 2009, 2013; Ludwig *et al.* 2016) and cyclic permafrost thawing typical of periglacial climates. Generally, the transformation of the oceanic (interstadial) to continental (stadial) phase not only inhibits the transgression of the ice sheet but also causes its recession. Then ablation became the main factor in the disappearance of ice masses (Jahn 1950). In the continental (stadial) phase of the Upper Pleniglacial a cold and dry climate stage (with the easterly winds) and a warm continental stage were distinguished. The latter progressed as the ice sheet vanished and gave way to oceanic influences and the associated predominance of westerly winds (Jahn 1950). These resulted in different interpretations of loess-forming wind directions in Europe: from the western sectors (e.g., Różycki 1976; Lindner 1976; Cegła 1972; Chlebowski and Lindner 1975, 1976, 1989, 1992; Chlebowski *et al.* 2003b; Paruch-Kulczycka *et al.* 2003; Dzierżek *et al.* 2020) and eastern sectors (e.g., Maruszczak 1967; Jersak 1970; Jersak *et al.* 1992; Marks *et al.* 2019; Pańczyk *et al.* 2020).

## Malacological record in the Upper Younger Loess

At least several dozen well-documented mollusc-bearing loess sites are known from southern and eastern Poland and western Ukraine (e.g., Tłumaczów, Grodzisko Dolne, Wola Chroberska, Kolodiiv, Halych, Kozyna; Text-fig. 2) yielding valuable palaeoenvironmental data for MIS 2 (e.g., Alexandrowicz 1995, 2011a, b, 2014; Alexandrowicz *et al*. 2002, 2013, 2014; Alexandrowicz and Dmytruk 2007). They allow the distinguishing of mollusc communities typical of a certain phase of loess accumulation, corresponding with certain climate and environmental conditions (Table 1).

The UYL shows a large variation in the species composition and the structure of mollusc assemblages, which is mostly related to the climatic conditions of loess deposition and the loess facies. The lowest frequency (and the lowest abundance) of molluscs is noted in the loess of upland plateaus, which is often devoid of malacological remains. A more abundant fauna occurs in loess deposited in river valleys, both in loess terraces and slope facies, and in marshy conditions (the co-called swamp loess) (Ložek 1991, 2001; Alexandrowicz 1995; Alexandrowicz and Alexandrowicz 2011).

The diversity of mollusc assemblages often indicates a mosaic of steppe-tundra habitats during loess accumulation in MIS 2 while the succession of molluscan faunas in the UYL perfectly reflects the conditions changing during aeolian deposition in the study area (Rousseau 1987). Especially noteworthy is the (usually) tripartite sequence of loess malacofauna noted in many sites and clearly related to the intensity of aeolian dust accumulation and the prevailing climate (Alexandrowicz 1995, 2011a, b; Alexandrowicz *et al*. 2002, 2013, 2014; Alexandrowicz and Dmytruk 2007).

The early phase of accumulation of the UYL (>25 ka BP) corresponds to a cool and wet climate documented by mollusc assemblages with *Trochulus hispidus* (L.) (Table 1). *T. hispidus* was accompanied by *Succinella oblonga* Drap., *Pupilla muscorum* (L.) and *Vallonia tenuilabris* (A. Br.). Locally some shade-loving species occurred such as *Arianta arbustorum* (L.), *Semilimax kotulae* West. and *Clausilia dubia* Drap. (Alexandrowicz 1995, 2011a, b, 2014; Alexandrowicz *et al*. 2002, 2014).

Along with deteriorating conditions and intensification of accumulation of aeolian dust in the main accumulation phase of UYL (25–15 ka BP), mollusc assemblages became less numerous and diversified under the influence of a very cold (freezing) and dry polar climate (Table 1). Malacocoenoses of arctic steppe predominating in the landscape were dominated by *Pupilla loessica* Lžk., *Pupilla muscorum densegyrata* Lžk. and *Pupilla muscorum* (L.) (*Pupilla*-fauna). In this assemblage *Vallonia tenuilabris* (A. Br.) and *Succinella oblonga* Drap. also occurred. In the most severe conditions, even single-species associations with *Pupilla loessica* Lžk. were found. They were correlated with the least favourable conditions for the fauna development and the most intensive loess accumulation (Alexandrowicz 1995, 2011a, b, 2014; Alexandrowicz and Alexandrowicz 2011; Alexandrowicz *et al*. 2013, 2014). However, it must be highlighted that even in the open areas the presence of malacofauna was favoured by the presence of herb cover (Ložek 1991). Molluscs survive the unfavourable periods in an anabiotic state, increasing their activity in the warmest seasons (Rousseau *et al*. 1994; Krolopp and Sümegi 1995). Some short-term episodes of increased humidity were also noted locally, favouring the development of molluscs with higher humidity demands (e.g., *Arianta arbustorum* (L.), *Columella columella* (Mart.)). They alternated with dry and severe climatic conditions (Ložek 1991; Alexandrowicz 1995, 2014; Alexandrowicz *et al*. 2013).

| Phase of LMg accumulation | Age [ka BP] | Characteristic species | Accompanying species | Climate and environment |
|---|---|---|---|---|
| Late | 15–14 | *Succinella oblonga* (Drap.) | *Pupilla muscorum* (L.), *Vallonia tenuilabris* (A. Br.), *Vertigo parcedentata* (A. Br.), *Columella columella* (Mart.), *Semilimax kotulae* (West.)<br>locally *Galba truncatula* (Müll.), *Pisidium obtusale* f. *lapponicum* Cless., *Pisidium stewarti* Preston | Progressing warming and humidity, tundra-type habitats<br>Development of periodic water bodies |
| Main | 25–15 | *Pupilla loessica* Lžk., *Pupilla muscorum densegyrata* Lžk, *Pupilla muscorum* (L.) | *Vallonia tenuilabris* (A. Br.), *Succinella oblonga* (Drap.), locally *Columella columella* (Mart.), *Trochulus hispidus* (L.) | Cold and dry polar climate, distinct continental features, predominance of arctic steppe, periodic development of herbaceous vegetation |
| Early | >25 | *Trochulus hispidus* (L.) | *Succinella oblonga* (Drap.), *Pupilla muscorum* (L.), *Vallonia tenuilabris* (Braun), *Arianta arbustorum* (L.), *Semilimax kotulae* (West.), *Clausilia dubia* Drap., *Columella columella* (Mart.) | Cool and wet climate, open and slightly shaded habitats |

Table 1. Malacological succession in the Upper Younger Loess (LMg) in southern Poland and Bug loess (bg) in western Ukraine against palaeoenvironmental conditions in MIS 2, based on Alexandrowicz (1995, 2011a, b, 2014), Alexandrowicz *et al*. (2002, 2013, 2014), Alexandrowicz and Dmytruk (2007). Chronology after Alexandrowicz (2014).

The late phase of accumulation of the UYL (15–14 ka BP; Table 1) was characterised by a decrease in the accumulation rate in the region. These changes were connected with gradual amelioration of the climatic conditions – especially with progressive warming and increasing humidity. The prevailing conditions, however, still favoured the cold-loving fauna with the dominant species *Succinella oblonga* Drap. (*Succinella*-fauna). The nominal species was often accompanied by *Pupilla muscorum* (L.), *Vallonia tenuilabris* (A. Br.), and sometimes *Vertigo parcedentata* (A. Br.), *Columella columella* (Mart.) and *Semilimax kotulae* West. (Alexandrowicz 1995, 2011a, b, 2014; Alexandrowicz *et al*. 2002, 2013, 2014). In this phase the moisture of the substratum increased locally, some wetlands appeared and sometimes small, periodic water bodies occurred. The latter was indicated by the occurrence of freshwater molluscs in loess series with abundant *Galba truncatula* (Müll.) and/or cold-loving bivalves *Pisidium obtusale* f. *lapponicum* Cless. and *Pisidium stewarti* Preston (Alexandrowicz 1995; Alexandrowicz *et al*. 2002; Alexandrowicz and Alexandrowicz 2011). It is noteworthy that the described mollusc assemblages share many similarities with the loess fauna of other European profiles (e.g., Ložek 1991, 2001; Sümegi 1995, 2005; Rousseau 1987, 2001; Frechen *et al*. 2007, Moine 2008, 2014, Antoine *et al*. 2009b; Sümegi *et al*. 2011).

## Pollen record in the Upper Younger Loess

Based on the pollen analysis carried out in benchmark profiles in western Ukraine and Poland (Komar *et al*. 2012) as well as in central Ukraine (Gerasimenko 2006; Gerasimenko and Rousseau 2008; Rousseau *et al*. 2011; Gozhik *et al*. 2014) it appears that accumulation of the UYL occurred in a cold steppe with sparse plant cover. Pollen spectra of loess series show the predominance of non-arboreal pollen (NAP) and the significant contribution of pollen of arcto-boreal plants (*Betula* sect. Nanae et Fruticosae and *Alnaster*) and Gramineae throughout the whole UYL unit. Arboreal *Betula* and *Picea* (and even single *Corylus*) pollen occur only in embryonic soils. These paleosols presumably correspond to the interstadials described in western Europe and which are correlated with the Greenland interstadials (Rousseau *et al*. 2007; 2021; Sima *et al*. 2013; Jary *et al*. 2021). In NAP of embryonic soils Herbetum mixtum predominates, being also quite abundant in the lowermost loess layers (Gerasimenko 2000).

Palynological studies of organic deposits located in Poland between the HCM and the front of the Vistulian ice sheet indicate that the mid-arctic climate (which transformed into a high-arctic one as the ice sheet approached) favoured the accumulation of UYL in these mountains (Mamakowa 2003). In the central part of eastern Poland (Granoszewski 2003) an increase in herbaceous pollen (up to 83%) and abundant taxa of dry and steppe habitats (including *Linum* t. *austriacum*, *Bupleurum*, *Jesione*, *Hernaria*, *Heliantheum* t. *nummularium*) points to the expansion of steppe-tundra communities at that time.

The organic sediments directly underlying the UYL in Nowa Huta near Cracow – dated by the radiocarbon method at 20 560 ± 735 y BP and 18 460 ± 250 y BP – document the NAP content of above 80% and relatively abundant pollen of *Betula* t. *nana* and *Salix*. These indicate the dominance of sedge-grass communities and wet tundra in the region, whereas in dry habitats the patches of tundra vegetation with *Heliantheum* t. *nummularium*, *Plantago media* and *Polygonum* t. *aviculare* occurred (Mamakowa and Środoń 1977).

## The influence of bedrock morphology on loess accumulation

Amongst numerous studies of the Upper Younger Loess in the western part of the Holy Cross Mountains and in Ukraine and Belarus (Chlebowski and Lindner 1975; Lindner 1976; Chlebowski *et al*. 2007; Dzierżek *et al*. 2020; Dzierżek and Lindner 2020), in particular those focused on the analysis of isolated loess patches provide important data on the conditions of UYL accumulation. These loess deposits are mainly preserved on the eastern slopes of higher grounds composed of pre-Quaternary rocks or on the elevated glacial landforms from the Odranian Glaciation. They have an almost latitudinal position, occur at an altitude of 200–300 m a.s.l. and are up to a dozen kilometres wide. They are usually limited by morphological edges, up to several metres high, on both the northern and the southern sides.

This morphological situation of loess patches (Lindner 1967, 1976; Madeyska 1982; Dzierżek *et al*. 2020) is in accordance with the results of modelling of the conditions of aeolian accumulation in dust tunnels and around civil structures (Luo *et al*. 2014; Raffaele and Bruno 2019). These experiments allow us to assume that the dust deposition in these patches was induced by westerly winds in zones of reduced air current velocity, i.e. mainly on the leeward side of the hills (Lindner 1976; Bromwich *et al*. 1993; Sima *et al*. 2009, 2013).

The schemes previously presented by Maruszczak (1967) and Jersak (1970) regarding the accumulation of Polish loess by winds from eastern sectors (including the windward slopes) cannot be reconciled with the actual distribution of the UYL loess patches under study, as well as with the regularities of aeolian accumulation in the leeward zones of elevated areas. This supports the earlier conclusion of Sima *et al.* (2009, 2013) and Rousseau *et al.* (2014).

According to Maruszczak (1967), the main mass of the loess dust of the described area was transported by easterly winds over a short distance in the near-surface levels of the atmosphere and deposited on the windward slopes. The development of these winds was determined by anticyclones associated with the SIS and the periglacial conditions prevailing at that time. Examples of decreasing thickness of the UYL towards the west were also supposed to provide evidence for an eastward direction of loess-forming winds (Jersak *et al.* 1992). This opinion and the consideration of the Vistula valley as a source of thicker material for the Opatów-Sandomierz Loess Belt are difficult to accept. It should also be noted that in the opinion of Maruszczak (1967), the accumulation of loess to the south and west of the periglacial zone – within the range of cyclones of the Mediterranean region – could, however, be the result of accumulation by westerly winds.

The observations also suggest that the bounding edges of the individual loess patches in the above-mentioned areas, as well as most of the UYL patches in the Lublin Upland, are accumulative in nature. The lack of large loess areas in the northern foreland of the Sudety Mountains (Jary 2007) and the western part of the HCM (Chlebowski and Lindner 1992) may point to a greater strength of the prevailing aeolian processes compared to eastern Poland and central Ukraine. A higher intensity of aeolian processes in the western part of the HCM may also be inferred from the distribution of sandstone tors in this area. They are corrasion and deflation in origin and were modelled by surface winds favouring the accumulation of the UYL (Lindner 1976; Chlebowski and Lindner 1992).

## The influence of bedrock on granulometric and heavy mineral composition of the Upper Younger Loess

### *Granulometric composition*

The analysis of the granulometric composition of the UYL was carried out in 55 loess profiles from the Małopolska Upland and the Holly Cross Mountains. Except for the loess from the northern part of the MU, which shows a clear increase in the percentage of the 0.01–0.05 mm fraction, no significant differences in the granulometric composition of this loess were noted (Chlebowski and Lindner 1992). The differences in the Malopolska Upland (MU) result from the fluvioglacial origin of the source material. Similarly, the loess of the northern margin of the Central Carpathians indicates a distinct connection with the local rocks of the Carpathian flysch (Łanczont 1995). According to Smalley *et al.* (2009) local material, especially fluvial in origin, is the main source of loess accumulation.

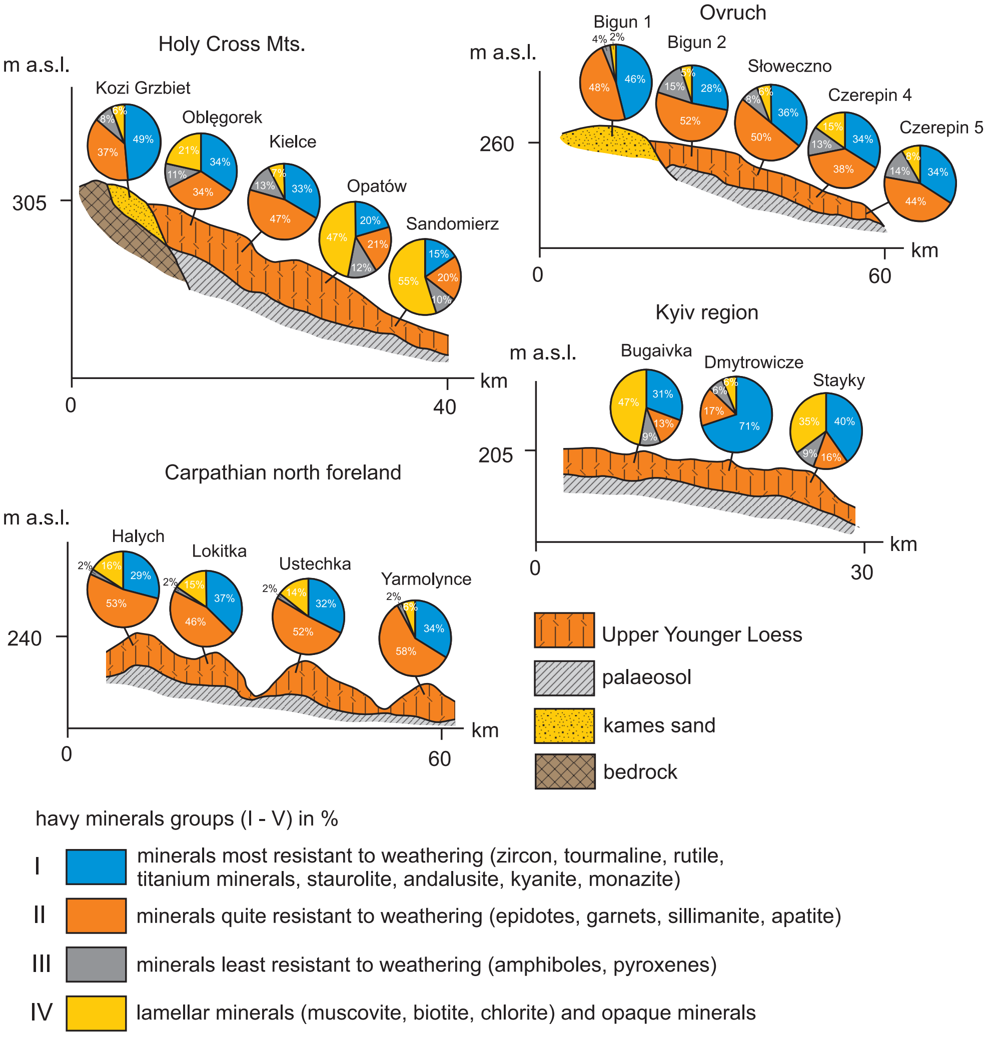
In the Sudety Mountains and their forelands, the UYL shows a decrease in grain size from north to south, whereas the largest average grain diameters are found in both the eastern and western parts of this area (Jary 2007; Jary *et al.* 2021). These are mainly related to the factors determining the local rate of loess dust accumulation. In profiles with a relatively high thickness of loess, the average diameters of loess particles are the largest (Jary 2007). The Upper Younger Loess of the LU also shows positively skewed (Sk1 > 0.3) grain size distribution (Dolecki 1987). This may indicate the conditions suitable for the activation of grains transported in suspension or saltation.

The collected data on the granulometric composition of the studied loess support the assumption that the main sources of loess material were pre-Quaternary rocks (Cretaceous sandstones and siltstones and Neogene sands) and Pleistocene sand covers, which is in agreement with the data presented by Rousseau *et al.* (2014) and Pańczyk *et al.* (2020). In the Sudeten loess the fluvial sediments of the palaeovalley of the Odra River weathered in periglacial conditions were also the source of the loess material (*cf.* Smalley *et al.* 2009; Badura *et al.* 2013; Waroszewski *et al.* 2021). Only the uppermost loess had an increased content of fine dust from further transport. The loess material was transported by low-level winds (over a relatively short distance – a few to tens of kilometres) being repeatedly accumulated and re-blown by these winds (Chlebowski and Lindner 1989; Antoine *et al.* 2009b; Rousseau *et al.* 2014; Römer *et al.* 2016). These are in accordance with the results of Smalley *et al.* (2009) who consider that dust particles around 2–6 μm diameter are easily carried in high suspension, sand grains (usually 200–600 μm) are moved efficiently by saltation, whereas loess particles (20–60 μm) travel in low-level suspension for rather short distances.

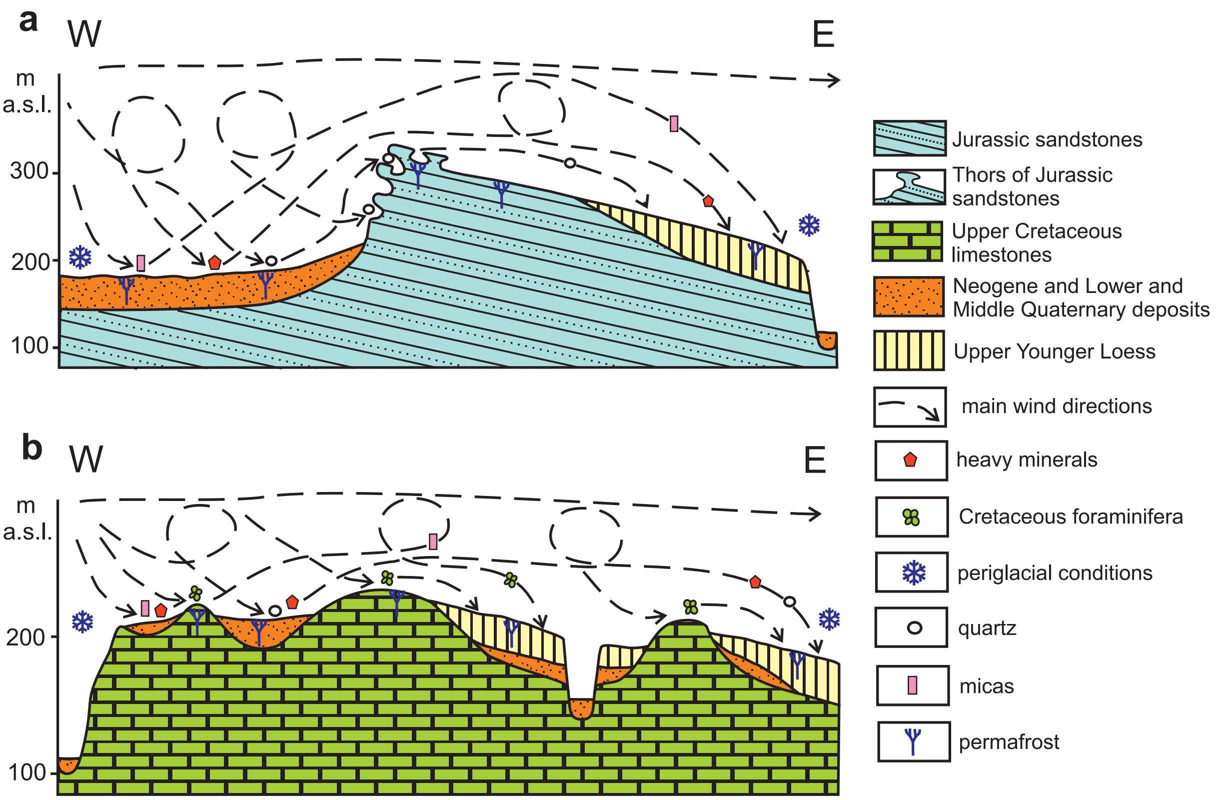
### *Heavy mineral composition*

The analysis of heavy minerals was carried out in 95 profiles (e.g., Wąchock and Lelów) of the UYL of the MU (Chlebowski *et al.* 2003b; Chlebowski and Lindner 1992) and the Sudety Region (e.g., Tłumaczów and Branice) (Chlebowski *et al.* 2004). Minerals were divided into 5 main groups: I – minerals most resistant to weathering (zircon, tourmaline, rutile, titanium minerals, staurolite, andalusite, disthene (kyanite), monazite), II – minerals quite resistant to weathering (epidotes, garnets, sillimanite, apatite), III – minerals least resistant to weathering (amphiboles, pyroxenes), IV – glauconite, V – lamellar minerals (muscovite, biotite, chlorite) and opaque minerals. This analysis also included samples of pre-Quaternary rocks from the near and further surroundings of loess, which were considered as probable sources of loess-forming material (Chlebowski and Lindner 1975, 1976; Waroszewski *et al.* 2021).

In the western part of the Holy Cross Mountains (MU) loess is enriched in pyroxenes derived from Permian volcanites and their weathering. In the loess profiles underlined by Palaeozoic volcanic rocks with frequent druses, amethyst grains were also present (Chlebowski and Lindner 1975, 1976). Both lamellar minerals and minerals quite resistant to weathering come from kame deposits (Text-fig. 5). Characteristic of loess deposited in the eastern part of the Holly Cross Mountains is the increased content of light muscovite (Chlebowski and Lindner 1975). Moreover, the analysis of the mineral composition of the light fraction of loess revealed the presence of foraminifera blown from weathered Cretaceous marls (Chlebowski and Lindner 1976).



Text-fig. 5. Mineral composition of selected loess profiles in Poland and Ukraine (based on Chlebowski and Lindner 1975; Chlebowski *et al.* 2007).



Text-fig. 6. Scheme of aeolian redeposition of minerals and foraminifera from bedrock to the UYL: a – in the Holy Cross Mountains (after Dzierżek and Lindner 2020, modified); b – in the Lublin Upland and the Volhynian Upland (after Paruch-Kulczycka *et al*. 2003, modified).

Analysis of the mineral composition of the UYL of the LU and the Bug loess of the VU also revealed a significant number of lamellar minerals and Maastrichtian microfossils (Chlebowski *et al.* 2003b) (Text-fig. 6). These were mainly foraminifera, including *Globigerinollides asperus* (Ehenberg), *Rugoglobigerina rugosa* (Plumer), *Heterohelix vistulaensis* Peryt, *Hedbergella telatynensis* Gawor-Biedowa, and calcareous dinocysts *Orthopithonella* sp. and *Obliguipithonella* sp. (Paruch-Kulczycka *et al.* 2003). The mineral composition of the Mid-Carpathian Foreland loess (Text-fig. 5) is dominated by minerals quite resistant (mostly garnet) and most resistant to weathering (mostly zircon and rutile) which directly corresponds to the mineral composition of the nearby Carpathian Flysch (Pańczyk *et al.* 2020). In the western part of the Podolian Upland, the additional areas of loess dust alimentation could be (besides the flysch rock) fluvioglacial deposits, the weathered crystalline bedrock and volcanites of the Romanian Carpathians (Chlebowski *et al.* 2003a). Smalley *et al.* (2009) underlined the important role of river transportation (movement of fine particles) in the process of loess formation on the mountain forelands.

Isotope dating of zircons in Ukrainian loess unequivocally confirms the Carpathian source of the material (Pańczyk *et al.* 2020).

The loess of the northern part of the area between Kyiv and Roxolany and Lebedivka on the Black Sea is characterised by a significant admixture of amphiboles, pyroxenes and muscovite. In contrast, the loess of the central and southern parts of this area was dominated by garnets. It also contained an admixture of small mineral fragments from the weathered rocks of the Crimean Peninsula and the Caspian region (Gozhik *et al.* 2001a, b; Chlebowski et al. 2003a). These seem to prove that the loess material of the northern area, apart from the local material, contained minerals from the blown glacial sediments of the Dnieperian Glaciation and could indicate the north or north-west direction of the loess-forming winds (Sima *et al.* 2013; Waroszewski *et al.* 2021). The opposite wind direction (from the south-east) prevailed in the southern area (Chlebowski *et al.* 2003a).

The analyses of Bug loess in the middle Dnieper basin revealed a similar composition of heavy minerals and the light fraction (Chlebowski *et al.* 2003b). All samples contained carbonates and microfossils (foraminifera) as well as glauconite and heavy minerals representing all groups differing in their resistance to weathering or susceptibility to aeolian transport. These facts may indicate the influence of the local bedrock on the mineral composition of the studied loess, accumulated at a relatively close distance to alimentation areas, which fits well with the interpretation of regional transport of the deposited material demonstrated by Rousseau *et al.* (2014). This bedrock comprised mainly the Middle Pleistocene (Dnieperian) glacial and fluvioglacial sediments, the Middle and Younger Pleistocene (Vistulian, Valdai) alluvial series and the clastic Neogene sediments rich in glauconite (Krasnov *et al.* 1971, 1975). Thus, it appears that the youngest loess was accumulated over a short distance with the participation of winds from the western and south-western sectors. This accumulation may have taken place at the expense of blowing of the older loess covers or the newly deposited Upper Younger Loess. This may be evidenced by the relatively high content of the most weathering-resistant minerals (zircon – 29%, rutile – 20%) that can survive several transport-accumulation cycles (Chlebowski *et al.* 2003b). A similar conclusion was reached in studies in western Europe (Römer *et al.* 2016).

The UYL in the main loess patches of northern Ukraine (Kalinovka and Novhorod-Siverskyi) and central Belarus (Novogrudok, Minsk and Orsha) (Sanko *et al.* 1980; Chlebowski *et al.* 2007) evidences the local variation in the content of some mineral groups, especially the main components of the heavy mineral assemblage. Loess patches of the southern part of the study area (Ovruch and Novhorod-Siverskyi) are characterised by high content (38–53%) of minerals quite resistant for weathering (mostly garnet) and relatively low amphibole contents (max. 15%) (Text-fig. 5). In contrast, the loess patches located in the northern regions of the study area (Novogrudok, Minsk and Orsha) have very high amphibole contents (47.5%) and relatively low garnet contents (14.1–24.4%) (Chlebowski *et al.* 2007). This pattern is justified by the more common occurrence of glacial and fluvioglacial deposits rich in dispersed material of magmatic and metamorphic rocks in the northern regions compared to the southern regions.

The studied regions differ in the carbonate and microfossil content. These do not occur in the loess patches of the northern region being abundant in the southern regions with Cretaceous sediments occurring in the bedrock. The exception is the loess of the Novogrudok area. This is related to the presence of Cretaceous sediments in the bedrock of the Middle Neman basin on the western side of this loess patches. Another unique mineralogical accent is the high content of most resistant minerals (even 71 % in the Dmytrowicze site, Text-fig. 5) noted in the loess profiles of Kyiv region. This indicates the influence of the other source of aeolian supply – presumably the locally exposed crystalline massifs built of rocks containing considerable amounts of this mineral (Chlebowski *et al.* 2007).

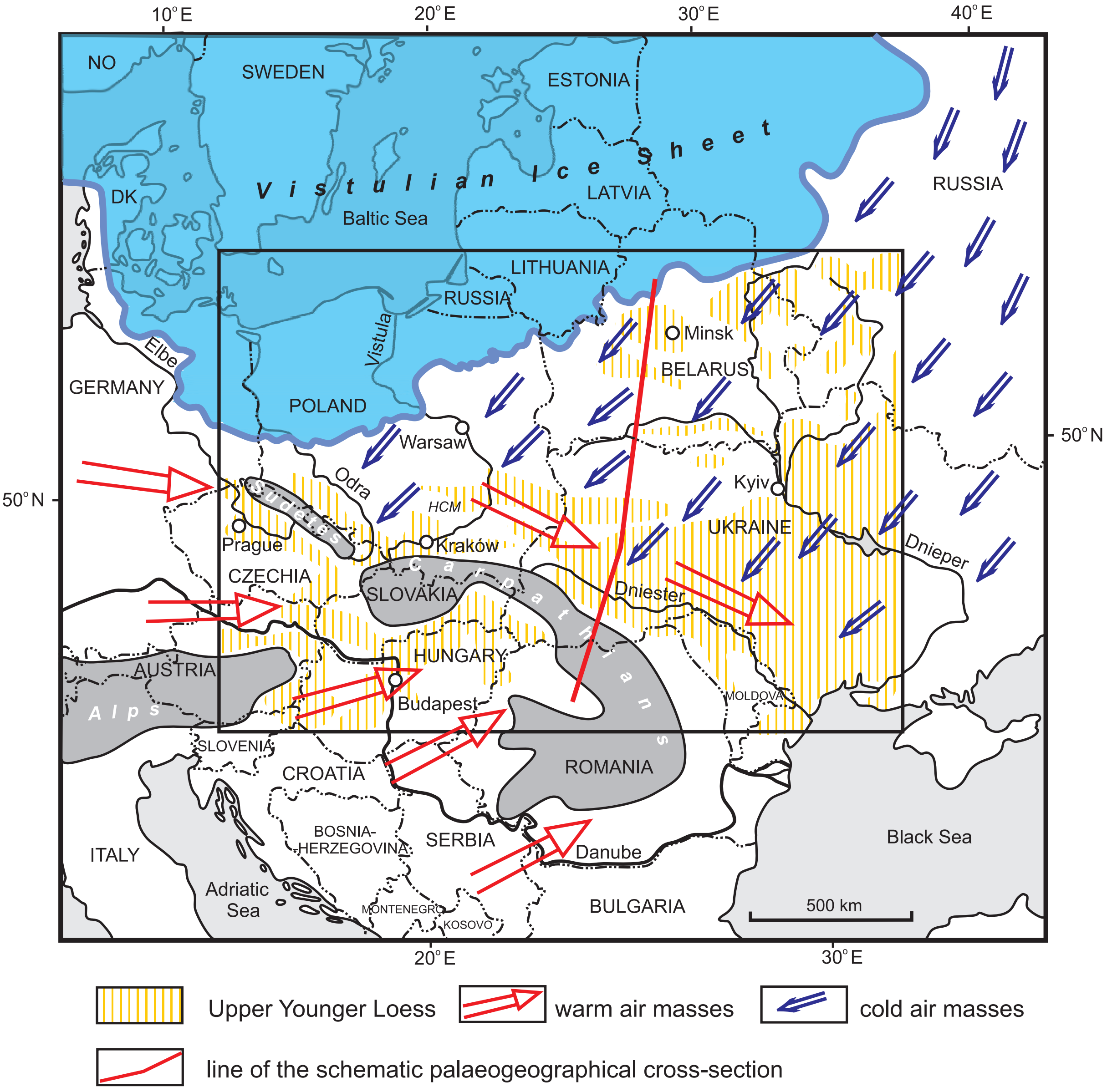
## DISCUSSION

Summarising the above characteristics of the Upper Younger Loess (Bug loess) in central and eastern Europe we support both the local origin of the material that builds this loess and the predominance of near-surface westerly and south-westerly loess-forming winds. We also consider the participation of winds in the upper levels of the atmosphere in loess accumulation (Chlebowski and Lindner 1992). This is in agreement with the results expressed by Rousseau *et al.* (2014) and Sima *et al.* (2009, 2013) and also with the longitudinal gradient in dust sedimentation and mass accumulation rates from western to eastern Europe described by Rousseau *et al.* (2021).

However, given the long-standing and repeated opinions that loess of this area is associated with eastern and north-eastern directions of loess-forming winds (Jahn 1950; Maruszczak 1967; Jersak 1970; Marks *et al.* 2019; Nawrocki *et al.* 2019; Pańczyk *et al.* 2020; Schaffernicht *et al.* 2020), we discuss these two views.

The opinion about the direction of loess-forming winds from the western sectors during the accumulation of the UYL (Text-fig. 7) is based on the following: 1) topographical position of this loess, 2) its mineralogical relations with bedrock and/or the immediate surroundings and 3) periglacial conditions in the foreland of the Scandinavian ice sheet during the LGM. Periglacial conditions and glacial climate are commonly associated with loess-forming processes (Jahn 1950), but opinions that loess accumulated in the steppe-tundra period preceding the maximum development of the SIS also occur (Schaffernicht *et al.* 2020).

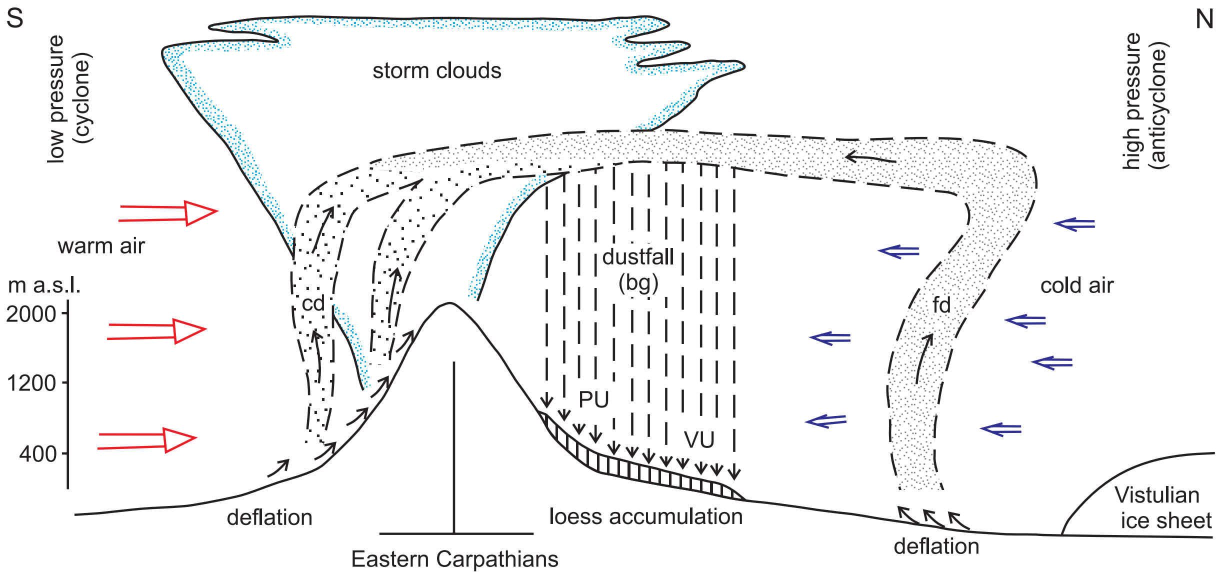
We think that both of them were quite right. The period of the ice sheet growth is associated with a distinct increase in solid precipitation, but also with an increase in humidity in the extraglacial zone (and the possibility of warming in the periglacial conditions). Thus, one should consider not only the opinion of Jahn (1950) on distinguishing within the continental phase (stadial) of glaciation a cold and dry (earlier)



Text-fig. 7. Presumptive distribution of loess-forming wind directions during LGM in central and eastern Europe. DK – Denmark; NO – Norway.

climate stage and a warmer (later) continental stage, but also the possibility of the co-existence of these conditions, as climatic fronts came into contact over vast areas of the ice sheet foreland.

An example of such contact of warm and cold, dry air masses is seen in the course of loess accumulation on the western slopes of the Rocky Mountains. In Nebraska and Kansas, a cold and dry climatic front with dust storms met an inflow of humid and warm air. This favoured precipitation which conditioned the accumulation of loess dust (Różycki 1979). The periodic presence of liquid precipitation in the ice sheet foreland is also indicated by the results of further studies. Bromwich *et al.* (2005) demonstrated the alternation of long and relatively dry periods with short episodes of wet summer seasons in the foreland of the Laurentide Ice Sheet (LIS). This results from the pattern of barometric lows moving parallel to the edge of the ice sheet in the Great Plains. Morphological analysis of the occurrence of loess patches in the LIS foreland during the LGM indicates a predominance of low-level winds from the NW



Text-fig. 8. Schematic palaeogeographical cross-section (model) of Bug loess accumulation north of the Eastern Carpathians. cd – ascending air current with coarse dust; fd – ascending air current with fine dust; PU – Podolian Upland; VU – Volhynian Upland.

(Muhs and Bettis III 2003). However, the palaeoclimate simulation indicates that cold winds blew from the NE along the ice margin. Bromwich *et al.* (2005) explained this apparent inconsistency. They found that sediment entrainment and deposition of loess occurred as a result of strong but infrequent north-westerly winds associated with the passage of a system of low-pressure centres through the Great Plains belt. However, based on the granulometric composition and origin of organic particles in lake sediments in the Eifel province (Germany), Dietrich and Seelos (2009) showed that during the LGM (21–18 ka BP) easterly winds were less strong and blew at low altitudes compared to the preceding period (36–24 BP).

Therefore, the occurrence of western and south-western atmospheric circulation during the Vistulian should be taken into account in central and eastern Europe (Florineth and Schlüchter 2000; Marks *et al.* 2019). This favoured the development of near-surface winds which picked up dust from large areas devoid of vegetation. These warm and humid air masses, coming into contact with the dry eastern air masses (controlling the ice sheet growth), caused loading of the dust grains with moisture and dust accumulation. The location of these contact zones might have changed frequently. This resulted in changes in the location of areas of intensified dust accumulation, and thus determined the formation of individual loess patches and more extensive loess covers in central and eastern Europe (Schaffermicht *et al.* 2020). Variable conditions of loess accumulation during the LGM and changes in the wind strength and direction are also observed in western and central Europe (e.g., Dietrich and Seelos 2009; Sima *et al.* 2009; 2013; Pinto and Ludwig 2020) and North America (Muhs and Bettis III 2003; Bromwich *et al.* 2005).

Mutual contact between warm and cold climate fronts is illustrated by the model of loess dust accumulation with the contribution of upper-level winds on the north-eastern side of the Eastern Carpathian arc (Text-fig. 8). It shows contact of cold air masses moved from the ice sheet during its maximum extent in the Vistulian Glaciation with warm air masses from the North Atlantic and the Mediterranean Sea, which controlled the formation of storm fronts (Florineth and Schlüchter 2000; Marks *et al.* 2019). Ascending air currents carried up dust (coarser from the west and finer from the east) which mixed and then fell, loaded with atmospheric moisture. This is in line with palaeoclimate modelling by Pinto and Ludwig (2020). They have proved the North Atlantic storm track activity during the LGM, which brought frequent extreme cyclones towards western and central Europe and the Mediterranean area. The role of the westerly cyclones in loess deposition generating dust storms in Europe at the contact with the anticyclonic flow from the SIS was also pointed out by Újvári *et al.* (2017) and Schaffernicht *et al.* (2020). Lefort *et al.* (2021) also drew attention to the vertical stratification of the winds during loess accumulation phases in western Europe. They consider that low-level intermittent katabatic winds controlled by the topography of the ice sheet were independent of the general atmospheric circulation system.

In the study area we consider strong, low-level winds from the western sector be responsible not only for the increased contribution of heavy minerals from the near vicinity in the loess profiles but also for the corrasion processes, resulting in thors formation in the HCM (Text-fig. 6). In turn, the easterly (north-easterly) dry air masses carried up fine dust (mostly in the upper part of the atmosphere) from the far forefield of the SIS. This was the main source of the fine-grained loess in the UYL profiles in the study area.

Both the paleoclimate modelling and the geological evidence show generally dry and cold climate in central Europe during the LGM, with short-term variability on the regional scale (Dietrich and Seelos 2009; Jipa 2014; Újvári *et al.* 2017; Marks *et al.* 2019; Pinto and Ludwig 2020). These also concern the seasonal change in wind direction and intensity of loess accumulations (Sima *et al.* 2009, 2013; Schaffernicht *et al.* 2020). Especially, the mountain massifs seem to be an important orographic factor affecting the pattern of air mass distribution during the LGM. Based on the analysis of a rising ELA trend towards the south-east in the northern slopes of the Rodna Mts (Eastern Carpathian) Kłapyta *et al.* (2020) suggest a predominance of snow-bearing winds from the northwest. Bokhorst *et al.* (2011) proved a domination of western winds during the Early and Middle Pleniglacial in central and eastern Europe, while the Late Pleniglacial was dominated by northwestern or northern winds.

The pattern of loess accumulation presented above explains the nearly latitudinal (and thus parallel to the extent of the SIS) course of the northern boundary of the loess in the described area. The presented scheme of loess accumulation is an attempt to reconcile opposing views regarding the western/south-western and eastern/north-eastern sectors of loess-forming winds during the Vistulian. The predominance of certain wind directions depended on the changing atmospheric circulation which was controlled by North Atlantic zonal circulation (Florineth and Schlüchter 2000; Pinto and Ludwig 2020). This may also explain the role of structures (including niveo-aeolian origin) of loess sedimentation determined by the periodic increase in humidity (Muhs and Bettis III 2003; Bettis III 2012), as well as the presence of conditions suitable for the development of loess malacofauna and other organisms (Moine *et al.* 2017).

Varying climatic conditions, interpreted as corresponding to the Greenland interstadial-stadial cycles, explain the relatively frequent occurrence of palaeosols and gley horizons in both the American loesses and the central and east European UYL (see Rousseau *et al.* 2007, 2011, 2021; Antoine *et al.* 2009, Moine *et al.* 2017; Jary *et al.* 2021). According to Hayward and Lowell (1993), if soil moisture is above 6%, the sediment entrainment disappears. The presence of moisture in the soil facilitates the capture of dust from a low cloud loaded with sediment previously taken from dry elevated areas (Bettis III 2012).

An alternative interpretation assumes a complex pathway of UYL-forming material, including the ‘indicator’ local bedrock minerals and foraminifera from Mesozoic rocks. First, the material was delivered to rivers and transported northward from the loess areas (cf. Smalley *et al.* 2009). Then it was carried south by northerly and north-easterly winds associated with an anticyclone over the SIS. The island character of loess occurrence in the most western and northern parts of the described area may result from the Late Vistulian corrasion-deflation processes. Assuming the above, loess accumulation in dry and cold conditions may have been ‘supported’ by the moist substrate (Muhs and Bettis III 2003; Bettis III 2012) as conceived by Cegła (1969), the sedimentological experiment (Cegła 1972) and the palaeoclimate simulations (Schaffernicht *et al.* 2020).

## CONCLUSIONS

Based on the collected material, the conditions of the Upper Younger Loess accumulation in central and eastern Europe may be summarised as follows:

- The Upper Younger Loess was accumulated under changing barometric pressure systems determined by the presence of the LGM ice sheet.
- Westerly and south-westerly winds predominated during the LGM. This is evidenced by the topographic position of loess patches on the eastern sides of morphological obstacles and the mineral composition of the studied loess. The near-surface winds from this sector prevailed. Periodically an increased air circulation from the east and north-east occurred.
- The natural barriers of the Carpathians and the Holy Cross Mountains played an important role in the UYL accumulation. Cold winds blowing from the ice sheet came into contact with warm winds blowing from the west and southwest in the zone of these mountain ranges. This caused the formation of storm fronts with air currents lifting the loess dust and then its falling due to rain moisture loading. This process should be considered in the analysis of the conditions of loess accumulation.

- The UYL accumulated under varying soil moisture conditions in the study area. This is indicated by niveo-aeolian structures preserved in loess profiles, gley horizons as well as pollen and mollusc assemblages.
- The presence of moisture, especially at the beginning and the end of MIS 2, resulted in the development of scarce steppe-tundra vegetation cover on the accumulation surface of some UYL layers.
- The heavy mineral composition and the presence of redeposited microfossils (foraminifera), as well as locally increased grain diameter and the presence of sandy inserts in some profiles point to the mainl local origin of the material that forms the UYL. This is also in agreement with Rousseau *et al*. (2014) for other European loess sequences of the same age showing that this may have been the main process at least in Europe.
- Increased content of resistant to weathering minerals and fine fraction in several parts of the loess profiles may indicate blowing of the older loess covers and reincorporation of the material into the UYL.

## Author contributions

L. Lindner was an author of the article concept, text and figures outline. The field data were collected and interpreted by L. Lindner, A. Bogucki, R. Chlebowski, O. Tomeniuk. Analysis of heavy minerals and granulometric analysis were carried out by R. Chlebowski, and L. Lindner. Stratigraphy of loess profiles and interpretation of structures was performed by L. Lindner, A. Bogucki. The archival malacological data were elaborated by M. Szymanek. J. Dzierżek was responsible for analysis of the influence of relief on loess accumulation and analysis of palaeoclimate data. All authors contributed in the discussion and interpretation of the results as well as working with the text of the manuscript. I confirm that all authors have approved the final version of the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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