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STRATIGRAPHY AND CONDITIONS OF ACCUMULATION OF THE YOUNGER LOESSES (VISTULIAN) IN THE HOLY CROSS MOUNTAINS AREA, POLAND

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Abstract:
The paper presents results of studies focused on occurrence and correlation of four main horizons of Younger Loesses: Lowest Younger Loess (LMn – after Maruszczak, 2001), Lower Younger Loess (LMd), Middle Younger Loess (LMs), and Upper Younger Loess (LMg) recorded in five sections (Politów, Wąchock, Nietulisko Małe, Komorniki and Bodzechów) in the Holy Cross Mountains area. All analysed loesses were accumulated during the Vistulian Glaciation (Weichselian). The horizons were distinguished based on separating interstadial tundra soils, coupled with thermoluminescence dating, and correlated with marine oxygen-isotope stages MIS 5d–2. The Lowermost Younger Loess (LMn) covers the Nietulisko I soil complex (Jersak, 1973), developed on deposits of the Odranian Glaciation (MIS 6) and representing a forest soil of the Eemian Interglacial (MIS 5e) and the Brørup warming (MIS 5c). A thin horizon of the Oldest Younger Loess and a thin sandy horizon, both probably corresponding to the Herning cooling phase (MIS 5d) at the boundary with the Eemian Interglacial, were distinguished within this complex. Based on previously performed grain-size and heavy mineral analysis of the Upper Younger Loess (LMg) and a topographic position of the loesses in four loessy islands of diverse regional extent, accumulation of this loess in the Holy Cross Mountains area is found to have been stimulated by the western winds. The proposed model of loess accumulation takes into account the influence of the topography of the area and its geological structure.

Key words: East-Central Europe, loess stratigraphy, TL-dating, wind transport

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INTRODUCTION

The Holy Cross Mountains (HCM) area is characteristic for its loesses (Fig. 1), in which a palaeosol from the last interglacial (Eemian) and younger palaeosol horizons representing interstadial conditions within the last glacial period (Vistulian) were recognised almost sixty years ago (e.g. Grabowska, 1961; Kosmowska, 1961; Jersak, 1961, 1965; Lindner, 1967). At Nietulisko Małe and Komorniki, these soils were described as the 'Nietulisko I type soil complex' and the 'Komorniki type soil' (Jersak, 1961, 1965, 1973: Jersak *et al*., 1992). The loesses and the separating palaeosols, as well as deposits of the preceding Odranian Glaciation, were TL-dated at Politów, Wąchock and Bodzechów (Fig. 2; Lindner *et al*., 1999; Lindner and Semil, 2000; Dzierżek *et al*., 2019, 2020). Among them, the Wąchock succession is of particular importance (Dzierżek *et al*., 2020), considered as a stratotype of loesses and palaeosols of the Last Glaciation (Vistulian) in the HCM area.

The distinguished loess and palaeosol horizons, and older glacial and glaciofluvial deposits distinguished in the studied sections (Fig. 2) were subjected to a detailed assessment. It was based on lithological similarity of deposits and available thermoluminescence (TL) ages in these sections. Such approach allowed for mutual comparison of the examined sections and correlation loess and palaeosols horizons with the main units of the current subdivision of the last glaciation (Vistulian) in western Europe and Poland (Marks *et al*., 2016, 2019), and with the Marine Isotope Stages (MIS) (Fig. 3), to correlate the accumulation of individual loess layers with specific units of the Vistulian. It seems particularly important to distinguish the oldest, thin loess layer corresponding to the early Vistulian cold stage (Herning). In loess profiles in the HCM area it has not been identified so far (cf. Maruszczak, 2001; Jary, 2007). This may encourage further discussion on the beginning of the accumulation of the younger loess in Poland. Additionally, previous performed grain-size analysis and composition of

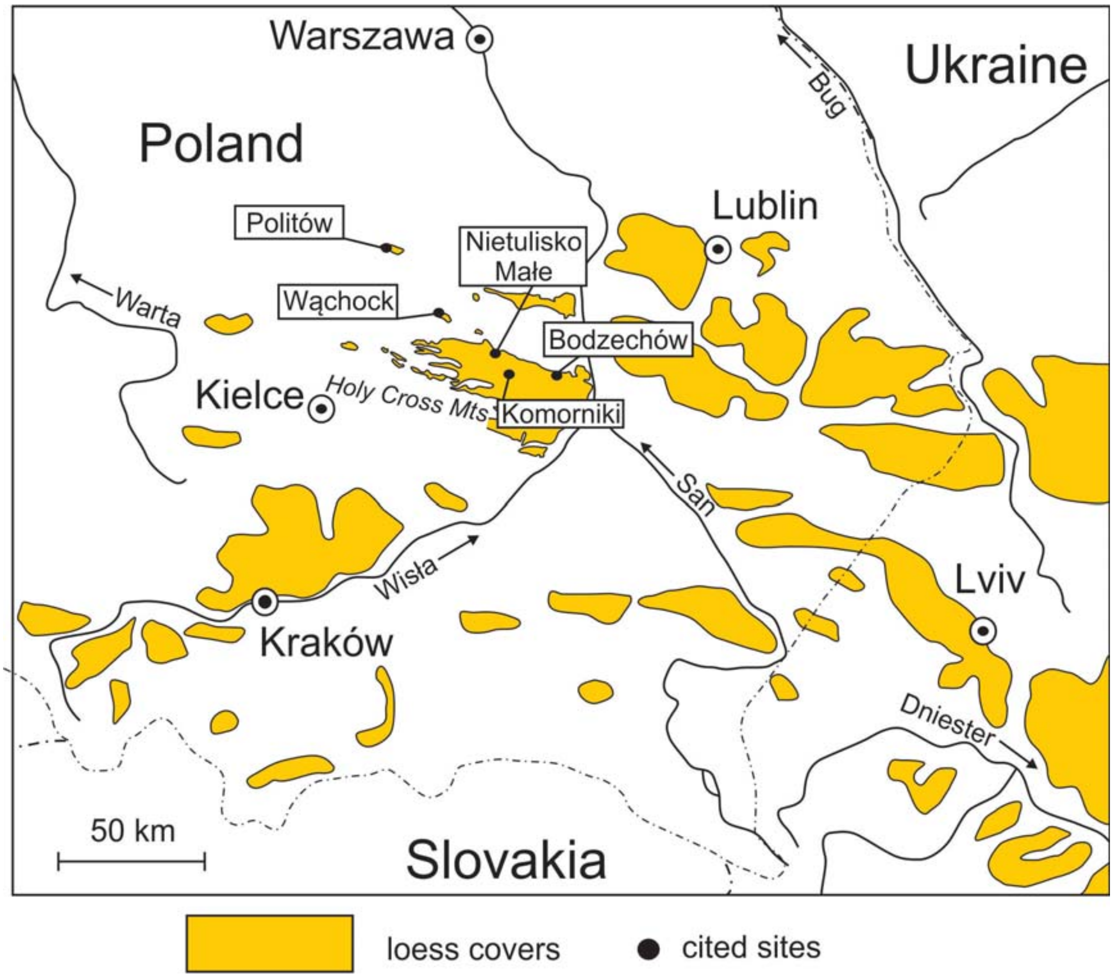

Fig. 1. Sketch-map with location of the analysed loess sites.

heavy mineral assemblages in the studied loess and in exposures of the surrounding rocks (Chlebowski and Lindner, 1992), as well as topographic setting of the loesses occurring as isolated patches (islands) have allowed to determine their accumulation conditions under the influence of the western winds (Chlebowski and Lindner, 1989, 1992, 1999).

GEOLOGICAL SETTING

The research area (HCM area) comprises in the new physico-geographical subdivision of Poland (Solon *et al*., 2018) the Holly Cross Mts, NE part of the Gielniów Hillock, the Suchedniów Plateau and the Sandomierz Upland. Younger Loesses, linked with the last glaciation (Vistulian), are the subject of this study in five sections located in three main loess patches in the HCM (Fig. 1). The Politów section in the west is located in the eastern part of the Borkowice loess island (Lindner, 1967) and is an almost latitudinal outcrop, 7 km long and 0.8 km–1 km wide. The surface of this loess patch drops down from 275–220 m a.s.l. in the western part of the area to 230–190 m a.s.l. in the east. The loess covers north-eastern and eastern slopes of hills built of Liassic (Lower Jurassic) sandstones and locally, it is overlain by glacial tills and kame sands from the Odranian Glaciation. They attain a thickness from 2 to 8 m, and are contain streaks and intercalations of sandy material up to 10 cm thick in the western part.

Loesses of the Wąchock loess island (Lindner and Prószyński, 1979) form also an almost latitudinal outcrop, up to 4 km long and 1.5 km wide. In the south-western part, their surface occurs at 300 m a.s.l., whereas towards the north-east, to the Kamienna River valley, it drops to 240 m a.s.l. The loesses are underlain by Triassic sandstones and siltstones, as well as glacial tills and ice-dammed sands and silts of the Odranian Glaciation. These loesses are over 10 m thick.

The remaining three sections, Nietulisko Małe, Komorniki and Bodzechów, are located in the northern part of the Sandomierz–Opatów loess island, characterised by the largest outcrop surface area. The length of this NW-SE-oriented loess outcrop is almost 70 km. Its width is 10–15 km in the west and even up to 30 km in the east, being limited by the Vistula River valley (Chlebowski and Lindner, 1992). In the western part of this outcrop, the loesses generally cover the slopes of the eastern extremities of the main hill ranges, built of Cambrian sandstones and quartzites, and Devonian sandstones and limestones (Czarnocki, 1938; Skompski, 2015). These loesses occur at 350–400 m a.s.l., and are located at 250–300 m a.s.l. in depressed areas only, where they overlie glacial tills and sands of the Sanian 2 (Elsterian) and the Older Loesses of the Odranian glaciations. In the eastern and northern part of this loess outcrop, the Younger Loesses occur at lower elevation (200–250 m a.s.l.) and they are underlain by the Older Loesses, and glacial and glaciofluvial deposits of the Odranian Glaciation. These loesses attain a thickness of about 8–10 m and are incised by numerous ravines.

MATERIAL AND METHODS

The analysed Younger Loesses from the HCM area were hitherto a topic of numerous studies, the most important of which are those by Jersak (1961, 1965, 1973). He documented classical occurrences of the 'Nietulisko I type soil complex' with an eroded forest soil of the Eemian Interglacial and the overlying black earth of the Brørup warming, and the 'Komorniki type' palaeosol, representing a main warming in the younger part of the Vistulian. Descriptions of these soils are based on their detailed palaeopedologic characteristics and meticulous biostratigraphic assessments, coupled with the characteristics of the contemporary vegetation, both representing forest and steppe-tundra settings.

The Wąchock loess section was among the first TL-dated successions in Poland (Lindner and Prószyński, 1979) and as such, it was extensively discussed in text-books and books on the Pleistocene chronostratigraphy (Mojski, 1984; Lindner, 1992). The TL ages analysed in this paper were determined in three laboratories: in Warsaw by M. Prószyński (Lindner and Prószyński, 1979), in Gdańsk by S. Fedorowicz (Lindner and Semil, 2000) and in Lublin by J. Kusiak (Lindner *et al.*, 1999).

The Upper Younger Loess in the study area was also a topic of grain-size and heavy mineral analyses. The granulometric characteristics of loesses were determined by separating on sieves and comparing 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 minerals composition was carried out in the fraction 0.05–0.01 mm. Heavy minerals were obtained using the traditional method with the use of bromoform. In the optical microscope 20 minerals or groups were separated (Chlebowski and Lindner, 1976). Heavy minerals were divided into: minerals least resistant to weathering (amphiboles and pyroxenes), relatively resistant to weathering (epidotes, garnets, syllimanite, apatite), most resistant to weathering (zircon, tourmaline, rutile, titanium, staurolite, andalusite, disthene, monazite), sheet minerals (muscovite, biotite, chlorite) and opaque minerals (iron oxides, manganese, sulphides). Sandy sediments from the surroundings of the loess patches and from a loess bedding were also included in the study. Nearly 100 loess sections were examined (Chlebowski, and Lindner, 1992) and only selected results of these analyses are presented in his paper (Fig. 4).

There is a large grain-size variability, with a larger admixture of sandy and coarse-silty material in the western parts of particular loess outcrops, and a smaller content of this material in the easternmost parts of these occurrences. In turn, bulk-sample analysis of heavy mineral composition in the loesses, predominated a local material in loess and proved the western direction of the loess-forming winds in the HCM.

A topographic position of the Younger Loesses in form of isolated outcrops (islands) in the study area was analysed, including their size, altitude and location in relation to the main ridges of the HCM (Fig. 4). This analysis takes into account contemporary models of aeolian accumulation (Luo *et al.*, 2014; Raffaele and Bruno, 2019) and results of studies on directions of aeolian deposition in natural (Lindner, 1976; Lindner and Chlebowski, 2001) and laboratory conditions (Cegła, 1972).

RESULTS AND DISCUSSION

Outline of stratigraphy

Taking into account all acquired data it is assumed that the Younger Loesses in the HCM area are underlain by a palaeosol from the last interglacial (Eemian), corresponding to MIS 5e (GJ1 of Maruszczak, 2001). At Nietulisko Małe (Fig. 2), this soil in its classical (stratotype) development is the lower (older) part of the 'Nietulisko I type soil complex' according to Jersak (1965, 1973). A characteristic feature of this complex is the subsoil horizon B (illuvial) of a lessivé soil, higher morphological horizons (A_0, A_1) of which were removed during younger erosional–denudation and/or deflation, due to which it was transformed into an eroded soil. A subsoil horizon B of this soil is up to 1 m thick (GJ1 in Fig. 2). It is characterised by a rusty hue due to high content of Fe and Mg compounds. A development of a lessivé soil with such a subsoil horizon B took place during the supremacy of interglacial deciduous forests (compare Jastrzębska-Mamełka, 1985; Granoszewski, 2003). The upper part of this complex comprises a thin loess (Oldest Younger Loess – MIS 5d), almost completely modified by younger pedogenic processes, influencing development of a black earth horizon up to several tens of centimetres thick. The black earth developed during the first (MIS 5c) interstadial warming/s (Gi/GJ1) of the Vistulian Glaciation.

An analogously developed soil complex preserved at Politów (Fig. 2) was initially correlated with the older interglacial interval (compare Lindner and Semil, 2000). It was formed on the Upper Older Loess (LSg), TL-dated at 246±36.9 ky BP. At Wąchock (Fig. 2) it occurs above aeolian (dilluvial?) sands, TL-dated at 157±23 ky BP. The black earth from the upper part of this complex was TL-dated at 101.9±5.3 ky BP at Politów and 148±23 ky BP at Wąchock, where it is correlated with the Brørup warming (Dzierżek *et al.*, 2020). At Komorniki the black earth is developed on a thin layer of sand and loess, and at Nietulisko Małe – on a thin loess layer (Oldest Younger Loess) preserved above the horizon B of the interglacial soil (Fig. 2).

At Bodzechów (Fig. 2), the horizon B of a soil from the last interglacial (GJ1) is >1.5 m thick, its TL-date is from 149±13 ky to 112±10 ky BP, and it is developed above sands and gravels that were TL-dated at 298±78 ky BP and which, similarly as at Komorniki (Fig. 2), should be linked with glaciofluvial accumulation during the Odranian Glaciation (MIS 6). At Bodzechów, a soil from the last interglacial is overlain by a massive loess complex (LMn + LMd + LMs), a lower part of which was TL-dated at 65.6±7.0 ky BP.

The age reinterpretation at Politów and Wąchock suggests that in the upper part of the preserved deposits there is the Lowermost Younger Loess (LMn – MIS 5b), up to 2 m thick, characterised by high calcium carbonate content. This loess is overlain by a tundra type interstadial soil (Gi/LMn), at Wąchock correlated with the Odderade warming – MIS 5a (Dzierżek *et al.*, 2020). At Politów it was TL-dated at 125.6±8.8 ky, and at Wąchock it is considered older than 72±1.1 ky. In the remaining sections of Nietulisko Małe, Komorniki and Bodzechów, traces of contemporary pedogenic processes are not preserved.

The Lower Younger Loess (LMd – MIS 4) should occur higher up in the analysed sections. At Wąchock it is up to 1 m thick, but it is not clearly distinguished in the other sections. The upper part of this loess at Wąchock was TL-dated at 65±1.0 ky and this loess is overlain by a subsequent, bipartite interstadial soil (Gi/LMd, lower part of MIS 3), correlated with the Oerel and Glinde warmings (Dzierżek *et al.*, 2020). This soil is covered by the Middle Younger Loess (LMs, middle part of MIS 3), with a high calcium carbonate content and additionally by sandy streaks at Politów. At Wąchock it was TL-dated at 64±9.0 ky to 24±2.5 ky BP.

At all sections, this loess is overlain by a subsequent tundra palaeosol (Gi/LMs, upper part of MIS 3), with a classical development at Komorniki (Fig. 2) as the 'Komorniki type soil' (Jersak, 1965, 1973). According to this author, the soil is composed of two genetic horizons: an organic accumulation horizon (A_1) and a brown subsoil horizon (B). It is decalcified and described as subarctic brown soil. In the other sections, particularly at Wąchock, the soil is represented by several (maximum three) pedogenic intervals favouring development of thin humus or humus-gley horizons formed in tundra conditions, and separated by thin streaks of loess material, also subjected to interstadial pedogenic processes. At Politów, this multiple soil horizon was TL-dated as older than 26.1 ky. At Wąchock, the age of this soil was determined from 24.0±2.5 ky to 15.8±1.8 ky by TL-ages of the over- and underlying loesses, and at Bodzechów it was TL-dated at 27.6±3.0 ky. The tripartite character of the youngest mid-loess interstadial soil from Wąchock and the mentioned ages, as well as the fact that the soil is incised by a 1 m deep frost wedge, suggest that its development should be linked with three warmings of this part of the Vistulian: Moershofd, Hengelo and Denekamp (Dzierżek *et al.*, 2020).

In all analysed sections, this palaeosol is covered by the Upper Younger Loess (LMg – MIS 2), characterised by a high calcium carbonate content and variable thickness, from slightly >2 m at Politów and Bodzechów to >6 m at Komorniki. The TL date of the basal parts of this loess was determined at Wąchock at 15.8±1.8 ky BP and at Bodzechów at 18±1.5 ky BP. The overstated TL age of this loess at Politów (54.4±8.2 ky BP) should be linked with the considerable admixture of sand, which as streaks occurs within the loess as an effect of blowing out of the nearby weathering covers of Liassic sandstones and siltstones.

Summing up, all hitherto identified loess horizons from the last glaciation and interstadial palaeosols distinguished by Maruszczak (2001) are preserved in the HCM area. Their correlation with marine oxygen-isotope stages (compare Dzierżek *et al.*, 2020) has allowed for an attempt to tie the loess accumulation episodes and the development of palaeosols with phases of advance and retreat of the ice-sheets from the last glaciation in northern Poland (Fig. 3).

Correlation of the Younger Loesses with the Scandinavian ice sheet phases

The accumulation of the Oldest Younger Loess and the Lowest Younger Loess (LMn) in the HCM occurred in the Early Vistulian, the interval that lastyed about 38,000 years (109−71 ky BP) and encompassed MIS 5d−a (Lisiecki and Raymo, 2005) (Fig. 3). At that time, there were cold interstadial conditions in Europe with at least two distinct cooler (Herning and Redestall) and two warmer (Amersfoort+Brørup and Odderade episodes. Gradual deterioration of climate after the Eemian resulted in temperature fall, gradual deforestation and expansion of tundra, as well as development of permafrost (Marks *et al.*, 2016, 2019; Dzieduszyńska *et al.*, 2020). In the Early Vistulian, a continental glaciation comprised a series of vast lobes covering Norway, central Sweden, northern fragments of Siberia, the Kara Sea and the polar archipelagos (Marks *et al.*, 2019). The Scandinavian ice-sheet advanced southwards to latitude 58º N, i.e. over 1000 km to the north from study area. The Lowest Younger Loess (LMn) was distinguished as an individual horizon at Politów and Wąchock, with a complete record of sedimentary conditions corresponding to the main climate stages preserved at Wąchock only (Dzierżek *et al.*, 2020).

The main accumulation phase of the Lowermost Younger Loesses took place probably in the Rederstall stadial (Fig. 3). In this time interval, thick (5 m) series of sandy deposits were formed within sequences of lake deposits (Behre, 1989). Three TL-dates (>40.5 ky, 85±1.2 ky and 70±1.1 ky BP) for this loess horizon confirm the accumulation time with the oldest part of the Vistulian, and one TL-date (122.1±8.3 ky BP) seems to be overstated (Fig. 2). A thin loess layer separating the Eemian soil from the Brørup soil was distinguished at Wąchock, Nietulisko Małe

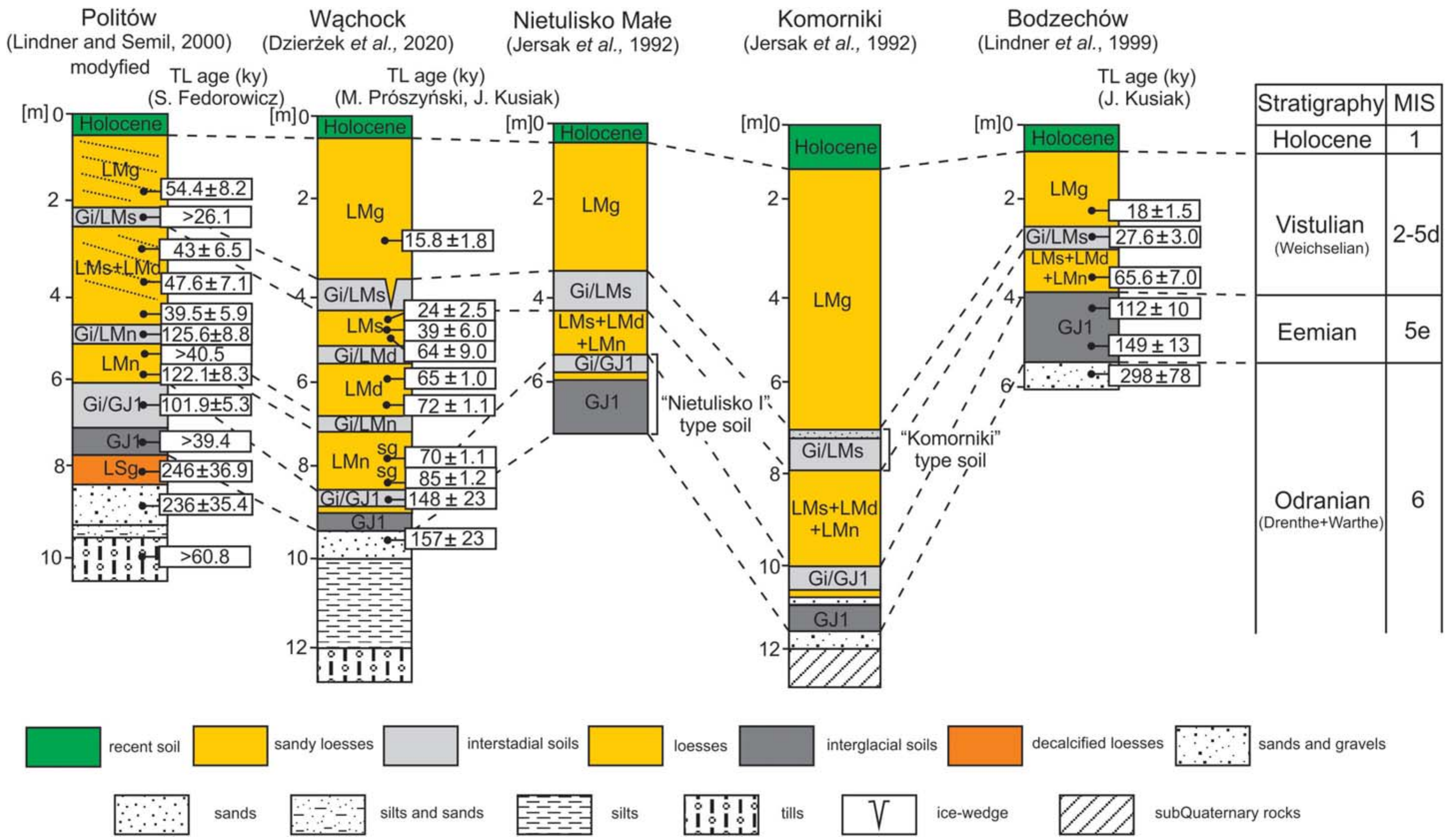

Fig. 2. Correlation of loesses and interstadial soils of the last glaciation (Vistulian) and soils of the last interglacial (Eemian) in the main loess sites of the HCM area; letter symbols after Maruszczak (2001).

and Komorniki (Dzierżek *et al*., 2020). It is most probably the oldest record of the Early Vistulian aeolian activity (Oldest Younger Loess) in Poland, not included in the classification of Maruszczak (1991, 2001), which can be correlated with the Herning stadial (MIS 5d) (Fig. 3).

The accumulation of the Lower Younger Loesses (LMd) took place in the Lower Plenivistulian (Marks *et al*., 2019), in Europe referred to the Middle Weichselian and Early Pleniglacial (Behre, 1989), and lasting 14 ky between 71 and 57 ky BP (Lisiecki and Raymo, 2005). This is the period of a significant global cooling (MIS 4), resulting in extension of the ice sheet cover in northern Europe. Accumulation of a sandy series, named Schalkholz after the stratotype site in Germany (Behre, 1989), is linked with this stadial in many successions of lacustrine and terrestrial deposits in central and northern Europe. The Świecie Stadial is its age equivalent in the Vistulian of Poland (Lindner, 1992; Mojski, 2005). According to many authors, the Scandinavian ice-sheet could advance at that time onto the area of northern and northeastern Poland (Makowska, 1986, 2019; Wysota, 2002; Krzywicki, 2002; Dzierżek, 2009; Dzierżek and Szymanek, 2013). The lithostratigraphic individuality of this stadial as a glacial till is recorded on numerous sheets of the Detailed Geological Map of Poland at the scale of 1:50 000, which would indicate a presence of the ice-sheet about 300–400 km north of the HCM. Three TL-dates obtained for the Lower Younger Loesses at Wąchock and Bodzechów point out to the Middle Weichselian but at Bodzechów these loesses do not form a separate stratigraphic horizon (Fig. 2).

The Middle Younger Loesses (LMs) were accumulated during the Middle Pelnivistulian (in the middle part of MIS 3), between 57 to 29 ky BP, probably mainly during the Lattrop cooling phase. This interval was characterised by numerous interstadial-like climate changes (Fig. 3). Five warming and four cooling episodes were recognised in the lacustrine successions of the Middle Plenivistulian (Behre, 1989). The Scandinavian ice sheet was generally diminished at that time, and its maximal range is stated to have reached (Marks *et al*., 2019) the Hel Peninsula and the Curonian Spit in the southern part of the Baltic Sea. The distance between the margin of this ice sheet and the northern part of the HCM was thus 400–500 km. This resulted in permafrost aggradation and intensification of periglacial processes in central Poland, recorded both in a topography and deposits (Dzierżek and Stańczuk, 2006; Dzieduszyńska *et al*., 2020). In Poland this interval is known as the Grudziądz Interstadial (Makowska, 1986; 2019; Lindner, 1992; Mojski, 2005). In the analysed loess sections, global climate changes are reflected either by phases of intensified aeolian processes or their lack. This interstadial is represented at Wąchock as arctic and tundra soils below and above a thin loess horizon (LMs). In the remaining sections, climate change resulted in periodical deflation (blowing out) of earlier deposits, and in some cases (Politów), by accumulation of coarser aeolian material. TL-dates from the Middle Younger Loesses in the studied sections correspond to the middle part of MIS 3 (Fig. 3).

The Upper Younger Loesses (LMg), recorded in all sections studied in the HCM area, were accumulated during the Upper Plenivistulian, which lasted from 29 ky to 14 ky BP (Lisiecki and Raymo, 2005). The Scandinavian ice sheet attained its maximal limit at that time, and its front was located about 200–300 km north of the study area. TL-dates obtained for this loess horizon at Wąchock and Bodzechów correspond to MIS 2 (Fig. 3). The age from Politów is overstated due to a contribution of coarser fractions of a local material. The Upper Younger Loesses represent usually a uniform complex, 2–6 m thick.

Summing up, in the analysed sections worth noting is a presence of several characteristic features of the Vistulian loesses and the disputable palaeogeographic elements. If a tentative correlation (so far unsupported by other evidence) of the thin, lowermost loess layer from Wąchock, Nietulisko Małe and Komorniki with the Herning stadial (MIS 5d) is correct, then a lack of this loess in other important loess sequences in Poland becomes an important issue (Maruszczak, 2001). The answer for this inconsistency seems simple. At the Eemian/Early Vistulian boundary a temperature fall, increasing climate continentality, scarcer vegetation cover and development of periglacial conditions occurred gradually. In the beginning of the Early Vistulian (Vistulian 1 after Mojski, 2005), there was no sufficient amount of weathered material, a source material for the loess in most area of Poland. The cold Herning stadial, lasting 13 ky, was a long 'preparatory' interval for later enhanced loess-forming processes in the Vistulian. A record of this loess in sequences located in the HCM area only may result from the fact that the nearby sandstone rocks, exposed even during the interglacial intervals, reacted fastest to intensification of physical weathering processes resulting from climate deterioration. Land surface of sandy areas were subjected to frost weathering and a volume of weathering products gradually increased with time. This resulted in the large thickness (up to 6 m) of the youngest Vistulian loesses (LMg) in the analysed sections.

In four sections (except Wąchock), the Lowermost Younger Loesses (LMn), Lower Younger Loesses (LMd) and Middle Younger Loesses (LMs) cannot be distinguished as separate horizons due to a lack of interstadial palaeosols. This may result from the fact that loesses from the Early Vistulian, the Lower and Middle Plenivistulian, and especially the interstadial soils separating them were not thick, which favoured their destruction by gradually enhanced aeolian processes. This was connected with consequent although irregular cooling towards the end of the Vistulian (compare Marks *et al*., 2016, 2019; Granoszewski, 2003; Dzieduszyńska *et al*., 2020). A maximum development of the Vistulian ice sheet terminated loess accumulation in the HCM area. Climate change and related ice sheet retreat in the Upper Plenivistulian, and especially in the Late Vistulian, are not recorded in the Upper Younger Loesses of the area, although they have been generally well recognised in the landscape, lacustrine and marine deposits (Lisiecki and Raymo, 2005; Dzierżek, 2009; Marks, 2012; Dzierżek and Szymanek, 2013; Kalińska *et al*., 2016). This

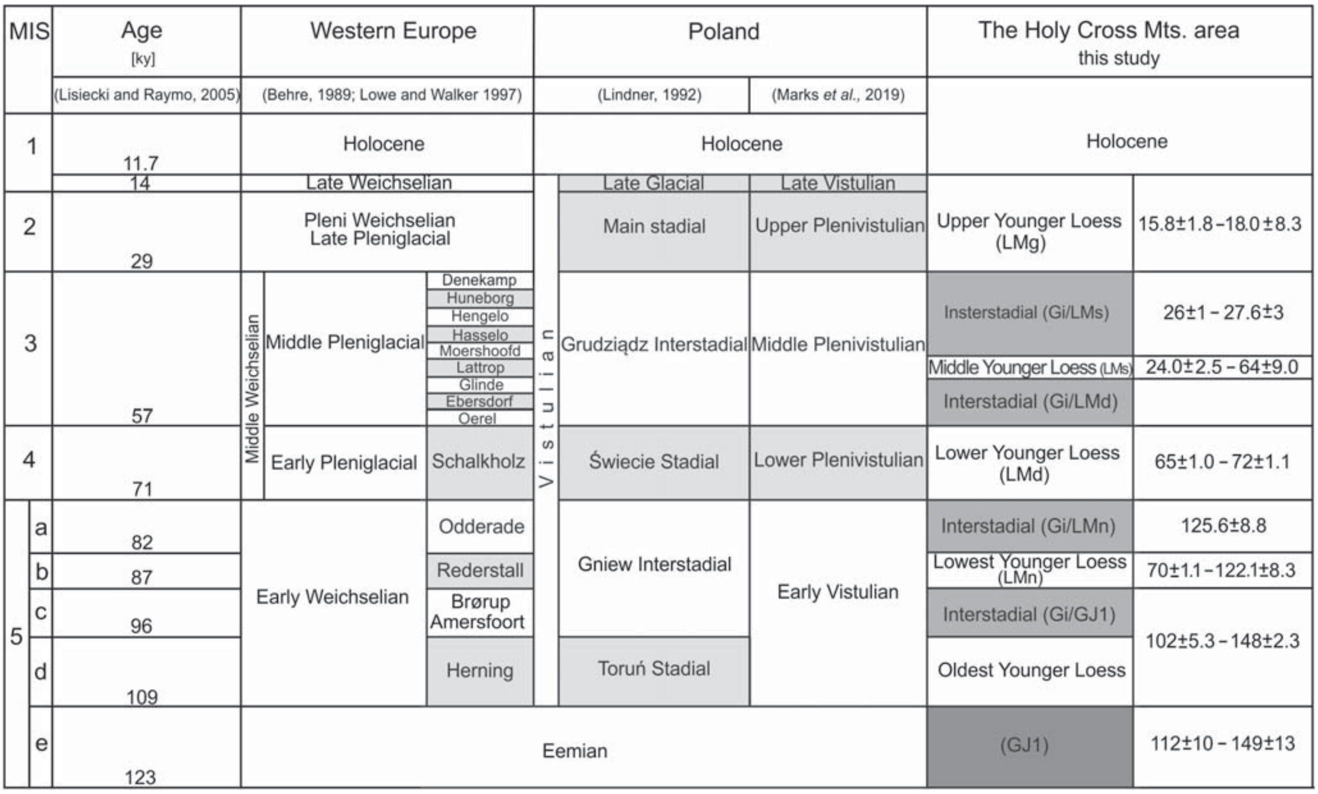

Fig. 3. Stratigraphic scheme of the Vistulian in western Europe and Poland, including the geochronology and TL-datings of the Younger Loesses in the HCM, discussed herein; letter symbols of loesses and palaeosols after Maruszczak (2001).

fact and the presence of the overstated TL-dates in the analysed sections may lead to a general conclusion that loess accumulation was preceded by ice sheet development and took place also in conditions typical for a far-distant periglacial zone.

Conditions of loess accumulation

The younger loesses of the last glaciation, preserved in the HCM area, were also subjected to detailed studies on their accumulation conditions (Jersak, 1970, Chlebowski and Lindner, 1975). Previous works were focused mostly on analysis of the youngest loess – determined herein as the Upper Younger Loess (LMg). The analysis was also focused on the study of the grain-size and heavy minerals composition in the loesses and the surrounding rocks (Chlebowski and Lindner, 1975, 1976, 1989, 1992), as well as the characteristics of a loess occurrence with regard to a geomorphological setting of the area. The Younger Loesses form larger and smaller outcrops named the loess islands (Lindner, 1967, 1971), surrounded both from the north and south by morphological scarps (Lindner, 1976).

Based on the most recent studies (Dzierżek *et al.*, 2019, 2020), it seems obvious that in most cases loess occurs in an eastern shadow of morphological culminations. A position of these loess outcrops in the central and eastern HCM excludes generally an occurrence of corrosion-deflation sandstone inlier rocks in the western part of the area. Results of the grain-size analyses of the Upper Younger Loess prove that in the case of the Borkowice and Oblęgorek loess islands, located in a shadow of basement culminations composed of Liassic and Buntsandstein sandstones and siltstones, numerous streaks and intercalations of sandy material occur within the loesses (see the Politów section in Fig. 2).

Grain-size analyses

The Upper Younger Loesses are dominated by fractions >0.05 mm (35%). A contribution of this grain-size fraction decreases in favour of the 0.01–0.05 mm fraction, reaching up to 40% in the Upper Younger Loess of the Wąchock island, located slightly to the east of the exposure of Buntsandstein sandstones and siltstones (Chlebowski and Lindner, 1992, 1999).

In the case of the largest loess outcrop in the HCM, located in the eastern shadow of the Łysogóry and Jeleniów ranges around Opatów and to the west of Sandomierz, a content of 0.01–0.05 mm fraction reaches locally 55–60%. In the easternmost part of this outcrop, the loess can be subdivided into a northern loess containing >50% of the 0.01–0.05 mm fraction and a southern loess containing <50% of the 0.01–0.05 mm fraction (Chlebowski and Lindner, 1992, 1999).

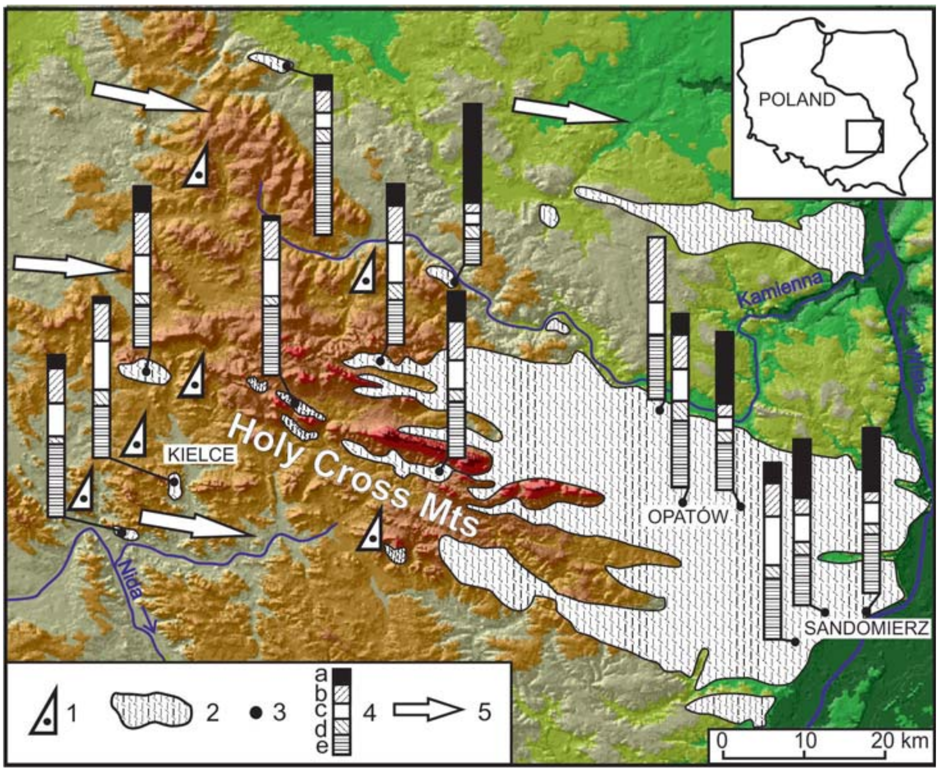

Fig. 4. Occurrence of Upper Younger Loesses covers in the HCM area on Digital Elevation Model, with heavy-mineral characteristic of selected sections (after Chlebowski and Lindner, 1992, modified). 1 – sandstone tors; 2 – loess; 3 – sampling sites; 4 – histograms of a percentage content (whole bar – 100%) of the main groups of heavy minerals: a – sheet minerals (muscovite, biotite, chlorite), b – minerals most resistant to weathering (zircon, tourmaline, rutile, titanium, staurolite, andalusite, disthene, monazite), c – minerals relatively resistant to weathering (epidotes, garnets, sillimanite, apatite), d – minerals least resistant to weathering (amphiboles, pyroxenes), e – opaque minerals; 5 – main wind direction.

Summarizing, the grain-size analysis of the Upper Younger Loess in the study area does not reveal significant differences in a percentage content of the main fractions. The content of the 0.01–0.05 mm fraction is higher (>50%) only in the northern part of Opatów–Sandomierz loess outcrop, which is related to a supply of material from blown-out Pleistocene alluvia of the Kamienna River. Data on grain-size composition of the analysed loess outcrops and the geomorphological context of their occurrence confirm earlier opinions on the western direction of loess-forming winds during the Vistulian Glaciation in the area of Poland (Łyczewska, 1969, 1971; Różycki, 1972, 1976, 1979; Lindner, 1976). This opinion can be partly warranted in a spatial distribution of the sandstone tors in the western part of the study area (Fig. 4). According to Urban (2016, 2019; Urban *et al.*, 2015), the origin of the HCM sandstone tors refers to lithological and structural features of the sandstones and to a set of gravitational processes responsible for their exposure, including a movement of sandstone blocks on the slope surface and a movement of the debris cover. Periglacial conditions during the last glaciation were favourable to such transformation processes. A contemporary appearance of rocks has also been influenced by wind processes, as indicated by presence of aeolian grains in the weathered material. The intensity of aeolian activity is associated with the Upper Plenivistulian and the Late Glacial (Urban, 2019).

Heavy mineral analyses

The Borkowice loess island is characterised by an eastwards drop of minerals resistant to erosion (epidotes, garnets, sillimanite, apatite) and most resistant to erosion (zircon, tourmaline, rutile, titanium, staurolite, andalusite, disthene and monazite), derived mainly from weathering covers of the Liassic sandstones and siltstones. In the Oblęgorek loess island the heavy mineral composition is similar as in the Borkowice island, however with a higher content of minerals most resistant to weathering (Fig. 4), derived from weathering covers of Buntsandstein sandstones and siltstones. There is also an increased content of sheet minerals (muscovite, biotite, chlorite), caused by deflation of residues of sandy material from the Middle Pleistocene kames preserved at higher elevations.

The Wąchock loess island is distinguished by a huge content of sheet minerals (50–80%) over the remaining groups of heavy minerals (Fig. 4) and it should be connected with a direct vicinity of sandy-silty kames and other glacial deposits recording the ice sheet marginal zone during the Odranian Glaciation. The most significant are muscovite, biotite and amphiboles, followed by chlorite and garnets, whereas minerals most resistant to transport and weathering zircon as rutile, tourmaline, staurolite and disthene are rare (Lindner and Chlebowski, 1992, 1999).

In the case of the Upper Younger Loess preserved near Opatów and Sandomierz (Fig. 4), a full assemblage of heavy minerals corresponds distinctly to basement rocks, including those of glacial origin (tills, sand) that contain weathering products of igneous rocks. There are mainly minerals that are poorly resistant to mechanical weathering as amphiboles, garnets, epidotes and biotite. Minerals resistant to weathering (zircon, tourmaline, rutile, staurolite and disthene) are also significant but occur in much smaller amounts. A high content of muscovite can be observed in all analysed samples. A total prevalence of sheet minerals (muscovite, biotite, chlorite) may indicate that the analysed samples represent loess silt that can be easily removed by wind and transported over large distances from the source area. This suggests that the material could be redeposited and thus can be considered as the source material for the silty-sandy deposits.

Analysis of a mineral composition of the Upper Younger Loess proves that presence of sheet minerals in loess (particularly of muscovite) that do not occur close to source areas indicates their supply by loess silt blown from more distant areas, regardless the admixture of a local material. The latter case suggests clear genetic relationships of loess with rocks and their weathering covers occurring in the basement and the closest vicinity. Such conclusions were confirmed both by the analyses of mineral composition of local material in the Sudetic loess islands (Chlebowski *et al.*, 2004) and in the Lublin and Volhynian uplands, where presence of foraminifers derived from the basement Cretaceous rocks was documented in the loess (Paruch-Kulczycka *et al.*, 2003).

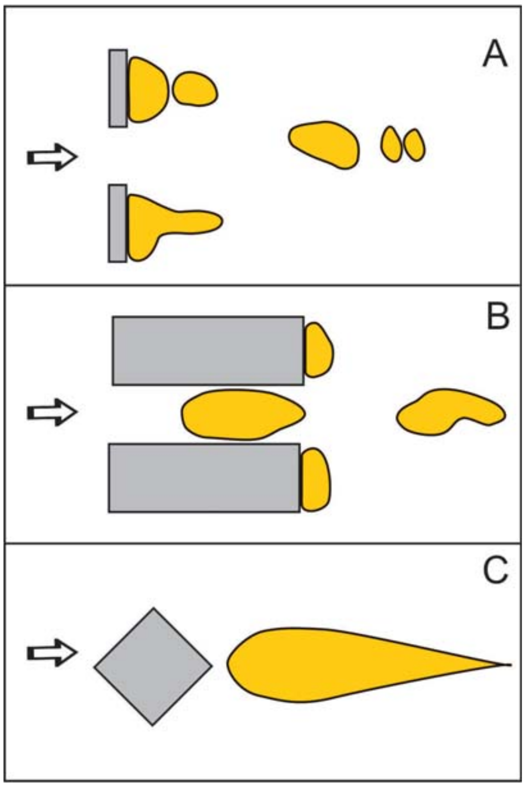

Fig. 5. Selected examples of present-day deposition of aeolian material (deep yellow) depending on a type of barrier (grey) at western winds (arrow), after Raffaele and Bruno (2019). A – narrow barriers, barrier length larger than distance between them; B – wide barriers, elongated, distance between barriers slightly smaller than their width; C – block-like barrier, walls oriented obliquely to wind direction.

Model of aeolian accumulation of the Younger Loesses in the HCM

In the study area, aeolian transport of the main loess-forming mass was rather short-distant and characterised by the activity of western winds blowing in the lower part of the atmosphere, at the simultaneous contribution of winds typical for its upper part. Performed observations indicate that distinct margins bounding particular loess islands or even large parallel-oriented outcrops of the Upper Younger Loess, are accumulative in character (Fig. 4). They were created by air vortexes formed in analogous conditions as the eddies in the leeward zones of bridge pillars and other barriers in river channels (comp. Lindner, 1976).

Such model of accumulation of the sandy material transported by low winds is commonly observed and presently described in urbanised areas built of sandy deposits and subjected to intense desiccation (Lou *et al.*, 2014; Raffaele and Bruno, 2019). Aeolian accumulation takes place in several modes and includes not only a wind force, but also shape and size of a barrier, advance angle, distance between subsequent barriers and others. Some schemes of deposition of aeolian material worked out by Raffaele and Bruno (2019) are presented (Fig. 5). Such model depositional system, linking all examples presented in the scheme, is recorded in a natural landscape depending on geology of the HCM. A model of accumulation of the Younger Loesses may be proposed for the area (Fig. 6), based on analysis of a topographic setting of loess covers and islands (Fig. 4) and contemporary observations. The model explains the size and topographic position of loess outcrops, and additionally confirms the generally western wind direction, although it allows also the possibility of local winds from the northern or southern sectors in the case of eddies. The turbulent character of the air masses leading to a formation of margins during loess accumulation in the Lublin Upland, particularly the margins marking the northern loess boundary, was pointed out by Mojski (2005).

Loess accumulation in the HCM area depended strictly on terrain morphology, which imposed transport directions and deposition sites for the silty material. It is clear (Fig. 4) that silty or sandy patches could have been accumulated behind small morphological barriers (Fig. 5A). They were also formed at the end or close to the walls of an aerodynamic tunnel that developed between elongated ranges built of basement rocks (Fig. 5B). The uplifted, NW-SE-oriented HCM massif may reflect a situation presented in Fig. 5C and the accumulation of the largest loess patch (Fig. 6A, B). A significant role of periglacial processes during the Vistulian, which not only favoured wind activ-

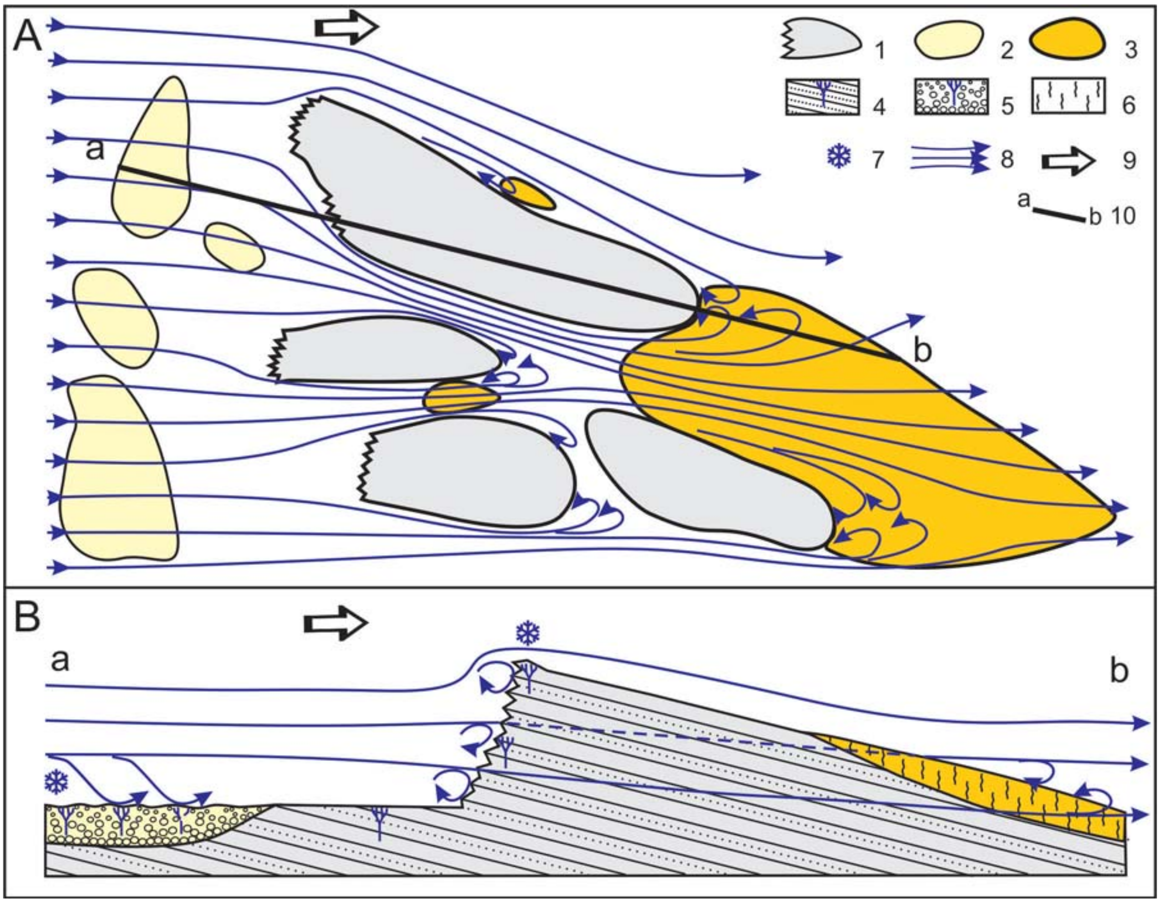

Fig. 6. Model of deposition of the Younger Loesses in the HCM based on Raffaele and Bruno (2019). A – sketch-map; B – schematic cross-section. 1 – basement elevations, partly in form of sculpted landforms; 2 – patch of sand; 3 – patch of loess; 4 – homoclinally arranged basement sandstones subjected to frost weathering, with sculpted landforms; 5 – sands subject to frost weathering; 6 – loess; 7 – periglacial conditions; 8 – contribution of local wind directions above landscape forms; 9 – main wind direction; 10 – schematic cross-section.

ity, but enhanced physical weathering of Quaternary sandy covers occurring in valleys and in the western foreland of the hills, should also be taken into account. Sculpted landforms built of sandstones, numerously occurring in the area, were subject to frost weathering and abrasion. These process supplied silty material, which was then deposited in aerodynamic shadows. Analysis of grain-size composition and spatial analysis of loess occurrence confirm such scenario of accumulation of the Upper Younger Loesses in the HCM area.

CONCLUSIONS

- In the analysed sections, the Younger Loesses are 4 to 9 m thick and lie on a well-documented palaeosol of the Eemian Interglacial. Their lithological and sedimentary features, separating palaeosols and TL-datings allow for a relatively precise correlation of the phases of loess-forming processes with climate conditions during the Vistulian. They also allow to refer these phases to the stratigraphic schemes of the Late Pleistocene, based on biostratigraphic and isotope studies in northern Europe.
- A horizon of the Lowermost Younger Loesses (LMn) is preserved at Politów and Wąchock, whereas traces of loess accumulation (Older Younger Loess) during the oldest Early Vistulian stadial (Herning) are recorded at Wąchock, Nietulisko Małe and Komorniki. The break in loess accumulation, during which tundra soils developed in the Brørup Interstadial, is documented not only in the stratotype section at Nietulisko Małe, but also at Politów, Komorniki and Wąchock.
- The Lowermost (LMn), Lower (LMd) and Middle (LMs) Younger Loesses accumulated in the Early Vistulian and in the Lower and Middle Plenivistulian at Nietulisko Małe, Komorniki and Bodzechów form a massive loess complex. This may result from a relatively low primary thickness of the separating tundra soils, which was a factor favouring their later erosion (deflation) during subsequent phases of enhanced aeolian activity. A Komorniki-type palaeosol (Gi/LMs), dated at the termination of the Middle Plenivistulian, is noted in all analysed sections of the HCM area.
- The Upper Younger Loesses (LMg) form the thickest bed within the analysed loesses, which is partly caused by rich production of silty material due to long-term

(entire Vistulian) weathering in periglacial conditions of the neighbouring sandy covers and exposed sandstones.

- A topographic position of the Upper Younger Loesses (LMg) in the neighbourhood and on slopes of mountain ranges, and grain-size and heavy minerals composition of the loesses indicate that the Upper Younger Loesses were accumulated in the HCM mainly by low winds blowing from the western sector. Local variability of directions of their accumulation was a natural phenomenon, in accordance with aerodynamic models of contemporary aeolian processes.

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