Geological Quarterly, 2007, **51** (2): 193–202

# Rate of loess accumulation in Europe in the Late Weichselian (Late Vistulian)

Stanisław FEDOROWICZ and Maria ŁANCZONT

Fedorowicz S. and Łanczont M. (2007) — Rate of loess accumulation in Europe in the Late Weichselian (Late Vistulian). Geol. Quart., **51** (2): 193–202. Warszawa.

The European loess profiles provides evidence of changes in climate in the last glacial cycle. The final stage of loess accumulation took place in the youngest part of the last glacial (28 to 12 ka BP). Loess accumulated in two periods: from 28 to 18 ka BP and from 18 to 13 ka BP. These two stages were separated by a short phase of weaker aeolian activity and weak pedogenesis (initial tundra gleyed soils). The loess sedimentation rate can be defined as a mass accumulation rate (MAR expressed in g/m$^2$/year). This value was calculated by Frechen *et al*. (2003) for several dozen loess sites across western and central Europe. In this paper we calculate the MAR for several loess sites in Poland and Ukraine. The MAR distribution across Poland and Ukraine is uneven in these two intervals. The MAR values oscillate between 100 to several thousand g/m$^2$/year. They markedly increase eastwards, which may be explained by the latitudinal gradient of periglacial climate in the LateWeichselian (= Late Vistulian). The MAR distribution along a N–S trend confirms its large range in western and central Europe. However, the most easterly profiles (Polish and Ukrainian ones) show less variable thicknesses as the MAR was stable at a relatively low level from several hundred to more than a thousand g/m$^2$/year. This stability of the MAR characterized both loess-forming intervals in this part of Europe.

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Key words: European loess, Upper Weichselian, mass accumulation rates (MAR), TL, optically stimulated luminescence (OSL).

## INTRODUCTION

The climatic conditions that existed in the Pleistocene periglacial zone in Europe were reflected in the accumulation of loess. The clearly delimited loess zone on this continent (Fig. 1) consists of a number of areas where loess is either part of landscape or constitutes a predominant element. The former includes the loess of western Europe, where it occurs as patches that tend to be small, are frequently isolated and are usually not very thick, with noticeable hiatuses in the successions, in particular in lower parts of the profiles. Central European loess covers are more continuous and up to a dozen or so metres thick. In southern-central and eastern Europe, loess is widespread, continuous and locally over 40 m thick; furthermore, these deposits frequently show stratigraphic continuity (Różycki, 1986; Maruszczak, 1991*a*; Mojski, 1993).

European loess deposits preserve evidence of climate change in the Pleistocene. Changes in the last glacial cycle, which took place in *ca*. the last 120 000 years from the end of the Eemian to the Holocene, are the best and most precisely recorded. This is because loess deposits of this interval are the most completely preserved and the most widespread. As regards the rhythm of global climate changes in this interval as reflected in the stable oxygen isotope composition of deep-sea deposits, loess and palaeosol horizons may be correlated with the corresponding stages and substages (OIS 5–2).

The Weichselian loess usually rests on Eemian Interglacial forest soil (OIS 5e). In the early glacial interval this substrate was covered by further deposits, corresponding to the OIS 5d–a substages, which were formed alternately during the cold and warm fluctuations of the Herning (5d), Amersfoort and Brörup (5c), Rederstall (5b) and Odderade (5a) stadials and interstadials. OIS 4 pertains to the first major episode of severe climate in the Weichselian. In the younger part of the glacial, in OIS 3, i.e. in the Interpleniglacial, a series (*ca*. a dozen) of small climate fluctuations with weakly expressed warmings were noted in Europe; the most salient ones are termed the Oerel, Glinde, Moershoofd, Hengelo and Denekamp (Behre, 1989). In Poland, Mojski (2005) refered to the Interpleniglacial part of

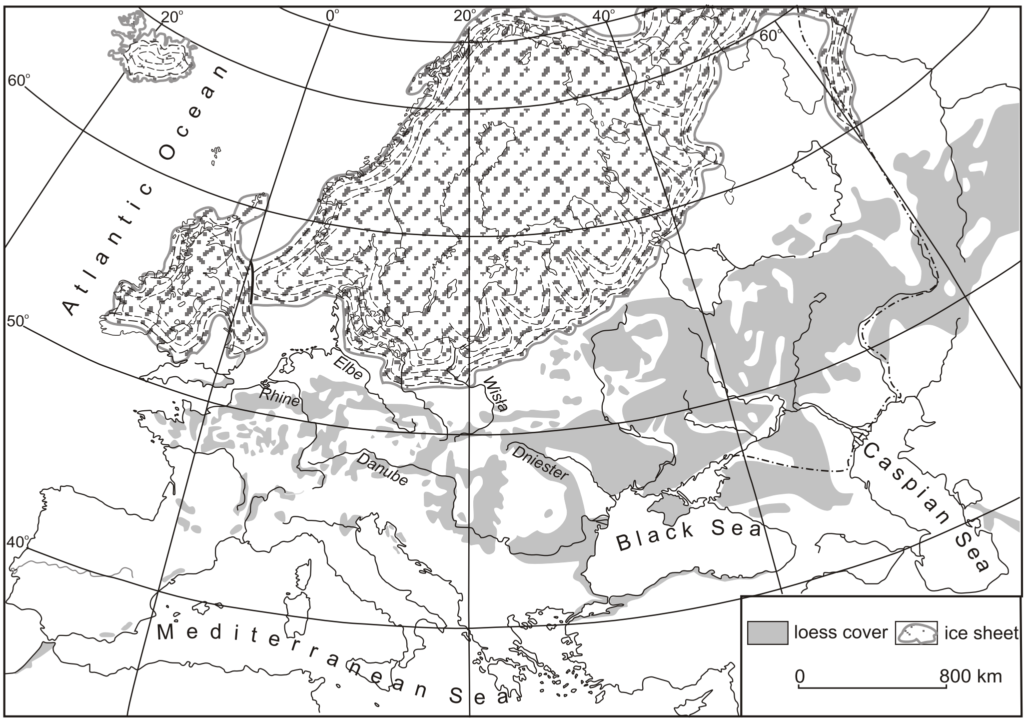


**Fig. 1. Distribution of loess covers in Europe (according to Wojtanowicz, unpubl.)**

The maximum extent of the last Scandinavian ice sheet is by Mojski (1993) and Marks (2005)

glaciation as the Grudziądz Interstadial that he further divided into an older and a younger part. The latter includes at least eight phase-interphase climatic fluctuations, two of which were identified in Poland: an older one of Hengelo age and a younger one of Denekamp age (Mojski, 2005). OIS 2, the youngest part of the last glacial, is the next phase of radical climate cooling, the maximum extent of the last Scandinavian ice sheet in Northern Europe (Mojski, 1993; Marks, 2005; Figs. 1–3) and very intensive periglacial processes.

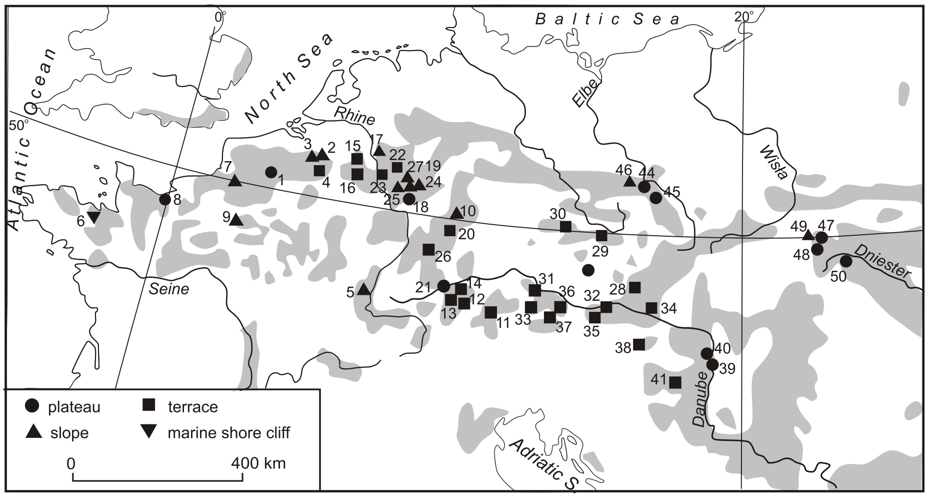


**Fig. 2. Location of loess sites discussed in the paper and containing loess deposited in OIS 2, including the type of geomorphological variation (according to Frechen *et al.*, 2003, modified and supplemented with the authors' own data from Poland and Ukraine)**

## OBJECTIVE AND METHOD

Generally speaking, loess accumulation in Poland, with some hiatuses, lasted for approx. 550 000 years (Maruszczak, 2001*b*) while in Lower Austria, the Hungarian Lowlands and Ukraine, loess covers had been forming since the Eopleistocene (Mojski, 1993; Gozhik *et al.*, 1995; Boguckyj and Łanczont, 2005). Additionally, in view of the reduced thicknesses and lithological features of older layers in particular, it can be deduced that loess covers were affected by erosion, denudation and glacial exaration in areas covered by ice sheets at different times (Mojski, 2005). The loess age may be determined directly, inter alia, by luminescence dating. Dating of the top and basal parts of individual loess layers often suggest a relatively short time for their formation (Fedorowicz, 2006).

The final stage of loess accumulation took place from 28 to 12 ka BP (Maruszczak, 1985, 1991*b*, 2001*b*; Frechen *et al.*, 2003). The climate of this interval was the most conducive for loess deposition in the entire Vistulian

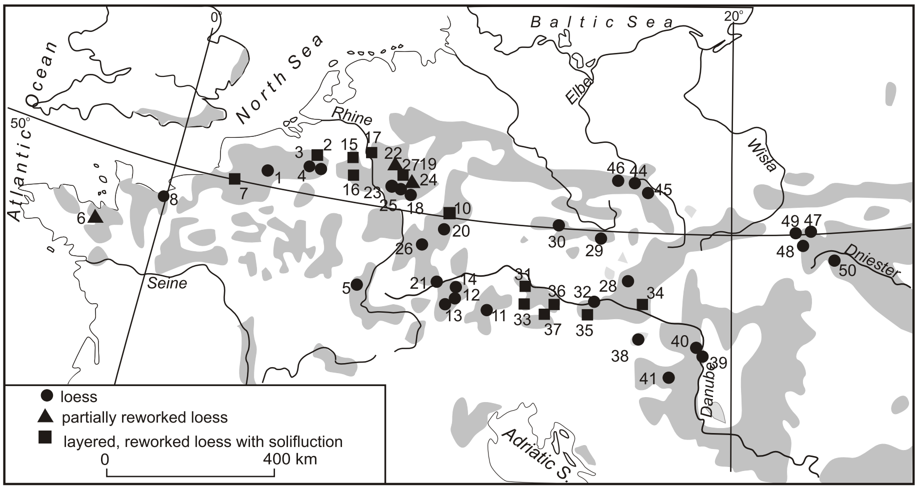


**Fig. 3. Site location and dominant loess facies at the sites discussed in this paper (according to Frechen *et al*., 2003, modified and supplemented with the authors' own data from Poland and Ukraine)**

(Łanczont and Wojtanowicz, 2000). This loess therefore usually has the largest thickness of any of the younger loess beds. It formed under severe climate conditions with aridity increasing gradually with time. Generally, loess patches in eastern Europe are more extensive, continuous and thicker than in western Europe (Maruszczak, 1991*a*), which may be explained by the eastwards-increasing continentality of climate. The loess is locally bipartite.

Serious difficulties arise when one attempts to determine the rate of loess accumulation over this interval. These result, for instance, from the uncertainty as to whether or not loess is complete at any given site, which might have been affected by various erosive processes, both during and after sedimentation. Thus, loess beds may include many gaps/hiatuses, their thickness being consequently reduced. Despite this, there have been frequent attempts to estimate this value. There are differences in how the sedimentation rate value is presented. Maruszczak (Maruszczak, 1991*b*, 2001*b*) provided an average loess accumulation rate in Poland in mm/year, while Frechen (Frechen *et al*., 2003) described the mineral mass accumulation rate (MAR) in $m^2$/year on the basis of loess research in western and central Europe (43 sites in 7 countries).

The results published by Frechen *et al*. (2003) inspired the authors to calculate the MAR for loess profiles in Poland and Western Ukraine, and to compare them with the values obtained for western and central Europe. The same facies scheme of loesses was used. Altogether seven Polish and Ukrainian loess sites were analysed. TL ages, which are the main starting point for our calculations, were obtained in the Gdańsk University laboratory.

In total, the analysis of loess TL results covered 50 sites from various European countries: France, Belgium, Germany, Austria, the Czech Republic, Slovakia, Hungary (Frechen *et al*., 2003), Poland and Ukraine (our research) (Fig. 2 and Table 1A–D). The common feature of these sites is the presence of loess that accumulated in the younger part of the Plenivistulian. Synthetic descriptions of the profiles from the first seven countries are given by Frechen *et al*. (2003). The remaining sites are discussed in detail by Boguckyj and Łanczont (2002), Łanczont and Boguckyj (2002), and Fedorowicz (2006). The thickness of loess from the last glacial, given in Table 1A–C, was estimated on the basis of data published by Frechen *et al.* (1997, 1999, 2001, 2003).

## MAR CALCULATION

Frechen *et al*. (2003) contains dating results of 43 European loess sites. Most luminescence ages were calculated by Frechen over the last 15 years. The remaining dates were obtained by Wintle, Lang and Zoller. The age analyses used various materials, both mineral and organic ones, including loess, animal remains and charcoal. Luminescence dating was used to date loess and loess-like deposits, and radiocarbon dating was used for organic material (Table 1A–C). The largest amount of data comes from the region of the Rhine and Danube valleys. Several samples were collected from various depths in the sites, the morphological setting of deposition having been accounted for. Three basic relief elements were taken into account: plateau, slope and terrace (Fig. 2). Thus, there is loess of plateau, slope and terrace topofacies. Six of 43 sites covered by the examination pertained to the plateau areas, and these were marked on the map as: 39, 1, 18, 40, 21, 8 and 23. One site: 6, Sables d'Orles Pins in French Brittany, was classified as a cliffed seashore.

Three loess types were distinguished (*cf.* Maruszczak, 1972): aeolian loess with little or no redeposition (1) and two loess types (2, 3) whose aeolian accumulation was accompanied by various syn- or postsedimentary slope processes (Fig. 3):

— primary/initial loess: in most cases uniform, weakly stratified, yellowish brown, porous, calcareous, silty,

— deluvial loess: laminated-stratified, redeposited as a result of slope deluvial and/or colluvial processes,

— loess redeposited by solifluction processes.

To calculate the MAR of mineral material contained in loess we used the formula applied by Kohfeld and Harrison (2003) to deep-sea sediment, ice core and loess. This specifies the mass of loess dust falling and accumulating on the surface (1 sq cm or 1 sq m) during the year. The formula accounts for the accumulation rate specified on the basis of at least two luminescence ages on samples collected from the same layer.

$$MAR = AR \cdot f \cdot BD$$

were: MAR — mass accumulation rate (g/$cm^2$/year), AR — accumulation rate (cm/year), f — coefficient specifying the content of aeolian material in the sample (for loess f= 1), BD — bulk density (g/$cm^3$).

The average bulk density (BD) is as follows:

— for Chinese loess 1.48 g/$cm^3$ (Kohfeld and Harrison, 2003),

Table 1

**Location of loess sites with information about loess thickness and dating methods used for MAR calculation**

| Location | Site (country) | Loess thickness [m] (OIS 2) | Dating method |
|---|---|---|---|
| **A** — loess sites in NW Europe | | | |
| 1 | Harmingnies (B) | 5.00 (1.80) | OSL |
| 2 | Kesselt (B) | 4.70 (1.50) | TL |
| 3 | Remicourt (B) | 4.00 (2.20) | OSL, TL |
| 4 | Rocourt (B) | 3.00 (2.00) | TL |
| 5 | Achenheim (F) | 3.00 (1.60) | TL |
| 6 | Sables d' Orles Pins (F) | 3.50 (2.40) | OSL |
| 7 | Saint Sauflieu (F) | 1.80 (2.30) | OSL, TL |
| 8 | Saint Romain (F) | 10.20 (1.40) | TL |
| 9 | Villiers-Adam (F) | 4.20 (1.50) | OSL |
| **B** — loess sites in central-western Europe | | | |
| 10 | Wiesbaden (D) | 4.20 (3.50) | OSL |
| 11 | Bobingen (D) | ? (2.45) | OSL |
| 12 | Böckingen (D) | 2.50 (2.20) | OSL |
| 13 | Bönnigheim A (D) | 2.80 (1.40) | OSL |
| 14 | Bönnigheim B (D) | 5.20 (3.00) | OSL |
| 15 | Elsbachtal (D) | 4.40 (1.80) | OSL |
| 16 | Garzweiler-Süd (D) | 6.00 (4.20) | OSL |
| 17 | Grafenberg (D) | 13.50 (10.50) | OSL |
| 18 | Kärlich (D) | 1.90 (0.50) | TL |
| 19 | Köblenz-Metternich (D) | 9.60 ( 8.50) | OSL |
| 20 | Mainz-Weisenau (D) | ? (4.40) | OSL |
| 21 | Nussloch (D) | 11.30 (9.90) | OSL, AMS, $^{14}C$ |
| 22 | Ockenfels (D) | 9.50 (7.30) | OSL |
| 23 | Remagen-Schwalbenberg (D) | 3.10 (2.60) | OSL |
| 24 | Schweinskopf (D) | 1.30 (0.40) | OSL |
| 25 | Tönchesberg (D) | 1.90 (1.45) | TL |
| 26 | Wallertheim (D) | ? (1.90) | TL |
| 27 | Wannenköpfe (D) | ? (1.60) | OSL |
| **C** — loess sites in central Europe | | | |
| 28 | Dolni Vestonice (Cz) | 5.80 (5.30) | OSL, $^{14}C$ |
| 29 | Kutna Hora (Cz) | 4.20 (1.70) | OSL |
| 30 | Zemechy (Cz) | 4.40 (2.50) | OSL |
| 31 | Altheim (A) | 2.00 (0.50) | OSL |
| 32 | Grubgraben (A) | 7.00 (1.00) | $^{14}C$ |
| 33 | Gunderding (A) | 3.50 (2.40) | OSL |
| 34 | Stillfried (A) | 2.00 (1.00) | TL |
| 35 | Stratzing (A) | 1.30 (0.40) | TL |
| 36 | Trindorf (A) | 3.50 (1.90) | OSL |
| 37 | Wels (A) | 2.00 (0.70) | TL, $^{14}C$ |
| 38 | Willendorf II (A) | 3.20 (1.55) | $^{14}C$, AMS-$^{14}C$ |
| 39 | Albertirsa (H) | 3.50 (2.60) | OSL |
| 40 | Mende (H) | 4.30 (2.20) | TL, OSL, $^{14}C$ |
| 41 | Paks (H) | 6.00 (5.30) | OSL |
| 42 | Cosaoutsi (R) | 14.00 (3.40) | $^{14}C$ |
| 43 | Mituc Malu (R) | 6.65 (3.34) | $^{14}C$, AMS-$^{14}C$ |
| **D** — Polish and Ukrainian loess sites | | | |
| 44 | Biały Kościół (Pl) | 6.55 (3.50) | TL, OSL |
| 45 | Dankowice (Pl) | 9.30 (5.80) | TL |
| 46 | Księginice Małe (Pl) | 8.55 (5.60) | TL |
| 47 | Dybawka (Pl) | 13.35 (6.70) | TL, OSL |
| 48 | Tarnawce (Pl) | 6.65 (1.50) | TL, OSL |
| 49 | Zarzecze (Pl) | 3.80 (2.35) | TL |
| 50 | Halyč (Uk) | 3.44 (3.44) | TL, OSL, $^{14}C$ |

The thickness of loess was estimated on the basis of data published by **A** — Frechen *et al*. (2001, 2003), **B** — Frechen *et al*. (1999, 2003), **C** — Frechen *et al*. (1997, 1999, 2003); the list of radiometric methods used in MAR calculations is according to Frechen (2003); B — Belgium, F — France, D — Germany, Cz — Czech Republic, A — Austria, H — Hungary, R — Romania, Pl — Poland, Uk — Ukraine; dating methods: OSL — optically stimulated luminescence, TL — thermoluminescence, AMS — accelerator mass spectrometry, $^{14}C$ — radiocarbon

— for European loess 1.65 g/cm$^3$ (Frechen *et al*., 2003).

In the calculations a bulk density of BD=1.65 g/cm$^3$ was adopted after Frechen (2003).

In this paper the set of MAR values calculated by Frechen *et al*. (2003) for loess from western and central European sites was extended by more MAR values computed through luminescence ages for the Polish and Ukrainian sites on the basis of our own research and on other research.

## WESTERN AND CENTRAL EUROPEAN LOESS PROFILES

Eemian palaeosol (referred to in this area as Rocourt after the Belgian site (4) where it was identified) is moderately common at loess-palaeosol sites in northwestern France and Belgium (Table 1A). At the French site of Saint Sauflieu (7) it is overlain by a palaeosol correlated with the Brörup and Odderade interstadials, OIS 5d–a (Behre, 1989). The terminal part of OIS 5, dated at 73 ka BP, is marked by the formation of steppe soil identified in two succeeding profiles at this site. A late glacial loess bed, deposited from 18 to 13 ka BP, has also been documented at Saint Sauflieu and it is of slope facies. In the French Villiers-Adam profile (9) loess formed on an Eemian palaeosol between 55 and 35 ka BP. There are organic interbed above the loess. The upper part of the profile includes loess accumulated between 25 and 20 ka BP. The Sables d'Orles Pins site (6) is located in the zone of a marine cliff edge. This site includes Late Pleniglacial Loess deposited in two phases: an older one from 26.4 to 19.7 ka BP and a younger one from 17.8 to 15.9 ka BP. Late glacial loess occurs also at the Saint Romain site (8). This loess was dated by A. Wintle *et al*. (1984) at 16.4–12.6 ka BP. The slope loess sample from the Villiers-Adam site (9) located in the Osie River valley yielded an age of 23.5 ka BP (Frechen *et al*., 2003). At the Belgian site of Harmingnies, loess-palaeosol deposits from the last interglacial-glacial interval have the largest thickness, reaching 5 m (Frechen *et al*., 2001*a*). The Rocourt palaeosol is overlain by deposits with Early Weichselian palaeosols where five climatic oscillations are recorded, which are related to OIS 5d–a. Artifacts of the Mousterian Culture from the Middle Palaeolithic were discovered in the lower part. The Middle Weichselian is represented by three layers. The lower one is correlated with OIS 4 and contains an interstadial steppe soil. The middle one consists of loess with a distinct tundra gley horizon while the highest layer reflects climate oscillations connected with the Moershooft and Denekamp interstadials. Frechen *et al.* (2001*b*) correlated the middle and upper layers with OIS 3. The Upper Weichselian (OIS 2) is represented by the next three layers. Besides these sites, in this part of Europe there are no other sites known where the stratigraphic continuity of Upper Weichselian loess-palaeosol sequence has been preserved.

In Belgium at Kesselt (2) the deposits of the last glacial are only *ca*. 2.7 m thick. Two intra-loess palaeosols separated by a thin loess layer were radiocarbon dated at 37 260±1850 ka BP and 22 270±380 ka BP. At the Rocourt site (4) the Eemian palaeosol is overlain by a bipartite loess 4 m thick. According to Wintle (1987), the lower loess part was deposited from 42 to 36 ka BP and the upper one between 17.1 and 13.2 ka BP. Pleniglacial loess was examined in detail by Frechen (Frechen *et al*., 2003) at the Remicourt site (3). The age of this loess was estimated at 25.8–18.7 ka BP.

In Southern England loess deposits are found along the southeastern sea coast and in the Thames valley. Individual luminescence ages obtained for a number of sites show that loess accumulation took place in three periods: before *ca*. 170 ka BP and in the intervals 125 to 50 ka BP and 23 to 10 ka BP. TL ages of late glacial loess obtained by Wintle (1981) at a few sites fall within the range of 18.8 to 13.0 ka BP.

Eemian palaeosol is also a key horizon at central European sites (Table 1B) located in the Rhine valley. It is found in Tönchesberg (25) and Köblenz–Metternich (19) (Boenigk and Frechen, 2001). At the Tönchesberg site, the Blake palaeomagnetic event dated at 117 ka BP has been found in a chernozem lying directly on Eemian forest soil. Both sites contain four Early Weichselian palaeosols with a total thickness of 4 m, i.e. similar to the thickness of deposits that accumulated later in the Mid and Late Weichselian. At the boundary between OIS 5a and 4 there is a thin marker layer of sandy silt. Its counterparts are also found at some loess sites in Alsace, the Rhine valley, and Moravia (Frechen *et al*., 2003). In the Mid Weichselian during OIS 3, loess formed in two phases in the interval 45–25 ka BP. It has been found at the sites mentioned above as well as at Remagen-Schwalbenberg (23). In the Late Weichselian, loess accumulated in two phases: 24–20 ka BP and 17–13 ka BP. These two loess beds occur at Tönchesberg (25), Köblenz-Metternich (19), and Schweinskopf (24).

The final phase of the Weichselian was marked by climate destabilisation. Many loess sites in Belgium, Netherlands, and the Rhine valley show a sedimentation gap corresponding to this phase. Late glacial loess has been observed at fewer sites in the northern part of the Rhine valley than in the southern part. Most loess has been affected by redeposition (reworked loess); there are also traces of solifluction and deluvial processes, found in the Grafenberg (17) and Garzweiler-Süd (16) sites.

As regards Southern Germany and Alsace, brown Eemian palaeosol has been found at the following sites: Nussloch (21), Böckingen (12), Bönnigheim (13 and 14) and Achenheim (5) (Frechen, 1999). The Nussloch (21) site contains a 2 metre bed of Middle Weichselian loess separated by two tundra gley soils and a 2 metre bed of Upper Weichselian loess, also separated by a tundra gley soil. The remaining sites contain Middle Weichselian loess with two palaeosols. The Upper parts of the profiles include Upper Weichselian loess beds 5 m thick with tundra gley interbeds. Two loess beds separated by three interstadial steppe soils occur on an Early Weichselian palaeosol at another site, Mainz-Weisenau (20). The total thickness of the deposits is 4 m.

As regards Austria, the Czech Republic and Slovakia (Table 1C), the last glacial deposits show that climatic conditions were similar to those in Southern Germany. An interglacial palaeosol (PK III in the Czech Republic) is overlain by three chernozem soils, which together form a soil succession marked as PK–II and correlated with OIS 5c–5a. It is overlain by Middle Weichselian loess correlated with OIS 3. Luminescence ages of samples collected from this loess range from 53.4 to 36.5 ka BP (Frechen *et al*., 1999). The palaeosol (PK I in the Czech Republic) overlying the loess was formed in the Denekamp (Frechen *et al*., 1999); it is overlain by Upper Weichselian loess. Luminescence ages of these deposits range from 29.5±1.5 to 17.1±3.0 ka BP; thus, they refer to the first older accumulation stage of the Late Pleniglacial. According to Frechen *et al.* (1999), the accumulation rate of this loess exceeded 1 mm/year.

Hungary's main loess source was alluvial sediments of the Danube and its tributaries. In the Hungarian Lowland the lower part of the loess sequence, referred to as the Mende-Basaharc, corresponds to the older part of the last glacial. Steppe and forest-steppe soil approximately 2 m thick, of a Basaharc type, formed in the Brörup Interstadial in the interval 75–70 ka (Mojski, 1993). Next a loess bed up to 10 m thick was formed. Its accumulation rate has been estimated to have been on average *ca*. 0.13 mm/year in the interval 77–45 ka BP (Frechen *et al*., 1997). Such a rapid accumulation rate is explained by the abundance of source material in the Danube and the Cisa River valleys. At that time Poland and Ukraine did not experience such conditions. This was in the interval 45–40 ka BP when forest-steppe chernozem soil, that often contains charcoal, was formed (the MF1 horizon in Hungary). Loess beds accumulated in the interval OIS 3–2; these are separated by the h2 horizon (Denekamp) and the h1 horizon (Frechen *et al*. 1997, Frechen *et al*., 2003).

## MAR OF WESTERN AND CENTRAL EUROPEAN LOESS

The accumulation of Upper Weichselian loess has been divided into two intervals from 28 to 18 ka BP (Upper Pleniglacial) and from 18 to 13 ka BP (late glacial) (Frechen *et al*., 2003). These two stages were separated by a short phase of weaker aeolian activity. In loess profiles this phase is often represented by an initial tundra gleyed soil (Nassböden) (Freising 1957; Zöller and Semmel, 2001). With regard to the interval 28–18 ka BP, MAR calculation results for primary loess (Fig. 4) fall within the range of 100 $g/m^2$/year and 7000 $g/m^2$/year. The highest values were obtained for areas located along the Rhine River system in Western Germany, e.g. Wallertheim (26 — terrace, 6930 g/m$^2$/year) and Nussloch (21 — plateau, 1213–6129 g/m$^2$/year). The lowest accumulation rate (93–450 g/m$^2$/year) was reported in Belgium at Kesselt (2 — slope), Remicourt (3 — slope), Rocourt (4 — terrace), and in Eastern France at Achenheim (5 — slope). With regard to the interval 18–13 ka BP, MAR values (Fig. 5) fall within the range of 200 and 450 g/m$^2$/year for areas located in France along seashores and along the Seine banks, and are significantly higher for terraces of the Rhine and Danube, i.e. reaching values of 800–1600 g/m$^2$/year and even of 1600–3200 g/m$^2$/year. The lowest MAR values were noted in Austria (32 — Grubgraben), the Czech Republic (28 — Dolni Vestonice) and Hungary (41 — Paks). Detailed results are given in Figures 4 and 5 for both intervals (cited in Frechen *et al*., 1997, 1999, 2003).

The above data indicate that MAR values, hence the accumulation rate, markedly increased eastwards, which, as already noted, may be explained by the latitudinal gradient of the periglacial climate in the Late Pleniglacial that was changing eastward from a maritime climate (on the Atlantic coast) to a more dry/continental one. The climate-dependent spatial variation of loess accumulation rate was also influenced by a regional factor, which is reflected in a clearly higher rate of loess accumulation in areas located along large river systems, in particular the Rhine. This was certainly associated with the abundant supply of loose, easily deflated sediment along river valley floors. These sediments were then rapidly accumulating from braided rivers strongly loaded with suspended matter fed by Alpine mountain glacier meltwater. Small thicknesses of loess that accumulated on slopes in the western part of Europe may be explained by local factors since accumulation was accompanied by more intensive redeposition in a more humid climate. It may be supposed that slope angle, aspect and location in relation to major wind directions were important factors.

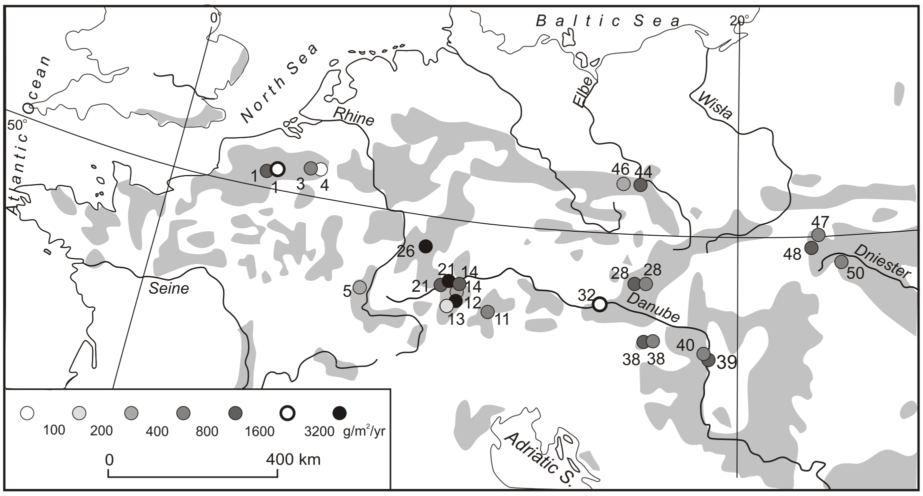


**Fig. 4. Mass accumulation rates for European loess accumulated during the Upper Pleniglacial period (28–18 ka BP)**

Data from Frechen *et al*. 2003 supplemented by the authors' own results from Polish and Ukrainian sites

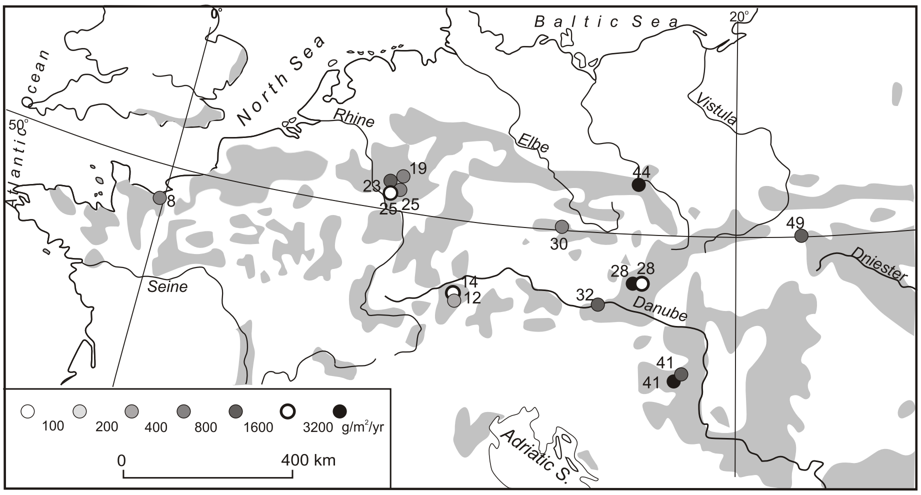


**Fig. 5. Mass accumulation rates for European loess accumulated in the Late Glacial period (18–13 ka BP)**

Data from Frechen *et al*. 2003 supplemented data by the authors' own results from Polish and Ukrainian sites

## POLISH AND UKRAINIAN LOESS

Polish loesses occur in the transition zone between western European and eastern European loesses (Maruszczak, 1991*a*). The loess of the last glacial cycle (Younger Loess — LM) is frequently fully developed, without any hiatuses. The most representative loess sequence is found in the eastern part of the South Poland Uplands (Maruszczak, 1991*b*). Four loess beds are separated by three interstadial palaeosols (marked as Gi): the bottom palaeosol on the lowest younger loess corresponds to the Odderade Interstadial (Gi/LMn), the middle one on the lower LM corresponds to the Glinde or Oerel interstadials (Gi/LMd), while the top one on the middle LM is associated with the Denekamp Interstadial (Gi/LMs) (Maruszczak, 1985, 1991*a*, 2001*a*). The upper LM (LMg) is the most typical and uniform loess, of a characteristic straw-colour, and with the highest content of carbonate. It usually constitutes more than half of the entire thickness of younger loess covers. Typically one, and less frequently two or three, gley horizons are found within it.

The loess of the South Poland Uplands constitutes the western frontier of Ukrainian loess, which forms the central-western part of the large loess area called the eastern European loess province and considered to be one of the largest such areas in the world. Ukraine has a few areas with extensive and thick loess covers in the western part of the country (Volhynian-Podolian Uplands and East Carpathian Foreland), in the Dnieper Valley, and in the vicinity of the Black Sea coast. In the western part of Ukraine loess-palaeosol sequences of last glacial frequently show a complete stratigraphic profile and start from the bottom with the Horohiv soil succession. Next one may observe Upper Pleistocene Loess with the Dubno set of palaeosols and the Rivne and Krasyliv initial horizons in the top loess layers, referred to as the upper bed of the Upper Pleistocene Loesses (Boguckyj, 1986). In terms of lithological features and thickness, the youngest bed is similar to the LMg in Poland. At present, the loess stratigraphy in Western Ukraine is studied in considerable detail by distinguishing the following layers: interglacial Horohiv palaeosol and a succession of early glacial Kolodiiv palaeosols (OIS 5), loess (OIS 4), loess-separated Dubno 2 and Dubno 1 palaeosols (OIS 3), loess correlated with OIS 2, with the Rivne and Krasyliv horizons.

It is difficult to unambiguously determine which of these 2–3 horizons of weak gleying occurring in the Polish and Ukrainian loess sequences of the Upper Plenivistulian can be dated at about 18 ka BP. It is possible that in the Ukrainian loess profiles the Rivne horizon developed at that time. Traces of the East European Gravettian settlement are locally found at this horizon (Boguckyj and Łanczont, 2002, 2003; Cyrek *et al.*, 2005; Fedorowicz, 2006; Łanczont and Boguckyj, 2007).

The analysis covered a few loess sites from SW and SE Poland and one site from the western part of Ukraine (Table 1D), in all of which primary loess is found:

— SW Poland, loess sites in the Sudeten Foreland: Biały Kościół — 44, Dankowice — 45, Księginice Małe — 46;

— SE Poland, loess sites in the Carpathian Foothills and Foreland: Dybawka — 47, Tarnawce — 48 and Zarzecze — 49;

— NW Ukraine, loess site in the East Carpathian Foreland: Halyč — 50.

Typical loess occurs in the Sudeten Foreland, occuring as two patches on the right-bank part of the Oder Basin (Jary *et al.*, 2004*a*, *b*). The Dankowice and Biały Kościół sites are close to each other (less than 5 km apart), and lie near Strzelin in the marginal foreland of the Sudetes. They represent a relatively continuous outcrop that covers the hilly plateau on the Mała Ślęza and Osława interfluve; this loess may be classified as plateau facies. The Księginice site is located in the vicinity of Sobótka farther within the foreland of the Sudetes, *ca*. 25 km NW from the above-mentioned outcrops. It represents small loess patches of slope facies on the Bystrzyca and Ślęża interfluve (Fig. 2).

The Dybawka and Tarnawce sites (Dynów Foothills) represent loess that forms a continuous cover on the Pleistocene terraces of the San River (Łanczont, 1993; Komar and Łanczont, 2002). Loess accumulated on the broad flat surface of the younger terrace (the so-called middle terrace) at a height of 225 m a.s.l. in Dybawka and on the older terrace (the "high terrace") at Tarnawce (250 m a.s.l.) while younger loess accumulated on slopes (Fig. 2). At Zarzecze (the Fore-Carpathian loess plateau) the profile is located in the side of the Mleczka River valley (the San Basin) within an erosional/denudational valley (Łanczont and Wojtanowicz, 2005).

The Halyč site is located in the East Carpathian Foreland in a region called Halyč Prydnistrov'ja. The loess analysed occurs on Pleistocene terrace IV (290 m a.s.l.), which may be correlated with the high terrace of the San in terms of age. It is a unique site because it enables evaluation of thickness changes in the younger loess across the terrace (the excavation is in a large brickyard). Loess thickness varies consider-

Table 2

**TL ages of the samples collected from Polish and Ukrainian loess sites**

| Sample | Depth [m] | Lab. No. UG | TL age [ka BP] |
|---|---|---|---|
| Z 1 | 1.00 | 5706 | 22.1±2.6 |
| Z 2 | 1.80 | 5707 | 25.5±3.1 |
| Z 3 | 2.30 | 5708 | 29.6±3.2 |
| DA 3 | 2.75 | 5689 | 11.6±1.6 |
| DA 4 | 3.45 | 5690 | 12.9±1.6 |
| DA 5 | 4.40 | 5691 | 10.4±1.4 |
| DA 6 | 5.15 | 5692 | 14.6±1.6 |
| DA 7 | 6.45 | 5693 | 15.0±1.8 |
| DA 8 | 7.35 | 5694 | 23.0±2.9 |
| DA 9 | 7.95 | 5695 | 15.8±2.0 |
| TA 1 | 1.60 | 5666 | 12.8±1.4 |
| TA 2 | 2.80 | 5667 | 16.8±1.5 |
| DN 1 | 1.20 | 5883 | 20.0±2.2 |
| DN 2 | 2.05 | 5884 | 14.3±1.5 |
| DN 3 | 2.80 | 5885 | 23.8±2.8 |
| DN 4 | 3.50 | 5886 | 21.9±2.5 |
| DN 5 | 4.10 | 5887 | 14.5±1.9 |
| DN 6 | 4.65 | 5888 | 23.7±2.8 |
| DN 7 | 5.30 | 5889 | 21.8±2.4 |
| BK 1 | 0.60 | 5771 | 18.8±2.3 |
| BK 2 | 1.00 | 5772 | 14.2±1.9 |
| BK 3 | 2.00 | 5773 | 16.9±2.1 |
| BK 4 | 3.00 | 5774 | 15.2±2.1 |
| KM 1 | 1.15 | 5733 | 8.3±1.1 |
| KM 2 | 1.75 | 5734 | 15.0±2.2 |
| KM 3 | 2.20 | 5735 | 13.0±2.1 |
| KM 4 | 2.60 | 5736 | 12.6±2.1 |
| KM 5 | 2.95 | 5737 | 13.7±2.3 |
| KM 6 | 3.55 | 5738 | 12.0±2.2 |
| KM 7 | 4.25 | 5739 | 14.9±2.3 |
| KM 9 | 5.15 | 5741 | 15.8±2.5 |
| KM 10 | 5.55 | 4742 | 15.8±2.5 |
| KM 11 | 6.30 | 5743 | 17.4±2.6 |
| KM 12 | 6.50 | 5744 | 40.8±5.3 |
| KM 13 | 7.35 | 5745 | 10.9±1.7 |
| H.IC.1 | 1.54 | 5630 | 17.4±2.6 |
| H.IC.2 | 2.00 | 5631 | 19.0±2.9 |
| H.IC.3 | 2.52 | 5632 | 20.8±3.4 |
| H.IC.4 | 2.90 | 5634 | 21.8±3.5 |
| H.IC.5 | 3.44 | 5635 | 26.4±4.0 |

Z — Zarzecze, DA — Dybawka, TA — Tarnawce, DN — Dankowice, BK — Biały Kościół, KM — Księginice Małe, H.IC — Halyč (IC archaeological site); laboratory symbol: UG — Gdańsk University ably on this terrace, from 10 m to *ca*. 3 m over a distance of 0.5 km. The loess clearly covers and masks an older, varied Eemian relief on the surface of terrace IV. The profile examined is associated with a positive element of this former relief and the loess has its minimum thickness here (Łanczont and Boguckyj, 2002).

## MAR OF POLISH AND UKRAINIAN LOESS

The MAR was calculated for loess from the younger part of the Pleniglacial of the last glacial (Upper Plenivistulian), i.e. OIS 2. All TL ages were obtained by Fedorowicz (Table 2) (Fedorowicz, 2006). The LMg accumulation rate in Poland has been estimated at *ca*. 0.5 mm/year, and at 0.8–1.0 mm/year in the phase of most rapid accumulation (Maruszczak, 1991*b*, 2001*b*). The loess was deposited generally continuously with a clearly defined interruption between 18 and 17 ka BP.

With reference to western European results, we also considered two depositional intervals: the first/older one from 28 to 18 ka BP and the second/younger one from 18 to 13 ka BP. MAR accumulation rates were calculated separately for each interval (Table 3).

The loess dust accumulation rate (AR in the Kohfeld and Harrison formula) specified by Maruszczak (1991*a*), which amounts on average to *ca*. 0.5 mm/year, corresponds to a MAR of 830 g/m$^2$/year. The MAR double when the accumulation rate was in the highest.

MAR values obtained for the sites range from *ca*. 200 to more than 3 000 g/m$^2$/year. The Dankowice loess yields the lowest value (215 g/m$^2$/year); the Tarnawce and Zarzecze loesses have very similar values ranging from 473 to 495 g/m$^2$/year. The MAR values of Księginice and Dybawka loess are also very similar (1 084–1 100 g/m$^2$/year). The Biały Kościół loess has a MAR value three times higher. At Halyč, where loess accumulated from 26.4 ka to 17.4 BP, the MAR value reaches 193 g/m$^2$/year in the lower part and 473 g/m$^2$/year in the upper part of the profile. The latter is similar to the MARs obtained for Tarnawce and Zarzecze.

It may be deduced from the TL ages obtained for the Sudeten Foreland profiles that at two distant sites (Biały Kościół and Księginice Małe) loess mainly accumulated in the second/younger time interval and that this process was very fast (the MAR is 1100 and 3300 g/m$^2$/year). However, in respect of the third site at Dankowice, which is located near Biały Kościół, accumulation was very slow (215 g/m$^2$/year) and took place in both time intervals (Table 3).

The distance between the Dybawka and Tarnawce sites in the Carpathian Foreland is small (*ca*. 1 km) as is that between the sites near Strzelin in the Sudeten Foreland. There is evidence of loess accumulation in the second/younger time interval; however, the Dybawka MAR was twice as high as the Tarnawce MAR. The former site is located nearer the valley bottom than the latter site and the sites also differ as regards the topofacies of accumulated loess (terrace topofacies and slope topofacies, respectively). In respect of Zarzecze, it seems that LMg accumulation took place only in the first/older time interval; its rate was not high and was similar to the Tarnawce value. At Halyč, loess sedimentation took place at a similar time (first/older interval) and at a similar rate to that at Zarzecze.

TL and OSL ages were obtained for the same samples from four sites: Dankowice, Dybawka, Tarnawce and Halyč (Fedorowicz, 2006). The ages, which were obtained for the same samples with using luminescence methods (TL and OSL), indirectly provide information about the period of grain exposure to sunlight during deposition. Grain exposure to sunlight for a few hours leads to fast zeroing of the OSL signal and a slower reduction of the TL signal. Short exposure (even for a few seconds) leads to OSL zeroing and only a slight reduction of the TL signal. Therefore, similar TL and OSL dating results point to long exposure of the grains under analysis; when TL dates are older than OSL dates, it means that the exposure time was shorter. The samples from the first three sites show very similar or even identical TL and OSL ages (Table 3). It is only at the Halyč site where TL ages are older than OSL ages (Fedorowicz, 2006).

The Polish sites in the Sudeten Foreland and the Ukrainian site are situated at *ca*. 500 km apart. At this distance the variation in LMg loess thickness is not very large (Table 1D) and does not show any direct relation to the geographic zone (and the palaeoclimatic gradient). The largest loess thickness, up to 6 m, was observed at Dankowice, Księginice Małe and Dybawka while the smallest one of *ca*. 2 m is at Tarnawce and Zarzecze. Halyč

Table 3

**Mass of accumulated LMg loess [g/m$^2$/year] at the Polish and Ukrainian sites**

| No. | Site | Geographical coordinates | Range of TL ages (ka BP) obtained for **OIS 2** loess *against the Vistulian loess* | MAR (g/m$^2$/year) | |
|---|---|---|---|---|---|
| | | | | TL | OSL |
| 44 | Biały Kościół | λ=17°01’30’’E<br>φ=50°43’35’’N | **18.8–14.2**<br>*82.6–14.2* | **3 300** | **nd** |
| 45 | Dankowice | λ=17°00’40’’E,<br>φ=50°43’15’’N | **23.8–14.3**<br>*63.5–14.3* | **215** | 199 |
| 46 | Księginice Małe | λ=16°45’15’’E<br>φ=50°51’40’’N | **15.0–8.3**<br>*63.8–8.3* | **1 100** | nd |
| 47 | Dybawka | λ=22°41’20”E<br>φ=49°47’15’’N | **15.8–10.3**<br>*76.4–10.3* | **1 084** | **1 188** |
| 48 | Tarnawce | λ=22°41’06’’E<br>φ=49°47’40’’N | **16.8–12.8**<br>*82.6–12.8* | **495** | 495 |
| 49 | Zarzecze | λ=22°32’05’’E<br>φ=49°59’50’’N | **25.5–22.1**<br>*72.4–22.1* | **485** | nd |
| 50 | Halyč | λ=24°12’12’’E<br>φ=49°01’51’’N | **26.4–17.4**<br>*26.4–17.4* | **473** | 272 |

nd — means that OSL dating was not carried out contains evidence of large thickness variation in the youngest layers within the same relief form (terrace).

The thickness of LMg loess covers and consequently MAR values have therefore been affected by regional and by strictly local conditions. These created a combination of factors that encouraged or hindered sediment accumulation, which resulted in the large variations in accumulation values observed. Besides the relief (slope angle and exposure), the proximity of potential source areas, and the loess-forming wind direction, these factors should also include the supportive role of orographic modification of winds (e.g. the tunnel effect), and the relative height of deposition above the valley bottom (vertical extent of accumulation) if the latter was the main "producer" of mineral mass.

## FINAL REMARKS

The eastward growth of loess cover continuity and thickness in Europe is a general pattern caused by the former east-west climate gradient (Maruszczak, 1991*a*); however, this was modified by a complex interrelation of local factors. These led to large differences in the thickness of loess layers of the same age even within one outcrop. These factors included the abundance of material from local source areas, morphological conditions, including direct subloess relief, and orographic conditions, notably the orientation in relation to loess-forming wind directions. The main direction of loess-forming winds in the extensive foreland of the Sudetes and the Carpathians in the younger depositional interval is generally associated from the WNW with a local component from the SW in the Halyč Dniester Basin (Chlebowski *et al*., 2004, Nawrocki *et al*., 2006). As early as in the 19th century Rehman (1891) proposed that loesses in the southern part of the Sandomierz Basin accumulated from north-westerly winds.

Both directly after accumulation and/or subsequently (in particular during the disappearance of permafrost) slope processes developed under new climatic conditions. Their impact on the loess cover depended on slope inclination and aspect. As a result, the MAR distribution is uneven, differing between the two temporal ranges: 28–18 ka BP (Fig. 4) and 18–13 ka BP (Fig. 5). The MAR distribution in a N–S direction indicates its large range in western Europe (Frechen *et al*., 2003). However, the most eastward sites (39, 40, 46, 47, 48, 49, and 50) show a consistent pattern were the MAR value was stable at a relatively low level from several hundred to more than one thousand g/m$^2$/year. The MAR stability pertains to both time intervals in this part of Europe.

The MAR values oscillate between 100 and several thousand g/m$^2$/year. The set of MAR values do not show a clearer arrangement that would allow the authors to determine certain spatial regularities. Sites where MAR values were reported as high in the first interval and small in the second interval may be adjacent to sites where these relations are reversed. In most cases the sites contain deposits from only one of the depositional intervals distinguished by Frechen *et al*. (2003). Only in five cases (sites 12, 14, 32, 28 and 44) was there identified loess whose luminescence ages fall within the two intervals (Figs. 4 and 5).

Luminescence ages obtained from samples of loess that correlate with OIS 2 in Poland and Ukraine, form sequence of values from 26.4 ka BP to several thousand years. Some of these belong to the older interval of loess accumulation that took place from 28 to 18 ka BP, e.g. in Zarzecze or Halyč. This may mean that deposition was locally slower in the younger accumulation phase; however, at these very sites (in particular at Zarzecze) one can not exclude the possibility that the youngest layers have been partially modified by postglacial changes. In some profiles (e.g. at Dankowice) the loess ages obtained fall within both intervals. The ages obtained for the remaining profiles (e.g. Księginice Małe, Dybawka) may be allocated to the second/younger interval of loess accumulation that occurred from 18 to 13 ka BP.

**Acknowledgements**. We are grateful to Prof. J. Wojtanowicz for giving his original map of loess distribution. We would like to express our gratitude to Prof. A. Boguckyj and Dr Z. Jary for cooperation on field investigations of the Halyč, Biały Kościół and Dankowice sites.

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