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Glacial Cycles of Loess Accumulation in Poland during the last 400 ka and Global Rhythms of Paleogeographical Events*

Cykle glacjalne akumulacji lessu w Polsce w ciągu ostatnich 400 ka i globalne rytmy zdarzeń paleogeograficznych

Abstract. Neopleistocene loesses are the most extensive and easiest to distinguish in Poland. Therefore, for the last glacial cycle not only climate variations but also changes of accumulation rate of loessy silt have been defined since a long time. Nowadays, the development of datings by physical methods facilitates studies of older loesses which have been poorly examined and are difficult to access. The analysis results of changes of loess accumulation conditions are presented here. Attention is given to differentiation of lithologic features, especially to accumulation rates of silt. A diagram of the accumulation rates is compared with diagrams of eolian dust content in Antarctic ice core and marine sediment cores, in which global rhythms are well recorded. The characteristics of loesses from the last glacial cycles are defined: 1) Vistulian (=Weichselian), 2) Wartanian (=Saalian II), 3) Odranian (=Saalian I), 4) Liwiecian (=pre-Saalian). Loesses from these cycles are linked to the δ^{18}O timescale of marine sediments.

Key words: glacial-interglacial cycle, interglacial soils s.s. and s.l., periglacial and peridesert loess, Neo- and Mesopleistocene, global events.

INTRODUCTION

The first modern attempt to correlate Polish loesses with glacial cycles was published by A. Jahn (1950, 1956). He concluded that "cycle of loess accumulation occurred mainly in phases of maximum extent and of retreat of an ice sheet". On the other hand, S.Z. Różycki (1972) thought that more important was loess accumulation in the earlier phases of the cycle. The problem of periodicity was differently presented by J. Jersak (1977), who,

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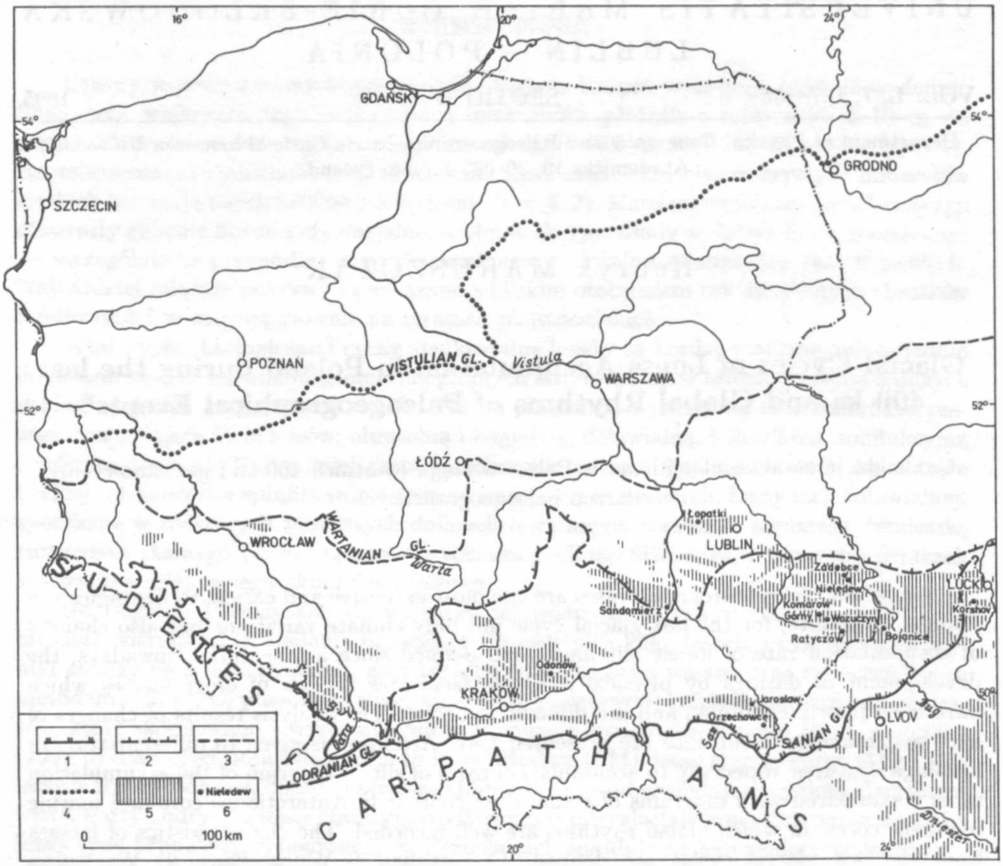


Fig. 1. Situation of the discussed profiles in relation to loess distribution and extents of the Scandinavian ice-sheet. Ice-sheet extents after L. Lindner (1987), partially modified. Loess extents after H. Maruszczak (1991) and according to International Quaternary Map of Europe; 1–4 — extents of ice-sheet: 1) Sanian, 2) Odranian, 3) Wartanian, 4) Vistulian; 5 — extent of proper loess over 2–3 m thick; 6 — loess profiles discussed in the text

besides accumulation, took into consideration also degradation, weathering and pedogenetic transformation of loesses. This approach was similar to that published earlier by J. Kukla (1969). Accordingly, we deal rather with the development cycle of loess covers than with that of loessy silt accumulation.

The problem of loesses periodicity can be considered from the sedimentological and paleogeographical point of wiev. The paleogeographical cycle is indirectly presented in all latest stratigraphic schemes of Polish loesses because the occurrence of intraloessy interglacial and interstadial soils is considered as the main classification criterion (J.E. Mojski 1969, J. Jersak 1969, 1985, 1991, H. Maruszczak 1976, 1980, 1987, 1991).

A more detailed reconstruction of the sedimentation conditions could be made mainly for the layers representing the last glacial cycle, i.e. for younger loesses. Due to their wide extent they were examined in many exposures a long time ago. For this cycle in detail were determined: a) differentiation of accumulation intensity of loessy silt in course of time; b) spatial dynamics of accumulation; c) paleoclimatic conditions of accumulation (H. Maruszczak 1980, 1987). Older loesses are less extensive and, as a rule, covered by younger ones, so they are less accessible to examination. Rather a few data concerning these loesses could be better interpreted only in the last years due to analyses of eolian dust content in marine sediments, the results of which were published, for example by S.A. Hovan et al. (1989), S.C. Clemens, W.L. Prell (1990). The results of special importance were obtained for Antarctic ice sheet layers up to 220 ka old (J. Jouzel et al. 1993). They simplified systematization of data concerning the upper older loesses representing the last but one glacial cycle (H. Maruszczak 1995). The results of this work stimulate compilation of very few data about loesses from still older glacial cycle.

BASIC DATA

Results of lithological and stratigraphical studies of Polish loesses were presented in a collective work "Main sections of loesses in Poland" (1991). A topical version of the stratigraphy of Polish loesses correlated with appropriate schemes worked out for south-eastern and western Europe was also published in the mentioned work (H. Maruszczak 1991). According to this stratigraphic scheme the last glacial cycle (Vistulian = Weichselian) is represented by younger loesses (LM), the last but one (i.e. Wartanian = Saalian II) by upper older loesses (LSg), and the preceding one (i.e. Odranian = Saalian I) by middle, lower and lowest older loesses (LSs+d+n). The characteristics of these loesses mentioned below was done largely on the basis of the results of detailed investigations of exposures, which situation in relation to the extent of the ice sheets is presented in Fig. 1.

Younger loesses, i.e. from the last glacial cycle, were examined in detail in several dozen profiles. Owing to that it was rather simple to determined the patterns of their vertical and horizontal differentiation, which was good basis to estimate the mean thickness of secondary stratigraphic units as well as changes of loess accumulation rate during this glacial cycle (H. Maruszczak 1980, 1987). As a good example of this differentiation the Komarów Górny profile is presented here (Fig. 2). However, it should be stressed that this profile is typical for slopes of cool expositions where bottom

LM layers are of bigger thickness. On the other hand, on slopes of warm expositions these layers are relatively thin; such a sequence of layers occurs, among others things, in the Jarosław profile (H. Maruszczak 1985).

Upper older loesses, i.e. from the last but one glacial cycle, are well known in a complete sequence only in two profiles (Odonów and Orzechowce) in Poland. The Wożuczyn profile could be mentioned as a third but it contains a considerable hiatus in the upper part of the LSg bed. To supplement this short list of Polish profiles, two Ukrainian profiles (Bojanice, Korshov) are taken into consideration. In these profiles equivalents of LSg layers occur also as a complete sequence. These profiles have been investigated since a long time by A. Bogucki from the Lvov University (A.B. Bogucki 1987, 1990, 1992, A. B. Bogucki et al. 1994). Differentiation of the LSg layers is presented here on the example of the Odonów profile (Fig. 3; this version of this profile record is published for the first time) and also of the Orzechowce profile (Fig. 4).

Middle, lower and lowest older loesses, i.e. from the Odranian glacial cycle, are known in a complete sequence — thus with an interglacial soil below and over them — mainly in the Nieledew profile (Fig. 5). The Wożuczyn could be mentioned as the second full profile in Poland, but the occurrence of a bottom interglacial soil is not sufficiently evidenced here (J. Buraczyński et al. 1985, 1988). In the Ratyczów profile the Odranian loesses were examined in borings but they were not adequate for univocal definition of the bottom limit of this stratigraphic unit (J. Buraczyński et al. 1978). Accordingly, the investigation results of the two mentioned Ukrainian profiles appear to be very important for analysis of this glacial cycle.

There is no foundation for detailed analysis of loesses from older glacial cycles. They are represented by the layers distinguished as the oldest loesses (LN1, LN2, LN3) which are very poorly preserved. Those accumulated before the advance of the Sanian (=Elsterian) ice sheet were probably degraded to a considerable degree. Only the layers younger than the mentioned glaciation, i.e. LN1, are preserved a little better but they are always weathered. The best developed ones in Poland were found only in the Zadębce profile (L. Dolecki 1994); in other profiles they were investigated mainly in borings (L. Dolecki 1991). In the profiles at Bojanice and Korshov they are very poorly preserved. That is why the LN1 layers representing the Liwiec (=pre-Saalian = Fuhne) glaciation are marked only schematically in the diagram of the intensity of loessy silt accumulation in Poland (Fig. 6d).

The stratigraphy of loesses occurring in the profiles included in this paper was determined mainly on the basis of paleopedologic criteria (oc-

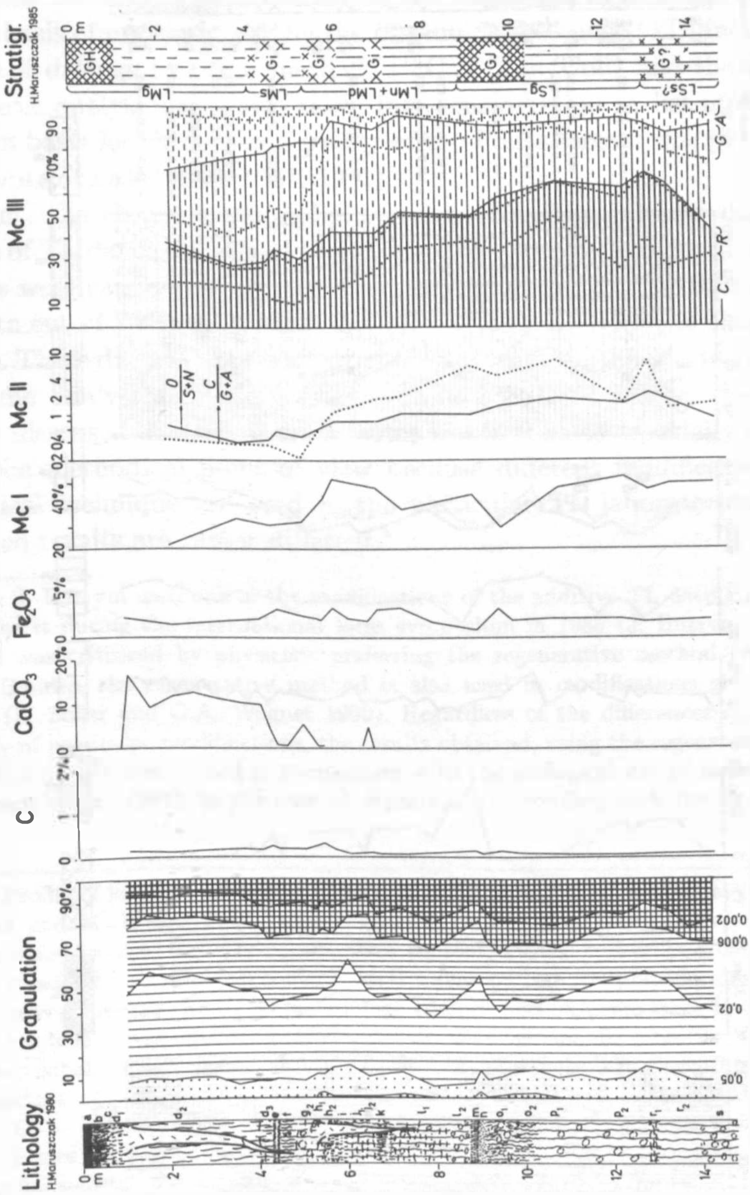
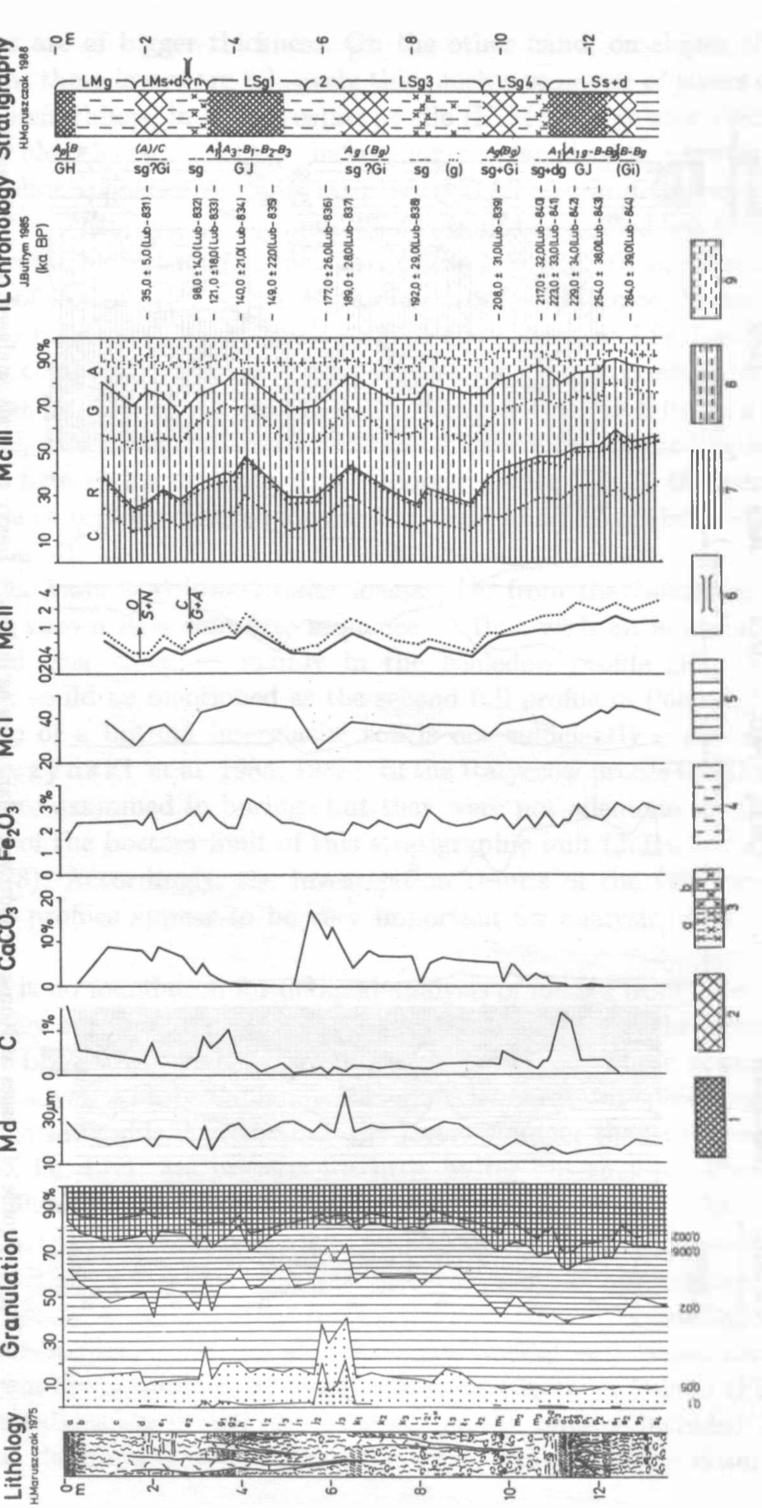


Fig. 2. Profile of loesses at Komarów Górny; explanations as in Fig. 3. Heavy minerals analysed by J. Morawski (vide H. Maruszczak and J. Morawski 1976)


Lithology
H.Maruszczak 1975
Granulation
Md
C
CaCO3
Fe2O3
Mc I
Mc II
Mc III
TL Chronology
J.Butrym 1985
(ka BP)
Stratigraphy
H.Maruszczak 1986
LMg
LMs+d
LSg1
LSg3
LSg4
LSs+d

currence of paleosols). To define the changes of accumulation rate of loessy silt, it was of course essential to determine the time intervals corresponding with the distinguished stratigraphic units. These intervals were fixed on the basis of many datings by the thermoluminescence (TL) method. The results of datings by other methods (^{14}C; FCl/P/Coll) and those of paleomagnetic analyses were also taken into consideration. A list of the results giving a basis for chronostratigraphy of the Polish loesses was published by H. Maruszczak (1980, 1987, 1991).

Thus, the chronostratigraphy was determined mainly on the basis of results of TL datings. It should be stressed that the datings for all examined profiles were carried out in one laboratory, namely by dr J. Butrym in the Department of Physical Geography, Maria Curie-Skłodowska University in Lublin. These datings were done from the beginning of the 80's to 1992, using the same analytical method (J. Butrym 1985). Therefore, the series of results disscused in this paper are comparable. This is especially important from the methodical point of view because different modifications of the analytical technique are used in the particular TL laboratories, and the obtained results are rather different.*

* Dr J. Butrym used one of the modifications of the additive TL dating method and presented it during the international loess symposium in 1985 (J. Butrym 1985). This method was critisized by physicists preferring the regenerative method (A.G. Wintle 1987). Besides, the regenerative method is also used in modifications giving different results (L. Zöller and G.A. Wagner 1990). Regardless of the differences caused by the specifity of particular modifications, the results obtained, using the regenerative method, are distinctly underestimated in comparison with the geological age of sediments. After S. Balescu et al. (1991), in the case of deposits corresponding with the oxygen-isotope

Fig. 3. Profile of loesses at Odonów. Heavy minerals analysed by M. Wilgat (vide H. Maruszczak and M. Wilgat 1978). Letter symbols of diagrams: Md — median grain size, C — humus content, $CaCO_3$ — carbonate content, Fe_2O_3 — free iron oxides content, McI — opaque heavy minerals content, McII — assemblage composition indices of transparent heavy minerals, McIII — assemblage composition of transparent heavy minerals. Letter symbols of transparent heavy minerals: C — zircon, R — rutile, G — garnet, A — amphibole, O — most resistant minerals, S — medium resistant minerals, N — non-resistant minerals. Letter symbols of stratigraphic units of loesses: LM — younger loesses, LS — older loesses, LN — oldest loesses, g — upper, s — middle, d — lower, n — lowest. Letter symbols of soil units: GH — Holocene soil, GJ — interglacial soil, Gi — interstadial soil, sg — soil sediments, dg — soil deluvia, /g/ — symptoms of pedogenesis development. Graphic signatures: 1 — Holocene and interglacial soils; 2 — interstadial soils; 3 — a/ soil sediments, b/ poorly developed interstadial soils; 4 — non-weathered, carbonate loesses; 5 — weathered, carbonate-free loesses; 6 — bigger hiatuses in profile; 7 — resistant heavy minerals; 8 — medium resistant heavy minerals; 9 — non-resistant heavy minerals

PRINCIPLES OF CORRELATION WITH GLOBAL RHYTHMS OF PALEOGEOGRAPHICAL EVENTS

In the last published stratigraphic schemes of Polish loesses, correlation of the distinguished units with oxygen isotope timescale of marine sediments was taken into consideration (H. Maruszczak 1987, 1991). Results of such correlation should be judged as rather hypothetical because the chronostratigraphic units of loesses were distinguished on the basis of TL datings, and marine stages on the basis of ^{18}O content determinations, which only indirectly inform about global rhythms of climate changes. For such a purpose an analysis of eolian dust content in marine sediments and in Antarctic ice-sheet seems to be more correct from the methodical point of view. Changes of dustfall rate were conditioned not only by climatic factors but also by many others limiting dust production and processes of its transport.

Drilling in the Antarctic ice-sheet in the "Vostok" station (78°28′S; 106°48′E) has been conducted since 1980 y. The dust record in ice layers up to 150 ka old was published a few years ago (J.P. Petit et al. 1990). It documented the rhythm of events during the last glacial and interglacial. The dust record in layers up to 220 ka was published in recent years (J. Jouzel et al. 1993, V.M. Kotlyakov and C. Lorius 1993). Thus, we obtained also a picture of changes occurring in the last but one glacial cycle which corresponds to marine stage 6. The dust record in ice core shows minimal dustfall intensity during intervals corresponding to marine stage 7 and 5, and great increase at stage 6, 4 and 2 (Fig. 6c). In the opinion of the authors mentioned the main source of dust, falling in the region of "Vostok" station, was in the desert and periglacial areas of Patagonia. The extent of these areas considerably increased in glacial periods.

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stage 5, the results are underestimated to about 40%. The results obtained in the Lublin laboratory did not show such big differences in comparison to the geological age. It resulted not exactly from using the additive method but rather from an indirect method for determination of the annual radiation dose with TL dosimeters of MTS-N type (LiF: Mg, Ti) — J. Butrym (1986). In such measurements the full annual dose is not determined (A.G. Wintle 1987). According to the experiment made in the TL laboratory in Gdańsk the results of annual dose determination with LiF dosimeters are underestimated to about 11–38% in comparison with spectrometer measurements (A. Bluszcz et al. 1991). Despite these limitations and methodical doubts datings by the TL method should be continued in order not to stop progress in stratigraphical studies on Quaternary deposits. However, the results obtained in different TL laboratories should not be mixed in one set. They could be compared only with a suitable critical interpretation. It was shown by J.E. Mojski (1992) presenting a chronostratigraphic correlation of glacial deposits (datings from Gdańsk laboratory) and loesses (datings from Lublin laboratory).

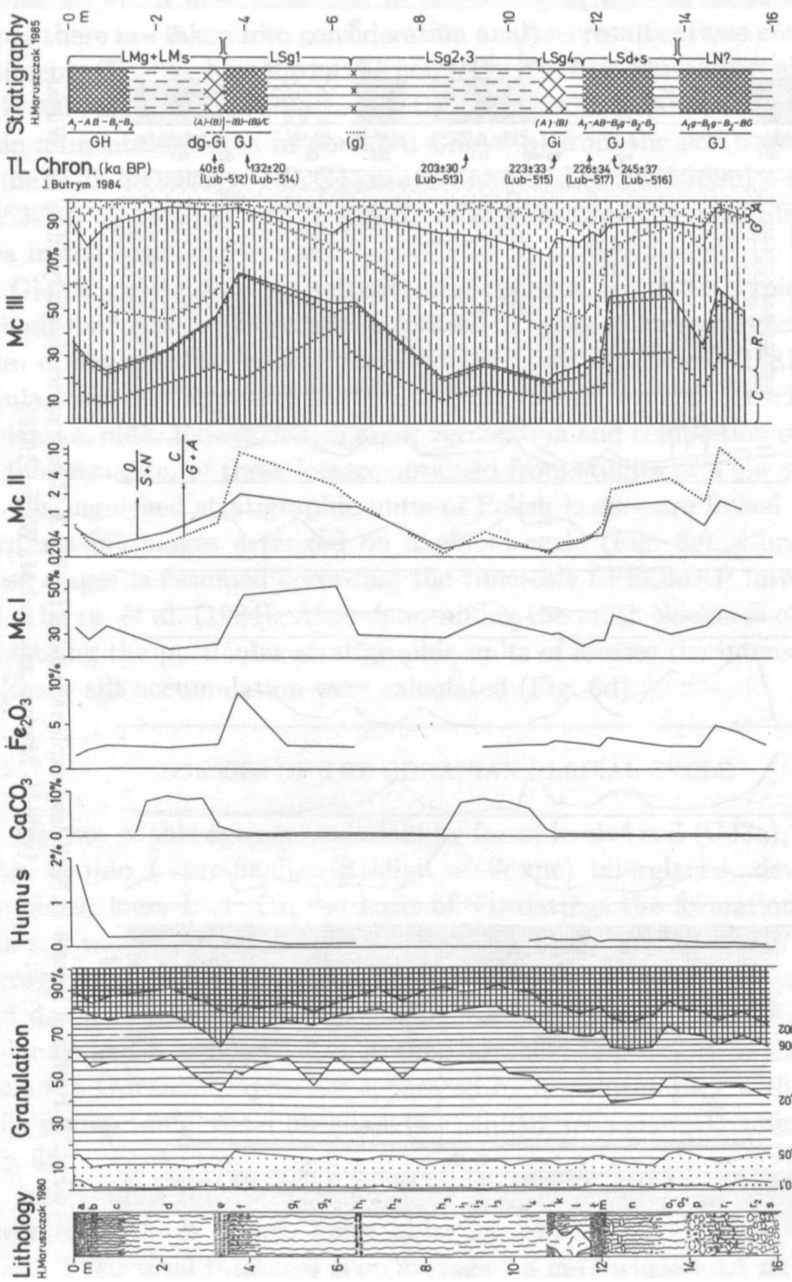

Fig. 4. Profile of loesses at Orzechowce; explanations as in Fig. 3. Heavy minerals analysed by J. Morawski (vide H. Maruszczak and J. Morawski 1976)

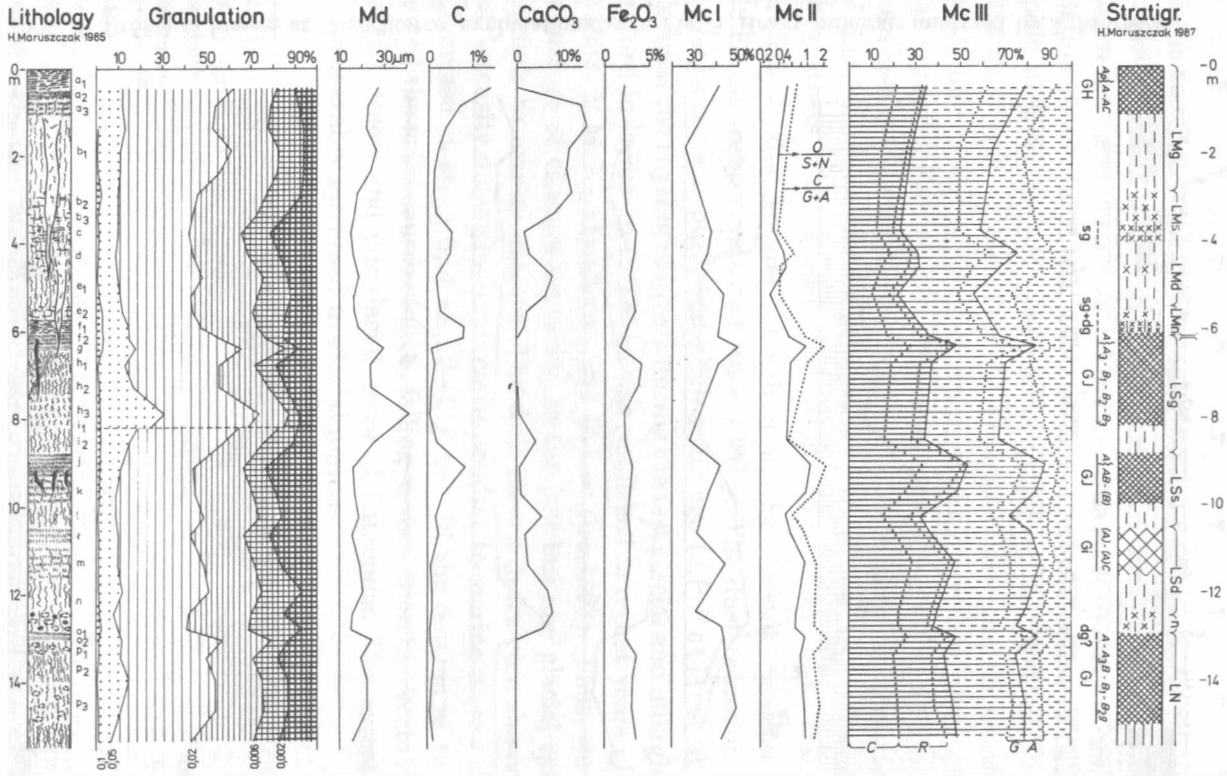

Fig. 5. Profile of loesses at Nieledew; explanations as in Fig. 3. Heavy minerals analysed by M. Wilgat (vide H. Maruszczak and M. Wilgat 1978)

Distinct changes of dustfall rhythms were also recorded in marine sediments which were examined in different geographical latitudes. In this paper there are taken into consideration analysis results of two cores of such sediments (Fig. 6a, b): a) from the north Pacific (S.A. Hovan et al. 1989) — V21-146 (37°41′N; 163°02′E) — at the site about 3,500 km eastwards of the main alimentation area in northern China; b) from the north-western part of the Indian Ocean (S. C. Clemens and W.L. Prell 1990) — RC27-61 (16°37′N; 59°52′E) — at the site about 300 km from the main alimentation area in the Arabian Peninsula.

Global rhythms of dustfall intensity changes, which are typical for the last glacial cycle, can be easily correlated with a curve of accumulation rates of younger loesses in Poland (H. Maruszczak 1980, 1987). Similar regularities also appear when considering loesses from two earlier glacial cycles, i.e. older loesses, which allow verification and completion of a picture of differentiation of these loesses obtained from studies of a few profiles.

Distinguished stratigraphic units of Polish loesses are linked with standard marine stages arranged on a global scale (Fig. 6e). Chronology of these stages is assumed according the timescale SPECMAP introduced by J. Imbrie et al. (1984). After determining the mean thickness of layers representing the particular stratigraphic units of loesses the intensity indices of loessy silt accumulation were calculated (Fig. 6d).

LOESSES OF THE ODRANIAN GLACIAL CYCLE

Loesses of this age are underlain by forest lessivé soil (GJ3a), correlated with Zbójno (=pre-Saalian/Saalian = Fuhne) interglacial, developed on the oldest loess LN1. On the basis of TL datings the formation period of this soil was determined on 330–310 ka (H. Maruszczak 1987). Thus, it corresponds to marine stage 9 (interval 339–303 ka). This soil was examined and dated in the Nieledew and Zadębce profiles in SE Poland and in the Bojanice and Korshov profiles in the Ukraine. From loesses of the following cycle the Odranian layers are separated by a pedocomplex with forest soil GJ2 representing the Lublinian (= Saalian I/Saalian II) interglacial — Fig. 6d.

Interstadial soils occurring in the Odranian loesses divide them into: lowest older loess (LSn), lower older loess (LSd) and middle older loess (LSs). Their total thickness is on average 3.8 m (Nieledew 4.1 m; Wożuczyn 4.0 m?; Korshov 3.8 m). In the mentioned profiles they probably represent 269–228 ka interval. Therefore, the mean accumulation rate was then about 0.08 mm/a. These are usually carbonate loesses, but $CaCO_3$ occurs here almost entirely in secondary forms (pseudomycelia, concretions). A considerable part of the Odranian loesses is pedogenetically transformed, which makes the definition of possible tendencies of grain-size changes during this glacial cycle very difficult.

The earliest phases of the Odranian are represented by products of denudation and soliflunctional displacement of the upper horizons of GJ3a soil. In places these horizons (A_1 and A_3)* were completely removed and its material was redeposited in close vicinity. In other places they occur in situ, only slightly disturbed or solifluctionally transformed. Signs of accumulation of fresh loessy silt were not found in them. These layers should be correlated with marine substages 8.6 and 8.5. As we are dealing here with a longlasting interval (about 299–269 ka), it seems that also other, more important phenomena including accumulation of fresh loessy silt were developing then.To find them additional studies of the discussed profiles or new sites of loesses of this age would be needed.

The lowest older loess (LSn) is 0.5–1.0 m thick, loamy; the content of the main fraction (0.05–0.02 mm) is about 30% which is similar or even slightly lower than that of fraction <0.005 mm. In the lower part there occur sometimes thin interbeddings of denudation products of underlying A_1 horizon of GJ3a soil. The upper part is distinguished by many signs of patchy gleying and by the occurrence of large $CaCO_3$ concretions, and has features of gleyed interstadial soil (Gi). On the basis of TL datings LSn layers should be correlated with marine substage 8.4 (269–257 ka), and the gleyed soil developed on them — with substage 8.3 (257–249 ka). The average accumulation rate of loessy silt was weak, only 0.05 mm/a. It seems to be very low in comparison to indices of accumulation intensity of eolian dust in marine sediments (Fig. 6). In this period the Odranian ice-sheet reached its maximum extent in Poland (L. Lindner et al. 1991). Environs of the discussed profiles (Nieledew, Zadębce, Bojanice, Korshov) lay then about 20–70 km from this ice-sheet front (Fig. 1). LSn accumulation happened in the periglacial zone, in conditions of discontinuous permafrost. It is confirmed by signs of segregational ground ice, and especially a pseudomorph of an ice wedge found in the Zadębce profile (L. Dolecki 1994). The height of this wedge is about 2 m, and it dissects the underlying soil GJ3a. Permafrost degradation occurred probably during the development of the interstadial gley soil; it is shown by strong gleying of the deposit filling this wedge.

* Letter symbols of soil horizons are given in the text according to the papers from the 70's, i.e. as in the figures enclosed here. At present other letter symbols are obligatory.

Lower older loess (LSd) 1.5–2.0 m thick contains a little more of the main fraction and relatively less clay fractions. Carbonate content in the bottom part is similar to that in LSn, and considerably smaller in upper part — pedogenetically transformed. Interstadial soil developed on this loess shows features of initial chernozem (of (A)–(A)C type) or of brown soil with horizons (A)–(A)B–C. The period of LSd accumulation should be correlated with marine substage 8.2 (249–238 ka) and interstadial soil developed on it — with substage 7.5. The mean rate of loess accumulation was distinctly bigger — about 0.15 mm/a. The accumulation climatic conditions were similar to those in the previous period. Permafrost occurrence of is evidenced by a pseudomorph of an ice wedge up to 3.0 m high, filled with material from LSd layers which was found in the Bojanice profile (A.B. Bogucki 1990, H. Maruszczak 1994).

Middle older loess (LSs) 1.0–1.5 m thick is similar to LSd. In the Bojanice profile it is completely transformed by pedogenesis. Similarly, in the Odonów profile LSd and LSs layers are transformed in soil horizons (Fig. 3). On the other hand, in the Nieledew profile bottom layers of yellowish loess containing a few percent of carbonates in secondary forms are preserved (Fig. 5). LSs samples were dated by the TL method for 244–212 ka BP interval. Thus, it probably corresponds to marine substage 7.4 (228–216 ka). The average accumulation rate was a little smaller (about 0.1 mm/a). Because of considerable pedogenetic transformation it is very difficult to find primary features of this loess. Pseudomorphs of ice wedges have not been found in it as yet. However, it should be stressed that on a global scale marine substage 7.4 was characterized by similar temperatures as substage 8.4 (D.G. Martinson et al. 1987). This could imply that LSs was accumulated in environment with occurring permafrost, as LSd was. Correctness of correlation of the LSs layers with marine substage 7.4 could be confirmed by comparison with curve of accumulation intensity of eolian dust in marine sediments of the NW part of the Indian Ocean. However, a similar curve drawn for the northern Pacific does not confirm such a correlation (Fig. 6).

On LSs layers a pedocomplex is developed, which contains forest soil of interglacial rank (GJ2) and a superimposed turfy horizon of features similar to chernozem (Gi). The development period of forest soil corresponds to marine substage 7.3 (216–205 ka) which was characterized by temperatures — reconstructed in a global scale — a little lower than in substage 5.5 (= Eemian interglacial). During this interval boreal forests (taiga) prevailed in Poland and in the northern part of Central Europe. Thus, paleobotanists, taking into account a definition of interglacial obligatory for them,

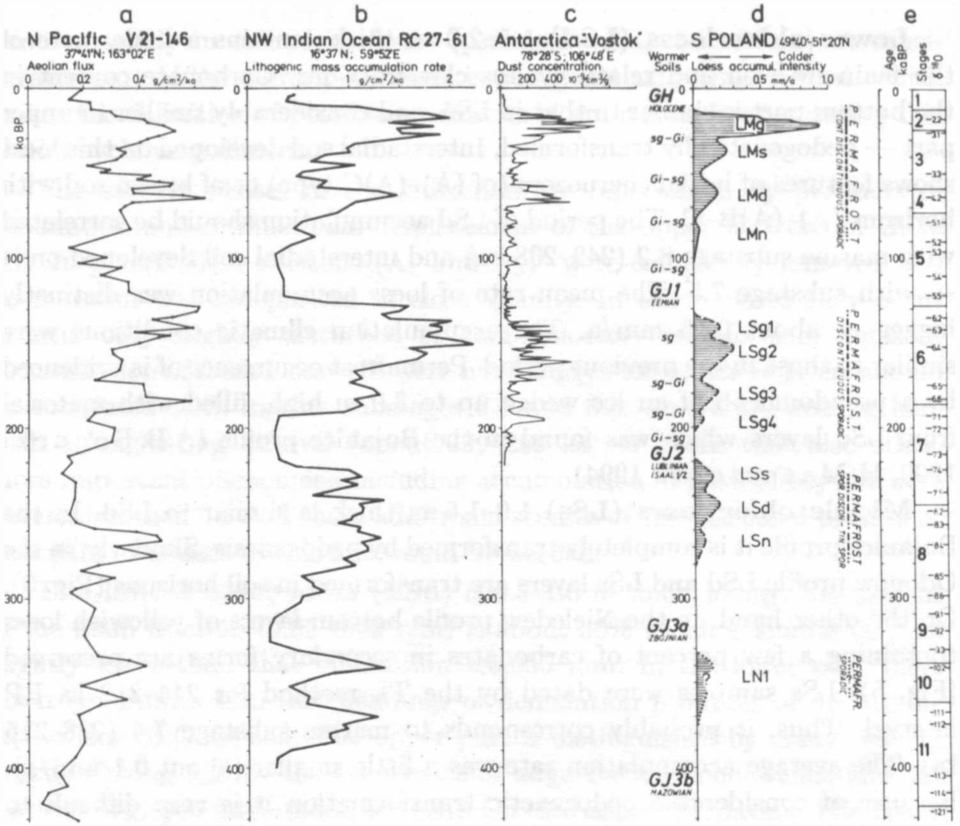

Fig. 6. Correlation of accumulation intensity curve of loess silt in Poland with diagrams of content changes of eolian dust in marine sediments and in the Antarctic ice-sheet; a — content of eolian dust in a core of marine sediments from north Pacific (after S.A. Hovan et al. 1989; b — content of lithogenic component in a core of marine sediments from NW part of Indian Ocean (after S.C. Clemens and W.L. Prell 1990); c — content of eolian dust in the Vostok ice core from the Antarctic ice-sheet (after J. Jouzel et al. 1993); d — accumulation intensity curve of loess silt against stratigraphic scheme of loesses and paleosols in southern Poland; explanation of stratigraphic symbols of loesses and paleosols as in Fig. 3; on the right — diagram presenting occurrence of permafrost traces in loess profiles; carried out by H. Maruszczak in 1995 y; e — oxygen isotope stages and substages of marine sediments — SPECMAP $\delta^{18}O$ (after J. Imbrie et al. 1984)

interpret this period as interstadial (Z. Janczyk-Kopikowa 1991). However, typical forest soils developed in boreal forest habitat, so it is admissible, from the paleopedologic point of view, to recognize this period as interglacial. These two different points of view rise the question: whether the interval separating the Odranian (Saalian I) glaciation from the Wartanian (Saalian II) glaciation had features of warm interstadial or rather cold interglacial? (H. Maruszczak 1991). This question has been discussed for several tens of years but now we can take into account arguments resulting from analysis of eolian dust content in Antarctic ice-sheet (Fig. 6c). This dust occurs in a minimal quantity in ice layers corresponding to 220–200 ka interval, similarly as in 130–100 ka interval corresponding to the last interglacial (J. Jouzel et al. 1993, V.M. Kotlyakov and C. Lorius 1993). Therefore, taking into consideration global rhythms of paleogeographical events, substage 7.3 can be considered as interglacial. In Polish literature it is distinguished as Lublinian interglacial = Saal. I/ Saal. II = Treene (H. Maruszczak 1987, M.D. Baraniecka 1990). In the stratigraphic scheme of Polish loesses it is represented by a soil denoted by GJ2.

LOESSES OF THE WARTANIAN GLACIAL CYCLE

The transitional period between Lublinian and Wartanian is represented by chernozem superimposed on forest soil GJ2. As a result of cooling forest communities were then transformed to park ones, probably largely of forest-steppe type, which resulted in the development of a thick humus horizon. Before the development phase of this horizon the forest soil was partially denuded ("decapitated") in places. Therefore, in some profiles chernozem is superimposed on the bottom part of the illuvial horizon of GJ2 soil. On such substratum, distinguished by a higher content of colloidal fraction, a horizon rich in humus was formed; even at present its humus content is about 1% (Nieledew, Odonów — Fig. 3, 5). Where upper horizons of GJ2 soil are preserved, the chernozem is distinctly separated from the illuvial horizon and is considerably poorer in humus (Łopatki, Orzechowce). Chernozem was developed in a cold climate, confirmed by poligonal cracks. At least two generations of such polygons occur. The younger is characterized by horizontal dimensions up to a few meters, and by cracks reaching 1.5 m in depth, i.e. even below GJ2 soil. Cracks of such dimensions indicate occurrence of strong seasonal frost (H. Maruszczak 1987). They are filled with material coming from the chernozem which development should be connected with marine substage 7.2.

Clearly distinguishable in some profiles is fresh loessy silt which accumulation should be also correlated with substage 7.2. This silt represents the first phases of the Wartanian glacial cycle, during which the upper older loesses (LSg) were formed. In Poland, three interstadial soils (Gi) or gley horizons and soil sediments (sg) important from the stratigraphic point of view were distinguished in LSg bed. They divided this bed into four secondary units (from top): LSg1; LSg2; LSg3; LSg4. Their more detailed characteristics is presented in another paper (H. Maruszczak 1994). The total thickness of the LSg layers is 7 m on average (Odonów 8.0 m; Wożuczyn 6.5 m; Orzechowce 8.0 m; Bojanice 5.5 m; Korshov 7.0 m). In the mentioned profiles full sequences of these loesses occur. They were formed in 205–135 ka BP interval. Therefore, the mean rate of loessy silt accumulation was then 0.1 mm/a, so it was a little higher than in the Odranian cycle. Unweathered LSg layers are usually carbonate; $CaCO_3$ content increases from several per cent in the oldest layers to 15% in the youngest ones, documenting increasing aridity and continentality of the climate with developing glacial cycle. The layers transformed by pedogenesis are distinguishable by considerable decrease of $CaCO_3$ content (Fig. 3). Increasing continentality during the glacial cycle is also documented by grain size, especially by Md index increase, which points to increasing content of the main loess fraction. It seems that the results of heavy minerals analysis also indicate regular changes occurring during the glacial cycle. The ratio of resistant heavy minerals to less resistant ones decreases from bottom to top of the loess bed (Fig. 3, Mc II). However, it was explained not by the influence of climatic changes during the glacial cycle but rather by time effect, i.e. increase of weathering signs with maturing of deposit (H. Maruszczak and J. Morawski 1976).

The earliest upper older loess (LSg4) is thin; in some profiles its layer was so thin that it was fully incorporated in developing chernozem. This unit is distinctly visible in the Odonów and Orzechowce profiles, where it is 1.0–1.5 m thick. In such profiles LSg4 is carbonate-free or it contains only up to 3% of $CaCO_3$. If we correlate these layers with the whole marine substage 7.2 (205–194 ka), we obtain an accumulation rate index of about 0.1 mm/a. Therefore, 0.05 mm/a index should be assumed as the mean one for profiles of two extreme types — i.e. with LSg4 layers or without them. It seems that such an index corresponds to the intensity of eolian dust accumulation in appropriate layers of the Antarctic ice-sheet or marine sediments (Fig. 6). The climatic conditions of LSg4 accumulation can be characterized by the crack polygons mentioned above. These structures are typical for areas with strong seasonal frost, and with mean annual temperatures about 0°C (H. Maruszczak 1987). On LSg4 layers an interstadial soil of brown earth type (Orzechowce) or with distinct signs of gleying (Odonów) was developed. This soil should be correlated with marine substage 7.1 (194–186 ka BP).

Early upper older loess (LSg3) 1.0–1.5 m thick can be distinguished in all studied profiles. However, its upper limit can be defined not in all profiles because top interstadial soil is poorly developed. The accumulation period of LSg3 should be correlated with marine substage 6.6 (183–171 ka) during which the Wartanian ice-sheet reached its maximum extent in Poland (H. Maruszczak 1993). The ice-sheet front was then at a distance of 100–200 km from the discussed sites of LSg. The mean rate of loess accumulation was then about 0.1 mm/a. Permafrost of discontinuous extent occurred in this area. It was documented by pseudomorphs of ice wedges up to 0.5 m wide and 2–3 m deep, which were found in Łopatki, Obrowiec and Bojanice. Such wedge dimensions indicate that in the coolest phases the mean annual temperatures were -2/-4°C. The top LSg3 layers were transformed in a subarctic gleyed soil of interstadial rank corresponding to marine substage 6.5, and as a matter of fact, only to its first phases because after J. Imbrie et al. (1984) the time limits of substage 6.5 were very broad (171–151 ka). In this interval rather intensive accumulation of eolian dust occurred in the Antartic ice-sheet layers and in marine sediments (Fig. 6).

Middle upper older loess (LSg2) is about 2–3 m thick. It should be correlated with the main part of marine substage 6.5 and with substage 6.4. Its accumulation period can be defined approximately for 170/165 — 150/146 ka. Accordingly, the mean accumulation rate would be slightly over 0.1 mm/a. In the culminant phase, which can be determined for 155–150 ka on the basis of correlation with curves of global rhythms (Fig. 6), the accumulation intensity probably increased to 0.3 mm/a. The climatic conditions were similar to those in the preceding period; it was documented by pseudomorphs of ice wedges found in Odonów and Bojanice. Gleyed soil corresponding to marine substage 6.3 was found over LSg2 layers only in a few profiles. Only weak signs of pedogenesis development were largely found in this stratigraphic horizon, indicating that loessy silt accumulation occurred then probably without a distinct break.

Late upper older loess (LSg1) is largely about 2 m thick. These layers were accumulated in 146–135/130 ka interval, i.e. they corresponded to marine substages 6.3 and 6.2. Hence, the accumulation rate was 0.1–0.2 mm/a. The climatic conditions were probably similar to those in two preceding periods. It was difficult to define them more exactly because in many profiles a large part of LSg1 layers was transformed by pedogenesis.

On LSg1 layers, a forest soil of interglacial rank (GJ1) was developed which was correlated with marine substage 5.5. This interglacial period, i.e. Eemian s.s., was warmer and lasted longer than the Holocene; it was documented by the development of thick (largely 1.5–2.0 m) soils. In southern Poland zonal lessivé soils (of type: A_1-A_e-B_t-C, which in the enclosed diagrams are denoted by symbols: A_1-A_3-B_1-B_2-B_3-C) were the most representative; they occurred in different varieties according to relief differentiation.

As they were examined in many profiles their diagnostic features were defined rather univocally (K. Konecka-Betley 1994). These features as well as typical pseudomorphs of cryogenic structures allow distinction of this soil from others occurring in loess profiles.

LOESSES OF THE VISTULIAN GLACIAL CYCLE

The transitient period between the Eemian and Vistulian, denoted by paleobotanists by EV, was registered by a humus turfy horizon superimposed on GJ1 soil. In this period a course of events was similar to that in the Wartanian cycle. Coolings (with flora of *Gramineae — Artemisia — Betula nana* type) and warmings (flora of *Pinus — Betula* type), studied by botanists (K. Mamakowa 1986), recurred several times. The phase of turfy horizon being superimposed should be correlated with EV2 phytophase (= Amersfoort s.l.), which probably corresponded to marine substage 5.3 (99–87 ka). Coolings preceding and succeeding the period of turfy horizon formation were registered by pseudomorphs of crack polygons well visible in GJ1 soil. Especially distinct is a younger set of these cracks with mineral infilling coming from the humus turfy horizon. Cracks reach 1.0–1.5 m in depth and form polygons several meters wide. From these data mean annual temperatures +1/-1°C were reconstructed (H. Maruszczak 1980, 1987). Cracks of this younger generation were probably formed in phytophase EV3 corresponding to marine substage 5.2.

The beginning of substage 5.2 is dated for 87 ka BP. However, loess accumulation in the discussed area started a little earlier. Datings by the TL method indicate that it happened about 100 ka BP (H. Maruszczak 1987, 1991). It seems to be consistent with the curves of eolian dust accumulation in the Antarctic ice-sheet and in oceans (Fig. 6). The accumulation cycle of younger loesses, which started about 100 ka BP, came to an end 15/12 ka BP. During this time interval a loess cover of 10 m mean thickness was formed; in western Poland extreme thickness does not exceed 9 m, and in eastern Poland it reaches 20–22 m (H. Maruszczak 1991). Thus, the mean accumulation rate was 0.11–0.12 mm/a, i.e. a little higher then during the Wartanian cycle. Three interstadial soils, important from the stratigraphic point of view, divide these loesses into the following units: lowest younger loess (LMn), lower younger loess (LMd), middle younger loess (LMs), and upper younger loess (LMg). As in the former cycle, the accumulation rate changed appropriately to climatic conditions. It is shown by differentiation regularities of grain size, chemical composition and also assemblage composition of heavy minerals in loess (Fig. 2, 5).

These regularities as well as the distribution pattern of younger loesses were discussed in detail with reference to the general outline of the glacial cycle of loessy silt accumulation (H. M a r u s z c z a k 1980, 1986, 1991).

The lowest younger loess (LMn) represents the early Vistulian. It usually occurs as weathered, loamy loess-like deposit of a thickness rarely reaching 2 m. In some profiles it was made largely of denudation products of underlying GJ1 soil. In others it was so thin that it was fully incorporated by the humus turfy horizon superimposed on forest soil; in such cases the thickness of this layer reached 0.5–0.6 m. The average thickness of LMn — mean for profiles of extreme types — can be estimated for 0.5–1.0 m. As it was accumulated during marine substages 5.3 and 5.2, i.e. from about 100 to 80/75 ka, the mean rate of its accumulation was only 0.03 mm/a. Over LMn layers an interstadial soil of brown earth or initial chernozem type developed. It should be correlated with marine substage 5.1. During accumulation of this loess mean annual temperatures were about 0°C. In such conditions strong seasonal frost occurred and polygons were formed with cracks filled by primary mineral material.

Lower younger loess (LMd) represents the lower Plenivistulian. Its thickness is usually about 1.5 m; only in extreme cases it reaches 2–3 m. This loess is usually carbonate, but $CaCO_3$ content rarely exceedes 3–5%. Its accumulation period corresponded to marine stage 4 (about 70–55 ka). Therefore, the mean accumulation rate was then considerably higher but did not exceed 0.1 mm/a. Curves of global events also indicated a substantial increase of its accumulation rate in this period, in comparison with the preceding stage. Pseudomorphs of ice wedges connected with LMd layers are 0.5–0.7 m wide and reach 2–3 m in depth. They form polygonal nets of horizontal dimensions 10–15 m. Such dimensions of wedges indicate that mean annual temperatures were then from -2 to -5°C; southern Poland was within the periglacial zone with discontinuous permafrost (H. M a r u s z c z a k 1980). Open steppe-tundra communities of phytophase EV5 (of *Gramineae-Betula nana* type) predominated in the landscape. On LMd layers a gleyed or brown subarctic soil was developed, which should be correlated with marine substage 3.3 (about 53 ka). It corresponds to the "soil of Komorniki type" distinguished in Poland by J. J e r s a k (1973), and also to the "Dubno soil" recognized by A.B. B o g u c k i (1987) in Volhynia and Podolia Uplands. Both authors mentioned correlated these soils with the Denekamp interstadial recognized by West-European authors. This correlation was made on the basis of dating results by the ^{14}C method in 24–29 ka BP interval. These datings were carried out for humic acids and the results were underestimated, because younger humic acids including Holocene ones infiltrated from the topographic surface after the formation period of the mentioned soils (H. Maruszczak et al. 1982, H. Maruszczak 1991). Therefore, pollen analyses seem to be more adequate for chronostratigraphy of the Dubno soil occurring in western Ukraine. Pollen diagrams show that this soil was formed in forest-tundra habitat, with a considerable participation of tree species (L.G. Bezuśko and A.B. Bogucki 1986, L.G. Bezuśko et al. 1989). After K.E. Behre (1989), in western Europe such plant communities occurred only in periods preceding the Denekamp interstadial, i.e. during the Glinde or Oerel interstadials. The results of TL datings of the soil developed on LMd layers correspond to the stratigraphical position ascribed to the Glinde interstadial (K.E. Behre 1989, p. 42).

Middle younger loess (LMs) represents the inter-Plenivistulian. It is carbonate and lithologically similar to LMd, but a little more differentiated with respect to pedogenetic transformation degree. In this bed a few layers of soil sediment type or horizons with gleying signs occur in some profiles (e.g. in Radymno and Hrubieszów-Feliks profiles). With this loess pseudomorphs of ice wedges are connected, of dimensions similar to those in LMd; they account for the fact that middle younger loess was also accumulated in the periglacial zone with discontinuous permafrost. The mean thickness of LMs is about 2 m. Its accumulation period should be correlated with marine stage 3 (about 50–32/28 ka). The mean accumulation rate was slightly higher than in the preceding stage and was about 0.1 mm/a. On LMs layers an interstadial gleyed soil developed, usually not so well visible as the former one.

Upper younger loess (LMg) represents the upper Plenivistulian. It is characterized by the most typical features of proper loess. It contains the highest amount of the main fraction and carbonates (up to 15%). A high content of carbonates causes the lightest, grey-yellowish colour and also considerable porosity of this loess. The last feature explains collapsibility of LMg under a load ("additional subsidence"); in fact these are the only collapsible layers of Polish loesses (Z. Frankowski 1994). This loess is the most representative also due to its considerable thickness which is 5–6 m on average; in some profiles it exceeds even 10 m. It corresponds to marine stage 2 (28–12 ka). In the first phase of this stage the ice-sheet in Poland's territory reached its maximum extent; the main zone of loess accumulation was distant over 200 km from the ice-sheet front (Fig. 1). Mean accumulation rate was about 0.4 mm/a but it was considerably differentiated; in maximum phases it increased to 0.8–1.0 mm/a. Pseudomorphs of large ice wedges are connected with the LMg layers. Dimensions of these wedges are following: width to 1.0–1.5 m, depth to 4–5 m, horizontal dimensions of the polygons of the highest rank from 20 to 25 m. These structures indicate that LMg was accumulated in the periglacial zone with continuous permafrost. Mean annual temperatures were then from -5 to -8°C (H. Maruszczak 1980). Thus, the climate was severe with most distinct features of continentality (aridity). In places within LMg layers 2–3 gleyed horizons occur, probably indicating a temporarily softer climate. The highest occurring gleyed horizon probably represents the active permafrost layer, with that the large ice wedges were connected. Degradation of these wedges started probably about 15 ka BP. Closer dating of this phase is not easy because in many profiles the youngest LMg layers are transformed by the Holocene pedogenesis. Soils developed in the Holocene (GH) are about 1.5 m thick, so the mentioned gleyed horizon occurs now within these soils in many profiles. Nowadays forest lessivé soils are zonal soils in Poland. They are similar to those which were developed during the Eemian interglacial. In areas strongly modified by human action, over the typical forest soil there is "superimposed" arable layer, which resembles the humus turfy horizon on GJ1 soil.

CONCLUSIONS AND FINAL REMARKS

1. Loess accumulation in Poland occurred in cycles corresponding to global rhythms of natural events. From the paleogeographical point of view the most significant rhythms were recorded in the recently published diagrams of accumulation intensity of eolian dust in the Antarctic ice-sheet (J. Jouzel et al. 1993) and in marine sediments (S.A. Hovan et al. 1989, C. Clemens and W.L. Prell 1990). During the last 400 ka phases of minimal accumulation intensity fell in marine stages 11, 9, 7 and 5. In Poland intraloessy forest soils of interglacial rank correspond to these stages and mark longer breaks in loess accumulation. These soils separate the successive glacial cycles of loess accumulation (Liwiecian = pre-Saalian; Odranian = Saalian I; Wartanian = Saalian II; Vistulian = Weichselian), which correspond to marine stages 10, 8, 6 and 4–2 (Fig. 6).

2. The main lithologic features of loesses are differentiated appropriately to climatic conditions changing during a glacial cycle. The most closely examined loesses from the last two cycles are characterized by distinct increase of $CaCO_3$ content from about 3% in bottom layers to about 15% in top layers. This fact seems to indicate increasing aridity and stronger features of climatic continentalism with the cycle development. Collapsibility under load characteristic for the most typical loess is connected with bigger porosity related to increase of carbonate content in the top loess layers. Curves of grain size distribution in loesses show also a tendency to

change. A distinct content increase of the main fraction (0.05–0.02 mm) in the upper layers was connected with increasing role — with the cycle development — of frost weathering (= dust production in source areas) and of the eolian factor (= atmospheric dust transport). It seems that similar regularities characterized loesses of two older cycles, which were known only in few profiles. Some regularities of changes occurring during the cycle are documented also by the results of heavy minerals analysis. However, the assemblage composition of heavy minerals does not reflect directly the climatic conditions of the accumulation period, because it was connected to some extent with weathering development in interstadial and interglacial periods.

3. Independently of some common regularities the analysed glacial cycles were different. Thus, the rate of loessy silt accumulation increased: from 0.08 mm/a in the Odranian cycle, 0.10 mm/a in the Wartanian cycle, to 0.11–0.12 mm/a in the Vistulian cycle. However, poor basis for calculation of these indices, especially for the Odranian loesses, does not allow us to draw more definite conclusions. Therefore, attention should be given to differentiation of the occurrence of ice wegde casts. Studies of these casts showed that the Vistulian glacial cycle was characterized by most severe climate and occurrence of strongly developed permafrost. This fact seems to confirm the presented results of the attempt to define changes of loess accumulation intensity. Tendency of the accumulation rate to increase from older to younger cycles was fully consistent with that appearing in diagrams of global rhythms drawn on the basis of studies of cores of Antartic ice and marine sediments. Accordingly, it can be suggested that a more older cycle of LN1 accumulation — not analysed closely in the text but marked in Fig. 6 — in the period of the Liwiecian glaciation was characterized by accumulation intensity smaller than 0.08 mm/a.

4. The intensity of loess accumulation in Poland was independent of ice-sheet extents during three glacials analysed in detail. Indices of this intensity were rather inversely proportional — during the glaciation with most extensive ice-sheet (Odranian) silt accumulation was weaker than during glaciation with the smallest extent of the ice-sheet (Vistulian). However, the accumulation rate depended on the degree of climate continentalism. Most continental climate was typical for the last glaciation which is confirmed by lithologic features of loesses and cryogenic structures connected with them. In such climatic conditions the thickest loess beds were formed and permafrost (= underground glaciation) developed more intensively, but the ice-sheet grew more slowly due to climate aridity.

5. On the basis of studies conducted in Poland the following pattern of glacial cycle of loess accumulation can be presented.

a) In the transitional stage between interglacial s.s. and glacial s.l., i.e. in early glacial, forest communities of temperate type were transformed into park (forest-tundra) and steppe-tundra ones. Interglacial forest soils were denuded, and when they were well preserved the humus horizon of turfy soil was superimposed on them. This horizon looks like a chernozem. Apart from the denudation products of interglacial soil, small amounts of fresh silt were accumulated — thin layers of loamy loess-like deposit were formed. The climate was characterized by mean annual temperatures about 0°C; in such conditions strong seasonal frost occurred, contraction cracks with primary mineral infilling were formed.

b) In lower pleniglacial, accumulation of fresh silt quickly increased but its mean rate was small, 0.05–0.10 mm/a. Beds of loess poor in carbonates, usually still loamy, were formed. In the environment of periglacial tundra with permafrost of sporadic and discontinuous extent, crack polygons with ice wedges were formed. Dimensions of wedges indicate that mean annual temperatures were from -2 to -4°C.

c–d) In middle and upper pleniglacial, mean accumulation rate considerably increased to 0.3–0.4 mm/a. The climate was more severe, with more distinct features of continentalism. In phases of strongest cooling the accumulation rate increased to 0.8–1.0 mm/a; continuous permafrost developed. Big ice wedges were formed recording mean annual temperatures from -5 to -8°C. However, in relatively warmer phases the accumulation rate decreased, and interstadial soils of subarctic gley or brown type were formed.

e) In late glacial permafrost declined due to warming up quickly developing during a few thousand of years. Loess accumulation gradually declined as the role of plant communities (forest-tundra and finally taiga type) increased.

f) In postglacial, after termination of silt accumulation, the loess cover was stabilized. In conditions of temperate climate forest soils were formed and epigenetic processes of loess transformation started to develop.

6. During the last 400 ka glacial cycles of loess accumulation proceeded variously. During the Liwiecian glaciation which was the shortest, role of stages corresponding with the biggest climate cooling was limited. Thus, this cycle was not fully developed (incomplete). During the next, already long-lasting Odranian glaciation, warming phases were distinctly marked in pleniglacial stages. Interstadial soils were then developed, and relatively thin loess layers were epigenetically transformed; mainly secondary forms of carbonates were preserved in them. Upper layers of the Odranian loess were

accumulated during distinct cooling in early stage 7, i.e. "warm" marine stage. Therefore, these layers have not features typical for upper pleniglacial. During the last but one glaciation (Wartanian) the phases of warming up were marked most weakly in pleniglacial stages. So, interstadial soils were not well developed causing relatively weak stratigraphic differentiation of the Wartanian loesses. During the last glaciation (Vistulian) loess cycle was the longest and was characterized by mostly differentiated events. Phases of warming up were marked very distinctly in middle pleniglacial. Therefore, Dutch authors also distinguished this period as interpleniglacial (T. H a m m e n et al. 1967, p. 92). Investigations of the core of the Greenland ice-sheet indicated that interpleniglacial was characterized by quick, great global changes of the climate — "Dansgard-Oeschger events" in the interval 55–25 ka (W.S. B r o e c k e r and G. D e n t o n 1989). Many authors considered that in eastern Europe, and especially in Siberia, this period had an interglacial rank, or distinguished it as "middle-Valdai megainterstadial" (N.V. K i n d and B.N. L e o n o v 1982, K.V. N i k i f o r o v a et al. 1984, H.A. A r s l a n o v et al. 1987). Interpleniglacial phases of warming up recorded in profiles of continental sediments corresponded to marine stage 3, i.e. to relatively warm period in the stratigraphic scheme of deep-sea deposits. After this period, rather short but sharply marked cooling occurred (marine stage 2) in the upper Plenivistulian. Thick deposit layers, corresponding best to the idea of typical loess, were formed then.

Differentiation of loess accumulation rhythms in the discussed glacials was similar to that of global rhythms of accumulation intensity of eolian dust in the Antartic ice-sheet and ocean bottoms. Therefore, these rhythms reflected general regularities of changes which appeared during interglacial-glacial cycles. The course of events in these cycles was differentiated appropriately to long-lasting climatic fluctuations. According to Milankovitch's theory, very important was interference of three cycles conditioned by: eccentricity of Earth's orbit (100 ka), inclination of Earth's axis (41 ka), precession (21 ka) (J. I m b r i e et al. 1984, D.G. M a r t i n s o n et al. 1987).

7. Among the presented cycles of loess accumulation in Poland the last but one (Wartanian) had the most "model" character. Only this cycle almost fully corresponded to one marine stage, i.e. stage 6. It was characterized by the simplest, typical sequence of events, with long-lasting cooling which was irregularly developing from early to maximum stage, and with subsequent rather quick warming up. During the last cycle (Vistulian) the course of events was much more complicated. It corresponded to a few marine stages, i.e.: a considerable part of stage 5, and stage 4, 3 and 2. Thus, when considering oxygen isotope stratigraphy, this cycle was bipartite, with two

"cold" stages (4 and 2). From this point of view the Odranian cycle was less complicated. It probably corresponded to full marine stage 8, and to important substage of cold recurrence during the "warm" stage 7. The oldest, shortest cycle (Liwiecian) was complicated but in a different manner. It probably corresponded to the phase of considerable cooling during stage 11, and to the whole short stage 10, i.e. "cool" one.

8. The presented pattern of accumulation cycle of Polish loess is consistent with the idea of long-lasting glacial (glacial s.l.) and short interglacial (interglacial s.s.). Stratigraphic correlation of loesses in Poland and in eastern and western adjacent European regions implies that the presented cycle pattern is suitable for loesses accumulated in the periglacial zone. It seems that it would not be fully adequate for SE Europe, where loesses of perimediterranean type occur (perimediterranean loess sensu H. Maruszczak 1990). It seems to be indicated by attempts to correlate Polish loesses and those occurring in the basin of the lower Danube. For regions in central Asia where peridesertic loesses occur, pattern of shorter glacial cycle (glacial s.s.) would be probably suitable. In any case, it seems that it would be good for Chinese loesses, because interglacial soils occurring in them were developing during a longer period than in Poland. For example, soil S1 occurring in the bottom of the Malan Loess (representing the last glacial) is assumed to have developed during the period lasting 50–60 ka (T. Liu et al. 1986, G. Kukla and Z. An 1989, Z. An et al. 1991) which corresponded to the whole marine stage 5. However, this period was rather complicated from the paleogeographic point of view. In some profiles soils of interglacial type were found, which were developing in a few phases (for example X. Fang et al. 1994) interrupted by short episodes of weak accumulation of silt (= "interglacial loess" — vide S.C. Porter et al. 1992).

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STRESZCZENIE

Najbardziej rozprzestrzenione i najłatwiejsze do wyodrębnienia są lessy młodoplejstoceńskie. Dla ostatniego cyklu glacjalnego już od dawna określano więc nie tylko zróżnicowanie warunków klimatycznych, ale także i tempa akumulacji pyłu lessowego w Polsce. Rozwój datowań metodami fizycznymi daje obecnie podstawy do podejmowania podobnych opracowań dla znacznie trudniej dostępnych i słabiej zbadanych lessów starszych. Datowania umożliwiły także korelowanie tych utworów z globalnymi rytmami zdarzeń paleogeograficznych, a w szczególności ze stadiami $\delta\,^{18}O$ osadów oceanicznych.

Danych faktycznych do niniejszego opracowania dostarczyły głównie wyniki badań lessów na terenie Polski, uzupełnione faktami odnoszącymi do dwu profili lessów z sąsiedniego regionu Ukrainy; rozmieszczenie uwzględnionych w opracowaniu profili przedstawia ryc. 1. Wybrane cechy litologiczne lessów przedstawione są na ryc. 2–5; uwzględnione są na nich wyniki badań warstw liczących do 400 ka. Oprócz cech litologicznych analizowano w szczególności zmiany tempa akumulacji pyłu lesowego. Wykres tego tempa porównano z wykresami zawartości pyłów kontynentalnego pochodzenia w rdzeniach lądolodu antarktycznego oraz osadów oceanicznych (ryc. 6a-d). Określono cechy charakteryzujące lessy czterech ostatnich cykli glacjalnych: 1) Vistulian (=Weichselian), 2) Wartanian (=Saalian II), 3) Odranian (=Saalian I), 4) Liwiecian (=pre-Saalian). Skorelowano lessy tych cykli ze stadiami oraz substadiami $\delta\,^{18}O$ osadów oceanicznych (ryc. 6e).

Rozwój zdarzeń w wymienionych cyklach był generalnie podobny. Dokumentują to wyniki badań cech fizycznych oraz składu chemicznego i mineralnego lessów, a także występujących wśród nich struktur kriogenicznych. Na takiej podstawie można przedstawić następujący model cyklu akumulacji lessu: a) wczesny glacjał — akumulowane głównie produkty denudacji spągowej gleby interglacjalnej oraz w niewielkich ilościach świeży pył lessowy; b) dolny pleniglacjał — rola akumulacji świeżego pyłu wzrasta, ale jej tempo nie przekracza 0,05–0,1 mm/a; c) środkowy i górny pleniglacjał — przeciętne tempo akumulacji wzrasta do 0,3–0,4 mm/a i w fazach maksymalnych sięga do 0,8–1,0 mm/a; d) późny glacjał — akumulacja świeżego pyłu wygasa szybko, odpowiednio do zmian klimatu i charakteru zbiorowisk roślinnych. Rola względna tych etapów rozwojowych była różna w omawianych cyklach glacjalnych. Każdy z nich miał więc pewne cechy indywidualne.

Najbardziej modelowy charakter miał cykl przedostatni (Wartanian); tylko ten cykl prawie w całości odpowiadał jednemu, tzn. 6 stadium $\delta\ ^{18}O$. Najbardziej złożony był cykl ostatni (Vistulian), odpowiadający kilku stadiom (znaczna część stadium 5 oraz stadia 4-3-2).

Natężenie akumulacji pyłu lessowego w omawianych cyklach było niezależne od zasięgu lądolodów. W pewnym sensie było ono odwrotnie proporcjonalne — w cyklu o najmniejszym zasięgu lądolodu (Vistulian) natężenie akumulacji pyłu było większe niż w cyklu o zasięgu największym (Odranian) — zasięgi lądolodów przedstawiono na ryc. 1, a natężenie akumulacji pyłu — ryc. 6d. Tempo akumulacji było zależne przede wszystkim od stopnia kontynentalizmu klimatycznego. Najbardziej kontynentalny był klimat w ostatnim cyklu. Poświadczają to wyniki badań cech litologicznych lessu, a przede wszystkim struktur kriogeniczych. Dlatego najbardziej miąższe warstwy, najbardziej typowego lessu powstały w ostatnim cyklu. Rozwinięta była wówczas najsilniej zmarzlina wieloletnia, czyli zlodowacenie podziemne, a lądolód narastał mniej efektywnie ze względu na suchość klimatu.

Przedstawiony model cyklu akumulacji lessu w Polsce odpowiada koncepcji długotrwałego glacjału (glacjał s.l.) i krótkotrwałego interglacjału (interglacjał s.s.). Uwzględniając korelacje stratygraficzne lessu w Polsce i sąsiadujących od wschodu oraz zachodu regionach Europy można sugerować, że taki model jest właściwy dla lessów peryglacjalnych. Dla lessów akumulowanych w regionach perydesertycznych w Azji byłby właściwy model krócej trwającego cyklu glacjalnego (glacjał s.s.). W każdym razie wydaje się on odpowiedni dla lessów chińskich. Okres rozwoju najmłodszej gleby interglacjalnej (S1), występującej w spągu lessu Malan (reprezentującego ostatni glacjał), autorzy chińscy obliczają bowiem na 50-60 ka. Natomiast występujący w spągu lessu młodszego w Polsce kompleks glebowy z interglacjału eemskiego i najwcześniejszego Vistulianu rozwijał się w ciągu około 30 ka (ryc. 6d).