

Evidence of cyclic dust deposition in the US Great plains during the last deglaciation from the high-resolution analysis of the Peoria Loess in the Eustis sequence (Nebraska, USA)

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Abstract

The Peoria Loess unit is a well-defined stratigraphical unit in the Upper Pleistocene of the North American Quaternary, deposited between 30–25 ka and about 12 ka ago. It has been indicated that this unit shows the highest known worldwide depositional rate for eolian deposits, as its thickness varies, near the source area, between 19 m and 46 m, extreme values that are not even recorded in the Chinese sequences. The results of our present investigation indicate that this particular unit is not homogenous. It shows different subunits where lithological variation can be observed through the occurrence of embryonic gley horizons alternating with laminated loess. Furthermore the grain-size analysis shows cycles corresponding to variations in the eolian dynamics responsible for dust transportation and deposition. A grain size index interpreted as characterizing the eolian dynamics (higher values corresponding to stronger wind conditions) shows higher values than those observed in Europe. A comparison of this index is proposed with the Greenland dust and $\delta^{18}\text{O}$ records. It shows that the main climatic history, as corresponding to events occurring mainly in North Atlantic domain, is recorded in the Peoria Loess deposits. However, the variation in the magnitude of the eolian events indicates differences from the European loess sequences. The strong North Atlantic coolings expressed by Heinrich events, as recorded in Europe by coarser deposits, are not differentiated in the studied sequence. Hence, they follow more closely observations obtained off California for the north-east Pacific domain.

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1. Introduction

During the last climatic cycle, the main loess deposits occurred in Europe during the 30–16 ka interval

(Antoine et al., 1999, 2001; Haesaerts et al., 2003) while in Asia they indicate a more or less constant sedimentation rate during marine stages 4 to 2 (Liu, 1985; Kukla et al., 1988; An et al., 1991; Liu et al., 1991; Ding et al., 1995). In North America, the main Upper Pleistocene eolian deposits correspond mostly to one single stratigraphical unit: the Peoria loess (Schultz and Stout, 1945, 1961; Follmer, 1996; Mason, 1998; Muhs and Bettis, 2000; Mason, 2001; Muhs and Zarate, 2001; Bettis et al., 2003a,b). It is bracketed by two soil complexes, not preserved in all the Great Plains, especially east of Mississippi: the Gilman Canyon soil-complex formation at its base, dated between 30 and 25 ka, and the Brady soil at its top, dated at roughly 12 ka (Feng et al., 1994a,b; Mason et al., 1994; Pye et al., 1995; Muhs et al., 1999, 2003; Muhs and Bettis, 2003). The Peoria loess is well identified and shows a varying thickness over the US Great Plains decreasing southward (Fig. 1). Considering this short deposition interval, the Peoria Loess shows, especially in Nebraska and Iowa, the highest worldwide depositional rate for eolian deposits. Its thickness indeed varies near the source area between 19 - 46 m implying strong wind dynamics as all the material has been windblown, at least in the area of the thickest records (Mason, 2001; Bettis et al., 2003a,b). These are extreme values that are not even recorded in the Chinese sequences (Liu, 1985;

Liu et al., 1991), especially those located at the northwestern boundary of the Chinese loess plateau (Ding et al., 1995). Loess sedimentation is highly variable and depends on the availability of eolian material but also on the location and position of dust traps which condition the significance of these particular deposits. Every main loess region yields characteristics which cannot be applied worldwide. However, there are general patterns expressed by various indices such as the stratigraphy (succession of paleosol-loess doublets), or grain-size variation, which have been observed over wide territories as in Europe or in China. Other studies of US loess series, albeit at less resolution than described in the present manuscript, especially on the Peoria Loess unit, tend to support this assumption (Mason, 1998; Muhs and Bettis, 2000; Bettis et al., 2003a,b). This is the case for similar low susceptibility and terrestrial mollusk fluctuations during the Peoria loess in two distant sites as discussed in Rossignol et al. (2004) Hence, investigating loess sequences at high resolution within a single domain following the same protocol eases comparisons between records and prevents erroneous interpretations.

The Eustis sequence, southern Nebraska (Fig. 1), is a famous US loess sequence that yields several loess units intercalated with interglacial and interstadial paleosols (Schultz and Stout, 1961). Its base yields

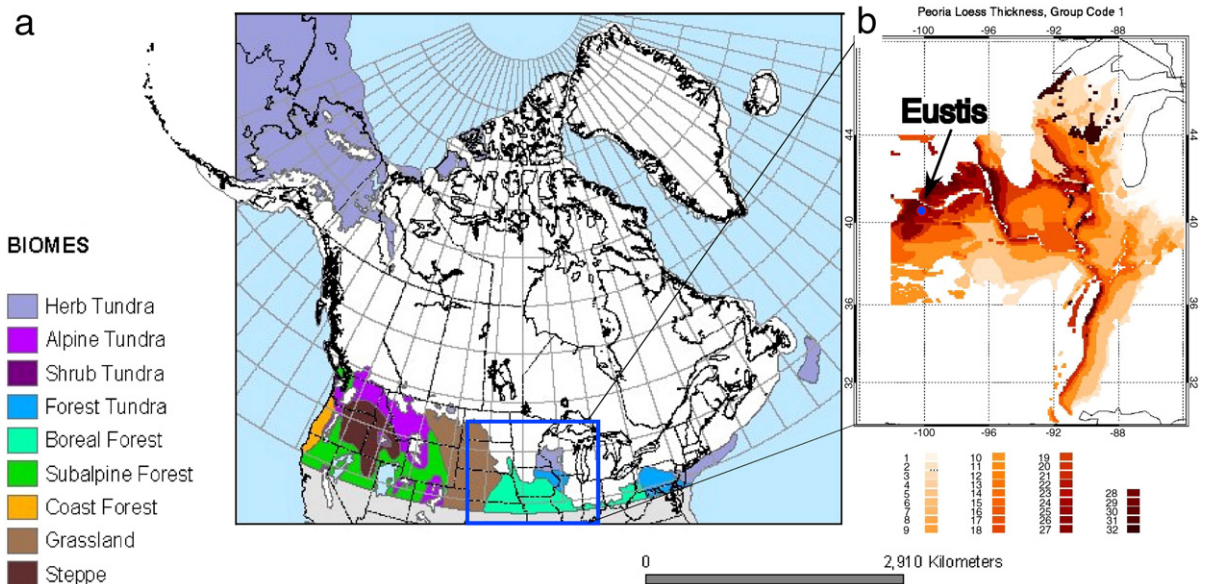


Fig. 1. Location of the studied sequence in North America. a) Reconstruction of the maximum extent of the Laurentide ice sheet during the last glacial maximum, with indication of the surrounding reconstructed biomes. (from S.A. Wolfe 2004 @ http://sts.gsc.nrcan.gc.ca/mapviewers/paleo_18k_fr.asp?k=D1). b) Reconstructed thickness (in meters) geographic variation of the Peoria Loess unit in mid-continent North America. (from Kohfeld and Muhs 2001 @ <http://www.ncdc.noaa.gov/paleo/loess/peoria/peoria.html>).

the Pearlette “O” Ash bed, now named “Lava Creek Tuff”, dated previously at about 0.69 Ma (Naeser et al., 1971) and more precisely now at 0.639 ± 0.002 Ma (Lanphere et al., 2002), and the top soil merges probably several paleosols, including the Brady soil, lasting the last 12 ka (Muhs et al., 2003; Muhs and Bettis, 2003). A previous study of both magnetic susceptibility and terrestrial mollusk assemblages of the Upper Pleistocene sequence (Rousseau and Kukla et al., 1994) indicated variations in the environments from moist to drier conditions during the deposition of the Peoria Loess through the recognition of three main subunits corresponding to previously described biostratigraphical mollusk zones (Leonard, 1952; Frankel, 1956a,b). A recent paper (Roberts et al., 2003) indicates unprecedented deposition rates based on

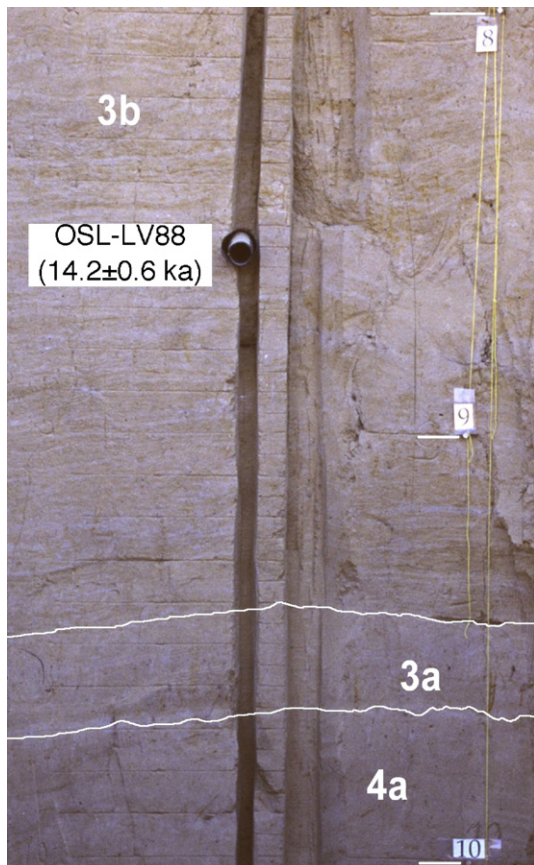


Fig. 2. Cleaned studied outcrop panels (between 8 and 10 m deep) after removing the weathered material in order to determine the stratigraphy labeled in white (sub-units 4a, 3a 3b). Location of a previous OSL sample by Roberts et al. (2003). The horizontal lines corresponds to the location of the MS readings and are every 10 cm, characterizing the location of the mollusk samples. The central column corresponds to the continuous sampling (5 cm thick) of sediment for grain size and $\delta^{13}\text{C}$ measurements.

OSL dating. Here, we investigate in detail the lithology and especially the grain size variations in the Upper Pleistocene sequence which has been neglected. We apply a multidisciplinary approach that we have already successfully followed for several European loess sequences (Antoine et al., 2001, 2002; Rousseau et al., 2002).

2. Material and methods

2.1. Stratigraphy

The stratigraphy was described (1/20 scale) after a careful cleaning of the outcrop through 4 to 7 wide vertical panels obtained after removing about a minimum of 50 cm of weathered material (Fig. 2). The correlation between the four panels was achieved using the main stratigraphical level-marks followed along the whole outcrop as the gley layers (HG). This preliminary step allowed the construction of a 18 m long continuous series. The Peoria Loess (PL) sequence in Eustis is thus represented by 16.3 m of loess deposits bracketed between the modern soil and the dark brown humic soil complex corresponding to the Gilman Canyon Formation (Fig. 3). Three main loess units (units 2, 3 and 4), respectively 2.15 m, 6.5 m and 7.5 m thick have been identified and subdivided into sub units in the field, according to sedimentological and pedological observations. The following succession, similar to that previously determined by Rousseau and Kukla (1994), can be described from the top to the bottom (Fig. 3):

Unit 0 Thin (5–7 cm) pale yellow unweathered dusty layer, strongly contrasting with the underlying dark soil.

Unit 1 It is composed of two subunits showing a progressive transition.

Unit 1a: Dark brown to black organic loam with granular structure (Mollic epipedon).

Unit 1b: Dark-brown to brown-clayey loam with a blocky structure, numerous earth worm casts and a strongly bioturbated lower boundary (Cambic, Bw, horizon).

Both units 1a and 1b are affected by a network of deep desiccation cracks (prismatic structure 5 to 10 cm). The succession 1a to 1b corresponds to the classical profile of a Mollisol developed upon the loess deposits in a grassland environment (Brady soil to the modern one).

Unit 2 The first loess unit is represented by a homogeneous light grey sandy loess (Unit 2a)

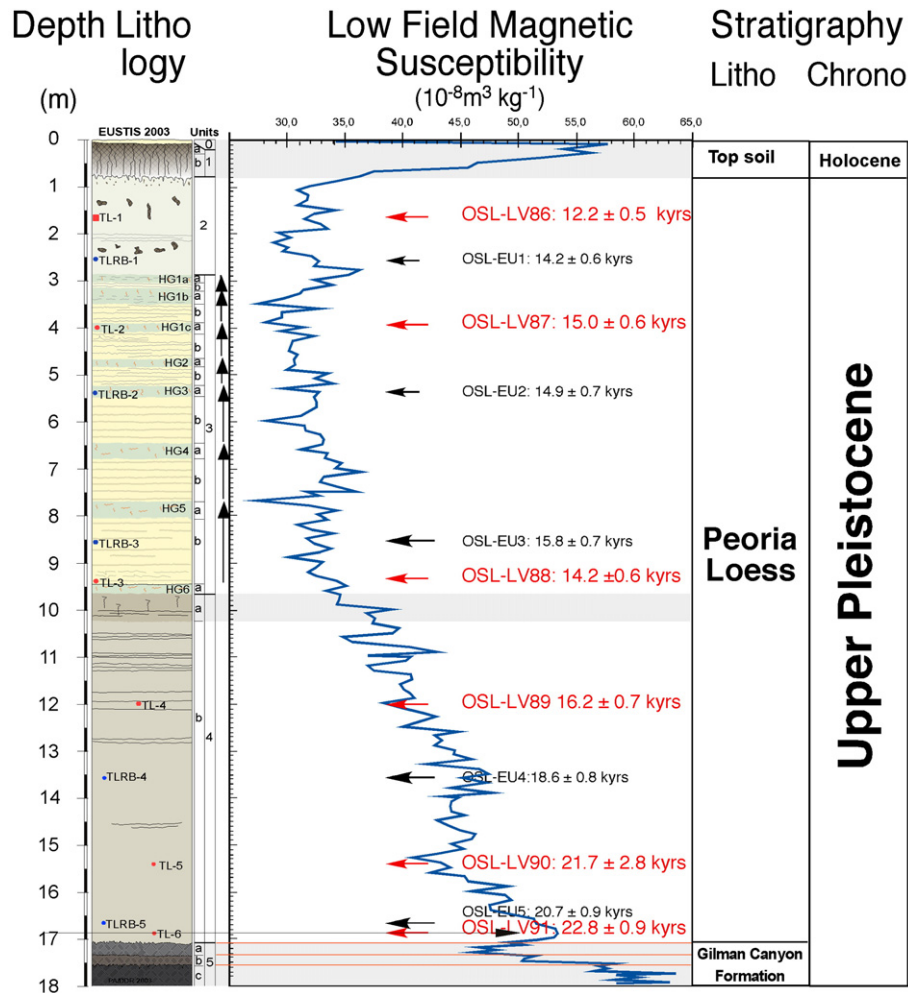


Fig. 3. Stratigraphy of the Upper Pleistocene loess–paleosol sequence at Eustis ash pit. Variation of the low field magnetic susceptibility and location of the samples taken for luminescence dates. Location of the OSL dates obtained by Roberts et al. (2003) in black (the original labels of the samples are Aber/57EA1 to Aber/57EA5), new OSL dates in red labelled LV. The vertical arrows indicate cyclic pattern of deposition observed in the laminated loess.

with large bioturbations (5–10 cm), infilled by dark material from the overlying soil horizon (crotovinas); a few irregular grey bands appear in the middle part of this unit at about 2 m.

Unit 3 It is composed over more than 6 m by a succession of grey hydromorphic horizons (3a) (embryonic gley soils) and of laminated light grey sandy loess (3b).

Sub-units 3a are individualized by a grey color, a more homogeneous facies and the occurrence of numerous orange oxidized root tracks, FeMn concretions (<1 mm) and calcified vegetal remains.

Sub-units 3b corresponds to an original, apparently laminated loess, characterized by the succession of irregular undulating grey and pale yellow bands, 0.5 to 1.5 cm thick (Fig. 4). On a weathered outcrop the grey bands appear in relief compared to the softer light brown layers, indicating a smaller average grain-size. This banded loess can be interpreted as the result of very high and contrasted loess sedimentation; the alternation of grey and yellow bands indicate a high frequency



Fig. 4. Details of a laminated loess sub unit. The scale on the left hand side is in centimeters.

succession of short phases of relative reduction and enhancement of wind speed (dust storms).

The occurrence of hydromorphic facies indicates (surface) humid conditions during the deposition of the grey bands, close to those that prevailed during the formation of subunits 3a (snow cover). In some places, as around the base at about 9 and 9.4 m, little cryodesiccation micro cracks and upturned layers have been observed indicating a humid periglacial environment during deposition of the banded loess. The whole unit 3 contains thin vegetal remains, and is organized in seven superimposed cycles, each of them terminated by an embryonic gley soil (HG 1 to HG 6).

Unit 4 This is the second main loess unit. It is clearly distinguished from the overlying loess unit 3 by the lack of the laminated facies, a more dense texture and a darker color. This loess (4b) is apparently homogeneous. Nevertheless in some parts thin laminations (1–3 mm) are visible after a careful cleaning of the outcrop with a brush. The lower part of this loess, which appears denser and darker, is also characterized by little insects (?) or earth worm casts (\varnothing : 4–8 mm). The lowest 0.4 m are very dense and rich in rootlet tracks with calcareous coatings. At the top of this loess unit, a brown grey compact horizon, with a lot of oxidized root tracks and numerous little FeMn nodules has been individualized (sub unit 4a). This horizon is interpreted as a little soil (embryonic) developed during a period of environmental stabilization,

preceding the main change observed at 9.45 m, with the appearance of the laminated loess containing gley horizons.

Unit 5 Unit 5 is a soil complex composed by 3 superimposed horizons:

5a Grey to brown grey, highly bioturbated loam, with very irregular upper and lower boundaries.

5b Brown grey loessic horizon with abundant bioturbations from 5a and 5c.

5c Dark brown to black compact clayey humic loam with prismatic structure, numerous rootlet tracks (<1 mm) and earth worm casts and biopores.

Unit 5 is interpreted as a chernozem-like soil complex including an *in situ* well developed soil horizon (5c), covered by humic colluvial and local eolian deposits (redeposited soil). The whole unit 5 is correlated with the Gilman Canyon formation.

2.2. Sampling and analytical processes

Ten readings of low field magnetic susceptibility (MS) were performed in the field on the cleaned surfaces using a Bartington MS2 and averaged, every 10 cm in the Peoria Loess deposits, and every 5 cm in the soil complexes (Fig. 3).

Sediment samples were taken from continuous columns cut in the loess walls, and sliced every 5 cm following the methodology developed within the EOLE project on European loess sequences (Antoine et al., 2001, 2002; Rousseau et al., 2002) (Fig. 2). This

Table 1

Analytical data and OSL-dating results: sample code and depth, water content (Δ , in % of dry sample weight), U, Th and K concentrations, effective dose rate (dose rate), equivalent dose (D_e) and OSL age

Sample	Δ (%)	U (ppm)	Th (ppm)	K (%)	Dose rate ^a (Gyr ka ⁻¹)	D_e ^b (Gy)	OSL age (ka)
LV86	10±5	4.04±0.10	13.42±0.29	2.31±0.06	4.75±0.16	58.3±1.4	12.2±0.5
LV87	10±5	3.65±0.10	13.63±0.31	2.11±0.05	4.41±0.15	66.3±1.5	15.0±0.6
LV88	10±5	3.81±0.10	13.28±0.28	2.50±0.06	4.73±0.16	67.2±1.8	14.2±0.6
LV89	10±5	3.68±0.09	13.37±0.26	2.36±0.06	4.55±0.16	73.7±1.6	16.2±0.7
LV90	10±5	3.71±0.09	13.85±0.28	2.48±0.06	4.70±0.16	102.1±12.7	21.7±2.8
LV91	20±5	3.96±0.11	14.02±0.28	2.41±0.06	4.26±0.14	97.4±2.2	22.8±0.9

^a Using an alpha effectiveness (a -value) of 0.04±0.001 (Mauz et al., 2006).

^b Mean and standard error given for all samples except LV90 where mean and standard deviation is given.

sampling allows an averaging of the grain-size signal every 5 cm preventing any gap between the various samples, which could occur using a succession of separated samples.

Particle size distributions were determined from homogenized 10 g sub-samples, dispersed by sodium hexametaphosphate (0.5%) during 2 h in a rotating agitator (400 ml/10 g), and then sieved at 160 μ m to remove the coarse fraction (CaCO₃ and FeMn concretions, calcified rootlets, mollusks shells fragments, etc.). The measurements were performed on a Laser coulter LS 230 and repeated at least three times in order to obtain good reproducibility of the results.

Sediment was also sampled every 5 cm for the $\delta^{13}\text{C}$ isotopes on the organic matter (100 g), and every 10 cm for the terrestrial mollusk assemblages (15 kg), all samples are presently in process.

Roberts et al. (2003) analyzed in Aberystwith five samples for luminescence dating. The OSL ages vary from 20.7±0.9 ka at the base to 14.2±0.6 ka at the top. During the time of our sampling, the sampling locations used by Roberts et al. (2003) were still visible. This together with in depth analysis of the stratigraphy allowed the precise correlation to the stratigraphy established here (Fig. 2). We took additional samples in hammered copper tubes for OSL dating (Table 1, Fig. 3) in order to i) increase the time resolution, ii) better constrain the stratigraphic units and the environmental variations present in the record, iii) improve possibilities for precisely correlating with other climate proxies. The measures were performed in Liverpool and laboratory procedures are described in detail by Packman et al. (2007). The single-aliquot regenerative-dose procedure (Murray and Wintle, 2000) was applied to 11–20 μ m quartz grains to determine the acquired geological dose since the last exposure to sunlight (known as the equivalent dose, D_e). Sample aliquots were stimulated by blue-green LEDs (470±30 nm) and the OSL signal transmission at 290–380 nm was detected via Schott

U340 filters (7.5 mm thick) on Risø OSL/TL readers.. All of the samples, except LV90, produced narrow dose distributions and a study of this sample revealed an extra component within the OSL signal (Packman et al., 2007). This ultra-fast component (UFC; Jain et al., 2003) has a greater rate of sensitivity change than the fast component resulting in a higher dose saturation level (D_0) for some aliquots. Sample LV90 produced a broad range in the D_e requiring a different approach for its determination to reduce the malign influence of the UFC. A “later-light” integral was employed rather than the initial OSL signal, as described in Packman et al. (2007). This method improved precision on the D_e for this sample, but it still retained the broadest range of values. The poor reproducibility of LV90 is therefore reflected in the error assigned to the D_e estimate for this sample.

Annual dose rates were calculated from radionuclide concentrations determined using high-resolution low-level γ -spectrometry and the burial depth of the sample. Further details about the techniques applied can be found in Mauz et al. (2002). Water content during burial was assessed to be similar to present-day levels.

3. Results

3.1. Grain-size (Fig. 5)

The Peoria Loess samples from Eustis indicate grain size variation between four consecutive classes ranging from clays (<4.6 μ m), fine silt (4.6–20.7 μ m), coarse silt (20.7–63.4 μ m) and fine sand (63.4–153.8 μ m). Five main zones showing a variable pattern among the four different classes can be identified (Fig. 5). i) Above the Gilman Canyon formation and upward 15.8 m, the coarse silt and fine sand fractions increase while the fine loam and clays strongly decrease (Grain Size Zone, GSZ, 1). This indicates that the deposition of the Peoria loess mostly started during strong eolian dynamics contrasting with the reduced one occurring during the

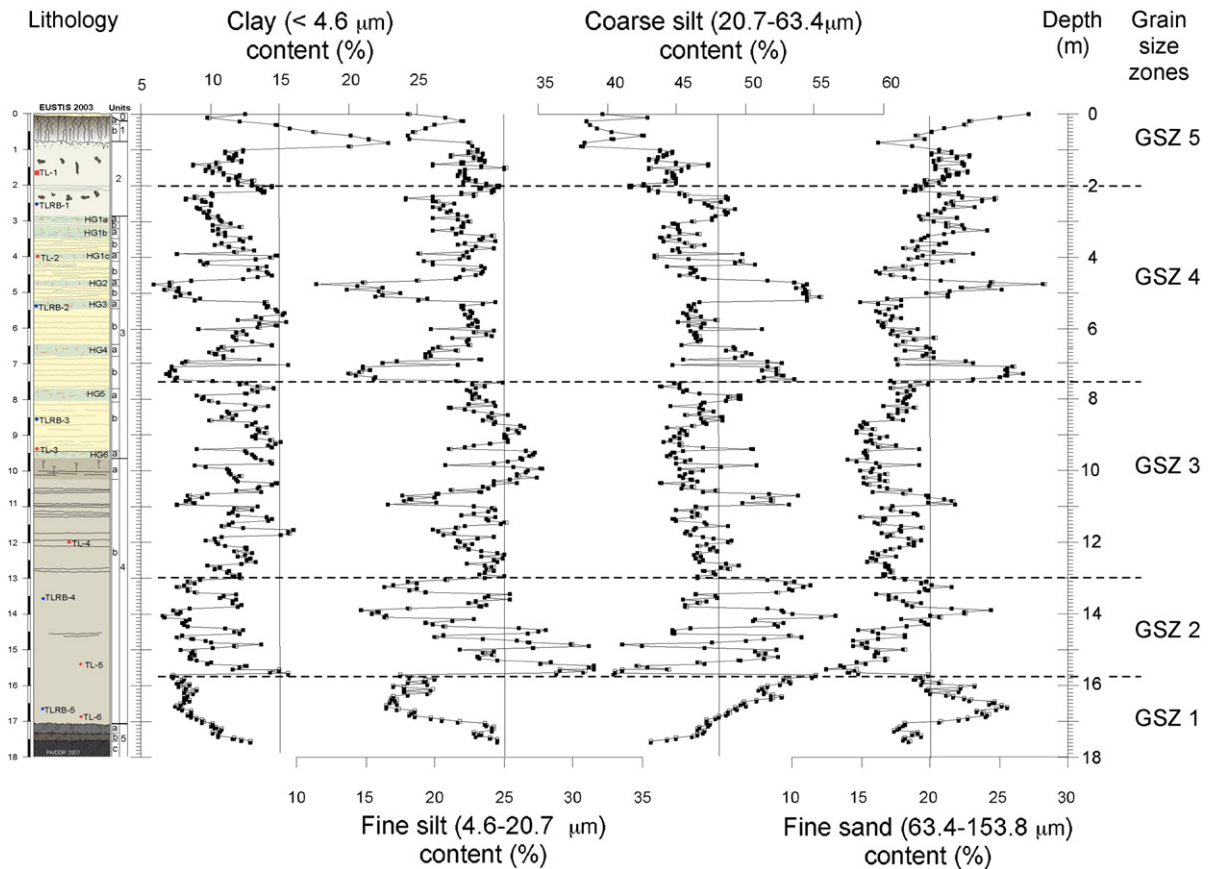


Fig. 5. Grain size analysis of the Peoria Loess and soils sequence in Eustis ash pit.

Gilman Canyon Formation development itself ii) Then after a sharp decrease in the coarse material and a proportional increase in the fine size fractions, characterizing a complete change in the eolian dynamics, large variations in fine and coarse loams between 15.8 m and 13 m show alternating eolian regimes or fluctuations in the source of the material (GSZ 2). iii) The following interval between 13 m and 7.5 m shows maximum values in the fine loam fractions reaching about 25% of the total composition with very few oscillations. This seems to indicate average wind conditions favoring the transport of coarse material (GSZ 3). iv) In the interval between 7.5 m and 2 m (GSZ 4), the proportion of fine-grained material decreases while thick intervals of coarse loam are recorded at 7.2 m and 4.8 m, the fine sand fraction remaining above 20% mainly in the upper part, between 4 m and 2 m. Such pattern seems to show a strengthening in the wind dynamics responsible for the dust transportation. v) The last interval, between 2 m and the top of the sequence, indicates a decrease in the proportion of coarse loam, contrary to an increase in fine

sand suggesting an increase in the wind regime (GSZ 5). A high proportion in clay marks the base of the soil, but immediately after, coarse material increases in between the soil, especially the fine sand fraction, possibly related to the composite origin of this unit. The top deposit material shows high values for the fine sand fraction, similar to those observed within the laminations interval.

The main embryonic soil, determined between 10.3 m and 9.8 m, does not show any particular grain-size structure. It is marked however by one of the highest proportions in fine loam recorded in the series. Furthermore, the laminations above this soil do not show any particular pattern in the different fractions, even in the main bands (pseudo-embryonic soils capping the laminations), ending every apparent observed cycle.

The Peoria Loess has been previously (Muhs and Bettis, 2000; Bettis et al., 2003b) subdivided into three subunits based on the grain size composition: lower PL with variable grain-size pattern, middle PL characterized by coarse material and upper PL mostly dominated

by fine-grained material. These zones were determined mainly in Iowa, at Loveland, probably reflecting differences in source materials (Muhs and Bettis, 2000), and at a lower resolution than in Eustis, because of the large thickness of the studied sequences. Our results obtained in Eustis nevertheless support such interpretation. Indeed the lower PL could be allocated in Eustis to the interval from the base of the Peoria loess upward to 13 m, the middle PL could correspond in Eustis to the interval between 13 m and 2 m, and the upper PL would be the uppermost 2 m.

3.2. MS variation (Fig. 3)

The low field magnetic susceptibility (MS) varies between about $25 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and $60 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The highest values are read in both the top soil and the Gilman Canyon humus soil horizon while the lowest occurs in the laminae. This corresponds to the classical general observation of high values in soils and paleosols while low values occur in loess units (Heller and Junda, 1981; Heller and Liu, 1982; Liu, 1985; Kukla et al., 1988; Kukla and An, 1989; Pye and Zhou, 1989; Kukla et al., 1990; An et al., 1991; Liu et al., 1991; Rousseau and Kukla, 1994; Shackleton et al., 1995; Rousseau et al., 1998a,b; Rousseau et al., 2001). From 17 m upwards to about 9 m, MS decreases gradually from about $60 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ to $30 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. Then between 9 m and 1 m, MS oscillates between $25 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and $35 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ but does not show strong and large variations. In the uppermost 1 m, MS shows a rapid increase from about $35 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ to $60 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ with a very last decrease at the top 10 cm corresponding to the uppermost pale yellow layer.

The comparison with the previously recorded measurements (Rousseau and Kukla, 1994) shows a good agreement between both records despite differences in the measured ranges. The depth evolution of MS is likely similar between both records. The large variations between 9.5 m and 7 m observed previously are not recorded even if a strong decrease is present in both records at about 7.7 m. Furthermore, the thin pale yellow top layer, inducing a very low MS, was not recorded in 1994, and thus corresponds to windblown redeposited material, possibly from the laminations as interpreted using grain-size analysis.

The previous interpretation can be reiterated by proposing that the bottom part, from 17 m to 9 m, indicates a gradual increase of an originally low deposition rate and gradual wetting of the climate leading to partial destruction of the magnetite in redox type weathering. Conversely, in the upper part of the

record, from 9 m upwards, the deposition is likely to have proceeded at a relatively high but uniform rate, as previously described by Rousseau and Kukla (1994).

3.3. OSL ages (Figs. 3, 6)

The OSL ages (Table 1) are in good agreement with those produced by Roberts et al. (2003). The intensive study of the luminescence characteristics of the samples indicates a distinctive OSL signature for LV90 compared to the five others (Packman et al., 2007). The main conclusion of this investigation is that the sample contains quartz from a different source area, and supports the interpretation on the variation in grain-size reported previously. When plotting the two sets versus depth, the succession does not show any particular disagreement except for LV 88 at 9.4 m and LV90 with the highest error. Two groups can be determined. From the bottom upward at about 10 m, the dates show a gradual evolution with decreasing age and depth. Then between 10 m and 2.5 m, the dates are within the same narrow range at about 14 ka. If the first group comes from a loess unit, which shows a gradual decrease in MS values, and has oscillating grain-size values, the second group is mostly yielded by the laminations, and supports a relatively high depositional rate as also interpreted from the MS values.

An age model can then be determined based on the available dates discussed according to their stratigraphic location. The age of 14.2 ± 0.6 ka at 9.4 m has been removed as it is out of the general age trend and so hence difficult to justify. The age on top at $12.2 \pm .5$ ka was also removed because of appearing far too young compared to the general stratigraphy. Indeed while luminescence ages date the last exposure of grains to sun light, ^{14}C ages date the death of the vegetation. Then a considerable time lapse can occur between ^{14}C and luminescence ages of the same stratigraphic level. However, in the present study, such a difference does not prevent using the paleosol stratigraphy to better constrain the age model as only the top soil and the Gilman Canyon Formation have been ^{14}C dated. The top soil represents at least the combination of younger pedogenesis at the end of marine isotope stage, i.e., at 12 ka. This implies that the top luminescence age, LV 86, should be rejected. Conversely, the Gilman Canyon Formation yielded consistent ^{14}C ages which after conversion into calendar ages indicate that the bottom luminescence age could be used. The determined preliminary time scale for the Peoria Loess record in Eustis then fits with the available OSL dates and allow data interpretation in terms of climate signals.

4. Interpretation

Loess sedimentation is probably episodic and a gradual influx of dust, as indicated by Kukla (1987) to justify his susceptibility age model in Chinese loess series, cannot be assumed. This is because, at least, in the laminations observed, we have evidenced individual layers which indeed could be related to individual pulses of dust or dust storms. However, our study does not yet have the resolution required for such assumptions. Furthermore, the dating techniques used prevent such a detailed interpretation. Dust storm events and their frequencies are highly questionable and difficult to identify clearly in the past. For example, in China, that the Gobi and Takla Makan deserts could produce the same amount of dust to the atmosphere, while the frequency of dust storms is much higher in Takla Makan compared to the Gobi Desert (Laurent et al., 2006). The grain size analysis indicates oscillations, which can be interpreted as corresponding to variations in the wind dynamics, variations in the source of the material or both. It has been demonstrated that the silt originates from the White River (Aleinikoff et al., 1998, 1999) and other Tertiary rocks, and thus not from the Laurentide ice sheet drainage (Mason et al., 1994; Muhs et al., 1999; Muhs and Bettis, 2000; Mason, 2001; Muhs and Zarate, 2001; Bettis et al., 2003a,b; Muhs et al., 2003; Muhs and Bettis, 2003). Furthermore, in sites bordering the NW Nebraskan dune fields, the Peoria Loess shows a modal diameter between 60 μm and 90 μm that Bettis et al. (2003b) and Mason et al. (1994) interpreted as too coarse to characterize suspension transport directly from the White River group outcrops which are more than 100 km away (Mason, 2001; Bettis et al., 2003b). Interestingly, Bettis et al. (2003b) noticed that thick loess can accumulate where saltating sand is absent, which is the case in our record in Eustis, while little long term loess accumulates where salting sand is present. Furthermore these authors indicate that laminations associated to a modal diameter higher than 60 μm characterizes a proximal Peoria Loess across western Nebraska as it occurs on a southwest–northeast trending band from northwest Kansas to northeast Nebraska, immediately southeast of the Nebraska Sand hills and other dune fields. In Eustis, the Peoria Loess indicates a modal diameter between 50 μm and 56 μm , which is also higher than the classical mode between 20 μm and 30 μm of the massive silt characterizing loess deposits (Pye, 1995). This lower modal value can be related to the distant dated locality to the southeast from the thickest proximal deposits.

Grain-size variation reflects the transport energy rather than the long term changes in strength of global atmospheric circulation. Present models of dust transportation are able to reproduce the transport of fine grain material <20 μm which corresponds to the silt part of our deposits. On the contrary the majority of the material deposited in Eustis requires higher energy related to wind transport. While the source of the material is the same, then variations in the grain-size should correspond to the variation in the transport energy. The study area is located close to the former Laurentide ice-sheet which was covering part of North America, which induced, according to model reconstructions, a more southward path of the Jet Stream (Kutzbach, 1987; Kutzbach et al., 1993). However, the time interval investigated also corresponds to a period of ice-sheet retreat which nevertheless affected the general circulation if Kutzbach's (1987, Kutzbach et al. 1993) experiments are correct. Grain-size variation is better interpreted by combining the grain classes to provide a grain-size index, GSI, which is the coarse sediment fraction (% between 20.7 μm and 63.4 μm) divided by the fine-sediment fraction (% <20.7 μm). The studies performed in European loess sequences, following the same protocol, interpret fluctuations in this index in terms of wind dynamics (Antoine et al., 2001; Rousseau et al., 2002). In these records, high values of GSI, related to strong wind speeds, are associated with loess units, whereas low GSI values, corresponding to low wind activity, are linked to the occurrence of soils, expressed as boreal soils or gley horizons. A similar ratio, named U ratio, was also applied to a European loess sequence to depict rapid changes and high-resolution correlations with other indicators (Vandenbergh et al., 1998). Hence, one could involve pedogenesis, diagenetic or reworking processes altering our results. The sampling protocol used, which consists in carefully cleaning the outcrops through wide panels of 3–4 m width over 2 m high allow the possible observation of bioturbation or reworking which was not observed in Eustis. The cleaning of the panels allowed precise depth measurement, correlation of the different panels together, and accurate location of the different samples used by previous investigators for luminescence dating. Furthermore, the ongoing study of the terrestrial mollusks sampled in parallel does not show any indication of reworking.

In Eustis, GSI values are rather high, varying between 2.2 and 3.4 and clearly above those observed in European sections (between 0.5 and 2) (Fig. 7). This is probably related to the location of the US sequence in the boundary belt transition zone between eolian

deposits and source area, whereas European loess deposits usually underwent long distance transport. In Eustis, the GSI variations indicate phases of stronger wind dynamics rather than variations in source materials, which apparently do not correspond to stratigraphic units — a correspondence that is usually observed in European loess sequences (Rousseau et al., 2002). The embryonic soils in Eustis do not correspond to low values in the GSI index and thus to reduced or stopped eolian dynamics. On the contrary some of these embryonic soils are related to high index values. This might be an artifact of the low-resolution sampling interval (5 cm) used and prevents unraveling the link between the lamination structure and eolian pattern, as was possible in several European loess sequences

(Nussloch, Antoine and Rousseau unpublished data) and as Feng et al. (1994a,b) suggested.

Using all available OSL ages (this study and (Roberts et al., 2003) for the Peoria Loess, and ¹⁴C dates (Feng et al., 1994a,b) from the top soil and the Gilman Canyon formation, a time frame for the upper Pleistocene sequence can be established (Fig. 7). The association of the grain-size analysis and the OSL dates clearly indicates a highly variable deposition rate. This restricts the usefulness of the normally used simple interpolation techniques for constructing an age model. We apply a protocol similar to those previously used for European loess sequences, and compare the grain-size record with the Greenland GRIP ice-core records. The assumption is that the deposition of dust leading to the loess formation

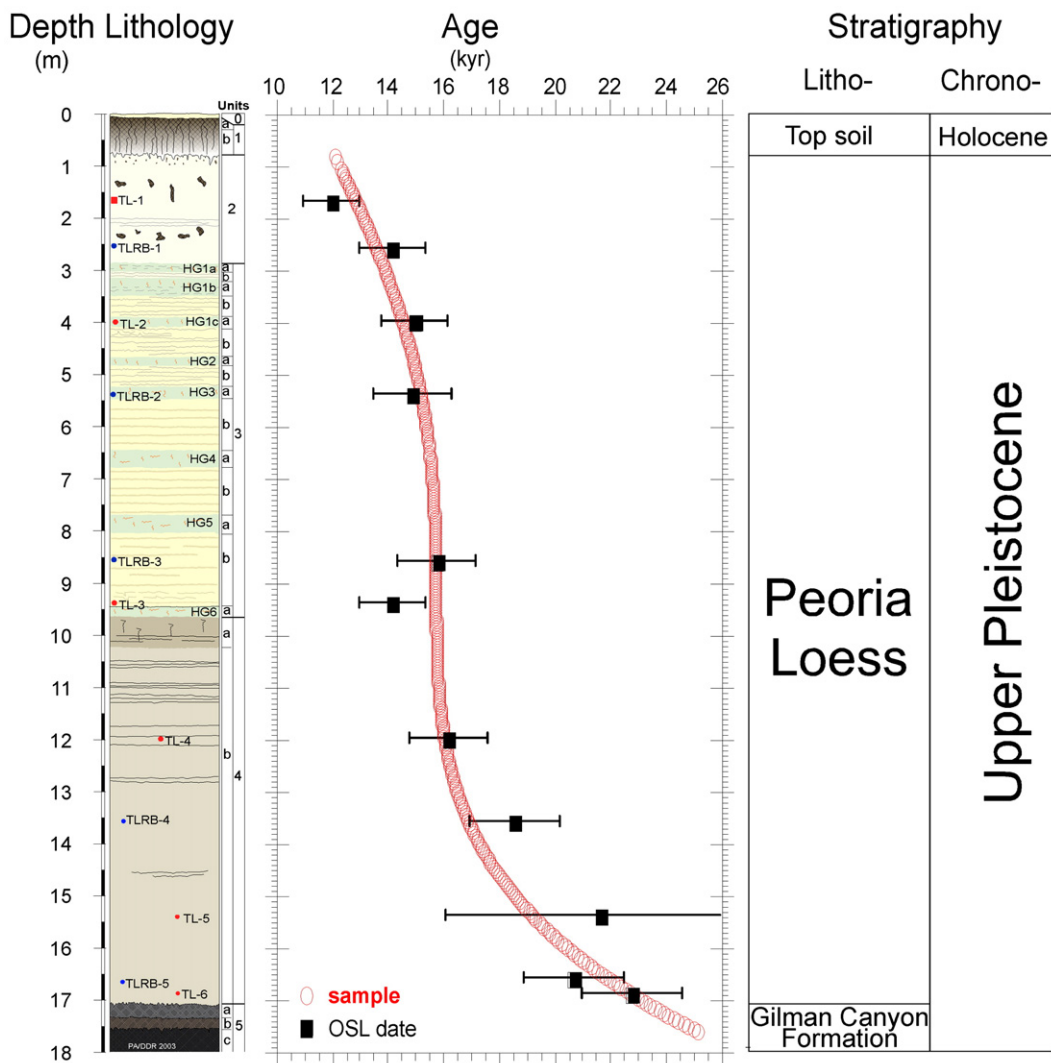


Fig. 6. Preliminary age model used for the Peoria Loess series in Eustis.

is related to the wind dynamics linked to the general atmospheric circulation, responsible for dust deposition in Greenland. The comparison between the GSI index and the $\delta^{18}\text{O}$ and dust records from the Greenland ice sheet (GRIP records from Johnsen et al., 2001) shows a different pattern than that observed in Western Europe. There, the variation in the GSI index is closely similar to the dust variations observed in Greenland, high values in GSI being linked to high dust concentration, indicating that both domains reacted or belonged to the same general atmospheric dynamics. Conversely in Eustis, there is no relationship between the GSI index and the Greenland dust record. The grain-size index seems to better show similarities with the variation in GRIP $\delta^{18}\text{O}$, which is related to the moisture source, and thus, relates to other dynamics. Furthermore, there is no relation between the pseudo-embryonic soils identified on top of the laminae and low values of the grain-size

index. Indeed, the laminae-like structure shows similarities with the so-called niveo–eolian deposits as described in European loess sequences and locally named “loess à doublets” (Lautridou, 1985), suggesting rapid and short events. Thus, following such assumptions, and considering the calibrated ages for both bracketing soils (Fig. 6), the Peoria Loess mostly deposited after the main loess deposits in Europe, appears coeval to the main dust concentration intervals in Greenland. This is after the occurrence of Dansgaard–Oeschger (DO) event 2 which can be synchronous and thus correlated to the top humus soil of the Gilman Canyon Formation (Wang et al., 2003). (Fig. 7).

The Peoria Loess deposits in the US Great Plains are located in between two major marine domains, respectively the Pacific and North Atlantic Oceans, which recorded precisely the last deglaciation. Indeed, several correlations have been proposed between the

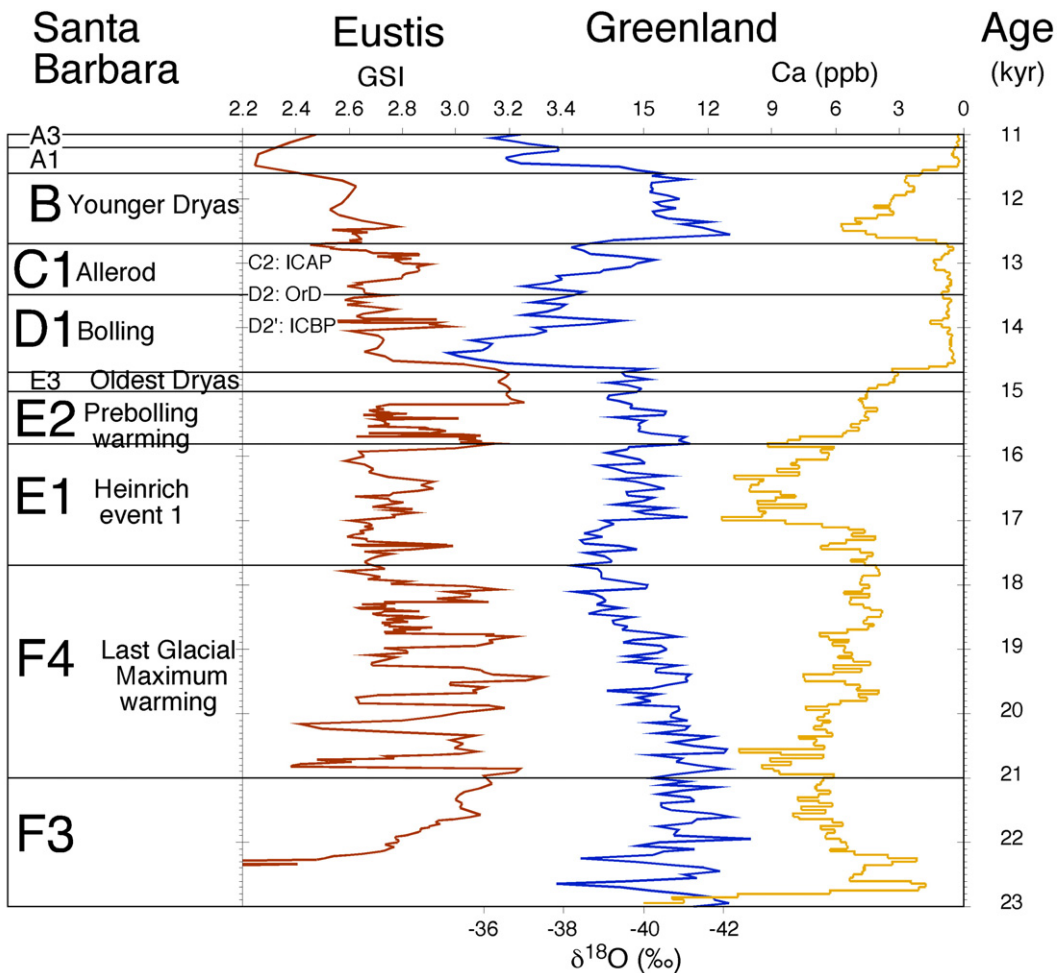


Fig. 7. Tentative variation in time of the GSI index, interpreted as an indicator of eolian dynamics, the highest values, the strongest wind strength (Antoine et al., 2001; Rousseau et al., 2002), and of the $\delta^{18}\text{O}$ and dust record in Greenland from the GRIP ice-core (Johnsen et al., 2001).

high resolution marine record from Santa Barbara basin, core ODP 893 A off California, representing the Eastern Pacific domain (Hendy et al., 2002), and the Greenland $\delta^{18}\text{O}$ record representing the North Atlantic one (Johnsen et al., 2001). The general synchronicity between these records suggests tied atmospheric teleconnections linking these two regions as a common response to global climatic forcings (Fig. 7). However, variations in the magnitude of these responses, and in some cases a difference in the intensity of the signal (reverse record) indicate also the prevalence of local/regional conditions. The wind direction determined mostly by the thickness of the deposits but also with other geochemical indices, (Mason et al., 1994; Muhs and Bettis, 2000; Bettis et al., 2003a,b) is mostly from the northwest according to the thickness of the deposits, although a wide anticyclone prevailed over the Laurentide ice-sheet (Kutzbach and Wright, 1985). Thus it appears problematic to interpret the variation in GSI in Eustis as related to any particular event occurring in the North Atlantic. Model simulation of the Last Glacial Maximum shows that the northwest winds over the Great Plains occurred mostly during winter (Whitlock et al., 2001) while southeastern winds prevailed in summer. Therefore because a precise biostratigraphy is unavailable in the area and as Eustis is downwind of the Pacific Ocean, even though thousands of kilometers away, we applied the climatostratigraphic biozones defined in the Santa Barbara basin (Hendy et al., 2002) to our GSI record in Eustis for comparison (Fig. 7).

First of all, the Santa Barbara climatostratigraphy requires some minor corrections as the Bolling and Allerod interstadials were not correctly defined by Hendy et al. (2002). Indeed three cold episodes have been identified during the Lateglacial interval (Alley and Clark, 1999). Especially, the Older Dryas, labeled in the Santa Barbara record as D2 cannot be allocated to the first cold event. In fact what has been labeled as D2 in the marine record corresponds instead to the Intra cold Bolling Period event (Alley and Clark, 1999) and D2 should relate to an event at about 13.5 ka on the GRIP time scale. Therefore, the D1 climatostratigraphic event corresponding to the Bolling interstadial would last between 14.7 and 13.5 ka and the Allerod from 13.5 ka to 12.7 ka. Second, when applying the refined Santa Barbara climatozonation to both Eustis GSI and the Greenland GRIP $\delta^{18}\text{O}$ and dust records, similar general patterns are determined although some differences can be noticed particularly during E1 and B climatostratigraphic events, which are better recorded with high magnitude in the North Atlantic domain

(Fig. 7). Indeed during E1 the eolian activity does not show any particular pattern, and this is assumed to occur during Heinrich event H1, although two main GSI peaks were noticed, a peculiarity that Bard et al. (2000) recorded about the composition of H1 event. The GSI values computed for climatostratigraphic event B also do not show any particular pattern. The eolian activity is again lower compared to the rest of the record although corresponding to the YD interval. One can however notice that the observed lamination cycles in Eustis occurred during events E1 to C2. The occurrence of the laminations with Heinrich event 1 is purely accidental as these structures are typical of proximal deposits to the source areas, which could correspond to a change in the eolian dynamics at that time. That the eolian dynamics do not seem to have been strengthened during Heinrich 1 event, by comparison with the record of H2 and H3 in the Nussloch loess sequence in Europe, is in agreement with the modeling results for the shut down of the thermohaline circulation due to iceberg discharge. This shows that the climatic changes associated were relatively minor outside the North Atlantic domain (Mikolajewicz and Crowley, 1997; Hostetler et al., 1999; Ganopolski and Rahmstorf, 2001a,b; Rahmstorf, 2002; Rahmstorf, 2003). Furthermore the “muted” record of Younger Dryas in the GSI in Eustis, despite growing evidence, especially paleolimnological (Porinchu et al., 2003; Briggs et al., 2005), speleothems (Vacco et al., 2005) and tree rings (Panyushkina et al., 2004), is not problematic. This is because the GSI is not directly temperature or precipitation related but characterizes the eolian dynamics and/or the availability of dust material. One could argue about minimizing depositional and post-depositional processes in forming the loess deposit at Eustis when interpreting such results. However, the mollusk assemblages sampled in parallel do not show any particular cold signal either (Rossignol in preparation) and no reworking is evidenced supporting previous investigations in both Eustis and Buzzard’s Roast sequences (Rousseau and Kukla, 1994; Rossignol et al., 2004).

Finally the GSI alternations in Eustis could therefore be better interpreted in terms of varying atmospheric circulation (Fig. 8). Thus the high values of GSI would correspond to periods of dominantly westerly circulation permitting the deposition of the eolian material, mostly in winter. Periods of low values would correspond on the contrary to dominantly other circulation, probably southeasterly as indicated by model results (Whitlock et al., 2001). If such interpretations are correct this would imply the supply of moisture from different sources. The origin of moisture in the Great



Fig. 8. Map of North America with the extent of the Laurentide ice-sheet at the LGM with anticyclone wind patterns modeled from COHMAP and those derived from the loess thickness measured in the field (after Muhs and Bettis, 2000 modified).

Plains presently is mainly from the Pacific Ocean, the Gulf of Mexico, and the northern latitudes. However, $\delta^{13}\text{C}$ variations in the Peoria Loess from localities further northeast of Eustis, in Illinois, have been interpreted as corresponding to paleo-ENSO events, supporting some enhancement of transport from the Pacific Ocean (Wang et al., 2000), although describing supplementary short variations attributed to moisture transport from the Gulf of Mexico. Furthermore complementary investigations in the same localities on the carbonate content and the soil color clearly indicate similarities with the Greenland $\delta^{18}\text{O}$ variation in the GISP2 ice-core (Wang et al., 2003). Our study cannot yet confirm this as further investigations are needed in Eustis, i.e., $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ on the organic matter and on the mollusk shells, but also from other sites.

5. Conclusion

The Peoria Loess is the main stratigraphic unit of the North American last climatic cycle. Previous investigations of this unit in Eustis intending to yield OSL dates

described it as a homogenous deposit, despite earlier studies describing it as non-homogenous. Our results support that the Peoria Loess is not homogenous. It shows different units among which one corresponds to laminations characterizing records close to source areas, yielding high grain-size values. Indeed, the comparison of the grain size results with European data obtained using the same protocol shows that the mode and the grain size index (GSI) in Eustis are higher than in Europe, indicating stronger eolian dynamics. Another comparison with climatic proxies from Greenland indicates that the Peoria Loess was deposited much later than in Europe, during a time when the eolian sedimentation was almost finished. Furthermore, contrary to the European loess sequences, the Eustis loess does not show any increase in the grain size during the time span corresponding to the North Atlantic Heinrich event 1. Thus, the Eustis record appears to indicate more similarities with other climatic records retrieved off California, in the Santa Barbara Basin, contrary to those from the North Atlantic Ocean domain.

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