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Abrupt millennial climatic changes from Nussloch (Germany) Upper Weichselian eolian records during the Last Glaciation

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Abstract

Increasing attention has been focussed on the massive iceberg discharges in the North Atlantic, Heinrich events, during the Last Glaciation, and their worldwide terrestrial counterparts. However, these events are particular episodes among more regular cyclic events named Dansgaard–Oeschger events in ice cores or Bond cycles in marine cores. Here we examine grain size, $\delta^{13}C$, and magnetic susceptibility data from Nussloch, one of the most complete west European eolian sequence examined so far. These indices indicate that, during the 31–19 kyr interval (using chronology provided by radiocarbon, OSL and TL dates), millennial scale variations occurred affecting both precipitation and vegetation. Furthermore, these are associated with oscillations in the wind strength matching the dust deposition rate in Greenland, as recorded in the GRIP ice core. Our study shows that the abrupt climatic changes, the Dansgaard–Oeschger events, are also recorded in the west European loess sequences. This implies an atmospheric mechanism linking dust deposition over Greenland and Europe, which is probably connected to global climatic events during the Last Glaciation. © 2002 Published by Elsevier Science Ltd.

1. Introduction

High-resolution studies on North Atlantic cores indicate that ice-bearing waters punctuated the Last Glacial–Interglacial interval inducing abrupt climatic shifts (Bond et al., 1992, 1997; Bond and Lotti, 1995). These changes affected the atmospheric circulation over Greenland, with a mean pacing of about 1470 ± 500 yr, a pacing similar to the ice-core Dansgaard–Oeschger $\delta^{18}O$ shifts over the Last Glaciation (Bond et al., 1997). Because of the location of both the marine and ice cores, these climatic oscillations changes are interpreted to have affected the North Hemisphere climate as well, and more especially Europe (Fig. 1). Among the available terrestrial sequences likely to register such oscillations, loess sequences, corresponding to eolian deposition in periglacial environments, can provide high-resolution records easily accessible (Kukla, 1977). Numerous studies indicate that, during the last climatic cycle, loess began depositing in Europe at about 70 kyr and terminated at about 15 kyr, including two periods of enhanced deposition at about 70–60 and 30–15 kyr (Lautridou and Sommé, 1974; Haesaerts, 1985; Rousseau et al., 1998; Antoine et al., 2001). These records also indicate that loess deposition was periodically interupted by formation of tundra gleys, from which a vegetation signal can be obtained. The Nussloch loess series is 18 m thick deposits, located on the Oddenvald plateau close to the right bank of the Rhine valley, near Heidelberg in Germany (49°21′N, 8°43′E). The different

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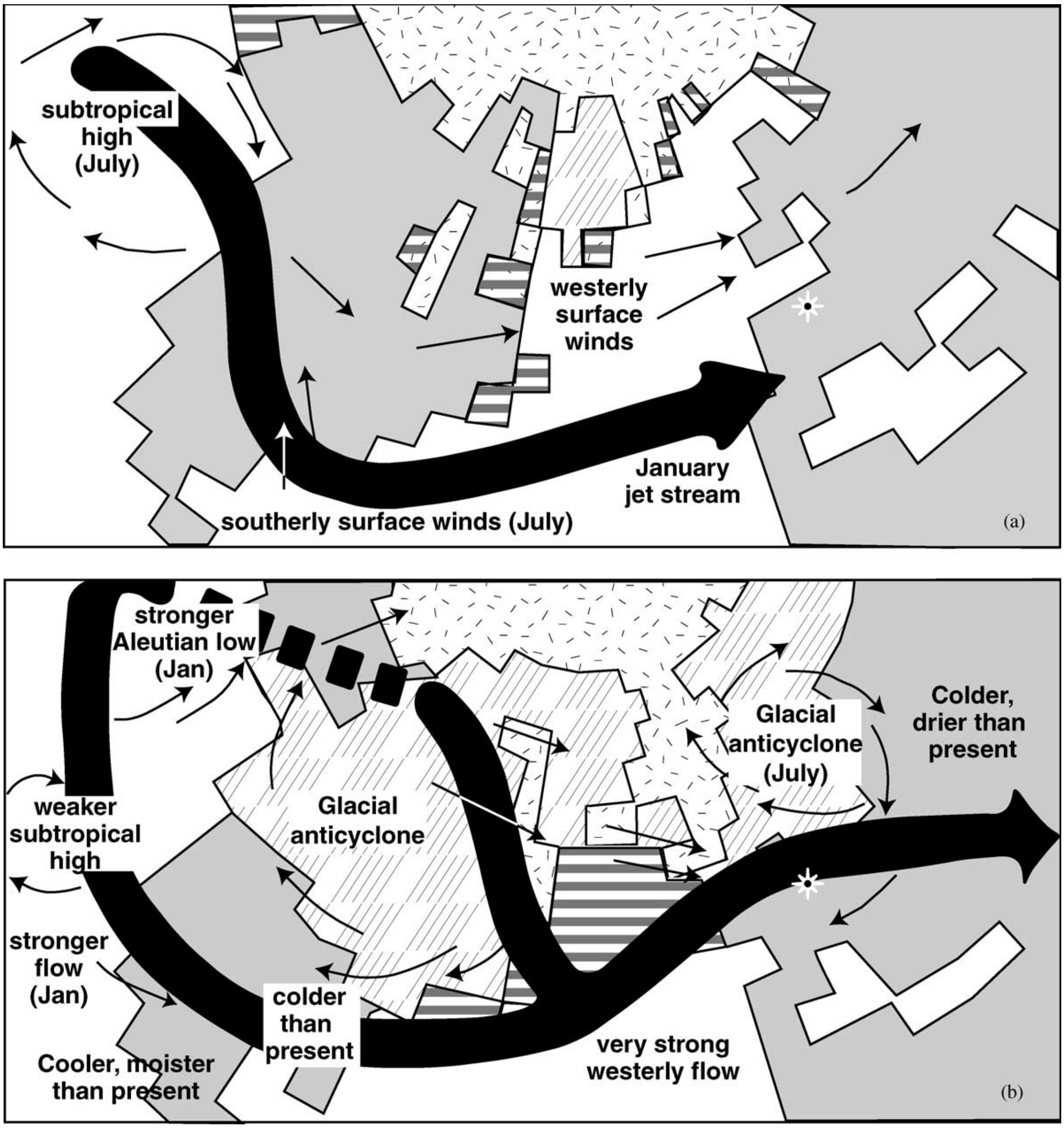

Fig. 1. Model of the present (a) and LGM (b) climate dynamics over the Northern Hemisphere (from COHMAP members (1988)). The white star locates the Nussloch series.

sedimentary units are clearly recognized, fitting the established European loess stratigraphy for the past 130 kyr (Antoine et al., 1999, 2001). The high-resolution chronology for the sequence (21 dates) is provided by both luminescence dating, using both TL/IR and OSL methods (Antoine et al., 2001), and ^{14}C dating of macro-remains of wood, bone, shells (conventional dating) and organic matter (AMS dating) (Hatté et al., 1998) (Fig. 2). The dates yielded by different methods support the interpretation of a complete Last Glacial climatic cycle for the whole section. More significantly, they also indicate that the Nussloch record contains a very expanded sub-sequence (10.6 m thick) that mainly accumulated around the Last Glacial maximum (LGM). Indeed, its age is bracketed between about 30.0 ± 1.9 kyr at the base and 19.8 ± 2.2 kyr in the top loess unit. The lower part of this loess sequence overlies a brown soil horizon (Bw horizon of Cambisol), luminescence dated at about 34 ± 3.2 kyr BP. Loess sediments of 10 m were sampled at 10 cm intervals. Each sample would roughly correspond to 113.2 yr in a simple linear interpretation, a resolution fine enough to detect rapid changes and to compare with marine and ice-core records.

Among the different grain-size fractions examined from each sample, we focussed on the 20–50 μm (coarse silt) and the <20 μm (fine silt and clay) fractions as they could be used to derive a grain-size index (20–50 μmm/

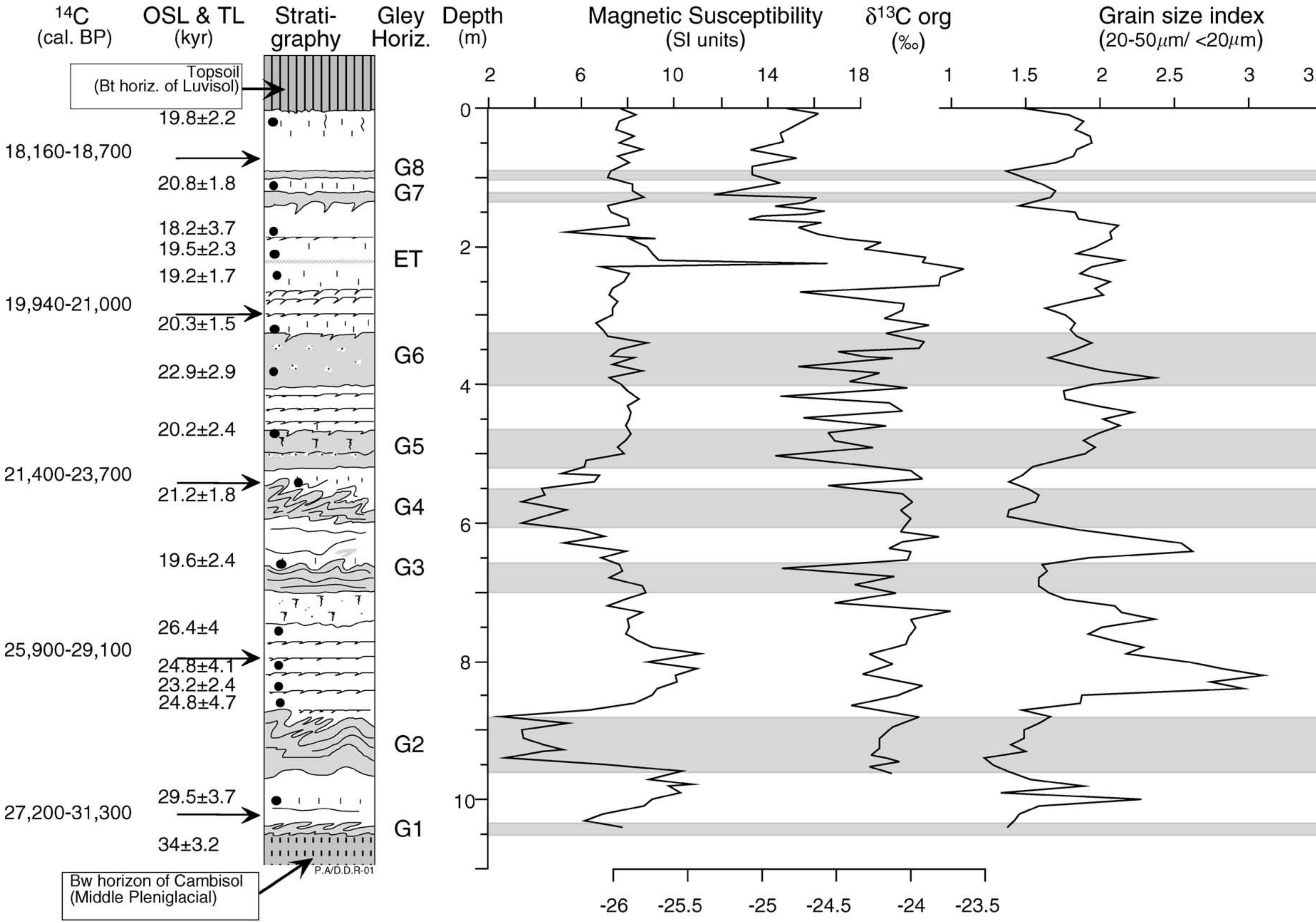

Fig. 2. Variations with depth of loess and paleosol indices in the highly expanded eolian deposits in Nussloch. The samples were taken at 10-cm intervals. Luminescence and ^{14}C dates are plotted with the stratigraphy. G, tundra gley horizons; ET, Eltwiller tuff. The grey zones materialize the tundra gley horizons.

<20 μm). In China, coarse silt in the modern dust is higher when the wind is strongest, so that grain-size variations in loess are considered to reflect variations in wind strength (Xiao et al., 1995). The tundra gleys correspond thus to an important decrease in loess deposition and to reduced wind speed as suggested by research in Belgium on the Kesselt sequence (Vandenberghe et al., 1998). In Nussloch, the grain-size index is considered to be a reliable index of the wind dynamics and a suitable indicator for atmospheric dust. The $\delta^{13}C$ of the preserved organic matter records the response of the vegetation to climatic variations (Cerling and Quade, 1993). In Western Europe, because there are only C3 plants (Hatté et al., 1998), variation in this ratio is interpreted as the response of the local vegetation to fluctuations in the water supply (the less depleted the more arid), as well as to CO_2 concentration. Finally, the magnetic susceptibility (MS) provides reliable evidence for the occurrence of soils, even those such as tundra gleys having weak morphological expression in the field; MS values are significantly higher in the loess than in the tundra gley horizons (Antoine et al., 2001). The highest MS values are recorded in the coarser loess beds (high grain-size index). Antoine et al. (2002) partly interpreted this variation by considering the decreasing eolian dynamics and the weathering of the magnetic minerals (magnetite transformed into hematite) which is characteristic in hydromorphic units like tundra gleys (Nawrocki et al., 1996)

2. Results and discussion

During the 31–19 kyr interval, the sequence shows eight loess units and eight tundra gleys (labeled G in Fig. 2). The MS values vary between 4 and 16 SI units, with the highest reading corresponding to the Eltwiller tuff (ET), a stratigraphic volcanic marker dated at about 20 kyr (luminescence dated between 19.5 ± 2.3 and 19.2 ± 1.7 kyr) (Antoine et al., 2001). The grain-size index varies between 1.2 and 3.1, with the lowest values characterizing tundra gleys, whilst the coarser material is deposited in loess units. This supports the interpretation that eolian reworking of coarse silts probably from the adjacent Rhine valley (high MS values) is punctuated by intervals of lower wind dynamics during soil formation. Increases in the grain-size index indicating stronger wind dynamics are mostly mirrored by peaks in the $\delta^{13}C$ record. This suggests that the windiest conditions were generally associated with drier environments and reduced vegetation cover. The tundra gley horizons conversely correspond to environments with increased vegetation, moister and reduced wind strength. Preliminary results from mollusc studies of the Nussloch samples support the variation in the vegetation indicated by the $\delta^{13}C$ oscillations. In addition, the top of the tundra gleys show a higher number of mollusc shells, indicating cooler conditions than in the loess units. These results clearly demonstrate that the high-resolution interval studied in Nussloch was recording abrupt environmental changes and is comparable with other proxy data, such as the Greenland GRIP dust ice-core record (Dansgaard et al., 1993; De Angelis et al., 1997; Fuhrer and Legrand, 1997; Steffensen, 1997) for the 31–19 kyr interval (Fig. 3).

Eight loess units associated with eight tundra gleys correspond to high and low atmospheric dust content over Greenland. The thickest or the coarsest loess deposits (high wind dynamics, low susceptibility and high $\delta^{13}C$) correspond to phases of higher dust content over Greenland. Even the strongly developed tundra gleys correlate with the long intervals of low dust values. Furthermore, the recognition of the succession of eight successive tundra-gley/loess units would suggest, assuming a uniform deposition rate, that the Nussloch sequence recorded a cyclicity of about 1500 yr, matching the 1536 ± 563 yr cycles determined in both North Atlantic and ice-core records for the same period (Bond et al., 1997). However, considering the decrease in sedimentation during the formation of the tundra gley horizons, the deposition of each loess unit was probably more rapid with accumulation rates perhaps reaching 2 m per 1000 yr.

Using age boundaries of 31 and 19 kyr for the base and the top of the dilated sequence, we derived an age model tuned to the ice record by assuming that the gley horizon formation was coeval to the intervals of low dust accumulation recorded in the ice cores (Fig. 3). The age model clearly fits most of the dates obtained via the different techniques. Furthermore, the structure of both records is almost similar supporting our assertion that there is a reliable relationship between the dust accumulation in the ice core and the Nussloch loess deposition. Finally, the mean duration of the gley–loess doublets preserved in Nussloch is about 1487.5 ± 970 yr, which again matches Bond cycles or Dansgaard–Oeschger events. Differences between ice-core and terrestrial records, however, are mostly related to the origin of the material itself. General circulation models usually consider that the major extensive deserts are the main source for past dust deposits (Mahowald et al., 1999). Combined Ne and Sr isotope studies of the silt fraction indicate that the dust from Greenland has a similar origin to Chinese loess deposits (Biscaye et al., 1997). The linking mechanism proposed involves a long-distance transport by the reinforced jet stream which outlined the Laurentide ice sheet during glacial times (COHMAP members, 1988) (Fig. 1). The origin of the Nussloch material, however, seems to be more complex. Preliminary studies of rare earth elements from the silt fraction indicate that the carbonates are local and the silicates allochthonous. The fine silt and clay particles

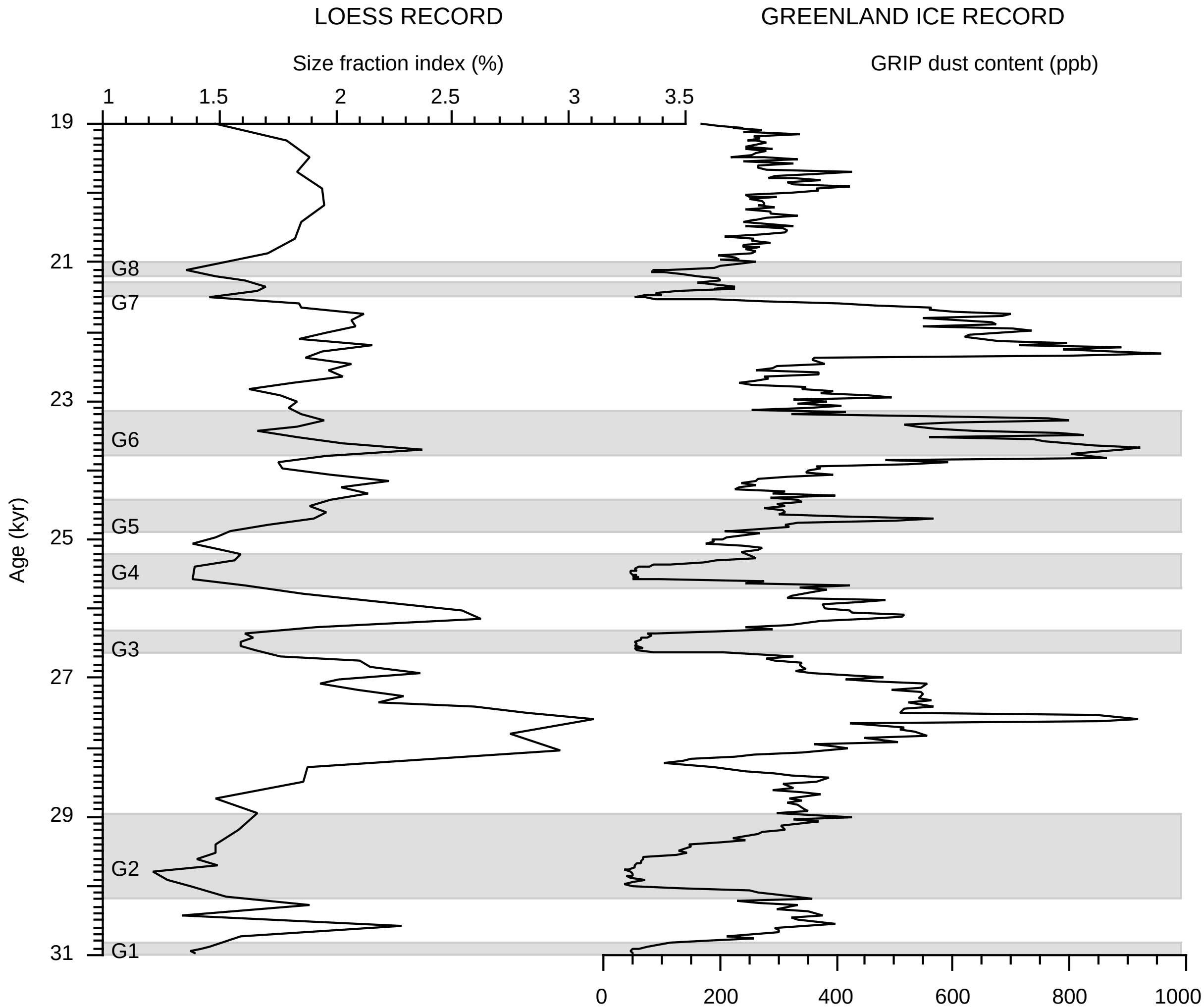

Fig. 3. Comparison between the grain-size variation in Nussloch and the atmospheric dust content over Greenland (Dansgaard et al., 1993; De Angelis et al., 1997; Fuhrer and Legrand, 1997; Steffensen, 1997) for the 31–19 kyr interval. The Nussloch time scale was calculated using the Analyseries software (Paillard et al., 1996). G, tundra gleys; see Fig. 2.

appear to have been derived from long-distance transport, whereas the local sandy and coarse silt particles were blown from the dry braided Rhine Valley during highly dynamic eolian events (Antoine et al., 2001). Preliminary Pb isotope data at Nussloch are different from Chinese and Greenland samples (Ben Othman et al., 2001) suggesting then a different source for the silt material. Pye (1995) has proposed a theoretical model concerning dust transport which has two main modes according to wind speed and strength in deflating areas: (i) transports fine grained silty material ($<20\,\mu m$) at high altitude over very long distances, (ii) transports coarser material over short distances. Taking into account our results, the Nussloch loess record matches the second model as coarse sand material has been blown from the nearby Rhine valley. This work shows that it may be necessary in the future to model more local conditions into simulations for the full glacial atmospheric circulation. For example, the dried-out English Channel and southern North Sea, might have provided important sources of dust for the western European loess as already suggested by Juvigné (1976) and Lautridou (1985) from heavy mineral studies and grain-size gradients in northwest European loess area. Our results demonstrate that during the past 31–19 kyr interval, the Western European climate was directly affected by millennial climatic variations matching those in North Atlantic and Greenland.

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References

Antoine, P., Rousseau, D.D., Lautridou, J.P., Hatté, C., 1999. Last Interglacial–Glacial climatic cycle in loess–paleosol successions of north-western France. Boreas 28, 551–563.

Antoine, P., Rousseau, D.D., Zöller, L., Lang, A., Munaut, A.V., Hatté, C., Fontugne, M., 2001. High-resolution record of the Last Interglacial–Glacial cycle in the loess palaeosol sequences of Nussloch (Rhine Valley—Germany). Quaternary International 76/77, 211–229.

Antoine, P., Rousseau, D.D., Hatté, C., Zöller, L., Lang, A., Fontugne, M., Moine, O., 2002. Evénements éoliens rapides en contexte loessique: l'exemple de la séquence du pléniglaciaire supérieur weichselien de Nussloch (Vallée du Rhin-Allemagne). Quaternaire, in press.

Ben Othman, D., Luck, J.M., Grousset, F., Rousseau, D.D., Albarède, F., 2001. Cu, Zn (and Pb) isotopes in aerosols and loess, EUG XI. Journal of Conference Asbtracts, Cambridge Publications, Strasbourg, p. 688.

Biscaye, P.E., Grousset, F.E., Revel, M., Van der Gaast, S., Zielinski, G.A., Vaars, A., Kukla, G., 1997. Asian provenance of glacial dust (Stage 2) in the GISP2 ice core, summit, Greenland. Journal of Geophysical Research 102, 26765–26781.

Bond, G.C., Lotti, R., 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. Science 267, 1005–1010.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. Nature 360, 245–249.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Science 278, 1257–1266.

Cerling, T.E., Quade, J., 1993. Stable carbon and oxygen isotopes in soil carbonates. In: Swart, P.K., Lohmann, K.C., McKenzie, J., Savin, S. (Eds.), Climate Change in Continental Isotopic Records. Geophysical Monograph. AGU, Washington, pp. 217–231.

COHMAP members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241, 1043–1052.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahi-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjöprnsdottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364, 218–220.

De Angelis, M., Steffensen, J.P., Legrand, M., Clausen, H., Hammer, C., 1997. Primary aerosol (sea salt and soil dust) deposited in Greenland ice during the last climatic cycle: comparison with east Antarctic records. Journal of Geophysical Research 102, 26681–26698.

Fuhrer, K., Legrand, M., 1997. Continental biogenic species in the Greenland Ice Core Project ice core: tracing back the biomass history of the North American continent. Journal of Geophysical Research 102, 26735–26745.

Haesaerts, P., 1985. Les loess du Pléistocène Supérieur en Belgique: comparaisons avec les séquences d'Europe Centrale. Bulletin de l'Association française d'Etude du Quaternaire 22-23, 105–115.

Hatté, C., Fontugne, M., Rousseau, D.D., Antoine, P., Zöller, L., Tisnérat-Laborde, N., Bentaleb, I., 1998. $\delta^{13}C$ variations of loess organic matter as a record of the vegetation response to climatic changes during the Weichselian. Geology 26, 583–586.

Juvigné, E., 1976. Contribution à la connaissance de la stratigraphie au Quaternaire par l'étude des minéraux denses transparents entre l'Eifel et le Massif Central français et plus particulièrement en Belgique, Liège, Liège, 235pp.

Kukla, G., 1977. Pleistocene land–sea correlations. 1. Europe. Earth Science Review 13, 307–374.

Lautridou, J.P., 1985. Le cycle périglaciaire Pléistocène en Europe du Nord-Ouest et plus particulièrement en Normandie., Thèse Doct. Etat Univ. Caen, Caen, 908pp.

Lautridou, J.P., Sommé, J., 1974. Les loess et les provinces climato-sédimentaires du Pléistocène supérieur dans le Nord-Ouest de la France. Essai de corrélation entre le Nord et la Normandie. Bulletin de l'Association française d'Etude du Quaternaire 40–41, 237–241.

Mahowald, N., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S.P., Prentice, I.C., Schulz, M., Rodhe, H., 1999. Dust sources and deposition during the last glacial maximum and current climate: a comparison of model results with paleodata from ice cores and marine sediments. Journal of Geophysical Research 104, 15895–15916.

Nawrocki, J., Wojcik, A., Bogucki, A., 1996. The magnetic susceptibility record in the Polish and western Ukrainian loess–paleosol conditioned by palaeoclimate. Boreas 25, 161–169.

Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh program performs time-series analysis. Eos Transactions on AGU 77, 379.

Pye, K., 1995. The nature, origin and accumulation of loess. Quaternary Science Reviews 14, 653–657.

Rousseau, D.D., Zöller, L., Valet, J.P., 1998. Late Pleistocene climatic variations at Achenheim, France based on a magnetic susceptibility and TL chronology of loess. Quaternary Research 49, 255–263.

Steffensen, J.P., 1997. The size distribution of microparticles from selected segments of the Greenland Ice Core Project ice core representing different climatic periods. Journal of Geophysical Research 102, 26755–26763.

Vandenberghe, J., Huijzer, B., Mücher, H., Laan, W., 1998. Short climatic oscillations in a western European loess sequence (Kesselt, Belgium). Journal of Quaternary Sciences 13, 471–485.

Xiao, J., Porter, S.C., An, Z., Kumai, H., Yoshikawa, S., 1995. Grain size of quartz as an indicator of winter monsoon strength on the Loess Plateau of Central China during the last 130,000 Yr. Quaternary Research 43, 22–29.