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New chronology and organic matter $\delta^{13}C$ paleoclimatic significance of Nußloch loess sequence (Rhine Valley, Germany)

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Abstract

Due to its high accumulation rate, the loess sequence of Nußloch (Rhine Valley, Germany) is well suited to a high-resolution study of continental paleoenvironmental changes over the last climatic cycle for northwestern Europe. As carbon isotope ratios of plants depend on environmental variations, $\delta^{13}C$ of loess-derived organic matter constitute reliable paleoclimatic proxies. We present here a new chronology of Nußloch loess sequence based on several ^{14}C and TL-dates. Our data show high correlations with global climate effects (Vostok-[CO_2]) or semi-global (GISP2-$\delta^{18}O$) and thus offer, in this way, a new approach to establish accurate chronologies in continental sequences. Furthermore, using a deconvolution of the $\delta^{13}C$ signal would provide a quantitative proxy of moisture supply and permit paleoprecipitation reconstructions. © 2000 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

On continents, studies of high-frequency climatic variability need expanded sequences. Peat bogs and lacustrine deposits provide good records of vegetation evolution during wet interglacial periods (Woillard, 1978) while loess sequences with high accumulation rates are well suited for records for dry and cold glacial periods. Loess sequences have been studied to estimate Quaternary climatic changes using sedimentology and paleopedology (Haesaerts, 1985; Lautridou, 1985; Antoine et al., 1994; Kemp et al., 1994; Xiao et al., 1995), magnetic susceptibility (Kukla, 1987; Anderson and Hallet, 1996), malacology (Rousseau and Wu, 1997) and carbonate stable isotopes (Gu et al., 1991; Frakes and Jianzhong, 1994). Preliminary studies performed on organic matter suggest that the carbon isotopic composition ($\delta^{13}C$) of loess sediment could be used as a record of the vegetation sensibility to climatic stresses. Lin et al. (1991) and Wang et al. (1997) point to radical vegetation changes recorded in plants' photosynthetic pathways (C3 and C4 plants), using this proxy in China's loess sequences. During photosynthesis, plants discriminate against ^{13}C because of differences in chemical and physical properties due to its heavier mass (O'Leary, 1981). Both major types of photosynthetic pathways have a characteristic isotopic signature. C4-plants living in drastic climatic conditions, with high insolation and/or hydrous stress, show a mean $\delta^{13}C$ of $-14 \pm 2‰$, whereas C3-plants, which prefer more temperate environments, present $\delta^{13}C$ values around $-26 \pm 2‰$ (O'Leary, 1988). Variability around the mean $\delta^{13}C$ values of terrestrial vegetation foliar results from environmental changes that influence stomatal conductance (e.g. light, temperature, humidity, available soil water, CO_2 concentration). Several studies have documented some of the factors underlying the variation in leaf $\delta^{13}C$ (Farquhar et al., 1982; Garten and Taylor, 1992; Feng and Epstein, 1995). The primary results show that $\delta^{13}C$ of C3-plants decreases with an increase in CO_2 concentration or with an increase of water availability. All these metabolic responses

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to environmental changes indicate that carbon isotopic composition of plants reflects climatic variations.

According to Head et al. (1989), sediment organic matter is formed by a multi-stage process that includes decomposition of all plant components into simple monomers. That is why sediment organic matter constitutes a record of past vegetation and $\delta^{13}C$ of organic matter has to reflect $\delta^{13}C$ of plants, and in this way reflects climatic variations. Carbon isotope compositions in organic matter have been investigated in the Nußloch loess sequence in the Rhine Valley, Germany. This site is well suited to study rapid small climatic variations: the total sequence reflects the climatic history of the area for ca 130,000 years, with an accumulation of around 18 m. This paper discusses the influence of variations of atmospheric CO_2 concentration and precipitation on carbon isotopic variations in loess organic matter at Nußloch.

2. General stratigraphy

The Nußloch section is located on the right bank of the Middle Rhine valley at 49°21′N, 8°43′E. In this area, the geomorphological setting is characterised by a very wide alluvial plain and the occurrence of an abrupt slope exposed to the main winds (Northwest to North during the Last Glacial Maximum). During the Weichselian Pleniglacial Stage, a very important loess accumulation took place at the junction between the upper part of the slope and the plateau and produced a series of loess morphologies similar to sand dunes separated by troughs ("gredas" of Léger, 1990). The detailed pedostratigraphical and sedimentological study of the Nußloch sections (Antoine et al., in prep.) indicates that the base of the sequence is represented by a soil complex, consisting of a BT horizon of brown-leached soil; clayey colluvium; reworked grey forested-soil; local loess; and humic steppe soil (Fig. 1, nos. 8–11).

On the other hand, the loess deposits by themselves are exceptionally well developed at Nußloch (16.8 m). In addition, the middle part of the sequence, between 11.2 and 14.1 m, shows two Interstadial soil horizons (Fig. 1): arctic-brown soils nos. 5 and 3 (Fig. 1). A third Interstadial level represented by organic bedded deposits including peaty layers locally appears around 13 m between these two soils in a thermokarstic depression (not represented in Fig. 1). This level has provided wood remains, pollen, and bones (*Bovidae*). The arctic-brown soils are marked by brown horizons showing a lower carbonate content, and a higher clay and organic carbon content (Fig. 1). The two soils correspond to halts in sedimentation, to a cooler and more humid climate and to a weak development of the vegetation. The top of the second boreal soil (Fig. 1, no. 3) represents a fundamental boundary which precedes the strongest phase of loess deposition (Fig. 1 no. 2) characterised by the highest sedimentation rate.

3. Sampling

The sequence was sampled about each 5–10 cm interval, following the sedimentological and pedological variations. 1–2 g of sediment were collected, and afterwards dried at 50°C for a maximum of 2 days. This step permits good preservation of organic matter, minimizing the influence of possible bacterial degradation. Sediment was then sieved, below 250 μm, to remove eventual roots. The fine fraction was decarbonated with HCl 0.6 N (non-hydrolysis of organic matter with this concentration was checked), rinsed, dried under 50°C, and homogenized. Carbon organic contents were determined with an elementary analyzer (Carlo Erba NA 1500) and are expressed in percent weight, with a relative precision of 1%. The mixture of He, N_2 and CO_2 going out of the elementary analyzer flows through a triple trap where CO_2 is separated from the other gases. Carbon isotope ratios on CO_2 are obtained with a dual inlet VG Optima mass spectrometer and $\delta^{13}C$ are expressed in per mil versus PDB standard, with an absolute precision of 0.1‰, with $\delta^{13}C = (R_{sple}/R_{std} - 1)*1000$ (‰) and $R = {}^{13}C/{}^{12}C$.

4. Chronological markers

The chronostratigraphical interpretation of the Nußloch loess profile is initially based on the detailed analysis of the sequence and on correlations with the northwest European loess stratigraphy, using palaeopedological, sedimentological and periglacial level-marks and tephrostratigraphy: Eemian BT, Early-Glacial humic soils complex at around 70 ky (Lautridou, 1985; Haesaerts, 1985; Van Vliet-Lanöe, 1990; Antoine et al., 1994) and the Eltville Tephra at 22 $\pm$ 3 ky (Semmel, 1967; Zöller et al., 1988).

Three samples for thermoluminescence (TL) dating had been taken from a previous section in the Nußloch quarry in 1986/1987 (Zöller et al., 1988). Samples for TL dating had been extracted from the fresh exposure in light-tight steel cylinders and processed under reduced red laboratory illumination. The polymineralic fine-grained fraction (4–11 μm, fine grain technique) was used for TL measurements and calculation of the radiation dose absorbed since deposition according to the total bleach-regeneration and the partial bleach techniques, respectively (Aitken, 1985). U, Th and K contents for dose-rate computation were measured by instrumental neutron activation analysis (INAA) and thick source alpha counting and atomic absorption spectrometry (AAS), respectively. For experimental details, see Zöller et al. (1988). Dates obtained are 34,800 $\pm$ 3700,

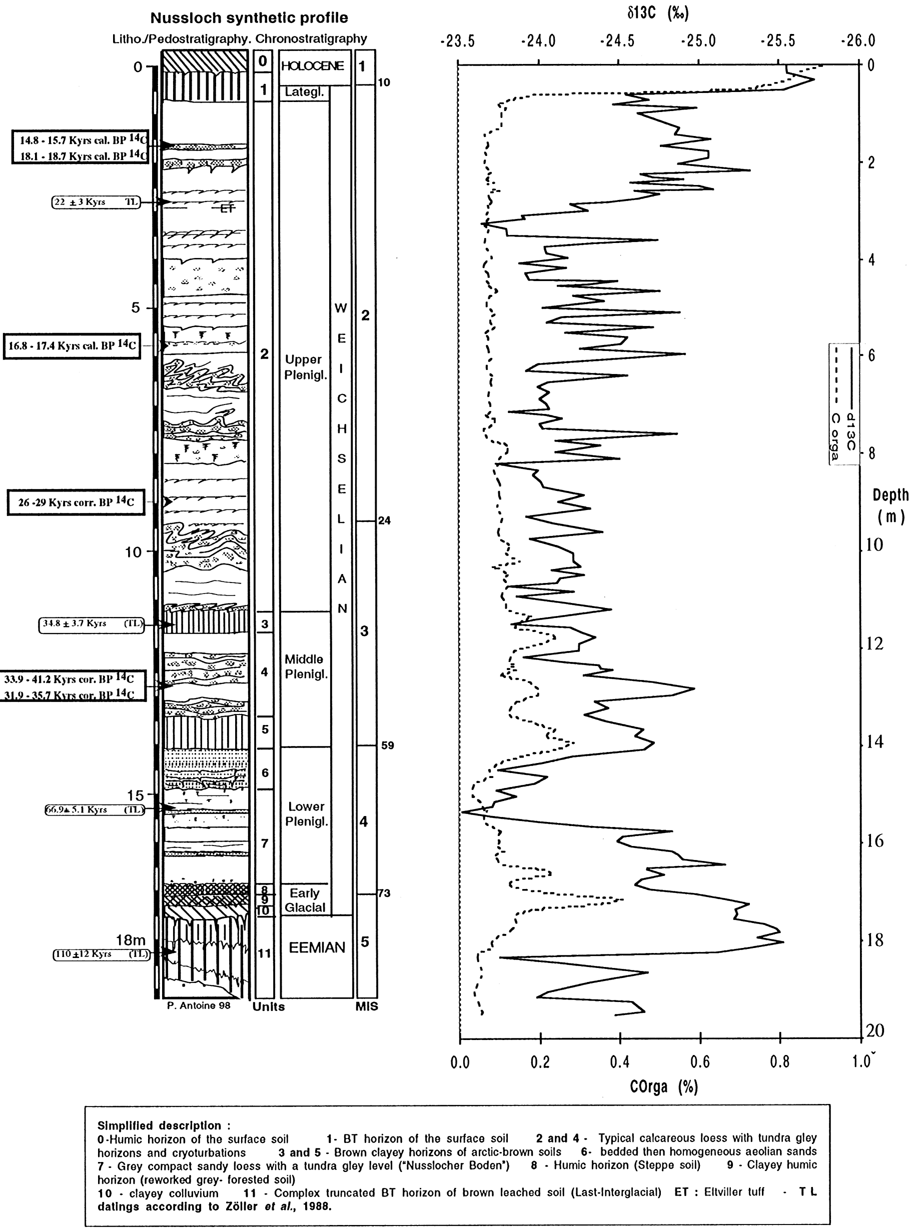

Fig. 1. Organic carbon content (dotted line) and organic matter $\delta^{13}C$ (solid line) in Nußloch. $\delta^{13}C$ is shown on an inverse scale. Organic carbon contents and $\delta^{13}C$ are plotted versus depth. The chronological controls used, TL-ages and ^{14}C-dates, are indicated on the right-hand side of graph. The sedimentological description is presented on the left-hand side.

66,900 ± 5100 and 110,000 ± 12,000 yr at 11.5, 15.4 and 18.2 m respectively (Zöller et al., 1988).

Some ^{14}C ages are available, obtained using either the AMS method (GIFA) or the β-counting method (GIF/LSM), all measured in Laboratoire des Sciences du Climat et de l'Environnement in Gif-sur-Yvette (France). The two first (GIFA-96221 and GIFA-96244) were obtained, respectively, on carbonate and on organic matter from snail shells, both at 1.6 m depth. Gastropod shells as material for ^{14}C dates have to be taken cautiously because carbonate recrystallization may be responsible for ^{14}C age rejuvenation. This effect is important and not easily assessed. Furthermore, it is well known that ^{14}C ages of continental gastropods carbonate could show aging as well. Gastropods use old carbonate as calcium source for shell building during their growth (Goodfriend, 1987). But even when the contribution of limestone to shell carbonate may comprise up to 33% of the shell, the associated organic matter is largely derived from plant material used as food resource; it contains a negligible amount of carbon derived from hemolymph bicarbonate (Goodfriend and Hood, 1983). We thus performed the dating on shell organic matter. This organic matter is collected on a glass fiber filter after total decarbonation of the gastropod shells, and analysis followed the classical AMS method. GIFA-96221 and GIFA-96244 gave, respectively, 15,300 ± 100 and 12,900 ± 100 yr conv. BP. These determinations were calibrated using the Stuiver and Reimer program (1993). The calibrated ages range between 14,800 and 15,700 and between 18,100 and 18,700 yr cal. BP, respectively. Two other dates were obtained directly on loess organic matter following the protocol proposed by Pessenda et al. (1996) and adapted to ^{14}C-AMS. GIFA-98366 and GIFA-98367 gave, respectively, 14,270 ± 120 and 24,020 ± 280 yr conv. BP at 5.8 and 9 m depth. The GIFA-98366 calibrated age ranges between 17,425 and 16,785 yr cal. BP. Using the new radiocarbon calibration reconstructed from annually laminated sediments of Lake Suigetsu (Kitagawa et al., 1998), the GIFA-98367 corrected age could range between 26,000 and 29,000 yr. From a laterally correlative unit around 13.2 m (Antoine et al., in prep.), we utilize several ^{14}C-dates obtained on wood (GIF/LSM-10442, GIFA-97291, GIFA-97294 and GIFA-97292) and one on bone (GIFA-97328). The dates obtained on wood gave a weighted average age of 32,200 ± 205 yr conv. BP and the last one, on bone, an age of 35,800 ± 1200 yr conv. BP. Corrected ages could range between 31,900 and 35,700 and between 33,900 and 41,200 yr cal. BP, respectively.

5. Results

Results are reported in Fig. 1, except for carbonate contents that varied between 3% in the Eemian BT and 30–40% in typical loess. Organic carbon content shows very low and constant values. They remain lower than 0.1%, except for paleosols at around 12, 14 and 17 m, where organic carbon content reaches 0.4%. $\delta^{13}C$ variations range within 2‰ of the mean values of − 24.3‰. The lightest values of $\delta^{13}C$ are encountered for the modern soil, Holocene and last interglacial period, with mean values of − 25.6‰, − 24.9‰ and − 25.1‰, respectively, while glacial stades are represented by a mean $\delta^{13}C$ value of − 24.1‰. However, a definite interpretation of the Eemian BT horizons $\delta^{13}C$ values cannot be proposed as of yet. Actually, this unit does not show any sediment accumulation, but rapid turnover of organic matter. Thus, a relatively thin section of sediment represents a long interval (1–1.5 m for about 30,000 yr) that integrates bioturbation and pedological processes, reflecting mixing of previously deposited loess and interglacial organic matter. Furthermore, this soil (BT horizon of a brown leached soil) is leached as shown by the slow and regular decrease in carbon and carbonate contents (not illustrated here). Deconvolution between pedogenesis and climatic signal is not possible at this step of the study. The interpretation of this stratigraphic part will be discussed later in the paper. Likewise, the three upper points of the Holocene sequence have to be considered carefully, because they are in the BT of the modern soil. The signal is thus more complex, reflecting a superimposition of climatic influence, pedogenesis and anthropogenic CO_2 effect.

6. Climatic signal conservation

For the loess strata, due to the rapid accumulation, pedogenesis is greatly reduced and organic matter is buried rapidly and homogeneously without an important effect of turnover. Thus, the isotopic signal might be only slightly altered.

These $\delta^{13}C$ values result from the degradation of a vegetation assemblage with a very strong predominance of C3-plants. This is in good agreement with palynological studies, which show the presence of trees throughout the last climatic cycle in northwestern Europe (Woillard, 1978). In Nußloch, past climates were not arid enough to support C4-photosynthetic pathway plants. This differs from results obtained for the Chinese Loess Plateau, where a 12‰ variation of $^{13}C/^{12}C$ ratio of loess organic matter (Lin et al., 1991; Wang et al., 1997) has been interpreted in terms of a transition between C4-vegetation and C3-plants.

7. CO_2 concentration influence

The carbon isotope ratio of atmospheric CO_2 showed variations through the last climatic cycle. However, Leuenberger et al. (1992) and Marino et al. (1992) found that during the last glaciation the atmospheric CO_2 isotope ratio, $\delta^{13}C$, was more positive than pre-industrial values by only 0.3 ± 0.2‰. Therefore, variation of carbon source $\delta^{13}C$ alone cannot explain the range of 2‰ recorded by organic matter $\delta^{13}C$ measurements in loess.

Carbon isotope fractionation by C3-plants depends on the atmospheric CO_2 supply. When the CO_2 concentration ($[CO_2]$) is high, a large fractionation is observed. But if $[CO_2]$ is low, growth is limited and cells use the available CO_2, independently of its isotopic nature (O'Leary, 1981; Woodward, 1993). Recent studies (Feng and Epstein, 1995) predict that $\delta^{13}C$ of plants decreases by about 0.02‰ per 1 ppm $[CO_2]$ increase. As atmospheric $[CO_2]$ changed by about 100 ppm between glacial and interglacial period (Jouzel et al., 1993) such oscillations have to be recorded by plants and the derived sedimentary organic matter $\delta^{13}C$. The 1.8‰ amplitude of the isotopic signals, corresponding to a $[CO_2]$ variation of 100 ppm, is in agreement with Feng and Epstein (1995). Furthermore, major trends recorded in the Vostok $[CO_2]$ (Jouzel et al., 1993) are observed in the $\delta^{13}C$ records, except in the lower part of the sequences (Eemian BT and Early-Glacial colluvium and soils) which is

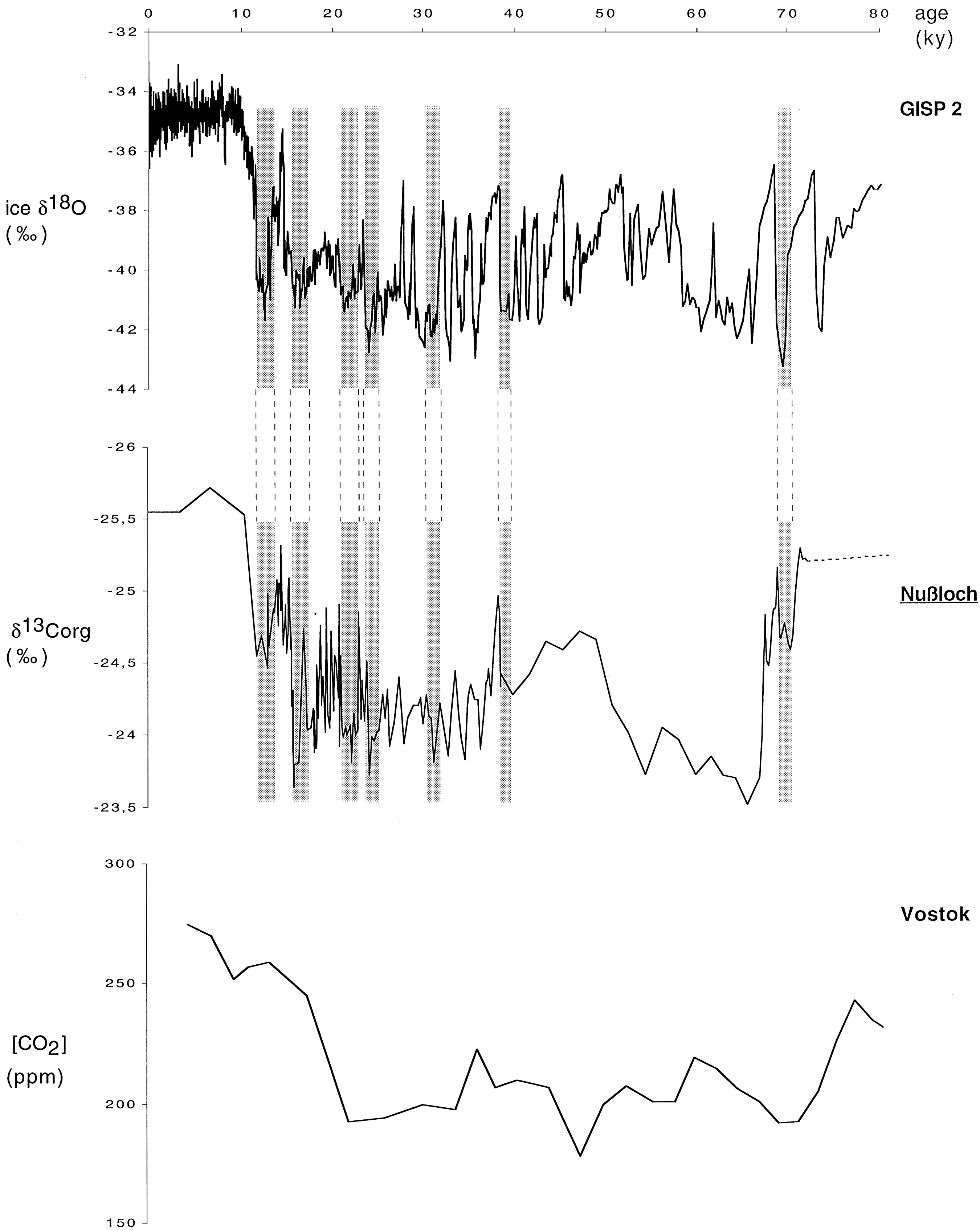

Fig. 2. Correlation between GISP2 $\delta^{18}O$ and Vostok [CO_2] records and $\delta^{13}C$ of organic matter in Nußloch, CO_2 level is expressed in ppm. Loess organic matter $\delta^{13}C$ is expressed in per mil versus PDB standard and shown on an inverse scale. GISP2 $\delta^{18}O$ is expressed in per mil versus SMOW standard.

modified by pedogenesis. Thus, it appears that the long-term trends of the $\delta^{13}C$ of the organic matter in loess clearly match the global [CO_2] variations.

8. Water availability influence

However, the rapid events recorded by loess $\delta^{13}C$ have to result from another forcing parameter with a high-frequency superimposed on the [CO_2] induced variations. The isotopic composition of both C3-plants and derived loess organic matter indeed depend on the water supply as well. The plant physiological response to a decrease in moisture is stomatal narrowing, limiting water loss by evapo-transpiration. Thus, fractionation due to stomatal diffusion is reduced leading to a reduction in carbon isotope fractionation and higher $\delta^{13}C$ values. The same isotopic response is induced by an increasing of soil strength (physical resistance to root penetration), such as occurs in dry soils (O'Leary, 1981). This leads us to interpret $\delta^{13}C$ variations at Nußloch as a function of the water availability: the highest $\delta^{13}C$ values are associated with the driest events. During the Upper Pleistocene, the location of the polar front has largely fluctuated latitudinally with associated changes in precipitation pattern in northwestern Europe. The rapid warming episodes associated with the so-called "Dansgaard-Oeschger events" (Bond et al., 1993; Dansgaard et al., 1993), recorded by $\delta^{18}O$ in the GISP2 core (Greenland Ice Sheet Project 2) (Grootes et al., 1993; Meese et al., 1994; Sowers et al., 1993; Stuiver et al., 1995), have been linked to such fluctuations. We assume that the Dansgaard–Oeschger events correspond to wet climatic episodes in Nußloch, and then are linked to the lowest $\delta^{13}C$ values of loess organic matter.

Using absolute and stratigraphical chronological markers and well-established correlations between our signal and, on the one hand, the [CO_2] record in Vostok ice and, on the other hand, $\delta^{18}O$ in GISP2, it is possible to obtain a refined chronology, more realistic than one based on a constant sedimentation rate between two chronological markers. Using AnalySeries software (Paillard et al., 1996), the refined chronology proposed in Fig. 2 is obtained. A sedimentation hiatus occurs between 114,000 and 72,000 yr, and the sedimentation rate is high between 72,000 and 65,000 yr ($\sim$ 0.2 m/ky). A slowdown occurs between 65,000 and 40,000 yr ($\sim$ 0.1 m/ky), and accumulation again is rapid after 40,000 yr ($\sim$ 0.5 m/ky). The modern soil shows a low sedimentation rate at only 0.04 m/ky. Our improvements stay thoroughly in agreement with chronological markers, considering their limits (error margins and stratigraphical significance). High correlation appears subsequent to the hiatus (Fig. 2), between $\delta^{13}C$ in loess and $\delta^{18}O$ in the GISP2 record ($r^2 = 0.61$) as well as between $\delta^{13}C$ and Vostok CO_2 ($r = 0.58$), suggesting that organic matter $\delta^{13}C$ clearly matches CO_2 variations and rapid climatic events.

9. $\delta^{13}C$ of loess organic matter as paleoprecipitation indicator

Plant $\delta^{13}C$ is influenced by $\delta^{13}C$ value of the atmospheric CO_2, CO_2 concentration and water availability. Some values for the two first parameters are available from the literature. Atmospheric $\delta^{13}C$ variations have been established for the last 40 ky by Leuenberger et al. (1982) and Marino et al. (1992), and variations of atmospheric CO_2 concentration are recorded in the Vostok ice core for the last climatic cycle (see, for example, Jouzel et al., 1993). Thus, a deconvolution of $\delta^{13}C$ of loess organic matter, at least for the last 40 ky, should permit reconstruction of moisture availability. However, direct correspondence of magnitudes is not yet possible because the effect of organic matter degradation in paleosols, inducing a shift between sediment organic matter $\delta^{13}C$ and plant $\delta^{13}C$, needs to be estimated. Further studies have to be done in order to find an independent criterion characteristic of organic matter degradation. Thus, $\delta^{13}C_{org}$ would be a reliable qualitative proxy for paleoprecipitation reconstruction along the whole sequence, as it is for the loessic parts.

10. Conclusion

Loess organic matter $\delta^{13}C$ provides a powerful tool for understanding climatic changes in continental records, and provides a reliable and complementary proxy of moisture supply. Thus, using absolute age controls and correlations between global climate effects (Vostok-[CO_2]) or semi-global (GISP2-$\delta^{18}O$), $\delta^{13}C$ of organic matter in European loess sequences offers a new approach to establish accurate chronologies in continental sequences. Furthermore, with an index of organic matter degradation, $\delta^{13}C_{org}$ would provide a reliable proxy for paleoprecipitation reconstruction.

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References

Aitken, M.J., 1985. Thermoluminescence Dating. Academic Press, London, pp. 359.

Anderson, R.S., Hallet, B., 1996. Simulating magnetic susceptibility profiles in loess as an aid in quantifying rates of dust deposition and pedogenic development. Quaternary Research 45, 1–16.

Antoine, P., Munaut, A.V., Sommé, J., 1994. Réponse des environments aux climats du début glaciaire weichselien: données de la France du Nord-Ouest. Quaternaire 5, 151–156.

Bond, G.C., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L.D., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North-Atlantic sediments and Greenland Ice. Nature 365, 143–147.

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

Farquhar, G.D., O'Leary, M.H., Berry, J.A., 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Australian Journal of Plant Physiology 9, 121–137.

Feng, X., Epstein, S., 1995. Carbon isotopes of trees from arid environments and implications for reconstructing atmospheric CO_2 concentration. Geochimica and Cosmochimica Acta 59, 2599–2608.

Frakes, L.A., Jianzhong, S., 1994. A carbon isotope record of the upper Chinese loess sequence: estimates of plant types during stadials and interstadials. Palaeogeography, Palaeoclimatology, Palaeoecology 108, 183–189.

Garten, C.T.J., Taylor, G.E.J., 1992. Foliar $\delta^{13}C$ within a temperate deciduous forest: spatial, temporal, and species sources of variation. Oecologia 90, 1–7.

Goodfriend, G.A., Hood, D.G., 1983. Carbon isotope analysis of land snail shells: implications for carbon sources and radiocarbon dating. Radiocarbon 25 (3), 810–830.

Goodfriend, G.A., 1987. Radiocarbon age anomalies in shell carbonate of land snails from semi-arid areas. Radiocarbon 29 (2), 159–167.

Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S., Jouzel, J., 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature 366, 552–554.

Gu, Z., Liu, R., Liu, Y., 1991. Response of stable isotopic composition of loess-paleosol carbonate to paleoenvironmental changes. In: Tungsheng, L. (Ed.), Loess, Environment and Global Change. Science Press, Beijing, China, pp. 82–92.

Haesaerts, P., 1985. Les loess du Pléistocène Supérieur en Belgique; comparaison avec les séquences de l'Europe Centrale. Bulletin de l'Association Française de l'Etude du Quaternaine. 22, 105–115.

Head, M.J., Zhou, W., Zhou, M., 1989. Evaluation of ^{14}C ages of organic fractions of paleosols from loess-paleosol sequences near Xian, China. Radiocarbon 31, 680–696.

Jouzel, J., Barkov, N.I., Barnola, J.M., Bender, M., Chappellaz, J., Genthon, C., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Petit, J.R., Raynaud, D., Raisbeck, G., Ritz, C., Sowers, T., Stievenard, M., Yiou, F., Yiou, P., 1993. Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period. Nature 364, 407–412.

Kemp, R.A., Derbyshire, E., Xingmin, M., Fahu, C., Baotian, P., 1994. Pedosedimentary reconstruction of a thick loess-paleosol sequence near Lanzhou in North-Central China. Quaternary Research 43, 30–45.

Kitagawa, H., Van der Plicht, J., 1998. Atmospheric radiocarbon calibation to 45,000 yr B.P.: Late Glacial fluctuations and cosmogenic isotope production. Science 279, 1187–1190.

Kukla, G., 1987. Loess stratigraphy in central China. Quaternary Science Reviews 6, 191–219.

Lautridou, J.P., 1985. Le cycle périglaciaire pleistocène en Europe du Nord-Ouest et plus particulièrement en Normandie. Thèse es Sciences, Univ. Caen, Centre de Géomorphologie Caen, 908p.

Lin, B., Liu, R., An, Z., 1991. Preliminary research on stable isotopic compositions of Chinese loess. In: Tungsheng, L. (Ed.), Loess, Environment and Global Change. Science Press, Beijing, China, pp. 124–131.

Léger, M., 1990. Loess landforms. Quaternary International 7 (8), 53–61.

Leuenberger, M., Siegenthaler, U., Langway, C.C., 1992. Carbon isotope composition of atmospheric CO_2 during the last ice age from an Antarctica ice core. Nature 357, 488–490.

Marino, B.D., McElroy, M.B., Salawitch, R.J., Spaulding, W.G., 1992. Glacial-to-interglacial variations in the carbon isotopic composition of atmospheric CO_2. Nature 357, 461–466.

Meese, D., Alley, R.B., Gow, T., Grootes, P.M., Mayewski, P.A., Ram, M., Taylor, K.C., Waddington, E., Zielinski, G., 1994. Preliminary depth-age scale of the GISP2 ice core. CRREL.

O'Leary, M.H., 1981. Carbon isotope fractionation in plants. Phytochemistry 20, 553–567.

O'Leary, M.H., 1988. Carbon isotopes in photosynthesis. Bioscience 38, 328–336.

Paillard, D., Labeyrie, L.D., Yiou, P., 1996. Macintosh program performs time-series analysis. In: Eos Trans AGU., p. 379.

Pessenda, L.C.R., Aravena, R., Melfi, A.J., Telles, E.C.C., Boulet, R., Valencia, E.P.E., Tomazello, M., 1996. The use of carbon isotopes (^{13}C, ^{14}C) in soil to evaluate vegetation changes during the Holocene in central Brazil. Radiocarbon 38 (2), 191–201.

Rousseau, D.-D., Wu, N., 1997. A new molluscan record of the monsoon variability over the past 130,000 yr in the Luochuan loess sequence, China. Geology 25, 275–278.

Semmel, A., 1967. Neue Fundstellen von vulkanischem Material in hessischen Lössen. Notizbl. hess.L.-Amt. Bodenforsch 95, 104–108.

Sowers, T., Bender, M., Labeyrie, L.D., Martinson, D., Jouzel, J., Raynaud, D., Pichon, J.-J., Korotkevich, Y., 1993. 135,000 year Vostok-SPECMAP common temporal framework. Palaeogeography, Palaeoclimatology, Palaeoecology 8, 737–766.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised calib 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Stuiver, M., Grootes, P.M., Braziunas, T.F., 1995. The GISP2 $\delta^{18}C$ climate record of the past 16,500 years and the role of the sun, ocean, and volcaneous. Quaternary Research 44, 341–354.

Van Vliet-Lanöe, B., 1990. Le Pédocomplexe de Warneton. Où en est-on? Bilan paléopédologique et micromorphologique. Quaternaire 1 (1), 65–76.

Wang, H., Ambrose, S.H., Liu, C.-L.J., Follmer, L.R., 1997. Paleosol stable isotope evidence for early hominid occupation of east asian temperate environments. Quaternary Research 48, 228–238.

Woillard, G.M., 1978. Grande Pile Peat Bog: A continuous pollen record for the last 140,000 years. Quaternary Research 9, 1–21.

Woodward, F.I., 1993. Plant response to past concentrations of CO_2. Vegetatio 104 (105), 145–155.

Xiao, J., Porter, S.C., Zhisheng, A., 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.

Zöller, L., Stremme, H., Wagner, G.A., 1988. Thermoluminezenz-Datierung an Löss-Paläoboden-Sequenzen von Nieder-, Mittel- und Oberrhein/ Bundesrepublik Deutschland. Chemical Geology (Isotope Geoscience Section) 73, 39–62.