

A 350,000-year climatic record from the loess sequence of Achenheim, Alsace, France

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Up to now the best Quaternary climatic sequences come from oceanic isotope studies, but terrestrial sequences are also well known, usually for pollen or ice core data. A new sequence providing climatic information for the last 500,000 years has been studied in the loess series of Achenheim (Alsace), using the mollusc record in relation to other stratigraphical data. Mollusc assemblages are analysed using a multivariate method. The correspondence analysis used here allows us to explain, in ecological terms, the general variability of the Achenheim set. Most Pleistocene mollusc species have the advantage that modern individuals live in the same assemblages. So, the known ecology and distribution of the modern molluscs allow us to conclude that the first two factors explain variations in temperature and moisture. Each loading, on a factor, of each association in its stratigraphical level contributes to characterizing the evolution of each climatic parameter through time. For the last five climatic cycles, these evolutions are expressed as a function of the depth within the series. As they are well preserved, the last three glacial cycles are studied in detail. They correspond to the last 350,000 years, are compared with SPECMAP data and particularly show correlations between continental and marine climatic indicators. The mollusc assemblages of the loess sequence also provide information on temperature and moisture conditions. The evolutions of each parameter are not identical during the last three cycles, indicating that the climatic history of one cycle cannot be transferred to the others. The mollusc assemblages also record the occurrence of an oscillatory system, especially during the Weichselian Upper Pleniglacial (isotopic stage 2) when it announces the Late Glacial variations. Similar oscillating excursions seem to have occurred during the older glacial stages.

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Continuous Pleistocene climatic records have been described from deep sea sediments (Emiliani 1966; Shackleton & Matthews 1977; Imbrie *et al.* 1984; Martinson *et al.* 1987), but terrestrial sequences also provide good data which can easily be correlated with oceanic results. The significant terrestrial records concern the last climatic cycle and come from polar ice sheets (Lorius *et al.* 1985; Dansgaard *et al.* 1969; Dansgaard *et al.* 1982) or pollen sequences (Woillard 1978; de Beaulieu & Reille 1984). Other records comprise more than one cycle but few of these give really informative data about the climatic oscillations of, for example, the last 500,000 years. Apart from the Macedonian sequence (van der Hammen *et al.* 1972), few long sequences recording several cycles have been investigated in Europe.

Loess sequences provide important palaeoclimatic information even taking into account the occurrence of discontinuities. It was demonstrated that long loess cyclothem can be cor-

related with interglacial-glacial cycles in marine ^{18}O records, especially in Central Europe (Kukla 1977) and China (Kukla 1987; Liu *et al.* 1985).

Kukla defined two key sites in central Europe, Cervený Kopec and Krems (Kukla 1977). However, recently, the loess site of Achenheim (France), famous for its fauna, was investigated by a multidisciplinary team, and has provided a more or less continuous record of the climatic changes during the last 500,000 years (Heim *et al.* 1982; Lautridou *et al.* 1985, 1986; Sommé *et al.* 1986). Five interglacial-glacial cycles have been recognized, which are correlated to Kukla's cycles with the help of pedostratigraphical and palaeontological analyses. Following Kukla's approach, the purpose of this paper is to compare the climatic variations recorded in the Achenheim sequences by mollusc assemblages with the SPEC-MAP isotopic stratigraphy, the oscillations of which are taken as representative of the global volume of glacial ice (Imbrie *et al.* 1984).

The complete Achenheim sequence

Achenheim is located in Alsace (France) in the Rhine graben, at 48°35'N-7°38'E and 170 m above sea level (Fig. 1). The ancient Hurst and Sundhauser quarries provide sections where a succession of different sedimentary environments has been recognized from the bottom to the top (Fig. 2): Rhine alluvial sandy deposits, Vosges alluvial sandy deposits with yellow 'canary' sandy loam, old loess deposits – lower, middle and upper – and a younger loess. The loess deposits, following the nomenclature of Schumacher (1914) and Werner (1957) start at the bottom with a pedo-complex, mostly with an interglacial soil (Bt horizon), and continue upwards into typical carbonate loess.

The stratigraphy of each cycle, previously described by Heim *et al.* (1984), can be summarized as follows (Fig. 2).

Fluviatile terrace formation. – From bottom to top (Fig. 2). Grey sands ('sables rhénans') with loamy-clayey layers, some metres thick. Cross-bedded red sands ('sables vosgiens'), 2–3 m thick; in the lower part cross-bedded and cryoturbated

red sands and grey loams (2 m), at the top with large cryoturbations. Greyish or yellowish loam (1–2 m thick) with iron beds and Fe–Mn concretions and with big flat calcareous concretions at the bottom. A yellow loam (1–2 m thick) with big rounded calcareous concretions ('limon jaune canari'). Finally, a 1–4 m thick sandy clayey loam, reddish brown with polyhedral structure ('Limon rouge de plateau').

The grey sands (top only visible) and red sands constitute the upper part of the fluviatile sediment. The material originates in both the Vosges mountains and the river Rhine but becomes purely Vosgian at the top (the red sands). In the past, these fluviatile deposits were related to a warm temperate phase, but the malacofauna indicates cold conditions (as described later). Cryoturbated red sands, grey loams and also the overlying red sands correspond to pleni-glacial conditions (a malacofauna with *Columella columella*) which later became less severe as indicated by the loess-like upper loams, especially the 'canari' loam (Puisségur 1978).

At the top, the reddish ('limon rouge de plateau') mud was traditionally attributed to the Mindel-Riss interglacial. Remains of *Citellus cf.*

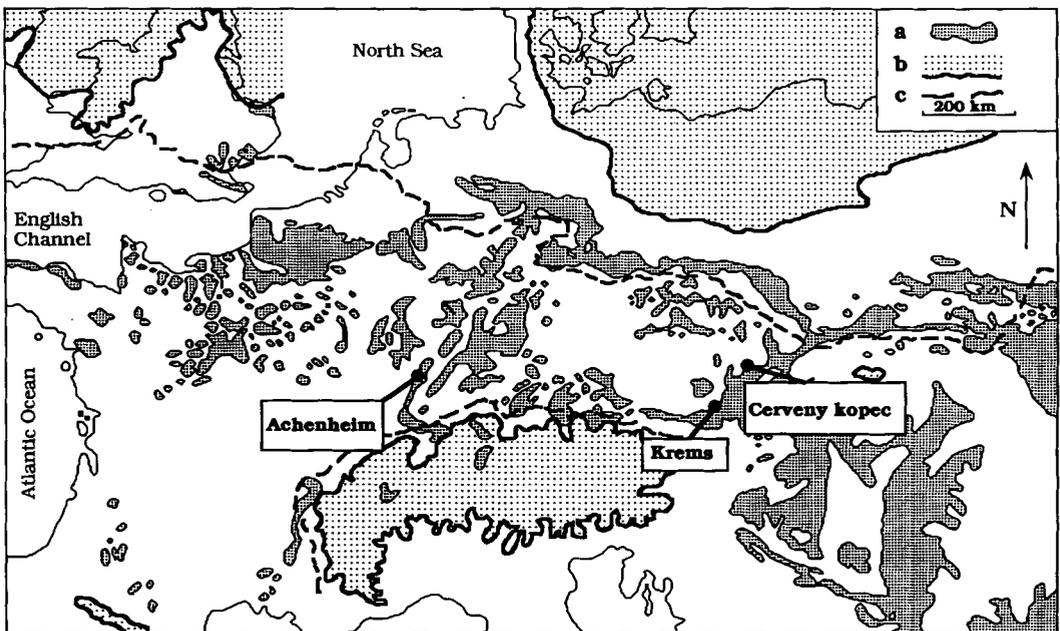


Fig. 1. Map of Western Europe with the location of Achenheim, Cerveny Kopec and Krems in the loess belt. Achenheim had a privileged position near the 'corridor', surrounded by the Alpine and Scandinavian glaciers, and the more open plain of Western Europe. a, loess; b, last maximum glacial advance; c, overall maximum glacial advance.

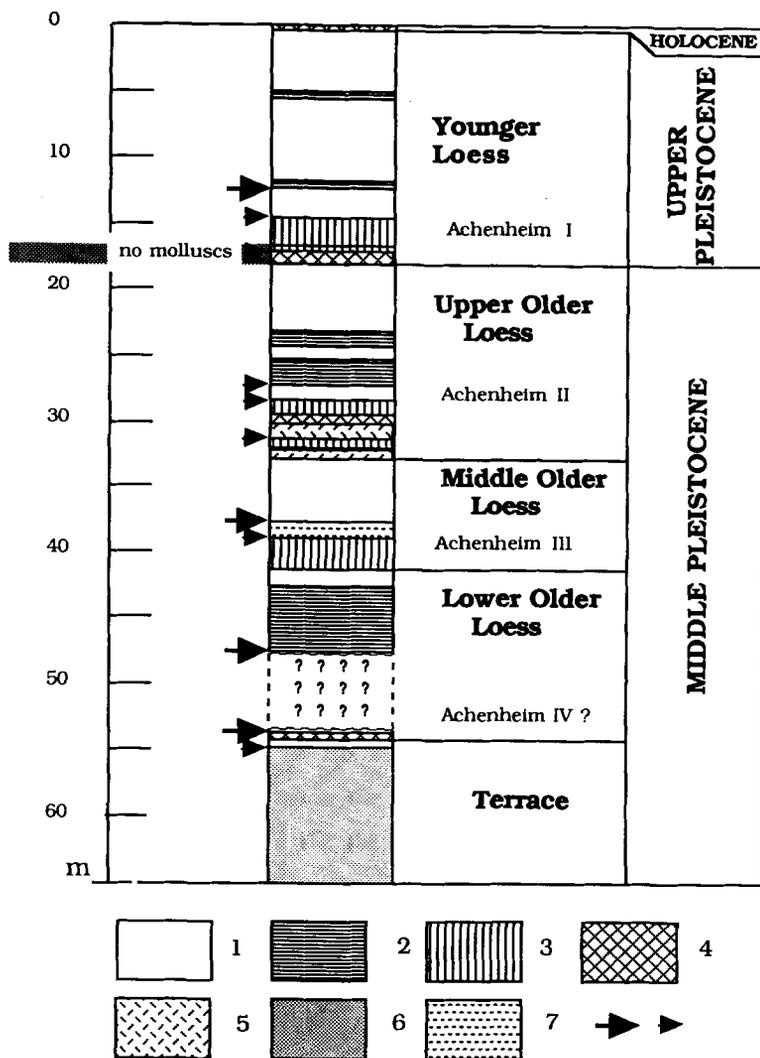


Fig. 2. Local pedosedimentary units with sedimentological interpretation. 1, loess; 2, pellet sands (stratified deposits); 3, humic soils; 4, Bt (interglacial) soil horizon; 5, colluvium; 6, fluvialite sands; 7, sandy layered loam. Arrows indicate discontinuities recognized in the field, the large ones being of notable stratigraphical value and taken into account in the time calibration of the sequence.

dietrichi with other micromammals (*Arvicola cf. mosbachensis*, *Microtus arvalis*, *M. ratticeps*, *M. gregalis*, *Sorex cf. araneus*), discovered in the lower part of the red sands were considered Mindel in age (Chaline & Thévenin 1972).

Lower Older Loess. – From bottom to top (Fig. 2). The lower part of the sequence is not observable but has been described by Schumacher (1914) and Wernert (1957). Noticeable first are slope deposits with alternating loamy, sandy, clayey and gravelly layers reworked from the terrace formations. Above follows a brownish clayey cal-

careous loam (1.5 m thick) which is the first appearance of typical loess at Achenheim.

Middle Older Loess. – From bottom to top (Fig. 2). The pedocomplex 'Achenheim III': a humic soil complex (very dark brown clayey loam with charcoal and a non-calcareous mottled (iron) horizon. Brownish pellet sands (1.4 m thick). A brownish loam, less and less sandy in the upper part and slightly stratified (1.9 m thick). A brownish loess, with pseudomycelia and big calcareous concretions, and then a yellowish loess (4 m thick).

The soil complex seems apparently simple and different in facies from the Achenheim I and II pedocomplexes. Pollen and mollusc contents indicate a climatic interglacial-early glacial evolution and determine breaks in the stratigraphy. The stratified sandy loams were deposited in an open pine forest environment with alternating humidity and dryness. Cryoturbations have not been observed, but an unconformity below the sands is recognized.

Upper Older Loess. – From bottom to top (Fig. 2). Pedocomplex 'Achenheim II' 4 m thick: colluvium with black forest soil, a reddish brown loamy-clayey horizon (Bt horizon) and a humic brownish loam with crotovines. Little greenish loess (1 m thick). Stratified brownish loamy sands (3 m thick) with sporadic lenses of gravel and pebbles having eroded into the lower layers (pellet sands). A 1 m thick loess. Loamy stratified sediments (2 m thick) with syngenetic frost wedges. Above this is a 5 m thick yellowish and yellow-brown loess, very calcareous (pseudomycelia), with cryoturbated horizons, a pseudo-gley at the top and large loess dolls.

The Upper Older Loess corresponds to an interglacial-glacial cycle, with a thickness comparable to that of the last cycle (max. 12 m) and similar facies of the soil complex and loess, the latter also being divided into two units. The stratigraphic system nevertheless seems related more closely to that of loess of Central Europe. No major unconformity has been recognized in this sequence.

The Younger Loess. – From bottom to top (Fig. 2). Pedocomplex 'Achenheim I': colluvium, a reddish brown clayey loamy horizon, non-calcareous, with prismatic structure and coatings, irregularly preserved, corresponding to a Bt horizon (brown podzolic soil). Above a thick dark brown clayey loam complex ('grand lehm') up to 5 m thick and including a black forest soil (0.4 m thick) overlain by several humic horizons. Pellet sands, having been eroded into the underlying 'Grand lehm'. Several yellowish or brownish grey loess horizons (8 m thick) with a frost-crack level and a stratified loam at the top (0.20 m thick). The last loess, 'the cover loess' (3–4 m thick), consists of typical yellowish loess with more brownish layers separated by small frost wedges; its bottom is characterized by a cryoturbated horizon, with small frost wedges (0.2–0.3 m deep),

assimilated to the Kesselt horizon, brownish cryoturbated soil (diagnostic horizon of western European stratigraphy) (Gullentops 1954).

The Younger Loess shows the typical stratigraphy of the Upper Pleistocene (Eemian–Weichselian). The pedocomplex 'Achenheim I' can easily be correlated with the same pedostratigraphic unit of the other loess areas (Warnton Soil complex – Rocourt Soil in Belgium and Northern France; Humic soils – Elbeuf I soil in Normandy; Stillfried A in Austria). The molluscs and the pollen content of the dark brown complex suggest an early Weichselian age of the deposit, with oscillating climatic conditions.

The overlying loess represents the whole Weichselian Pleniglacial, clearly divided into two main units by the cryoturbated horizon (Kesselt horizon), which follows after a short warm interval (according to soil and mollusc fauna) and precedes the regular deposition of the Upper Pleniglacial Cover Loess deposited during the last glacial maximum. By its morphostratigraphic characteristics and its facies, this cryoturbated horizon corresponds to the same type of level defined at Kesselt (Belgium) (Gullentops 1954) and observed in the same stratigraphic conditions over great distances in Belgium and northern France (Sommé 1977; Lautridou 1985). Its occurrence in the loess of Alsace confirms the stratigraphic importance of this level in the Weichselian Pleniglacial. Once more, the unconformity at the base of the loess deposits corresponds to a great erosional hiatus which is common in all the Lower Pleniglacial of the northwest European stratigraphy (Paepe & Sommé 1970; Paepe & Zagwijn 1972; Sommé 1977; Lautridou 1985).

Each loess cyclothem has been interpreted as an interglacial-glacial cycle and correlated with the isotopic stratigraphy (Heim *et al.* 1982; Lautridou *et al.* 1985, 1986; Sommé *et al.* 1986).

Thus the 60 m of the Achenheim sections record at least five glacial cycles. From the whole data, these cycles show a climatic evolution which, especially for the three last cycles, is nearly continuous in spite of discontinuities recognized in the stratigraphy. Some of these discontinuities are important and represent major erosional events (Fig. 2) which have stratigraphic value and which will be taken into account in the time calibration of the sequence by reference to the stratigraphic framework of the region which includes Achenheim (Sommé *et al.* 1980). The evidence of three true interglacial soils, of interglacial and pleni-

glacial malacofaunas and of interglacial pollen, indicates that the cycles are possible to correlate with Kukla's glacial stages B, C, D, E and F (Lautridou *et al.* 1986; Chaline & Thévenin 1972).

The mollusc profile

Sampling of sediments was done in the field for malacological and pollen investigations. While pollens are restricted to the pedocomplex soils, the terrestrial molluscs are present almost throughout the sequence and 197 of the 215 samples were fossiliferous. Today, molluscs provide good environmental information because they are closely connected to their biotope. Consequently variations in the fossil faunal assemblages can be correlated with Quaternary climatic oscillations. During interglacials, mollusc faunas contain a large percentage of forest and semi-forest species, whereas during pleniglacial stages assemblages comprise alpine-arctic and sometimes North Asiatic species.

The mollusc species used in the multivariate analyses are ecologically grouped in accordance with Lozek (1964) and Puisségur (1976).

G1 (forest species). *Acanthinula aculeata*, *Aegopinella* sp., *Aegopinella nitidula*, *Aegopinella pura*, *Aegopsis verticillus*, forest *Clausilia*, *Cochlodina laminata*, *Ena montana*, *Helicodonta obvolvata*, *Monachoides* sp., *Orcula dolium*, *Pagodulina pagodula*, *Trichia villosa*, *Vertigo pusilla*.

G2 (semiforest species). *Aegopinella minor*, *Discus rotundatus*, *Euobresia diaphana*, Great species (*Arianta arbustorum*, *Bradybaena fruticum* or *Cepaea* sp.), *Helix pomatia*, *Vitrea crystallina*.

G3 (marshy forest species). *Clausilia pumila*, *Perforatella bidentata*.

G4 (steppe species). *Ceciloides acicula*, *Candidula unifasciata*, *Chondrula tridens*, *Helicopsis striata*, *Pupilla sterri*.

G5 (open ground environment). *Catinella arenaria*, *Columella columella*, *Pupilla loessica*, *P. muscorum*, *Vallonia costata*, *V. pulchella*, *Vallonia tenuilabris*, *Vertigo parcedentata*, *V. pygmaea*.

G6 (xerophilous species). *Cochlicopa lubricella*, *Euomphalia strigella*.

G7 (mesophilous species). *Abida secale*, *Clausilia dubia*, *Clausilia parvula*, *Cochlicopa lubrica*,

Euconulus fulvus, *Helicigona lapicida*, *Nesovitrea hammonis*, *Oxychilus* sp., *Punctum pygmaeum*, *Trichia hispida*, *Vertigo alpestris*.

G7' (Limacidae s.l.). *Limax* sp.

G8 (hygrophilous species). *Carychium tridentatum*, *Succinea oblonga*, *Vertigo angustior*, *V. substriata*.

G9 (palustral species). *Carychium minimum*, *Oxyloma sarsi*, *Pupilla alpicola*, *Succinea putris*, *Vallonia enniensis*, *V. antivertigo*, *V. genesii*.

The richness and abundance of the malacological material makes possible a synthetic analysis based on multivariate analysis. Classical methods, like principal components, make it necessary to use the correlation matrix and analysed columns or rows. The method used here, correspondence analysis (Benzecri *et al.* 1973), proceeds differently. Each element (point) I is represented in a J dimension space by its coordinates on each J variable (k_{ij} ; and $\sum k_{ij} = k_i$), but is also allocated a weight ($= k_i/k$, $k = \sum k_i$, $\sum k = 1$). For example, three assemblages yield the following counts for three species a, b, c:

assemblage 1: a = 2, b = 4, c = 8, $k_i = 14$,

assemblage 2: a = 4, b = 8, c = 16, $k_i = 28$,

assemblage 3: a = 3, b = 10, c = 0, $k_i = 13$;
 $k = 55$.

The coordinates (k_{ij}) of each assemblage will be: 2/14, 4/14 and 8/14 for the first two and 3/13, 10/13 and 0 for the third. The weights will be 14/55, 28/55 and 13/55. Since this procedure is available for both rows and columns, they yield superimposable factors (reference axes of the hyperspace) that allow the simultaneous plotting of both variables and individuals (rows). For the Achenheim data, the mollusc species are columns and mollusc associations belonging to one stratigraphical level are rows. To avoid too much deviation in the variability, the data are coded following an abundance class principle (Rousseau 1987). Apart from *Pupilla loessica*, which is extinct, all the fossil species have modern equivalents living in identical assemblages to those during the Pleistocene. The advantage of correspondence analysis is thus that the modern ecology and distribution of the mollusc species can be used to interpret the general variability of the data set and characterize each reference axis.

The first axis discriminates, according to the positive coordinates, species and associations characteristic of an open temperate woodland

(i.e. comparable to those presently occurring in Burgundy) and, on the negative side, species and associations characteristic of cold open ground environments such as tundra. In fact a thermal gradient, temperate to pleniglacial, parallel to this axis, is determined (Fig. 3). On the second axis, distribution of the species and the associations depends on a moisture gradient: damper, marshy (negative coordinates) to dry grassland (positive coordinates) (Fig. 3). Species and malacological associations are consequently distributed between four major poles according to their ecological requirements and to the ecological properties of their habitats (Rousseau 1987). The multivariate analysis allows us in this way to determine, with great precision and according to modern molluscan assemblages, the climatic oscillations. Once more, cluster analysis of molluscan faunas, which allows the testing of reworked material, confirmed that there were no cases of redeposition of the molluscs, as already

observed in the quality of the shell preservation (Rousseau 1987).

Following this interpretation of the variability of the Achenheim set, palaeoclimatic curves can be drawn by plotting the loadings of each association, belonging to one stratigraphic level, onto the first two factors, interpreted as representatives of climatic parameters, following the principle indicated in Fig. 4. The evolution of temperature as a function of depth in the sequence obtained by this method (Fig. 5) is in general agreement with results from for example palynological or pedological studies (Lautridou *et al.* 1986; Aitken *et al.* 1986). As the three last interglacial-glacial cycles are well preserved, these results allow a comparison between the continental and oceanic records. Of course some hiatuses occurring in the sequence are characterized by erosion levels and discontinuities which have morphoclimatic significance and these will be taken into account in the following interpretation.

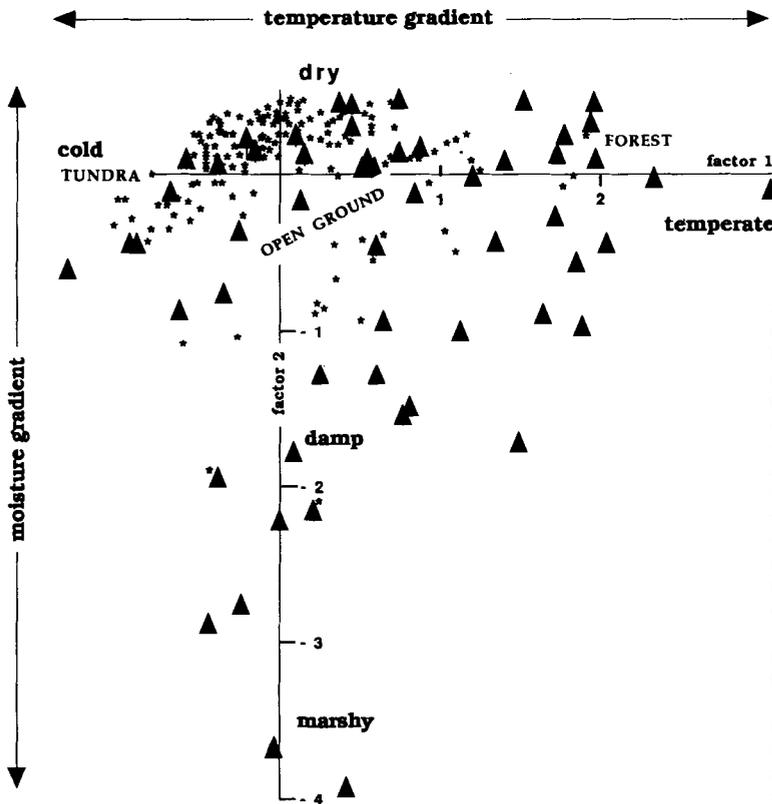


Fig. 3. Correspondence analysis of the Achenheim malacofaunas. Plot of the species (columns) and of the malacological associations (rows), each one associated with one stratigraphic level, on the first factor plane (axes 1-2). From the ecological characteristics of the species and the composition of the associations, four poles are determined: temperate to cold (temperature gradient parallel to the first axis); dry to damp and marshy (moisture gradient parallel to the second axis). The temperate pole is characterized by forest species living in middle latitudes in western Europe, all the other taxa correspond to an open ground environment. Species are shown by triangles, associations by stars.

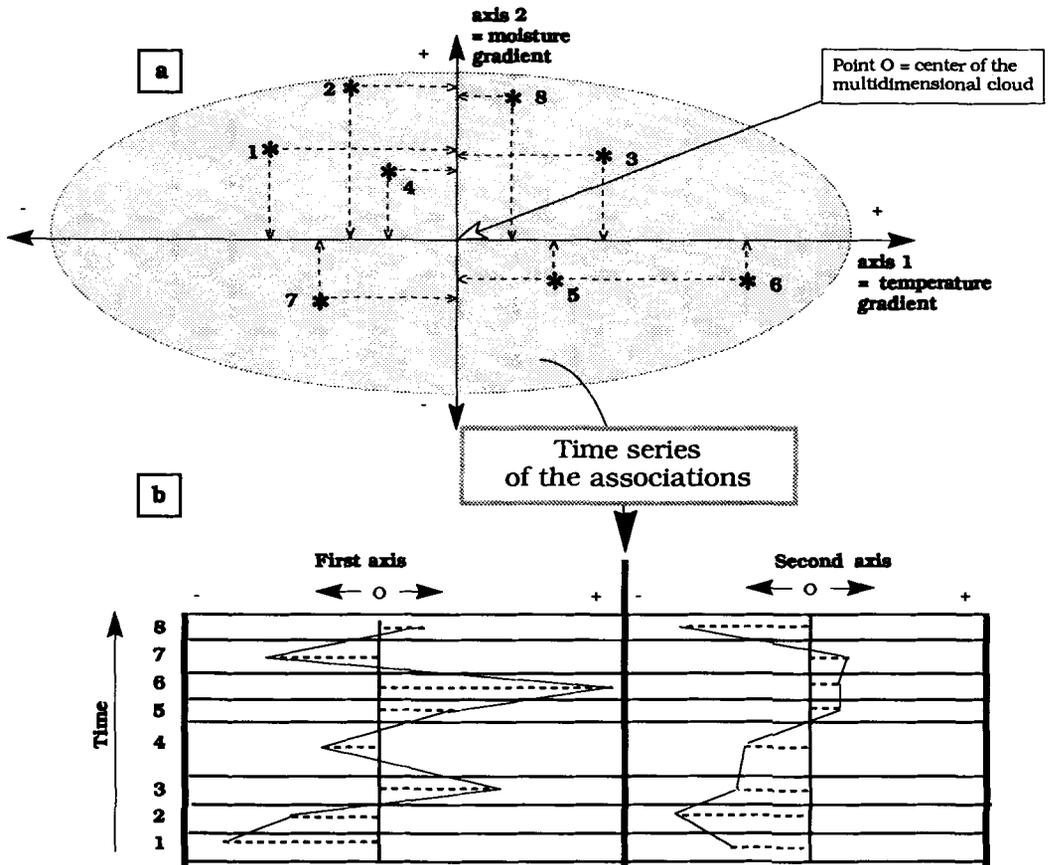


Fig. 4. Principle of drawing the climatic curves. (a) Eight associations in the hyperspace cloud with occurrence of the first two reference axes. Loadings plotting of each association on each axis (or factor) is shown by the dotted lines with an arrow. (b) Time series of the associations with regard to their loadings on the first two axes (or factors) after having placed each association in its stratigraphic position.

Calibration of the last interglacial-glacial cycles and the climatic records

Assuming a constant deposition rate for the last three interglacial-glacial cycles, in which all the most important climatic events determined in the marine chronology have been recognized, each stratigraphic unit has its thickness weighted by interpolation with the SPECMAP oxygen isotope average record (Imbrie *et al.* 1984). We calibrate our curve by taking into account the major discontinuities and the general significance of pedocomplexes in the bipartite subdivision of the

cycles. The adopted equation is the following:

$$T_m = T_1 + \frac{\sum_{i=1}^m a_i(T_2 - T_1)}{\sum_{i=1}^m a_i}$$

where a_i is the thickness of level i , n the total number of levels comprised between two reference time points T_1 and T_2 , T_m being the calibration of the level m . The last cycle could be considered a test for our procedure, because ^{14}C and TL dates are available (Evin *et al.* 1980; Aitken *et al.* 1986; Buraczinski & Butrym 1987). The plots of malacofaunas on the first factor analysis (the temperature factor) are scaled for

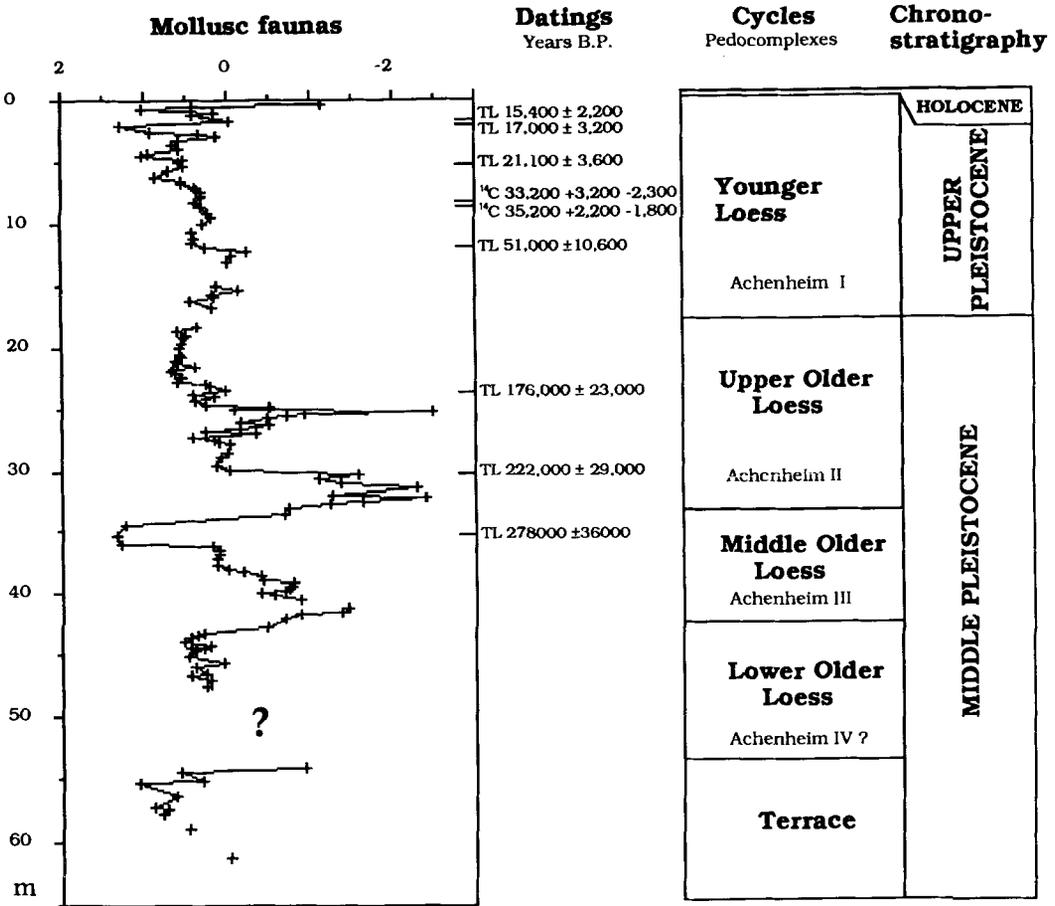


Fig. 5. Plot of the malacological association loadings on the first factor, interpreted as indicating climate (mainly temperature), against depth in the complete Achenheim sequence. Location of datings in the sequence.

the sake of comparison to have similar amplitudes as the $\delta^{18}\text{O}$ variations. The major trends observed in the biological variations correspond strikingly with those determined in the isotopic record. But the lack of malacological data made the test of some calibrations difficult, notably for the last cycle. Nevertheless, the examination of other data (pollen, micromorphology, geomorphology, TL and ^{14}C datings) allows us to get around this problem.

The last cycle (Fig. 6). – The limits of stage 5 are defined in agreement with pedomorphology and the palynological data of the pedocomplex Achenheim I (Lautridou *et al.* 1986; Sommé *et al.* 1986). In the interglacial palaeosol at the base,

the Bt horizon without malacofauna is attributed to the Eemian (event 5.5) and the overlying black forest soil, also without malacofauna but with pollens, to the 5.3 event. The validity of this chronological allocation is attested by the Bt soil truncation due to a main erosional phase attributed to a cold event not recorded by any malacofauna. So the conventional 99,000 BP age is thus attributed by micromorphology to the black soil in order to allow the good calibration of the uppermost levels. The upper boundary of stage 5 is fixed at 71,000 BP in agreement with the SPECMAP data. The temperature variations are in agreement with the palynological data, which indicate a more steppe-like environment.

Stage 4 is not well preserved in the Achenheim

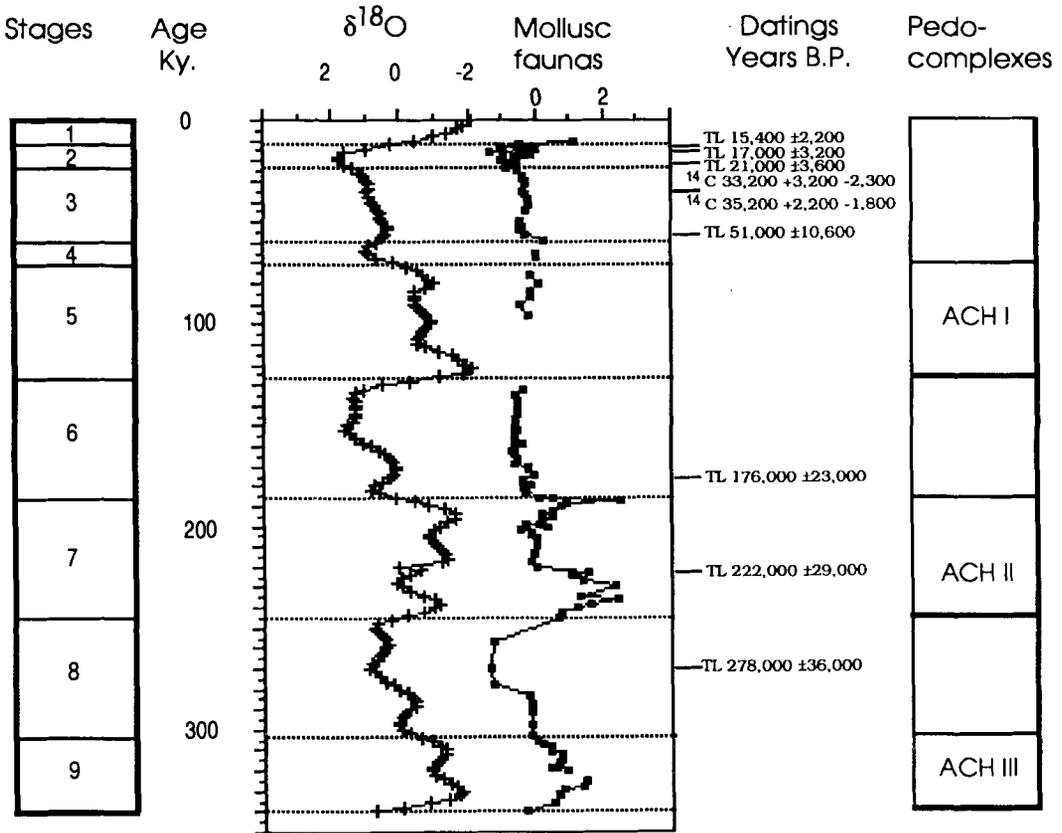


Fig. 6. Time series of molluscs from the Achenheim sequence. Variations in smoothed and stacked $\delta^{18}\text{O}$ (crosses) during the last three climatic cycles (0–339,000 BP) are from Imbrie *et al.* (1984). Plot of the variations in malacological associations (dark squares) on the temperature factor (first factor of the multivariate analysis) against the proposed calibration of the levels (sedimentation rate/age) and the isotopic stratigraphy. The factor values are scaled for the sake of comparison to have similar amplitudes as the $\delta^{18}\text{O}$ variations. Ach I, II, III are pedocomplexes.

sequence. Six related stratigraphical levels are surrounded by two discontinuities, where the upper one has a main stratigraphical value. This important erosional level, corresponding to the Lower Pleniglacial as defined in Northwest Europe (Somme *et al.* 1986; Zagwijn & Paepé 1968), is correlated to the 4.2 event at 65,000 BP. This date fixes the upper limit of our calibration. Two levels yielded malacofauna. Nevertheless, taking geomorphological and pedosedimentary information into account, they are interpreted as preceding the 4.2 event.

Stage 3 is well preserved and also surrounded by the major discontinuity previously mentioned at the base, and a level with large ice-wedges on the top. The conventional limits 24,000 BP and 59,000 BP are used. Stratified sediment observed

at the base level yielded an age of 51,000 ± 10,600 BP by TL (Aitken *et al.* 1986), which corresponds to the calibrated age. The evolution of temperature at this time was relatively monotonous and in agreement with variations determined for the oceanic isotopic curve. But a more pronounced cooling than indicated by the isotopic data is observed at the base of the Achenheim record.

The chronostratigraphic limits of stage 2 are defined following conventional values: 12,000 BP at the bottom of the top sequence soil and 24,000 BP for the level with great wedges which identifies this unit in the local stratigraphy. Dates provided by calibration are in agreement with those obtained by the ^{14}C and TL methods at the site. The position of the Kesselt level in our calibration

is in agreement with the TL datings obtained in Achenheim (Aitken *et al.* 1986) and is close to the new estimates proposed by Juvigné & Wintle (1988). The cold maximum falls near 15,000 BP, followed by a significant warming interrupted by a new cooling. These dates agree with those obtained from the Atlantic Ocean for the same period (Duplessy *et al.* 1981; Ruddiman & McIntyre 1981a; Bard *et al.* 1987). The recorded temperature variations in the Achenheim sequence indicate the occurrence of an oscillatory system throughout stage 2, which has had a morphosedimentary effect in other loess sites too, in Belgium and Northwestern France (Sommé *et al.* 1986; Sommé *et al.* 1980; Lautridou 1985). Such variations are also observed in for example Vostok and Camp Century ice-cores (Lorius *et al.* 1985; Dansgaard *et al.* 1969) and in the Xifeng loess section (Kukla 1987). This record implies that the climatic oscillatory system of the Late Glacial was not initiated at the end of the Pleniglacial, but corresponds to the end of a general system characterizing stage 2 itself. The detailed record of the Upper Recent Loess appears as a particularly interesting model for the climatic evolution of this period.

In brief, the last cycle, as recorded in the calibrated Achenheim sequence, is in agreement with conventional SPECMAP and general palaeoclimatic data. Although erosional hiatuses of first stratigraphical order occur, the calibration of the ages as a function of their thickness is satisfactory and allows the application of this method also on the two underlying cycles, which probably yield a complete record of sedimentation.

The penultimate cycle (Fig. 6). – Stage 7 is recorded in the pedocomplex Achenheim II, with 245,000 BP fixed as the lower limit. The upper limit (186,000 BP) is located at the top of pellet sands (stratified sediment) overlying a loess. The variations in temperature as determined by the molluscs are similar to those recorded by $\delta^{18}\text{O}$, in spite of a small interval due to the occurrence of two soils. The first warming corresponds to a soil, cut at its top by a small erosional level, which is not taken into account in the calibration. In the same way the second warming is represented by a truncated Bt horizon (incomplete interglacial soil). The loess in the pedocomplex Achenheim II is interpreted as a marker (diagnostic horizon of the central European loess stratigraphy) and indicates the first significant cooling in this part

of the sequence. The overlying stratified sediment indicates a warming trend which is inscribed in the logic of the curve, but the magnitude of this event is probably overestimated, as seen by comparison with the isotopic curve. However, that the malacological association indicates a clear warming is attested by the occurrence of taxa like *Discus rotundatus*, *Helicodonta obvoluta*, *Arianta arbustorum*. The location of this mollusc assemblage on the first factor which is interpreted as a temperature factor indicates a similarity of this component with typical temperate associations.

Stage 6 begins with the typical loess deposits, which correspond to a great cooling period during which we observe again, more softened, the oscillatory system determined in stage 2. The small event observed in the oxygen curve, corresponding to a cool period, is also recognized in the mollusc curve. A TL dating is in agreement with the proposed calibration (Buraczinski & Butrym 1987).

The antepenultimate cycle (Fig. 6). – Stage 9 is recorded in the pedocomplex Achenheim III and 339,000 BP is fixed for the lower limit. According to the pedostratigraphy, the upper limit (303,000) is located at the basis of a brown loam overlying a main stratigraphical discontinuity. Two different warmings are separated by a slight cooling. The interval between the two records is explained, as previously, by the occurrence of a discontinuity, represented by the truncation of a soil which was not taken into account in the calibration.

The loam at the beginning of stage 8 represents the first significant cooling of the sequence. It is overlain by a stratified sediment which records a slight warming, significantly less marked than in the isotopic curve. On top of this follows the cooling characterized by a loess with a typical *Pupilla* fauna (Evin *et al.* 1980; Rousseau 1986). The large interval between the samples here does not allow as precise a comparison of the different events with the isotopic curve as previously.

Discussion

Globally seen, the variations recorded by the terrestrial molluscs and the age interpolations are in agreement with TL and ^{14}C datings and with the astronomical calibrations of the $\delta^{18}\text{O}$ record. The three sequences indicate a clear cyclic evolution in the mollusc record as well as in the

Parallel projections of the temperature and moisture curves allow us to conclude that during the last three cycles, their evolutions were not homologous. Estimation of the moisture indicates that the Achenheim sequence was generally deposited under dry soil surface conditions.

In stage 9 a warm peak corresponds to an increase in moisture, but as temperature decreases conditions became dry. Strikingly, the cold maximum of stage 8 coincided with moister conditions, with a maximum during the transitional phase between the cold peak and the warmest part of stage 7. Thereafter the evolutions of temperature and moisture are parallel. The cold maximum of stage 6 coincided with dry conditions (Fig. 7). Unfortunately interglacial event 5.5 is not preserved in the Achenheim mollusc record. But up to the maximum cold stage 2 the environmental conditions were dry, stage 2 revealing alternating dry and moister environments in close connection with the fluctuations in temperature (Fig. 7). These results imply two main fundamental developments. First, continental conditions during the last cycle, mainly during the pleniglacial stages, cannot be generalized to all the previous climatic cycles and need to be further tested by GCM. Second, the generally assumed cold and dry continent during the pleniglacial stages, as recently suggested by Ruddiman & McIntyre (1981b), has to be moderated with regard to the location of the studied sites and with respect to the maximum ice sheet advances which generated changes in the atmospheric circulation.

The important point to determine is the magnitude and general climatic significance of the mollusc fauna variations. First, references are provided by present climatic data. For example, the malacofauna significant of the cold maxima in stage 2 is a *Columella columella* fauna and *C. columella* is considered as a moisture loving species. At the present time such an association can be observed in the Scandinavian mountain tundras, e.g. at Abisko (68°21'N, 18°49'E) close to lake Torneträsk in Sweden. Here the average annual temperature at low altitudes is -1°C and the annual precipitation 300 mm, with a maximum in summer (40 mm in July). The reference to present conditions allows us to relativize the moisture variations observed in the Achenheim record. Apart from the interglacial periods, most of the hygrometric oscillations indicate dry conditions with great deficits in the summer precipi-

tation regime, as observed by Woillard in La Grande Pile (Woillard 1978), B. Van Vliet Lanoé by micromorphology in Weichselian sections (van Vliet-Lanoé 1988), and Guiot with transfer function applied to the La Grande Pile and Les Echets sections (Guiot *et al.* 1989). Nevertheless, the increasing moisture determined during the last glacial maximum, isotopic stage 2, is in agreement with the simulation results of Jousaume (1989) using the LMD 3 D model. For this period she observed that in Europe her moisture estimates indicated increased values which do not agree with the palaeo-data. She recognized increasing moisture in winter and in summer for western Europe while palaeo-data (especially results from transfer functions applied to pollen assemblages) and other simulation models indicate a drying trend. The precise interpretation of the mollusc assemblages, indicating important variations by the loss of indicator species, suggest major climatic changes which up to now have not been recognized (Rousseau 1986). The fact that the Achenheim record shows the same trends while having been obtained in a way other than via circulation models implies that this locality is really a first-rate site for palaeoclimatic and biostratigraphic studies in Europe.

From the evidence of the temperature and moisture curves, the Achenheim record shows an oscillating system during stage 2 similar to the record found during the Late Glacial and which can also be observed in the previous cycles (Fig. 7). This is of fundamental interest because it was also found in the ice cores, with more details (e.g. Camp Century; Dansgaard *et al.* 1969). This means, first, that cold maxima are never simple phenomena, as described in smooth curves; second, that the oscillatory variations during the Late Glacial are not typical of this period alone, but belong to the general 'system' which begins with the cold maxima. Such variations can also contribute to explaining the disagreements which are often observed in the literature concerning the recognition and dating of short-lived but important events like Younger Dryas, which are inscribed in a general oscillatory system, but not necessarily globally well preserved, and consequently invite different interpretations.

Conclusions

Information obtained from Achenheim gives us

the first mollusc-based unambiguous description of climatic variations from a continental section covering the last three climatic cycles.

Well preserved, they have been time-scaled by interpolation with the SPECMAP isotopic stage limits. Evaluation of the ages is in agreement with the radiometric ages (applied only to the last cycle) and TL. They allow the comparison between climatic information derived from the mollusc faunas with the SPECMAP oxygen isotope record tuned to an astronomic chronology. All the major climatic events are recorded in both the isotopic and mollusc temperature estimate curves, with generally more precise data for the cold maxima during stage 2. The climatic oscillatory system determined in stage 2, which announces the Late Glacial variations, seems to be indicated also in the older excursions of the isotopic oceanic curve.

The comparison between the estimated temperature and moisture shows that these two parameters have not evolved in the same way. If interglacial periods appear to be generally relatively moist, pleniglacial periods provide differences in amplitudes: stages 2 and 8 indicate moister conditions than stage 6.

Under these conditions, the mollusc associations in Achenheim offer us the possibility of measuring climatic parameters and their variations in time as parallel to the $\delta^{18}\text{O}$ variations. Although the primary interest is to reconstruct the local palaeoenvironments, these parameters also provide more general climate-history information. So it is hoped that, in a second step, the transfer functions which are in progress will greatly extend climatic information on continental conditions.

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