Terrestrial molluscs as indicators of global aeolian dust fluxes during glacial stages

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This paper represents an approach to discerning the kind of climatic signal that land snails might record. The study uses previous analyses of the Achenheim molluscs, whose time series can be compared with ice-core records or marine records. Terrestrial molluscs are characteristic of the environment in which they live, mainly mirroring prevailing climate and vegetation. As a result of this relatively close connection between biotope and mollusc assemblages, reconstructions of past environments can be made that agree generally with results from pollen analyses. In this way, malacofaunas in loess sections permit determination of environmental variability and climatic change. Loess deposits, however, correspond to a particular environment. Decreasing or increasing dust deposition affects the molluscan assemblages by altering the environmental conditions for better or for worse. The variation in the mollusc diversity index in Achenheim shows a striking correspondence with dust-flux variation. There is only a low correlation between diversity index and temperature, precipitation or moisture estimates.

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A major question of palaeoclimatology is how to correlate different kinds of palaeoclimatic records in order to provide data to validate general climate modelling results, in order to understand global climatic dynamics or Milankovitch cycles. Radioisotopes are useful tools for providing reliable correlations among marine records. Kent (1982) demonstrated that the study of magnetic susceptibility, which records the dust content of marine sediments, permits stratigraphic correlations between marine and continental records. He showed that variation in the magnetic susceptibility is correlated closely to that of ^{18}O, implying some climatic significance. Indeed the accumulation rate of aeolian content in marine records is a function of continentality of climate. More recently, similar conclusions were derived from a study of the dust content in polar ice cores (Hammer *et al.* 1985). This analysis confirmed that dust fluxes have to be considered as climatic indicators, permitting comparisons between marine, polar and continental (mainly loess sequences) records. For example, high-frequency transport of aeolian dust is evidenced during isotopic stages, 2, 4 and 6 in different kinds of records (marine cores S8-78 (Robinson 1986) and RC11-120 (Kent 1982); polar ice cores at Vostok (Petit *et al.* 1990) and Dye 3 (Hammer *et al.* 1985); continental deposits, such as the Chinese loess sequences (Kukla 1987; Kukla & An 1989)) for the last 186,000 years, according to the SPECMAP (Imbrie *et al.* 1984) chronology. For continental sequences, Kukla hypothesized that magnetic susceptibility is related inversely to the density of the vegetation cover. This assumption was supported by the few pollen grains recognized in the Chinese loess (they never exceed 60 in loess deposits). Nevertheless, faunal remains, especially molluscs, provide additional information on the past climate of loess sequences.

Previous results

The Achenheim loess series (Alsace, France 48°35′ N, 7°38′E; Fig. 1) provides a continental record of the last five climatic cycles (Lautridou *et al.* 1985), the last three being almost continuous (Rousseau & Puisségur 1990). A previous paper (Rousseau & Puisségur 1990) presented the chronological calibration of the sequence and the interpretation of the results provided by a multivariate analysis of the malacofaunas preserved in the deposits. The first correspondence analysis axis discriminates between forest and tundra-like or loess steppe environments (Rousseau 1987). Climatic significance thus can be assigned to this

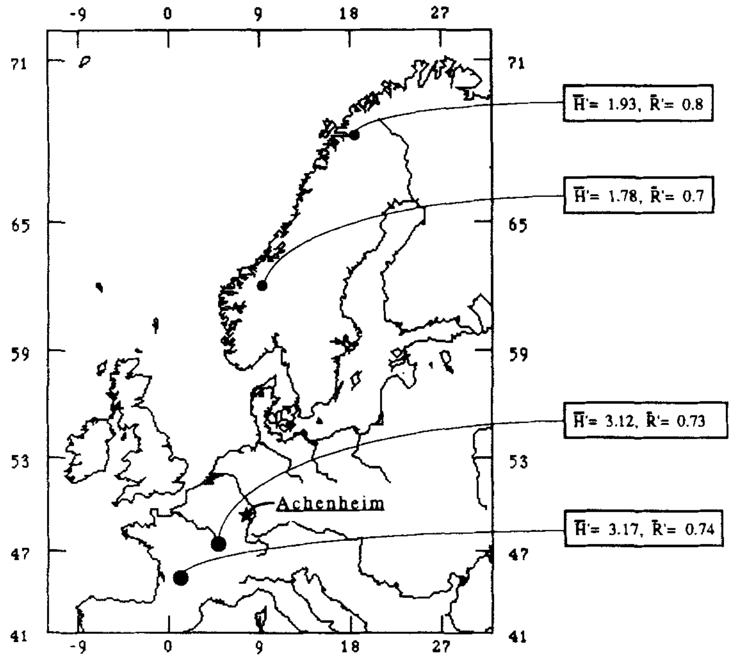

Fig. 1. Comparison of mean values for diversity (H') and equitability (R) between montane tundra in Scandinavia and forest environments in France.

axis, in agreement with the present ecology of the species, allowing comparisons with the marine isotopic record. The second axis, discriminating between species from dry and marshy environments, is associated with a moisture gradient. A time series of molluscs during the past three cycles was proposed based on the rate of sediment deposition and controlled by ^{14}C and TL measurements (Rousseau & Puisségur 1990). This time-scale provides a relatively good correspondence with the classical SPECMAP marine $\delta^{18}O$ record (Imbrie *et al.* 1984).

As shown previously, the fluctuations in the molluscan fauna composition are related to 'climatic' or moisture changes (Rousseau & Puisségur 1990). Such interpretation is classical for biological remains, both in continental and marine records, but variations in the diversity of the assemblages also imply that not only mollusc communities recorded impacts of these factors.

The structure of malacological communities

The structure of the molluscan communities can be described in terms of diversity, H' ($H' = -\Sigma_1^n p_k \log_2 p_k$; p_k being the frequency of one species in a determined assemblage), with H' varying between 0 and 4. The choice of the Shannon index, instead of other indexes (Maguran 1988), was made in order to establish accurate and direct comparisons with previous studies made on recent mollusc assemblages in Poland (Dyduch-Falniowska 1988). Interglacial faunas roughly show high values, around 3.0, with forest species dominant. Pleniglacial conditions are characterized by tundra or loess steppe taxa whose assemblages indicate a low diversity, around 1.0, which may reflect high stress in the assemblage, by comparison with the present Scandinavian analogue (Fig. 1). During the past 186,000 years, the lowest values, ranging between 0.3 and 2, were obtained during Oxygen Isotope Stages 2, 4 and 6 (Fig. 3B).

The modern analogues of the Achenheim fossil assemblages occur in western Europe where there is a decrease of species from south to north (more than 100 taxa in France and 25–30 species in northern Scandinavia) (Kerney & Cameron 1979). This decrease shows the climatic impact on the malacofauna at the species level, and has been used for climatic transfer functions (Rousseau 1991). However, if modern data from tundra mountains in Scandinavia and from forests in France are computed, the diversity shows considerable variation. The mean values range between 1.8 and 3.17 (Fig. 1). These data correspond to samples taken from areas not or only weakly influenced by human activity. These values from recent snail assemblages are never as low as in the Achenheim sequences, especially during the Pleniglacial phases. So how can such stress in the snail communities be interpreted?

A cluster analysis made on the results of the first correspondence analysis indicates that the assemblages corresponding to pleniglacial conditions come from poorly vegetated places (loess steppe or tundra-like) (Rousseau 1987). Archaeological investigations (Lautridou *et al.* 1985) show no human activity in Achenheim during the loess deposition. Although other factors, such as temperature, precipitation or moisture can be evoked, no statistical correlation exists between estimates of these parameters and diversity during the pleniglacial phases. Plots of depth against time show that high sedimentation rates occur during Oxygen Isotope Stages 6, 4 and 2, with the highest values occurring during the last stage (Fig. 2). Those results are similar to those from marine sites (S8-78 (Robinson 1986) and RC11-120 (Kent 1982)) and polar ice-cores (Vostok (Petit *et al.* 1990) and Dye 3 (Hammer *et al.* 1985)). Additional information is gained by comparing trends in the snail diversity with the climate signal at Achenheim or the Vostok dust content, which seems appropriate because of the global implications of this ice record (Fig. 3). The purpose of this paper is not to discuss the Vostok chronology, so comparsions are based on the correlations proposed by Petit *et al.* (1990) between Vostok and marine isotopic chronologies.

The Achenheim mollusc sequence shows its lowest diversity during Oxygen Isotope Stages 2 and 6 (Fig. 3). The Achenheim sequence also indicates a high sedimentation rate at that time (Fig. 2). A major dust event centred on Oxygen Isotope Stage 2 in the Vostok core has the highest magnitude of the entire record. This is interpreted as a major aeolian input in the climatic system. A second major dust in Vostok, lower in magnitude, occurs during marine stage 4. In the Achenheim sequence, stage 4 is incomplete, mainly because of a hiatus indicating significant erosion (Figs. 2 and 3). Indeed the glacial peak of stage 4 corresponds to an erosion level associated with gravels all over northwestern Europe (Sommé *et al.* 1980). However, the lower part shows a high sedimentation rate (Fig. 2), so the Vostok dust flux in stage 4 corresponds to less dust deposition at Achenheim and the molluscan diversity at the end of stage 4 was still low

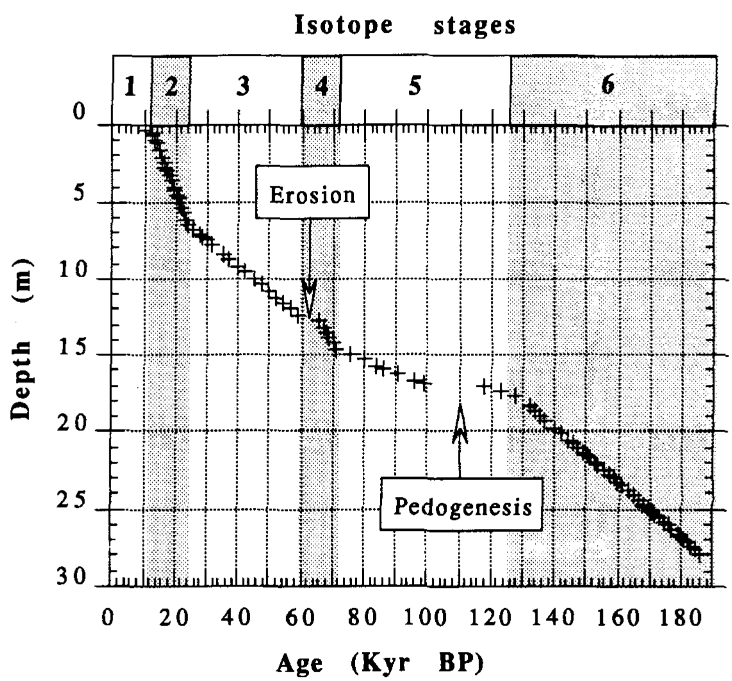

Fig. 2. Depth versus time during the last 186,000 years from the lower boundary of isotopic stage 6 in the Achenheim loess sequence.

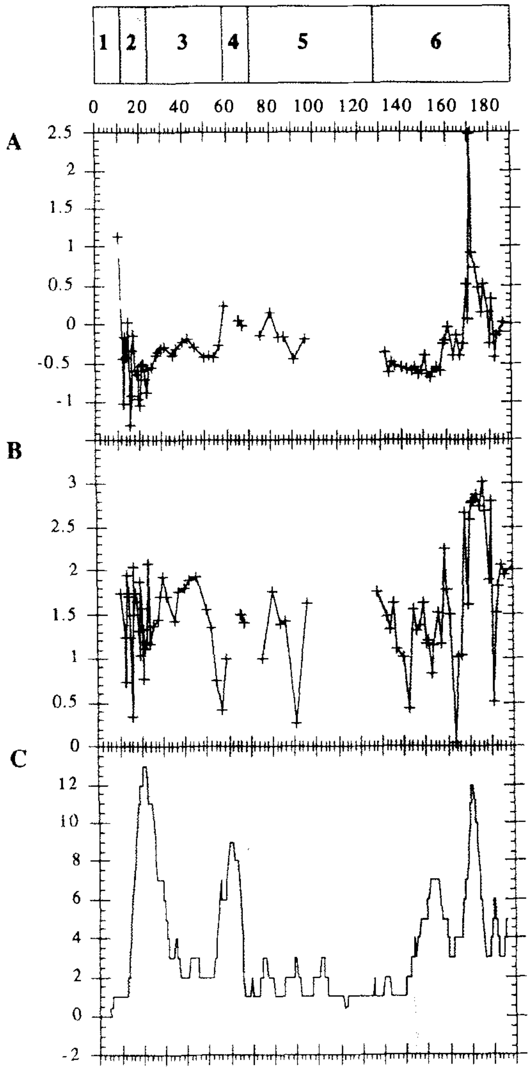

Fig. 3. Comparison between the signals provided by the land snails in Achenheim and the dust flux as recorded in the Vostok ice-core over the last 186,000 years. A: general climatic trend interpreted as a 'climatic' factor. B: variation in the diversity. C: Vostok dust flux ($\times 10^{-9}$ cm/year). The marine isotopic stratigraphy on the top of the figure is according to SPECMAP (Imbrie *et al.* 1984) and correlations between Vostok and SPECMAP are from Petit *et al.* (1990). Ages in kyears BP.

(Fig. 3). Diversity also was low in the Achenheim record during Oxygen Isotope Stage 6 (Fig. 3). The Vostok ice core also recorded high dust fluxes then, with three peaks, the second showing the highest magnitude during stage 6. It was, however, slightly lower than that of stage 2.

During stages 2 and 6, the best documented in the Achenheim sequence, snail assemblages show very low species diversity (Fig. 3), with values between 0.35 and 2. Moreover, their equitability ($R = H'/H'_{max}$, $H'_{max} = \log_2 n$; n being the number of species in a determined assemblage), which measures the distribution of individuals among species, is variable, with values varying between 0.3 and 1 (Fig. 4). Similar values for equitability occur at present, but the diversity values ranging between 1.15 and 2.53, as environmental conditions are unfavourable for malacofaunas (human impact, substratum) (Dyduch-Falniowska 1988). Consequently, diversified equitability and low diversity is interpreted as indicating particularly unfavourable environmental conditions for snails to develop. In the Achenheim sequence, diversity and equitability are correlated during pleniglacial phases (Fig. 4). However, pleniglacial assemblages are composed of species characteristic of cold environments and by taxa with a high ecological tolerance, which permits them to live in a wide range of environments. Consequently, the environmental stress affecting the pleniglacal malacofaunas comprises a combination of low temperature, variable precipitation and moisture, which permits the calculation of climatic transfer functions (Rousseau 1991), to which now the dust flux, which seems to be correlatable with low diversity, might be added.

Conclusions

Striking correspondences have shown that the signals recorded by loess snail communities correspond not only to a 'climatic factor *sensu lato*', but also to specific climatic signals corresponding to environmental factors, such as temperature, precipitation, and moisture. Results from the comparison between the Vostok ice-core and the Achenheim loess sequence now show that molluscs, by variations in their community structure, also can record variations in the aeolian dust input during the glacial stages. Malacofaunas, indicators of biodiversity as well as temperature and precipitation, are thus a good tool for continental palaeoclimatic investigations.

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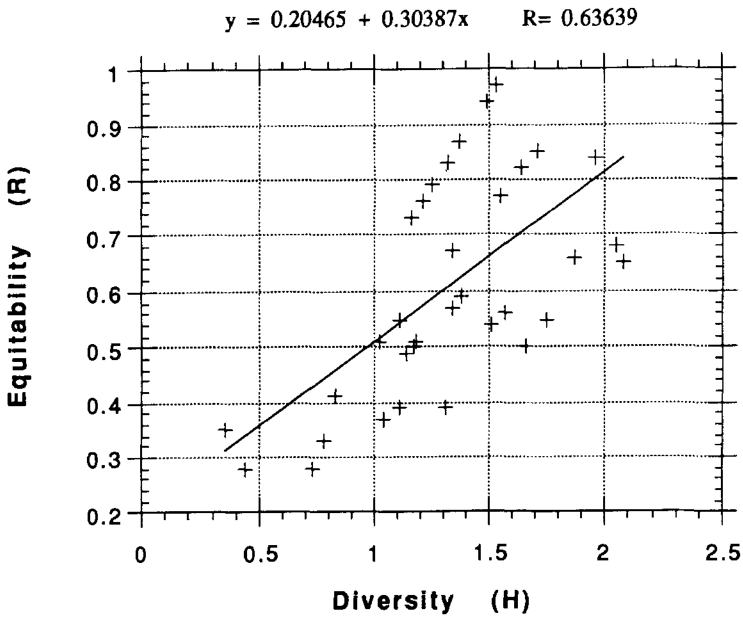

Fig. 4. Variation of the diversity (H') and equitability (R) indexes from malacofaunas during pleniglacial (Oxygen Isotopic Stages 6, 4 and 2) climatic conditions of the last 186,000 years.

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