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Loess biostratigraphy: new advances and approaches in mollusk studies

Denis-Didier Rousseau *

Paléoenvironnements et Palynologie, Institut des Sciences de l'Evolution (UMR CNRS 5554), Université Montpellier II, Place Eugene Bataillon, case 61, 34095 Montpellier Cedex 05, France
Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

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Abstract

Since the beginning of the 20th century, loess biostratigraphy has been strongly influenced by investigations of mollusks, these shells constituting the major fossil remains found in loess sequences. The earlier studies mostly involved identifying species and determining biozones or assemblages with regard to the presence or absence of key species, using the classic concept of biozones. Although this provided accurate elements with which to define an indicative biostratigraphy, the time resolution was not always sufficiently precise to connect those studies with the more recent and high resolution analyses that are now routine in Quaternary investigations. This paper reviews mollusk studies carried out in Northern Hemisphere loess sequences and shows that a consideration of them, as both biostratigraphic and palaeoclimatic indices, enhances their potential and opens up particularly interesting areas of research. The first example demonstrates that the last glacial mollusk assemblages in North America show compositional similarities to those in Europe. The climatic interpretation, however, appears more restricted by local conditions. The second example shows that climatic conditions can be used to infer variations in the composition of biozones and, thus, address the significance of the distributional pattern of key species. The third example demonstrates the value of high-resolution studies and the potential of comparing the results of mollusk analyses with other proxies as an underpinning of the biological interpretation. Finally, the need for more high-resolution investigations in both North America and Asia is stressed. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Loess biostratigraphy has always been based on the very few faunal or floral remains that loess scientists have been lucky enough to find (Heim et al., 1982; Kukla, 1975; Veklitch, 1969; Zhao, 1996). Although vertebrates provide a rather broad basis for such studies (Bouchud and Wernert, 1961), for years, other fossils such as pollen (Bastin, 1969; Frenzel, 1964, 1987; Gerasimenko, 1988; Sun et al., 1995; Zelikson, 1986), phytoliths (Wu et al., 1995) and mollusks provided reliable biostratigraphical references, applied according to the state of the art at the time of investigation. Numerous examples can be

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* Paléoenvironnements et Palynologie, Institut des Sciences de l'Evolution (UMR CNRS 5554), Université Montpellier II, Place Eugene Bataillon, case 61, 34095 Montpellier Cedex 05, France. Tel.: +33-467-144-652; fax: +33-467-042-032.

E-mail address: denis@dstu.univ-montp2.fr (D.-D. Rousseau).

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cited in Europe, in the Great Plains of North America and even China, where mollusk assemblages were, and are still, intensively studied. In Europe, it is clear that the investigations of the mollusk fauna carried out in western, central and eastern Europe have provided a reliable picture of conditions across this extensive area (Alexandrowicz, 1985, 1986; Alexandrowicz et al., 1989; Grossu, 1957; Kovanda, 1979; Krolopp, 1995; Lozek, 1964, 1965, 1966, 1969, 1990; Mazenot, 1951, 1953, 1956, 1957, 1959; Mazenot and Cailleux, 1957; Preece, 1990; Puisségur, 1978; Rousseau, 1986, 1987a,b, 1990, 1991; Rousseau and Puisségur, 1988, 1990; Rousseau et al., 2000; Sala, 1990; Wagner, 1979a,b,c; Wernert, 1949, 1955, 1957). In the USA, several investigators have concentrated on the Great Plains (Frankel, 1956a,b; Leonard, 1952, 1959; Rousseau and Kukla, 1994). In contrast, surprisingly few workers have so far investigated the mollusk assemblages of China (Chen et al., 1982; Keen, 1995; Rousseau and Wu, 1997, 1999; Wu et al., 1996).

The old concept of biostratigraphical zonation has been widely used to study the succession of biological units and to correlate between deposits. This was mainly achieved by palynological studies, although pollen grains are by no means well preserved in many loess–palaeosol sequences. Biostratigraphic zones have also been designed on the basis of mollusk studies and have allowed precise correlations, both between different sequences within a single region and between different regions. Index taxa provide some information on the age of the deposits with respect to their first or last occurrences, as widely practiced in classic biostratigraphy. They can also provide information about the general environmental conditions occurring in a specified region. However, the age information is generally rather crude and, in a way, old fashioned when still used. This includes examples even by the author of the present review.

The aim of this paper is to review some previous biostratigraphical studies of mollusks in the loess of

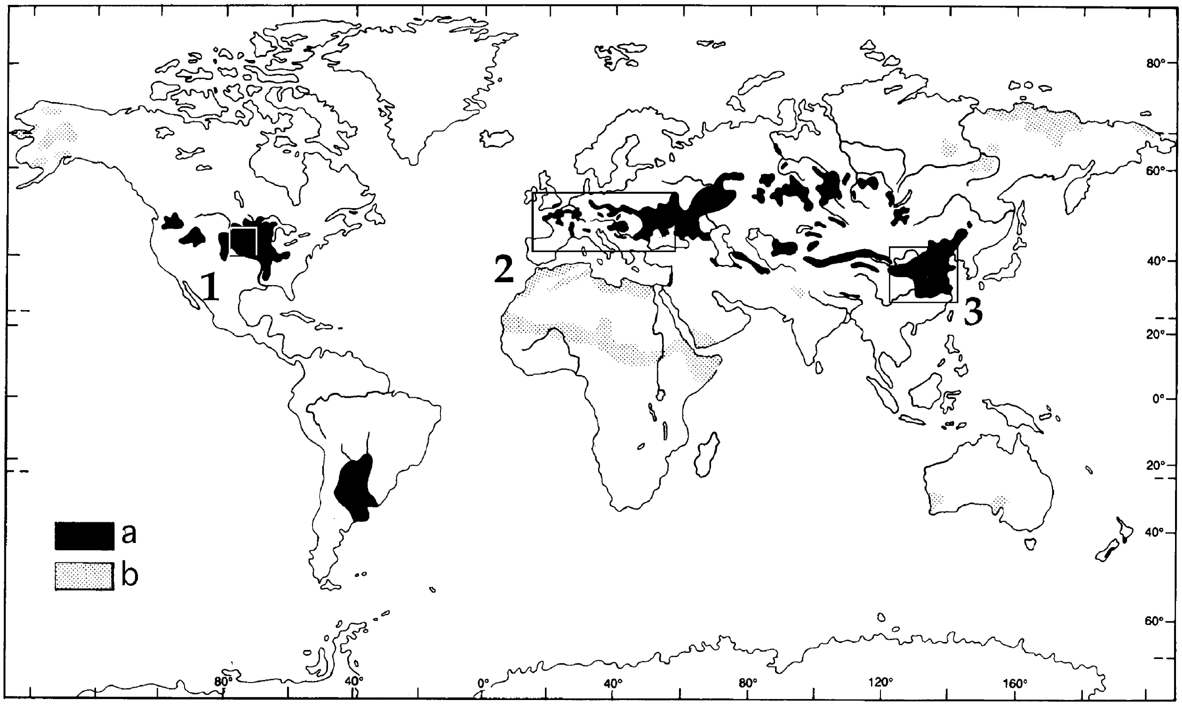

Fig. 1. Distribution of the loess sediment (from Pecsi, 1990, modified); 1, 2, 3 examples are discussed in the text; (a) loess sediments, (b) loess derivates sediments.

the Northern Hemisphere (Fig. 1), and to consider how their principal results, especially in high-resolution studies, can provide as ‘added value’ in terms of the biostratigraphy of loess sequences.

2. Basic biozonation: an example from the Great Plains of North America

The Upper Pleistocene loess deposits in the Great Plains are represented by the Peoria Silt, overlying the Gilman Canyon (^{14}C ages around 20–24 kyears) and Sangamonian (last interglacial) geosols. The Peoria Silt is a loess unit composed of three sub-units: a lower loess, bedded layers (intercalation of loams and pseudo-gleys) and an upper loess. Mollusk shells are very abundant and rather well preserved. This allowed the definition of an Upper Pleistocene biostratigraphy for the aeolian deposits of the Great Plains on the basis of the occurrence of identified species within the established stratigraphical units, i.e. *Discus shimeki*, *D. cronkhitei*, *Columella alticola*, (Table 1) (Leonard, 1952). Frankel (1956a,b), reinvestigating the loess deposits of Nebraska and Kansas, indicated a change in the mollusk content from the bottom to the top of the Upper Pleistocene. Leonard (1959) determined two main mollusk zones. As noted by Frankel, these biozones, named Iowan and Tazewellian, show an increase in species richness with a larger number of individuals in the upper zone. Such observations permitted correlation from place to place of the different outcrops of the Peoria Silt right across the Great Plains basin. Leonard (1959) also discussed the ecological significance of these two mollusk zones. He reported on the older one (Iowan) from Kansas, Oklahoma, northern Texas and Nebraska, and the younger one (Tazewellian) from Kansas, southern and central Nebraska, western Iowa and central Illinois. However, because the aim of the study was mostly to refine the biostratigraphy of the Great Plains, this ruled out any precise interpretation in terms of past environmental or climatic changes. More recent high-resolution sampling of the Peoria Silt in Eustis (Nebraska), where the thickness is significant, has provided some insight into this problem (Rousseau and Kukla, 1994).

In Eustis, three main mollusk zones (MZ) were distinguished and named MZ 1, MZ 2 and MZ 3 according to the diversity, abundance and the species content of the mollusk assemblages. They correspond with the zonation described earlier by Leonard (1952) in Kansas (Fig. 2). The wide distribution of the zones, and the similarity of the species content from place to place, show that they represent well defined biostratigraphic units that reflect particular environmental conditions that are relatively uniform over large expanses of the Great Plains. The composition of mollusk assemblages in MZ 1 and MZ 3 is, however, strikingly reminiscent of the pleniglacial assemblages of the European loess belt. The older community of a grassland environment could be compared with the European low diversity loess-steppe *Pupilla* association (Lozek, 1964; Puisségur, 1976; Rousseau, 1987b). The assemblage of the younger zone (MZ 3) shows more species and individuals, more diversity, and an environment in which some sparse arboreal vegetation is present. It can be compared with the European tundra-like *Columella* associations, in which the boreal *C. columella* and the boreo-alpine *Vertigo genesii*, among others, are well represented. In North America, *C. alticola* represents similar ecological characteristics to *C. columella* in Europe.

The extensive distribution of the Iowan and Tazewellian faunal zones in the Great Plains implies also that the results from the Eustis section do not reflect merely local microclimatic variation. They show changes of more general regional significance, expressed through the correspondence analysis of the species counts at Eustis. In this study, this method involved the simultaneous analysis of the species counts and the mollusk assemblages. It permits the determination of the species and the assemblages, which are weighted according to the general variability and, thus, are the most significant for use as environmental indices (Rousseau, 1987b). The results indicate that the maximum cooling appeared in mid-sequence, and that a trend towards decreasing moisture occurred from the bottom to the top the sequence. The deposition of the Peoria Silt in the Eustis sequence took place when both Laurentide and Cordilleran ice sheets expanded, reaching their maximum extent at around 18,000 years B.P. (Andrews, 1987; Hughes, 1987) followed by retreat

Table 1
Biostratigraphy of Crete–Loveland gravels, sands and silts (Illinoian age), lower (Iowan) and upper (Tazwellian) faunal zones of the Peoria loess (Wisconsinan age) and Bignell loess (post-Bradyan age) (from Leonard, 1952, modified)

Species	Crete–Loveland	Peoria-lower	Peoria-upper	Bignell
Anguispira alternata				●
Stenotrema monodon aliciae				●
Trodopsis albolabris				●
Vallonia pulchella				●
Gastrocopta armifera	●		●	●
Hendersonia occulta			●	●
Succinea grosvenori	●		●	●
S. ovalis			●	●
Hawaiia minuscula	●	●	●	●
Heliodiscus parallelus	●	●	●	●
G. holzingeri	●		●	
C. alticola			●	
Striatura milium			●	
Vertigo coloradensis			●	
Ver. modesta			●	
Carychium axiguum	●		●	
Cionella lubrica			●	
Pupilla blandi	●	●	●	
D. cronkhitei	●		●	
D. shimeki			●	
Ver. tridentata	●	●	●	
Euconulus fulvus		●	●	
H. singleyanus		●	●	
Ver. gouldi paradoxa		●	●	
Ver. milium		●	●	
Deroceras laeve	●	●	●	
P. muscorum	●	●	●	
Retinella electrina	●	●	●	
Zonitoides arboreus	●	●	●	
V. gracilicosta	●	●	●	
S. avara		●		
Helisoma trivolvis	●			
Pupoides albilabris	●			
Strobilops labyrinthica	●			
Car. perexiguum	●			
G. cristata	●			
G. tappaniana	●			
Str. sparsicosta	●			
Ver. ovata	●			

(Fig. 2). The growth in ice volume required low temperature, but also an adequate moisture supply, both indicated by the MZ 1 and MZ 2 environments in the periglacial area of the Nebraskan loess hills. Thus, while the first two mollusk zones in Eustis are indicative of relatively high annual precipitation and milder temperatures, the upper MZ 3 shows that cold and relatively dry conditions paralleled the ice retreat. However, these interpretations must be regarded with extreme caution because they relate to only one sequence. Temperature reconstructions appear significant in terms of ice behaviour, while moisture levels appear to conform with regional climatic conditions.

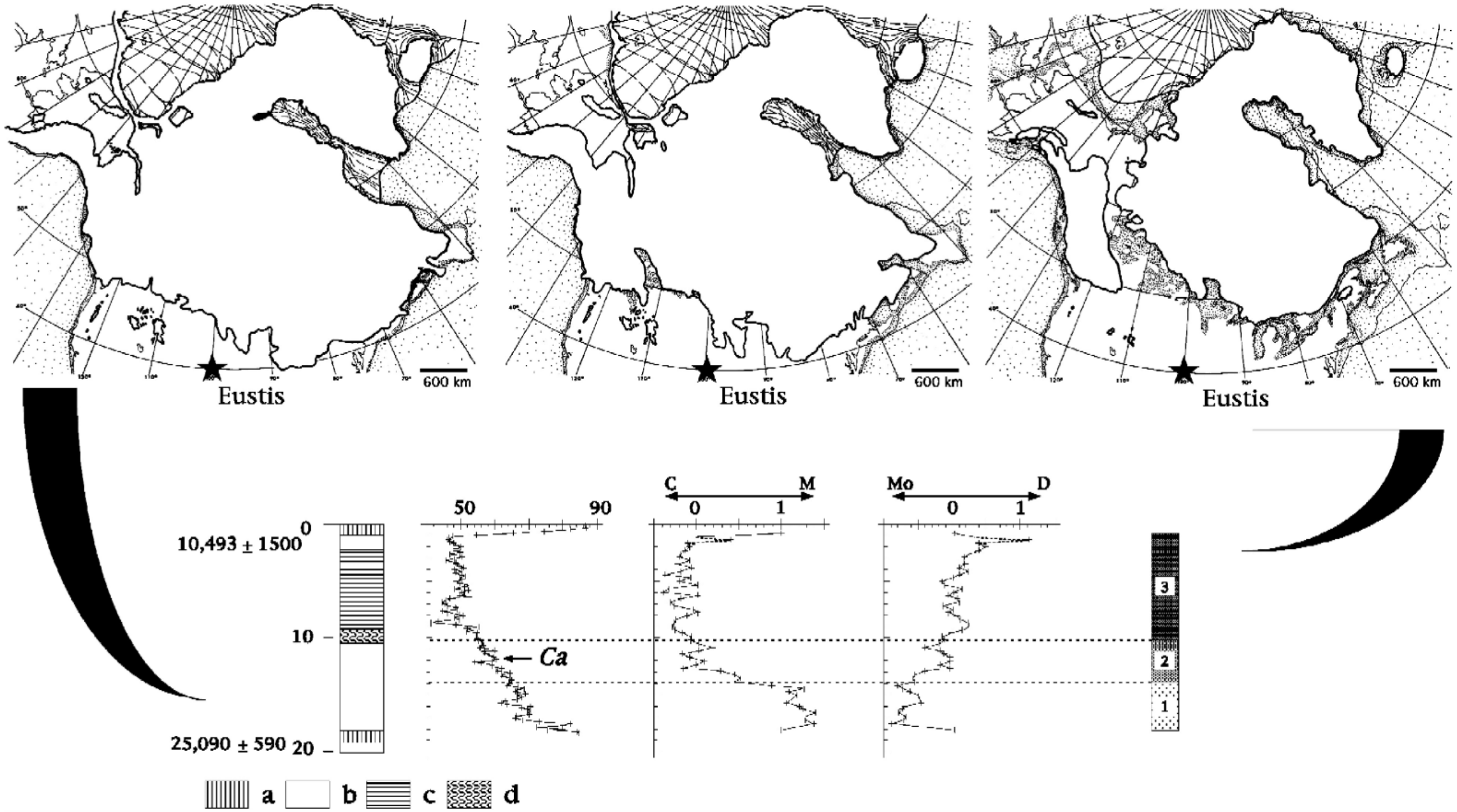

Fig. 2. Time series of the Eustis (Nebraska) Upper Pleistocene sequence. Mollusk zones identified. The temperature and moisture gradients are derived from correspondence analysis of the mollusk assemblages and comparison with the low field magnetic susceptibility (from Rousseau and Kukla, 1994, modified). Reconstructions of the North American ice sheets at 18, 14 and 12 kyears, simulated using a geomorphological model (from Hughes, 1987, modified). (a) Soil, (b) loess, (c) bedded deposits, (d) pseudo-gley.

3. Comparison between different units

Contrary to the pleniglacial assemblages in the Great Plains of North America, the species composition of the mollusk assemblages in the loess deposits of western Europe is always of poorer diversity than in central Europe (Fig. 3). These two main cold assemblages, i.e. the *Pupilla* and the *Columella* communities, essentially correspond to loess steppe and tundra-like environments, respectively. However, the presence or absence of some characteristic species, when comparing the two assemblages of the main regions, suggests an interpretation implying precipitation or temperature variations over Europe rather than accepting the concept of a central origin, as mentioned by Lozek (1964).

The general climate during the Last Pleniglacial in the European loess belt can be compared to the present climate of the cold temperate latitudes of the Earth. Temperature contrasts are important, with long, cold winters, followed by a brief thermal break corresponding to summer, with temperatures higher

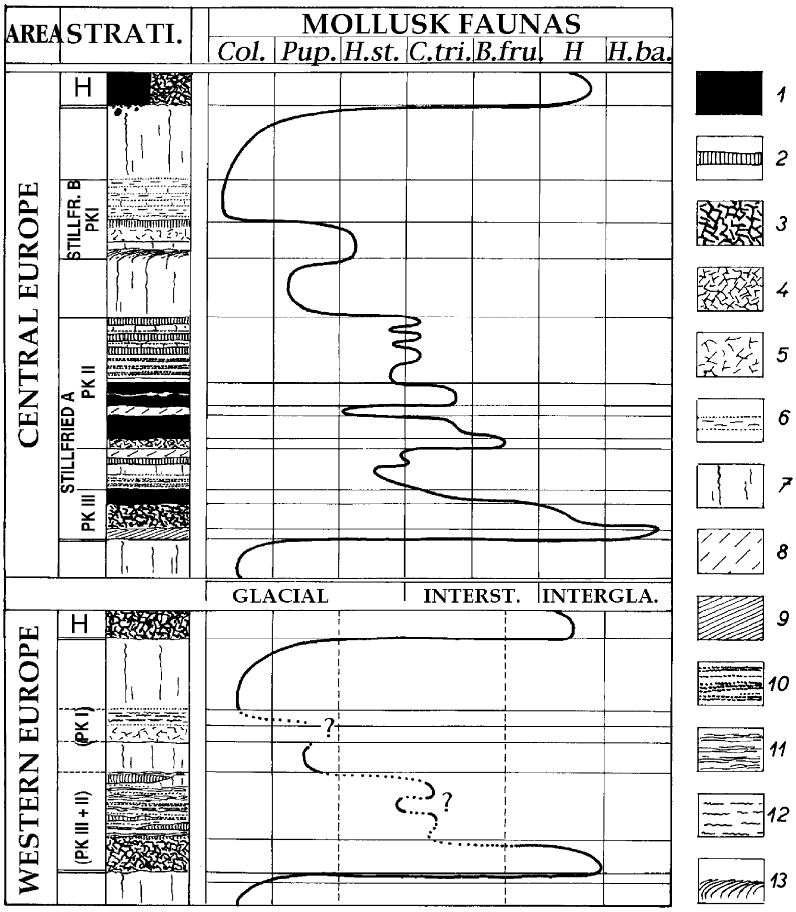

Fig. 3. Comparison of the upper Pleistocene mollusk sequences in western and central European loess series (from Lozek, 1969, modified). Lithology: (1) chernozem, (2) initial stage of a chernozem, (3) brown leached soil, (4) type brown soil, (5) soil slightly decalcified, (6) grey horizon of the loess, (7) typical loess, (8) colluvium, (9) reworked loess, (10) pellet sands, (11) humic soils, (12) horizons slightly deformed by solifluction, (13) soils deformed by solifluction. H—Holocene, R—Rissian, PK—soil pedocomplex. Mollusk assemblages. Col.—*Columella*, Pup.—*Pupilla*, H.st.—*Helicopsis striata*, C.tri.—*Chondrula tridens*, B.fru.—*Bradybaena fruticum*, H.—*Helix*, H.ba.—*Helicigona banatica*. Interst.—Interstadial., Intergla.—Interglacial.

than 10°C. This is in agreement with Berger's (1979, 1988) reconstruction of past insolation. The precipitation regime is continental. Appropriate distinctions must be made between oceanic and continental facies with respect to relative exposure, notably the western or eastern maritime regions and the continental interior, a clear constraining factor affecting the precipitation regime.

A review of the localities where Weichselian cold climate mollusk faunas occur, in western France and Britain, shows that the tundra-like assemblage, typified by *C. columella*, spread to the extreme western parts of the continent in sheltered site (Bréhat, Jersey, north of France, England: Rousseau et al., 1990) (Fig. 4). In comparison with central European faunas of the same type, however, those of western Europe are impoverished in terms of species numbers leading to two different domains being recognized.

The investigations of Lozek (1968) and Kukla (1977) indicate that the loess of the European belt originated under cold, continental climatic conditions with long, severe, but relatively dry winters, followed by humid and fairly warm conditions, followed by a dry phase that persisted until the next winter. In fact, these interpretations apply only to central Europe. The differentiation between western and central European mollusk assemblages implies that these interpretations cannot be strictly applied to

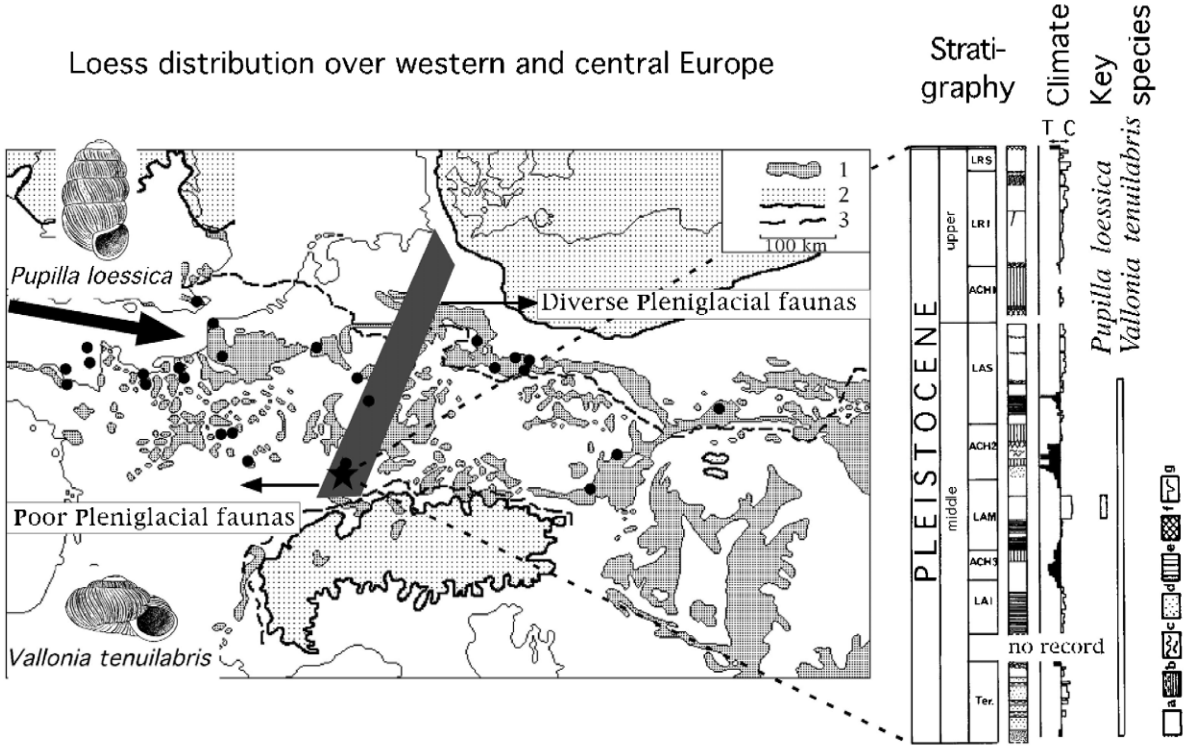

Fig. 4. Distribution of the loess sediment over Europe with reconstruction of the continental ice caps. The dots correspond to mollusk sequences reviewed in Rousseau et al. (1990). The grey oblique zone indicates the boundary between the two discussed mollusk domains corresponding to poor pleniglacial faunas towards the west and highly diverse pleniglacial faunas eastward. Stratigraphy, climatic and environmental variations of Achenheim, and pleniglacial biomes evolution with particular emphasis on *P. loessica* (figured at the bottom from Lozek, 1990) and *V. tenuilabris* (figured near the top from Lozek, 1990) in Achenheim (from Rousseau, 1986, modified). The black arrows indicate the main wind direction. (1) Loess, (2) last glacial advance, (3) maximum glacial advance. Lithology: (a) loess, (b) bedded formations, (c) colluvium, (d) fluviatile sands, (e) humic soils, (f) Bt soil horizon, (g) frost wedges.

the whole of Europe. Other data provide complementary support for this interpretation. These include the following.

(a) Lautridou's investigations in Normandy and Brittany determined that, for the last climatic cycle, westerly winds contributed significantly to loess sedimentation in this region. He concluded (Lautridou, 1985) that summers were moist and cloudy during the pleniglacial. Furthermore, Lautridou and Sommé's (1981) investigations on fossil ice-wedges show that deep and continuous permafrost was present during the Weichselian glacial in western Europe. Pursuing this line of research, Van Vliet-Lanoë (1988) has investigated the Weichselian European permafrost in some detail. She concludes that, taking into account field experience in the Arctic, the physical limits relevant to existing permafrost cannot be applied in the same terms for the last western European Pleniglacial. Rather, she explains the occurrence of continuous permafrost in this part of mid-latitude Europe in terms of relative moisture and low insolation levels.

(b) Joussaume's (1989) results of the modelling of the last glacial maximum indicate the occurrence: (1) of the strongest cooling in western Europe; (2) of high precipitation during both winter and summer in western Europe with strong westerly winds; and (3) of a warming in central Europe. These results are partly supported by Thompson Webb et al. (1993) who also indicate drier conditions in eastern Europe. However, a disagreement remains concerning temperature reconstructions.

The period for vegetation and land snails development was less favorable westwards than eastwards. However, given that moisture is also a major limiting factor in land and snail development (Rousseau, 1989), greater precipitation towards the west apparently led to a degree of selection among the tolerant cold species. Thus, the impoverishment of Upper Pleistocene pleniglacial faunas from east to west seems to have corresponded with increasing atmospheric moisture or precipitation, at least during the growth interval. Such an interpretation appears as paradox. For a vegetal point of view, a steppe formation, represented by a *Pupilla* assemblage, would indicate low precipitation with a strong evaporation, whereas tundra, represented by a *Columella* assemblage, would imply low precipitation with almost no evaporation. Thus, a discrepancy appears to exist between vegetation and mollusk evidence that cannot be tested, because pollen is not recorded in sufficient concentrations within the studied loess sequences. This might then be regarded as a limitation on the use of mollusks in environmental reconstruction, but this question is given further consideration below.

The mollusk dynamics of the Pleniglacial within the last climatic cycle can be thus considered as a model that is testable using long-term extrapolation, i.e. the four last cycles. This takes into account that, in the Achenheim sequence (a key reference site in the Rhine valley), the analysis of the malacofauna has demonstrated that each climatic cycle has its own course and characteristics (Rousseau, 1987b, 1991) (Fig. 4). When reviewing the numerous mollusk studies from Upper Pleistocene sequences in Northwestern Europe, Rousseau et al. (1990) noticed that *P. loessica* and *Vallonia tenuilabris* are never mentioned. Furthermore, *C. columella*, *P. alpicola*, *Vertigo parcedentata* and *Ver. genesii* are always present in central European deposits, dating from the Middle Pleistocene to the Late-Glacial, whereas a variable distribution is indicated for western Europe. The investigation by Rousseau et al. (1990) concluded that *P. loessica* and *V. tenuilabris* (Fig. 4) are biogeographical and biostratigraphical indicators of domains, the extent of which varied during the Pleistocene. In fact, studies of the Pleniglacial mollusk dynamics in Europe over different cycles suggest that it is vital to consider both the occurrence of climatic events and the location of the analyzed loess sites with respect to the southern limits of Scandinavian ice cap.

It is important to emphasize that the *Pupilla* assemblages seem to be associated with the amount of precipitation to a greater degree than those of *Columella*, a situation similar to that found in the Great Plains, where the *Columella* assemblage occurs on top of the loess sequence at a time when the conditions were at their driest. Although *C. columella* is generally interpreted as a moisture-demanding species, the view can be taken that the *Columella* assemblage might correspond rather more with a decrease in precipitation. One element in such an interpretation can be derived from looking at the present distribution of *C. columella* in Europe. This species occurs mostly in Scandinavia, in the tundra-mountain environments. Two localities where *C. columella* has been recognized, Kongsvold (62°21′N, 9°37′E—Norway) and Abisko (62°18′N, 18°49′E—Sweden) have an annual precipitation of 473 and 300 mm, respectively. Such precipitation totals might well be considered to be low for a moisture-demanding species. In fact, while the precipitation regime remains low, the determining factor is the availability of moisture at the ground level, a condition driven by a low evaporation.

4. “Expanded” biostratigraphy: Chinese loess mollusk assemblages

One of the first analyses of the Chinese mollusk assemblages in the thick loess in Shaanxi Province indicated the occurrence of terrestrial species right down the Luochuan sequence, i.e. throughout the complete Quaternary record (Chen et al., 1982). Two main assemblages, the *Cathaica* and the *Metodontia*, were identified and interpreted as corresponding to cold and dry, or warm and wet, environments representing monsoon conditions (Chen et al., 1985) (Fig. 5). However, the time resolution, as presented in Fig. 5, was not high to permit any detailed comparison with other proxies. Subsequent investigations of the Luochuan sequence have since provided extensive material for more precise interpretation and comparison. Studying the variations in time of the particular species *Cathaica* sp. and *Metodontia beresowskii*, Wu et al. (1996) interpreted the data as indicating that the peak occurrence of individuals during the last climatic cycle corresponded with global oscillations, as expressed in the Atlantic Ocean record and related to the main phases of iceberg discharge. A similar interpretation was proposed by Porter and An (1995), on the basis of grain size analysis in the same region. Considering the mollusk assemblages within the fossil deposits on the basis of the present distribution of identified species, it is possible to show high-resolution variations that may be related to cycles of humidity and aridity.

Identified snail species can be clustered into ecological groups as determined by Rousseau and Wu (1997), with the species considered according to their moisture requirements. The xerophilous (taxa living in dry places, exposed to the sun) species consist of *V. tenera*, *P. aeoli*, *Cathaica richtofeni*, *Cat. pulveratrix*, and *Cat. pulveraticula*. The hy-

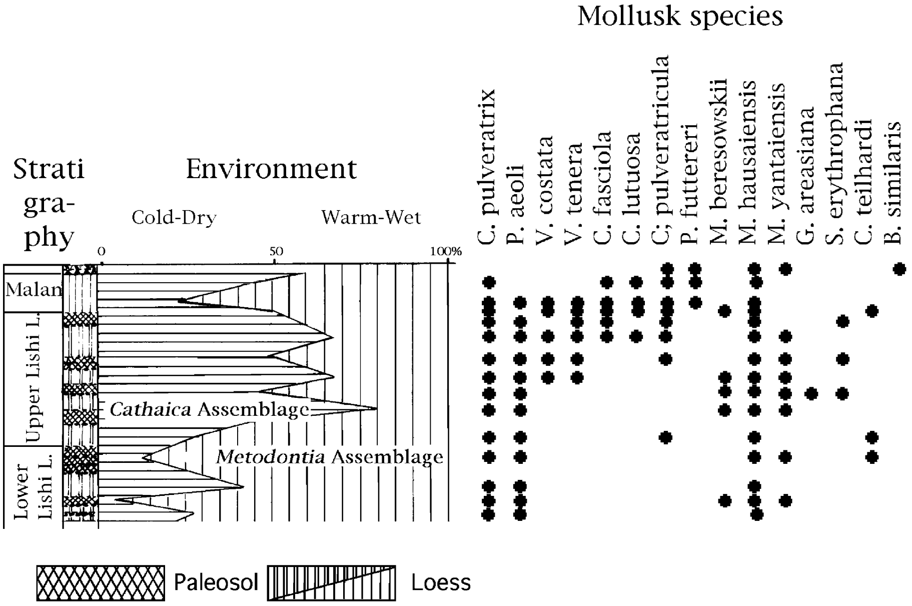

Fig. 5. Biostratigraphy and environmental changes reflected by the fossil snails of the upper Luochuan sequence (from Chen et al. 1985, modified).

grophilous (warmth- and moisture-loving taxa) set includes *Macrochlamys angigyra*, *Opeas striatissimum*, *Vitrea pygmaea*, *Gastrocopta armigerella*, *Punctum orphanum*, *M. yantaiensis*, *M. huaiensis*, *M. beresowski*, *Kaliella lamprocystis* and *Succinea* sp. A third group can be extracted from the previous one, as it includes the species belonging to *Macrochlamys*, *Opeas*, *Vitrea*, *Gastrocopta* and *Punctum*, species that live in particularly warm and wet habitats, and currently distributed in southeastern China (Chen and Gao, 1987; Yen, 1939). Their fossil occurrence in the studied section is an indicator of humid conditions associated with particularly strong summer monsoons.

Using a time scale based on the susceptibility model of Kukla et al. (1988), a comparison of variations in the different groups during the last 244,000 years shows two different scenarios for the S1–L1 (the last climatic cycle) and S2–L2 (the penultimate cycle) intervals (Fig. 6). The total number of individuals is higher in L2–S2 than in the younger sequence. The oriental taxa show maximum values of between about 160,000 and 170,000 years that correspond to the most strongly weathered L2SS2 subunit within the L2 loess. More generally, the L2–S2 sequence shows higher values of the oriental species than is found in L1–S1, although the variation in the magnetic susceptibility signal indicates the same magnitude in both cycles. The warm and moist species indicate at least three main maxima of small magnitude, labelled 2, 3 and 4, during the interval 10,000–100,000 years. However, the interval 130,000–244,000 years is marked by a strong maximum centered at about 170,000 years, with smaller peaks at about 140,000, 220,000 and 240,000 years. The oriental and hygrophilous taxa indicate similar maxima between 244,000 and 130,000 years, although they differ during the S1–L1 cycle, especially during the deposition of the L1SS1 subunit (Fig. 6). Finally, the xerophilous species show two main maxima, with counts (805 and 585) that are higher in the older sequence than the maximum of about 70,000 years in the younger sequence. Contrary to the situation for the moist taxa, the maxima for these species does not correspond exactly with the minimum readings in the magnetic susceptibility record, the latter being interpreted as representing the coldest conditions. In both the S1–L1 and S2–L2 sequences, changes in the xerophilous species show a lead of about 5,000 years with respect to the changes in the magnetic susceptibility signal in the loess deposits. The converse is true of the moist species (Rousseau and Wu, 1999).

Comparison with other proxy data from pedological or magnetic investigations makes it possible to interpret the Chinese mollusks in terms of monsoon-induced indicators. Variations in the hygrophilous, oriental and xerophilous species fit the Fe_d/Fe_t maxima (Guo et al., 1998) calculated from the Changwu sequence (100 km far from Luochuan). This endorses the view that phases with increased summer or winter monsoons occurred during the glacial intervals of the last 244,000 years BP. It has been demonstrated in modern environments that conditions detrimental to mollusk development and growth result in low diversity and reduced numbers of identified individuals (Dyduch-Falniowska, 1988; Rousseau et al., 1993). Thus, the differences observed between S2–L2 and S1–L1 sequences can be interpreted, according to these assumptions, as corresponding with times in the younger S1–L1 series that were less favorable for mollusks. This conforms with the work of Hovan et al. (1989), suggesting increasing aridity over the region during the past 500,000 years. Other mollusk records exist elsewhere in the Chinese Loess Plateau (Keen, 1995; Wu et al.,1999), but they are not continuous and they concern only the last climatic cycle (Upper Pleistocene).

The snail assemblages at Luochuan, interpreted as belonging to xerophilous, hygrophilous, and oriental groups, record environmental changes related to the monsoon variations. The correspondence between the mollusk and pedological records may indicate that their variations are representative of the Southeast Asia monsoonal regime during the last 244,000 years. If that is the case, potential correlation with monsoon events identified in other “monsoon regions,” such as the Indian Ocean and Africa might be considered. An example is provided by the strong monsoon signal yielded by the hygrophilous and oriental mollusk taxa at about 176 kyears in the Luochuan sequence. This corresponds not only with a well expressed monsoon event in the Indian Ocean, but also with the record of the Mediterranean sapropels that are representative of the African monsoon.

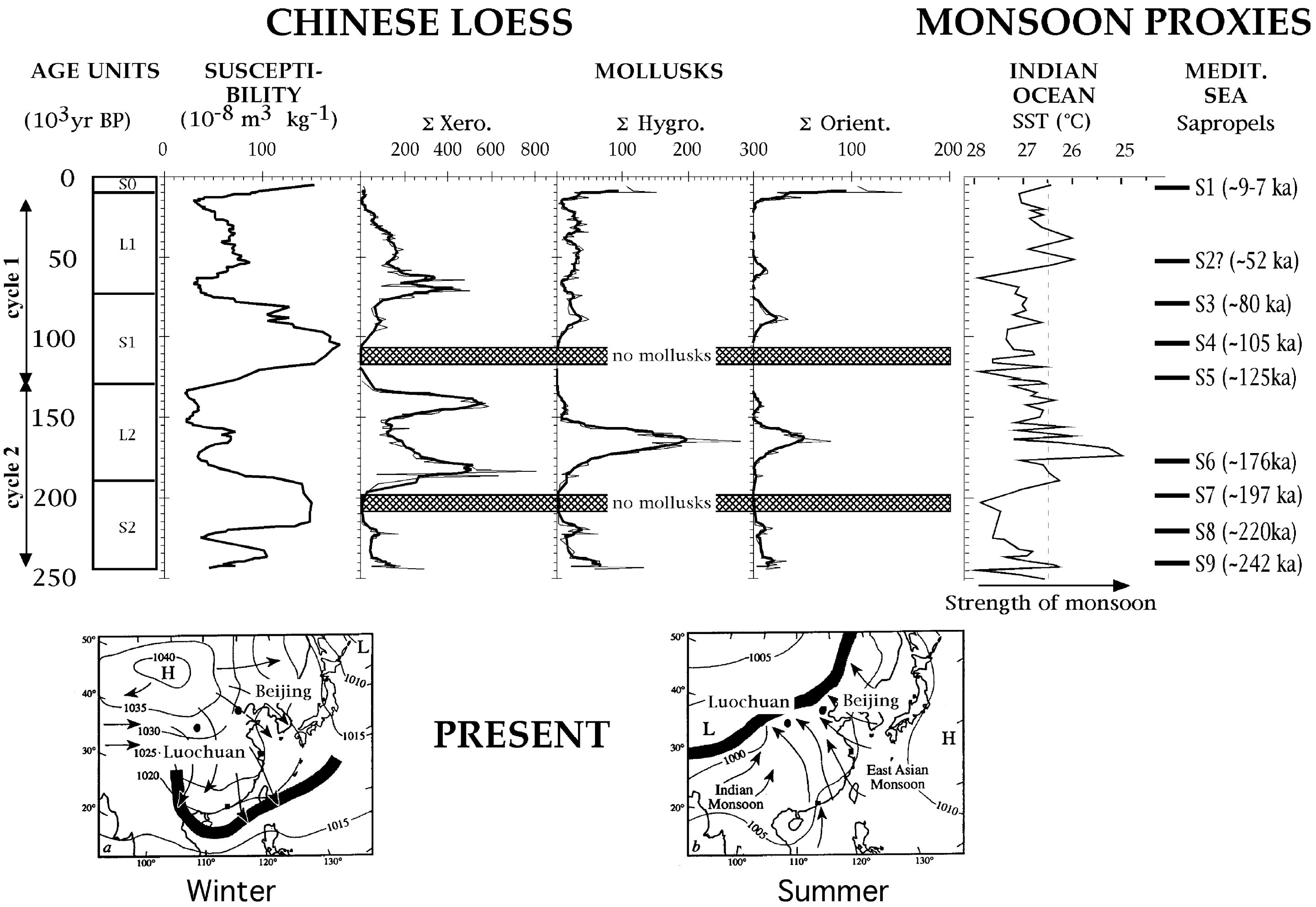

Fig. 6. Comparison of the mollusk variations at Luochuan (Chinese Loess Plateau) during the last two climatic cycles (last 250 kyears) (from Rousseau and Wu, 1999, modified) with other monsoon proxies from the Indian Ocean and the Mediterranean Sea (Clemens et al., 1991; Rossignol-Strick, 1983). The mollusk species have been grouped according to their ecological characteristics. Indication of the present meteorological conditions during winter and summer SE Asian monsoons (from Porter and An, 1995, modified).

In the Indian Ocean, Clemens et al. (1991) demonstrate a strong contrast in the sea surface temperature over this area at that time. In the Mediterranean, Sapropel S6 occurs at about 175 kyears (Rossignol-Strick, 1983), being one of the best developed in the last 600 kyears. Both indices suggest a strong monsoon signal (Masson et al., 2000) that fits the mollusk results well (Fig. 6). However, although such correspondence appears interesting, more investigations are needed before extrapolation can be undertaken with confidence over such great distances.

5. Conclusions

This review, although by no means exhaustive, is concerned with recent developments in loess biostratigraphy using mollusk assemblages. This discussion rests upon a framework provided by the investigations of the author as a means of presenting various aspects of the present state of the art. From a general point of view, new advances in loess biostratigraphy require high-resolution investigations and quasi-continuous records. The three examples presented in this paper clearly show how important the resolution is and what benefit may be gained from comparisons with several palaeoclimatic proxies. The last two examples also stress the importance of sufficiently long records for comparisons with other records or proxies. The first of these shows that comparison of mollusk records within a large domain allows us to recognize two main biogeographic regions, the boundaries of which varied to east and west during the Quaternary. The second example shows how comparison of the long mollusk record from China can form the basis of the reconstruction of the monsoonal regime during the last 250,000 years (Rousseau et al., 2000). It is further shown that the use of statistical methods such as correspondence analysis can provide distinct improvements, as is evident in the first example, although this is not always so, as indicated in the third example.

This review shows that mollusk faunas are not strictly identical from one cycle to another, and that they may display longitudinal and temporal variations. Their composition is an expression of both local and global climatic conditions. Thus, they contribute to a fuller understanding of stratigraphical events that represent the responses of the environment to climate and climatic change. At one site, a local ecostratigraphy may be proposed, based on the succession in the recognized assemblages, which can be related to a more general chronostratigraphy, including the interglacial–glacial cycles of Kukla (1977) and Kukla and Cilek (1996) or the $\delta^{18}O$ SPECMAP chronology (Imbrie et al., 1984). In fact, if the occurrence of mollusk faunas belonging to particular biomes (biome being used in its basic biogeographical sense) is primarily due to decreased temperatures, a factor commonly invoked in the literature, important variations in the pleniglacial assemblages are responses to different precipitation regimes in the regions they occupied. The different examples presented in this paper support this interpretation although the studies cited come from different geographical contexts.

Recent advances in loess biostratigraphy offer a powerful tool that, according to the numerous sequences investigated, provide accurate and precise proxy data that cannot be ignored in any consideration of aeolian deposits as an indicator of global climatic change.

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