A new molluscan record of the monsoon variability over the past 130 000 yr in the Luochuan loess sequence, China

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ABSTRACT

This paper presents a new record of monsoon changes that occurred in China during the late Pleistocene. Study of terrestrial mollusks from the loess sequence in Luochuan indicates alternating strengthened summer and winter paleomonsoons. These variations—based on the content of xerophilous, hygrophilous, and oriental species—are in very good agreement with the variation inferred from pedology, sedimentology, and climate modeling. The three occurrences of currently southeastern species in the sequence indicate that the climate conditions were warmer and wetter than today at about 88, 60, and 10 ka. The main occurrence of xerophilous taxa between 75 and 65 ka is interpreted as drier than today, in agreement with other proxy data. These results demonstrate that fossil terrestrial mollusk data can provide reliable information on past monsoon variability in Asia.

INTRODUCTION

Intensive studies of the Chinese loess sequences have been used to reconstruct climate history from the onset of Northern Hemisphere glaciations (2.4 Ma) to the present (Heller and Liu, 1982; Kukla, 1987). The alternation of paleosols and loess units all along the Loess Plateau permits the development of a general stratigraphy for the Chinese Quaternary (Liu et al., 1985). Moreover, the recognition of different paleomagnetic reversals has provided a chronological framework for these continental deposits and has permitted correlations with marine isotope stratigraphy (Kukla et al., 1990).

Among the numerous geologic approaches to the study of the Chinese loess sequences, geophysics and sedimentology have contributed greatly to the knowledge and the interpretation of environmental changes (Liu et al., 1985). The intensity of magnetic susceptibility is high in interglacial paleosols and lower in the loess units (Kukla and An, 1989). Variations of this signal correlate with the dust record in the Pacific Ocean off China (Hovan and Rea, 1991). The study of the distribution of grain size has indicated the origin of the loess material from the neighboring deserts (Gobi and Takla Makan) but also has recognized the effect of orbital periodicities (Ding et al., 1992). Recently, the grain-size variations in the last glacial loess (Malan Loess) were correlated with climatic oscillations corresponding to massive iceberg discharges into the North Atlantic (Porter and An, 1995).

All these studies show the importance of the Chinese loess sequences in providing a better understanding of climate change since 2.4 Ma. The bioclimatic approach of these sequences, however, has not been well developed. Descriptions of vertebrate assemblages have been made (Xue, 1984) with a sampling interval precluding any precise correlation with the events or variations previously mentioned. Pollen analyses over the Loess Plateau indicate a temperate vegetation with different vegetation patterns controlled

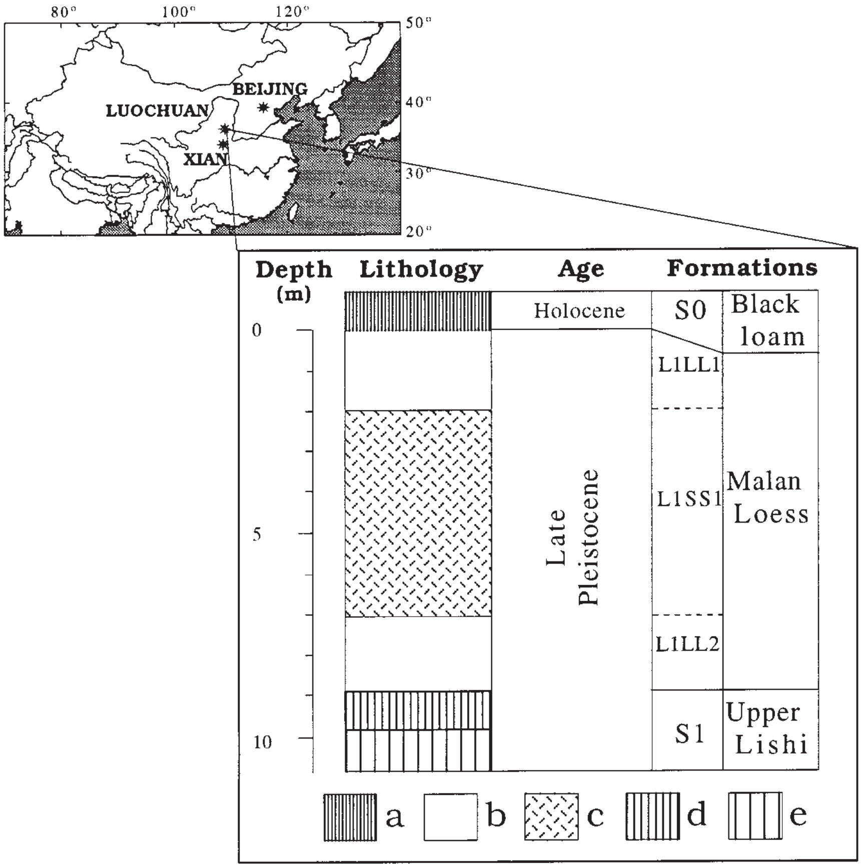

Figure 1. Location of Luochuan section and general sequence deposited during late Pleistocene in Luochuan. Base of Holocene soil is taken as reference for depth measurements. Key: a—humus soil, b—loess, c—weathered loess, d—bioturbated soil, e—soil B horizon with carbonate nodules at its base.

by global climate changes (Sun et al., 1995). The study of phytoliths provided complementary data, estimates of annual average temperature and precipitation since 30 ka (Wu et al., 1995).

Finally, although mollusks have been studied intensively in European loess sequences, malacological faunas have only been noted as being present in some Chinese loess sequences. A particularly loose sampling in the Luochuan sequence (132 m thick) indicated the occurrence of terrestrial mollusks throughout the interval corresponding to the past 2.4 Ma (Chen et al. 1982). Keen (1995) recently published a new mollusk investigation in the Chinese loess, for biostratigraphical purposes, that shows differences in the composition between interglacial and glacial mollusk assemblages. In both studies, however, the sampling interval did not permit precise characterization of the environmental changes that terrestrial mollusks can provide. For this reason, we investigated the Luochuan sequence (Fig. 1) at a higher resolution, focusing our study on the late Pleistocene, which is the best analyzed and the best known.

STRATIGRAPHY AND METHODOLOGY

The town of Luochuan (35°45'N; 109°25'E) is located 190 km north-northeast of Xian, in an area where the average elevation is 1000 m. The studied section is situated near the Potou hamlet on the slope of a gully running to the Heimugou stream. Luochuan is located at the northern limit of the summer monsoon, within the East Asian monsoon system (Zhang and Liu, 1992; Yoshino, 1978; Ramage, 1971).

The late Pleistocene stratigraphy of the Chinese loess sequence encompasses two different formations. The S1 pedocomplex of the interglacial soil and early last glacial belongs to the Upper Lishi Formation (Liu et al., 1985) (Fig. 1). The loess deposit, which comprises at least two loess subunits (L1LL2 and L1LL1, bracketing a weakly weathered paleosol, L1SS1) corresponds to the Malan Loess (Kukla and An, 1989). The Holocene soil (S0) is named Black Loam (Kukla and An, 1989). Numerous thermoluminescence dates in Luochuan (Forman, 1991, Xiao et al., 1995) and the correlations with marine cores allows us to propose the following chronology: S1 seems to represent the terrestrial equivalent of marine isotope stage 5; L1LL2, stage 4; L1SS1, stage 3; L1LL1, stage 2; and S0, stage 1, i.e., the Holocene (Fig. 1) (Kukla et al., 1990).

We measured the low-field magnetic susceptibility every 10 cm in the loess and every 5 cm in the paleosols down to the base of S1, using a portable Bartington magnetometer as used by Kukla in the same section in 1987; only 10 measurements at each level were averaged (Kukla and An, 1989). Parallel to our measurements, 118 samples (10 L each) were taken for the malacological study. Each sample was washed and sieved in the field, the smallest mesh being 0.5 mm. The mollusk shells were picked under a binocular microscope. All the identifiable mollusk remains were considered in the total count of individuals (N_I) following the process described by Puisségur (1976), and the abundance was expressed as number of individuals per unit volume.

RESULTS AND DISCUSSION

The intensity of magnetic susceptibility varies between 30 and 190×10^{-8} $m^3 \cdot kg^{-1}$ (Fig. 2). The highest values are found in S1 and S0. Starting at the bottom of the section, the intensity increases strongly over 0.75 m from 45.9 to 184.5 × 10^{-8} $m^3 \cdot kg^{-1}$. Then the values drop progressively to reach 31.4×10^{-8} $m^3 \cdot kg^{-1}$ within L1LL2. The top of S1 is characterized by several oscillations corresponding to the pedologic variation easily observable in the field. The transition between S1 and L1LL2 is marked by a strong drop in the intensity over about 0.5 m. At the top of L1LL2, the intensity increases again. Within L1SS1, it shows a minimum of 60×10^{-8} $m^3 \cdot kg^{-1}$ at 4.5 m depth. Finally, the values progressively drop again within L1LL1 to reach 30.7×10^{-8} $m^3 \cdot kg^{-1}$ at 0.6 m depth and then increase again to 104 × 10^{-8} $m^3 \cdot kg^{-1}$ at 0.7 m above the L1-S0 boundary (Fig. 2). The intensity variations that we measured are similar to those published by Kukla and An (1989), confirming the reliability of our record and making feasible a precise stratigraphic framework for our mollusk sampling.

Almost all the levels yielded shells of terrestrial mollusks; the minimum count was 1 shell at the base, and the maximum was 512 in L1LL2 (Fig. 2). In the upper half of S1, N_I varies parallel to the magnetic susceptibility. However, in the rest of the section, the two types of data are not parallel. At the S1-L1LL2 boundary, N_I increases very rapidly from 73 to 277 individuals per sample at 8.40 m. The L1LL2 subunit has the highest values of N_I in the sequence: 512 at 7.90 m, and 495 at 6.90 m. There is an intervening minimum of 103 individuals. Then, within subunits L1SS1 and L1LL1, N_I shows a relatively regular trend toward lower values and reaches the minimum of 7 at 1 m depth. N_I increases again near the top of L1LL1 and within S0. Variation in the snail count in Luochuan does not show a general pattern that parallels the magnetic susceptibility. This result is in contrast to the results obtained for the last glacial maximum in a loess sequence in Nebraska, United States (Rousseau and Kukla, 1994).

These results can be interpreted in several ways. N_I, in the upper part of unit S1, drops strongly. A possible explanation may be dissolution of the shells due to early pedogenic processes. This explanation would favor the interpretation of the pedogenic origin of the magnetic grains present in the sediment (Zhou et al., 1990). We must, however, keep in mind that the species count is similar to that of the rest of the sequence (Fig. 2). The L1LL2 subunit corresponds to samples yielding the maximum N_I count. To the contrary, N_I varies inversely with the magnetic susceptibility intensity. Two major facts are clearly recognizable: (1) the rapid increase of N_I just above the S1-L1 boundary, and (2) the strong decrease in N_I centered on about 7.5 m, despite the lack of any major oscillation of the magnetic susceptibility. The drop of N_I within

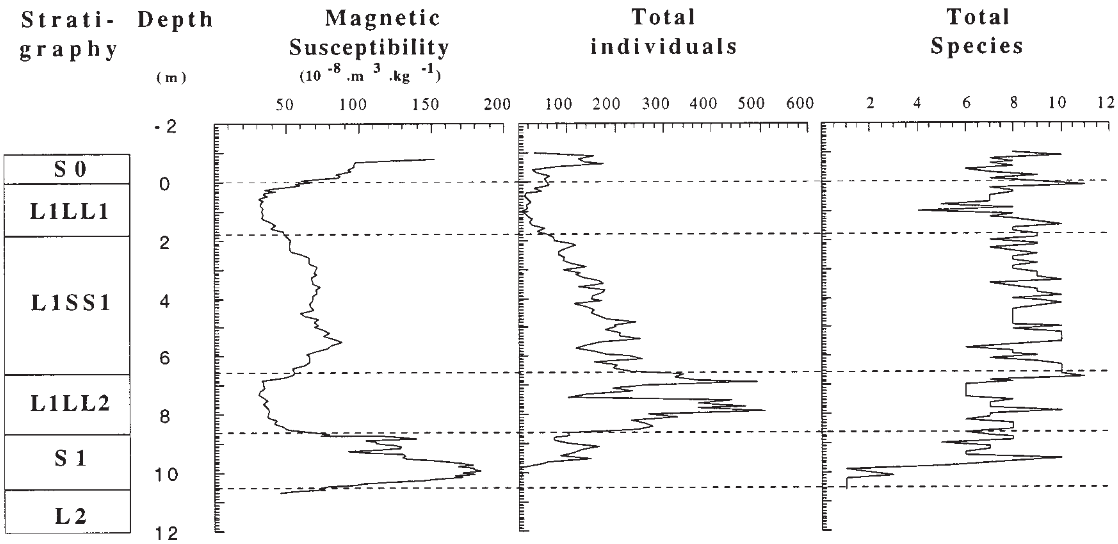

Figure 2. Variation of magnetic susceptibility, total individuals, and total species identified for the Luochuan section vs. depth. Counts are expressed in number per unit volume (10 L of sediment).

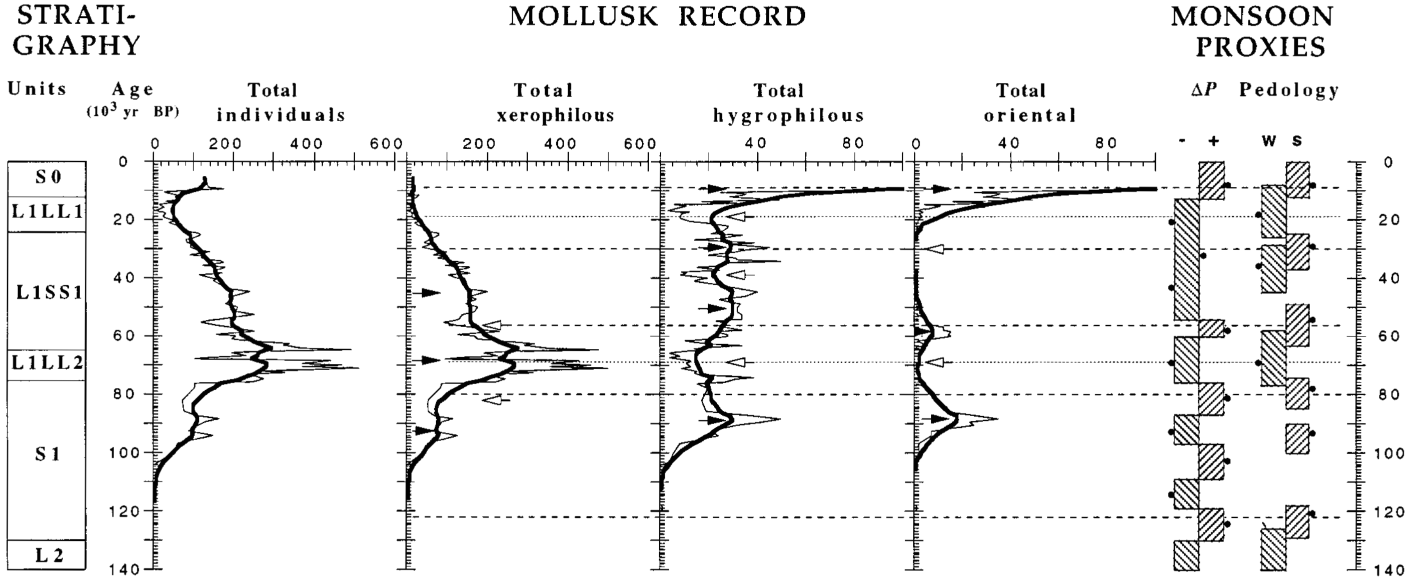

Figure 3. Variations of malacological record during late Pleistocene at Luochuan. Counts are expressed in number of individuals per unit volume of sediment (10 L). Thick lines are smoothed curves (Stineman function). Comparison with monsoon proxies deduced from modeling (Δ*P*, from Prell and Kutzbach, 1987) and pedological analyses (Liu et al., 1995). Positive (wet) and negative (dry) values of precipitation index shown by plus and minus. Indices of strengthened winter or summer monsoon shown by W and S. Solid circles locate peak values for each proxy, and arrows point to maxima (solid) and minima (open) in mollusk curves. Dashed line, wet conditions, and dotted line, dry conditions, in both pedology and model analyses. Ages based on magnetic susceptibility model (Kukla and An, 1989; Kukla et al., 1990).

L1LL1 is associated with a drop in the number of species of terrestrial mollusks, which seems to show particularly strong conditions as emphasized by the low values of magnetic susceptibility (Fig. 2). In that case, no pedogenic process, such as decalcification, seems to have affected the mollusk assemblages.

Although individual or species counts are basic elements for the interpretation of the loess sequence, paleoclimatic information can be derived from the ecological characteristics of the different species identified. The fossil individuals from the Luochuan sequence have living representatives in Asia from which the environmental preferences of the fossil taxa can be extrapolated. Two main groups were identified in the present study according to the moisture requirements of each taxon. The xerophilous (taxa living in dry places, exposed to the sun) species consist of *Vallonia tenera*, *Pupilla aeoli*, *Cathaica richtofeni*, *C. pulveratrix*, and *C. pulveraticula*; the hygrophilous (warmth and moisture loving taxa) set includes *Macrochlamys angigyra*, *Opeas striatissimum*, *Vitrea pygmaea*, *Gastrocopta armigerella*, *Punctum orphanum*, *Metodontia yantaiensis*, *M. huaiensis*, *M. beresowski*, *Kaliella lamprocystis*, and *Succinea* sp.

The composition of the snail fauna shows a high proportion of xerophilous species throughout the section, whereas the hygrophilous species never exceed 100 individuals per unit volume, except at the base of the Holocene (Fig. 3). Such a compositional mix is interesting considering the location of Luochuan in northern central China. The highest abundance of xerophilous taxa was between 75 and 65 ka, i.e., in the L1LL2 subunit. After this interval, the N_I values of xerophilous species decrease, show a plateau at about 52 ka, and then decrease to the lowest values in the L1LL1 subunit. The smooth curve of the xerophilous taxa indicates a main maxima centered at 93–85 ka. At the top of the sequence, the Holocene soil shows very few individuals of this group.

During glacial times (i.e., marine stages 2 and 4), two particular mollusk assemblages are identified according mainly to moisture and temperature differences between winter and summer (Puisségur, 1976). However, during stage 3, the differentiation is much more difficult, showing dry and moist tolerant species all together. In the Luochuan sequence, similar distribution occurred during the late Pleistocene. Although compared to the xerophilous fossils, the number of individuals is considerably lower, the variation through time of the hygrophilous taxa provides interesting information about environmental dynamics. The smoothed curve shows three minima, centered at about 65, 40, and 20 ka. The first minimum coincides with the high values of the xerophilous taxa (Fig. 3), but the other two seem to correspond to a relatively significant decrease in the moisture conditions in the area, contrary to the Holocene soil, which presents the highest count of hygrophilous species at its base. Among these hygrophilous taxa, *Macrochlamys*, *Opeas*, *Vitrea*, *Gastrocopta*, and *Punctum* are species living in particular warm and wet habitats, currently distributed in southeastern China. Their occurrence in the section indicates particularly strong summer monsoons. These taxa show a maximum at about 88, 60, and 10 ka. Currently they are characteristic of particularly warm and wet environments rich in humus, as observed in southeast China. Today's arboreal vegetation in the Luochuan area is mainly restricted to very few places on gully slopes. The occurrence of these southern species in the Loess Plateau indicates that conditions favorable to their growth in such a northern position may correspond to an inland (northwesterly) shift of their distribution mostly controlled by monsoons. Consequently, the Luochuan sequence shows that at least three times during the past 130 000 yr, climatic conditions (warmer and wetter than present) allowed presently southerly species to live and grow in this locality at about 92–86, 60–56, and 14–10 ka. This result appears to be of particular importance as the Luochuan area is now in a key position.

We compared our results to other paleomonsoon proxies to improve our interpretation of a possible connection of the snail assemblages in Luochuan with any variation to the Asian climatic system. Two different proxies of the Asian monsoon are used because they are derived from completely different data sets: modeled output and geologic analyses.

Prell and Kutzbach (1987) studied monsoon variability over the past 150 000 yr, showing that most of the variation occurred at orbital periodicities. They identified monsoon maxima (positive changes in precipitation, i.e., $\Delta P > 0$) over the 0°–30°N band, which coincides with precession maxima and Northern Hemisphere insolation maxima during interglacial or interstadial intervals (Fig. 3). During glacial times, the signal is weaker and shows a higher variability from point to point in the area considered. Minima in the model are shown at about 93, 69, 43, and 20.5 ka, respectively, whereas minima at 70, 40, and 20 ka occur in the smoothed curve of the hygrophilous taxa (Fig. 3). On the contrary, the xerophilous taxa show maxima at about 93, 70–65, and 45 ka.

Such results seem to indicate that the mollusk record in Luochuan is in general agreement with this model output, which presents a general assessment of the variability of the paleomonsoon system, and consequently a more global signal.

The study of both the chemical weathering index and the SiO_2/TiO_2 ratio permitted Liu et al. (1995) to describe independent variations in summer- and winter-monsoon indices during the last climatic cycle. Xiao et al. (1995) published another index of the winter monsoon, based on the maximum grain size of quartz, which shows variations similar to those in the winter monsoon index by Liu et al. (1995). The summer monsoon index shows maxima at about 78, 54, 29, and 8 ka, which are interpreted as strengthened precipitation. These peaks coincide with the high values of the hygrophilous species in the Luochuan sequence at about 54, 29, and 8 ka (Fig. 3). Moreover, the highest values in the pedological study, indicating a strengthened winter monsoon at about 69, 37, and 18 ka, correspond to the lowest values of the hygrophilous taxa, meaning drier conditions, at 68, 38, and 20 ka. On the other hand, the high values of the geologic winter monsoon indices at 69, 37, and 18 ka correlate with the 69 and 37 ka peaks of the xerophilous taxa, whereas nothing is noticed at 18 ka. Overall, the mollusk assemblages indicate events that are recorded by other totally independent indices.

These two comparisons with different monsoon proxies strongly emphasize that the snail assemblages in Luochuan, interpreted in terms of xerophilous, hygrophilous, and oriental groups, record environmental changes that were related to the monsoon variations that occurred in Southeast Asia during the late Pleistocene. Moreover, the general decrease of both the xerophilous and the total mollusk content during the last glacial maximum can be explained by strengthening of the winter monsoon wind regime at that time. The study of quartz grain size in the Luochuan section led Xiao et al. (1995) to conclude that the winter monsoon during the past 130 000 yr was the strongest during deposition of the L1LL1 subunit, inducing the strongest outflow of cold, dry continental air (based on maximum values in the maximum grain size) from central Asia over this area. These climatic conditions were thus strong enough to limit severely the growth of species more tolerant to dryness and their diversity (number of species) (Fig. 2) (Rousseau et al., 1994). However, during L1LL2 deposition, which is also reported to correspond to a strong winter monsoon circulation, but of lower magnitude, nothing similar occurred (Fig. 3). This interpretation of the mollusk diversity during the last glacial maximum concerns only the Luochuan locality, and further investigations at other locations in the Loess Plateau will be necessary to confirm or reject it as being a regional signal. However the mollusk record from the Luochuan loess sequence provides data that agree with other proxies of the paleomonsoons.

CONCLUSIONS

This study clearly indicates that high-resolution investigations of the mollusk assemblages in Chinese loess sequences provide reliable and complementary proxies of the monsoon regime variations over southeast Asia. These changes are not necessarily recorded by magnetic susceptibility data. However, the agreement with different and independent indicators makes the mollusk assemblages a useful tool to understand the climatic changes in this area. Further investigations in the Loess Plateau will allow us to determine the dynamics of the snail population during the late Pleistocene in order to understand how the terrestrial mollusk assemblages reacted at a regional scale. This will provide a good comparison with the mollusk dynamics at the same time in Europe. Investigations of present assemblages in progress may then allow us to build transfer functions to provide quantitative reconstructions of temperature and precipitation variability over the late Pleistocene.

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