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Mollusk Record of Monsoon Variability during the L2–S2 Cycle in the Luochuan Loess Sequence, China

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Molluscan changes that occurred in China over the S2–L2 upper middle Pleistocene series may be caused by monsoon variation. Study of terrestrial mollusks from the loess sequence in Luochuan, gathered in ecological groups according to the moisture and temperature requirements of the identified species, indicates alternating strengthened summer and winter paleomonsoons between 130,000 and 244,000 yr. The four occurrences of species, currently distributed in S.E. China in the sequence, indicate that the climate conditions were warmer and wetter than today between about 242,000 and 233,000 yr, at about 210,000, 164,000, and 140,000 yr. The main occurrence of xerophilous taxa at about 180,000, 154,000, and 138,000 yr is interpreted as indicating a drier environment than today. Such suggestions are in agreement with other proxy data such as grain size distribution. Higher numbers of individuals in the different ecological groups from the S2–L2 sequence indicate more favorable general environmental conditions than in the youngest S1–L1. This may agree with an increase in the regional aridity, since 500,000 yr, deduced from the study of the eolian flux in the northwestern Pacific downwind from China.

INTRODUCTION

Terrestrial mollusks are particularly good environmental indices in loess sequences. As they characterize different types of biotops, land snails permit precise reconstructions of past environments. In the Chinese loess plateau, mollusk studies are rather rare. On the west side, Keen *et al.* (1995) described variations in the mollusk content of three upper Pleistocene sections. However, because too many samples were barren, the interpretation was mostly devoted to biostratigraphy. In the Luochuan sequence, on the eastern side of the loess plateau, Chen *et al.* (1985) indicated that mollusks seem to occur all along the loess-paleosols succession covering the last 2.4 millions yr (Kukla, 1987). A new investigation of the late Pleistocene at Luochuan at higher resolution (Rousseau and Wu, 1997) showed that variations of the malacological record correlate with a paleoprecipitation index reconstructed for South Asia (Prell and Kutzbach, 1987) and indices of strengthened winter and summer monsoons on the Chinese Loess Plateau (Guo *et al.*, 1996; Liu *et al.*, 1995). However, the lack of monsoon proxies extending further back in previous glacial–interglacial cycles precludes any study of the monsoon variability and potential comparison between them. Recently, Guo *et al.* (1998) published a study of a long record of iron oxide ratios in Changwu. They interpreted the determined variations in term of strengthened summer monsoon. This is the reason we decided to continue sampling down the Luochuan sequence in order to provide independent monsoon proxies which could be compared with future studies in the loess plateau or in the neighboring Pacific Ocean or China Sea. Here we present the results of the analysis of terrestrial mollusks at Luochuan from the L2–S2 units, which correspond to the past 130,000–244,000 yr. The aim of this study is to expand the use of the mollusk assemblages as monsoon indices during the penultimate glacial–interglacial cycle in the Loess Plateau and then analyze the variability of the last two climatic cycles. Hovan *et al.* (1989) indicated an increase in the regional aridity during the last 500,000 yr by comparing the record of the magnetic susceptibility from the Chinese Loess Plateau and an eolian flux calculated from Pacific cores V21-146 downwind from China. If magnetic and sedimentary indices indicate such a trend, are the mollusks (1) recording variations similar to those recognized in the late Pleistocene or (2) showing differences in magnitude compared to the last interglacial–glacial cycle?

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STRATIGRAPHY AND METHODOLOGY

Luochuan is located north of Xian city in the central Chinese Loess Plateau (Fig. 1). A general presentation of the studied locality has been already published in various papers (Kukla and An, 1989; Rousseau and Wu, 1997).

The stratigraphy studied in this paper encompasses two main units within the Upper Lishi formation. The S2 soil complex includes two interglacial soils, S2SS2 and S2SS1, bracketing a loess subunit S2LL1 (Kukla and An, 1989) (Fig. 1). The loess deposit comprises three eolian subunits (L2LL3, L2LL2, and L1LL1), which bracket two weathered subunits, L2SS2 and L2SS1 (Kukla and An, 1989). Weathering appears stronger in S2SS1 than in S2SS2, as also determined by Guo *et al.* (1998) (Fig. 1). Kukla *et al.* (1990) determined the chronology of the Luochuan sequence by using recognized paleomagnetism boundaries and a susceptibility model. The S2 soil complex represents the terrestrial equivalent of marine isotope stage 7, and L2 represents stage 6 (Kukla *et al.,* 1990). Studies of marine cores from the Pacific Ocean (Hovan *et al.,* 1989; Shackleton *et al.,* 1995) roughly support these correlations.

The methods used concern the measurement of the low field susceptibility and the sampling of the sediment (10 liters each) for the mollusk study (Fig. 2). They are similar to those described in Rousseau and Wu (1997).

RESULTS AND DISCUSSION

The intensity of magnetic susceptibility varies between 21.5 and $150.7 \times 10^{-8}.m^3.kg^{-1}$ (Fig. 3), magnitudes similar to those recorded for the late Pleistocene S1–L1 interval (Rousseau and Wu, 1997). 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.

All eighty-eight levels sampled yielded shells of terrestrial mollusks; the minimum count was 10 shells at the base, and the maximum was 824 in L2LL3 (Figs. 2 and 3). N_I varies in S2, similar to the pattern in the S1 soil complex of the late Pleistocene series: the values are very low in the strongly weathered soil (down to 10 individuals counted). However, N_I shows a different pattern in the overlying loess unit L2. Although the maximum values (824 individuals) occurred after the soil complex–loess boundary in the L2LL3 subunit, another maximum is reached on top of the L2SS1 subunit and at the bottom of the L2LL1 subunit, reaching 603 individuals. N_I decreases relatively regularly toward lower values and reaches a minimum of 61 on top of the sequence.

N_I values in S2SS1 are relatively low compared to those from the L2 unit. An explanation similar to that previously proposed for the late Pleistocene sequence (Rousseau and Wu, 1997) may be the dissolution of the shells due to early pedogenic processes. Evidence consistent with this explanation is the drop in the number of species, despite the fact that the general environmental conditions should have been favorable for the development and growth of mollusks. Under temperate conditions, the number of species is always higher than in glacial environments as the ecological niches are more varied and numerous (Rousseau, 1989; Rousseau *et al.,* 1994; Solem, 1984).

Two major points must be underlined. The rapid increase of N_I just above the S2–L2 boundary is similar to the abrupt increase observed at the S1–L1 boundary, indicating that the mollusk dynamics may have been the same in response to these major environmental changes (Rousseau and Kukla, 1999; Rousseau and Wu, 1997). The drop of N_I values within L2LL2 and L2LL1 associated with a decrease in the number of species can, however, indicate particularly severe environmental conditions, both arid and cold (Fig. 3).

To derive paleoclimatic information from the mollusk assemblages, we first used the refined chronology proposed by Shackleton *et al.* (1995) for the Luochuan sequence after calibrating the continental sequence with the marine core ODP 677. We used the ecological groups determined in Rousseau and Wu (1997), which consider the species according to their moisture requirements. 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. A third group can be extracted from the previous one as it gathers the species belonging to *Macrochlamys, Opeas, Vitrea, Gastrocopta,* and *Punctum,* which live in particularly warm and wet habitats and are 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.

The composition of the snail fauna of the studied sequence shows numerous xerophilous shells in the L2 loess unit, whereas the hygrophilous species exceed 100 individuals per unit volume at the bottom of S2SS1 and on top of L2LL3 and in L2SS2 (Fig. 3). The highest abundance of xerophilous taxa occurred between 184,000 and 176,000 yr, and the values increased again to another maximum of about 550 at 140,000 yr in the L2SS1 subunit. The smooth curve of the xerophilous taxa indicates two main maxima at about 138,000 and 178,000 yr. The variation of the hygrophilous taxa shows oscillations complementary to those of the previous group. The highest values are reached at about 164,000 yr, but another maximum occurs at about 158,000 yr. Other maxima of lesser magnitude are centered about 140,000, 210,000 yr, between 233,000 and 244,000 yr. The oriental taxa show maxima similar to those of the hygrophilous species, with their main maxima at about 164,000 yr (Fig. 3). Considering these results and the ecological requirements of the identified species, the L2–S2 sequence

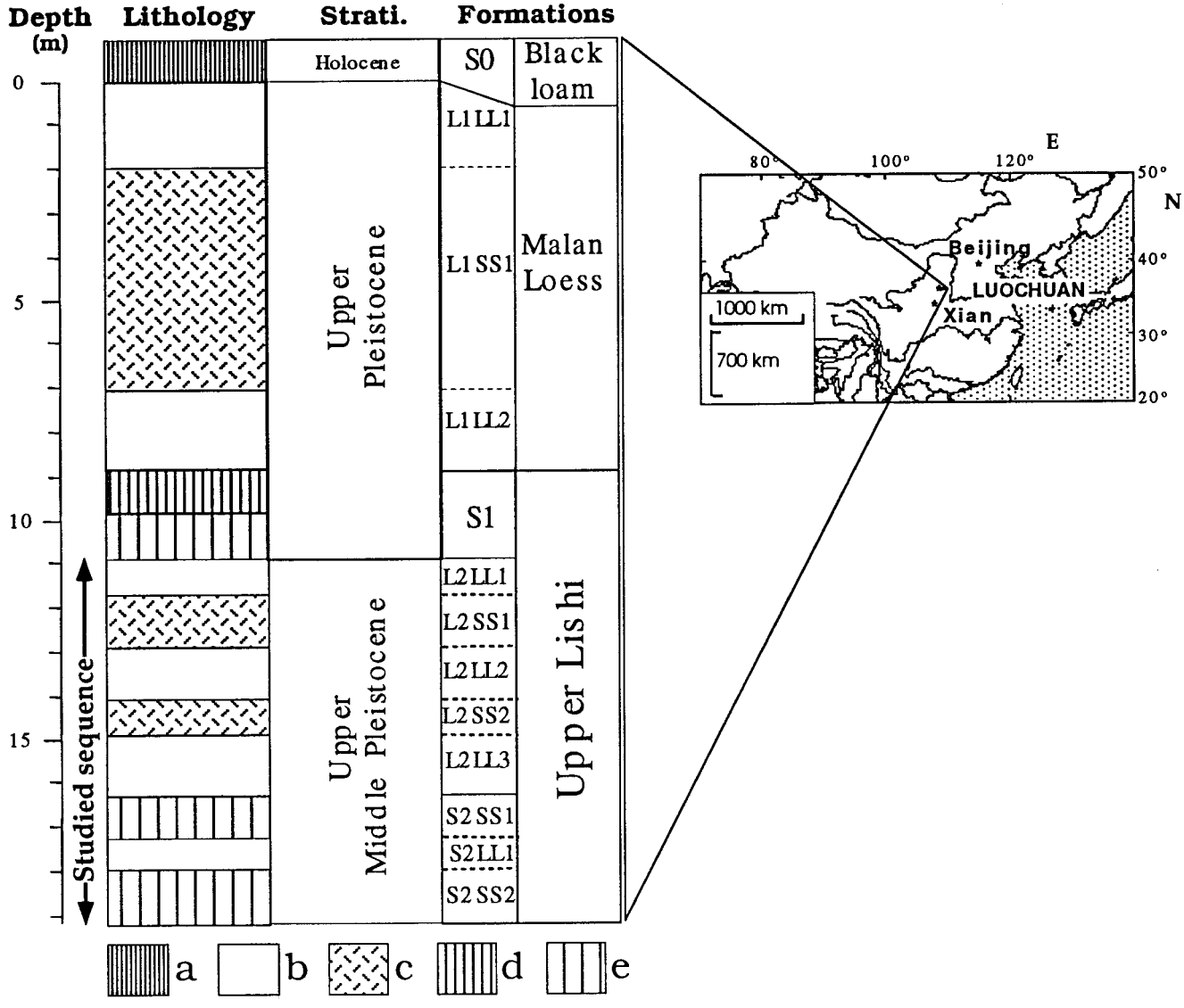

FIG. 1. Location of Luochuan section and stratigraphy of the upper and late middle Pleistocene. The names of the units and subunits are according to Kukla and An (1989). The low-field magnetic susceptibility was measured every 10 cm in the loess and every 5 cm in the paleosols down to the base of S2, using a portable Bartington magnetometer, as used by Kukla in the same section in 1987. Only 10 readings at each level were measured and averaged (Kukla and An, 1989). Parallel to our measurements, 88 samples (10 liters each) were taken for the malacological study, some of them being duplicates of a single level when moving from one section to another. Key: a, humus soil; b, loess; c, weathered loess; d, bioturbated soil; e, soil B horizon with carbonate nodules at its base.

in Luochuan shows at least four intervals of climatic conditions that were warmer and wetter than present between 130,000 and 244,000 yr, allowing southerly species to live and grow in the central Chinese Loess Plateau. On the other hand, the curve of the xerophilous taxa indicates that the winter monsoon was strengthened three times during the deposition of the L2 unit, at about 180,000, 154,000, and 138,000 yr (Fig. 3).

The comparison of the variations of the different groups during the last two interglacial–glacial cycles, i.e., the last 244,000 yr, shows two different scenarios for S1–L1 and S2–L2 intervals (Fig. 4). The maximum values of N_I are higher in L2–S2 than in the youngest sequence. The oriental taxa show the maximum values between about 160,000 and 170,000 yr that correspond to the strongest weathered L2SS2 subunit within the L2 loess. More generally, the L2–S2 sequence shows higher values of the oriental species than L1–S1 though the variation of the magnetic susceptibility remains similar in both cycles. A similar interpretation was given by Guo *et al.* (1998) when comparing the pedological monsoon index with the magnetic susceptibility records, interpreted as a monsoon proxy (An *et al.,* 1991), at Changwu and Xifeng. The same interpretation can be derived from the counts of the hygrophilous taxa although other differences occur. These warm and moist species indicate at least three main maxima of small

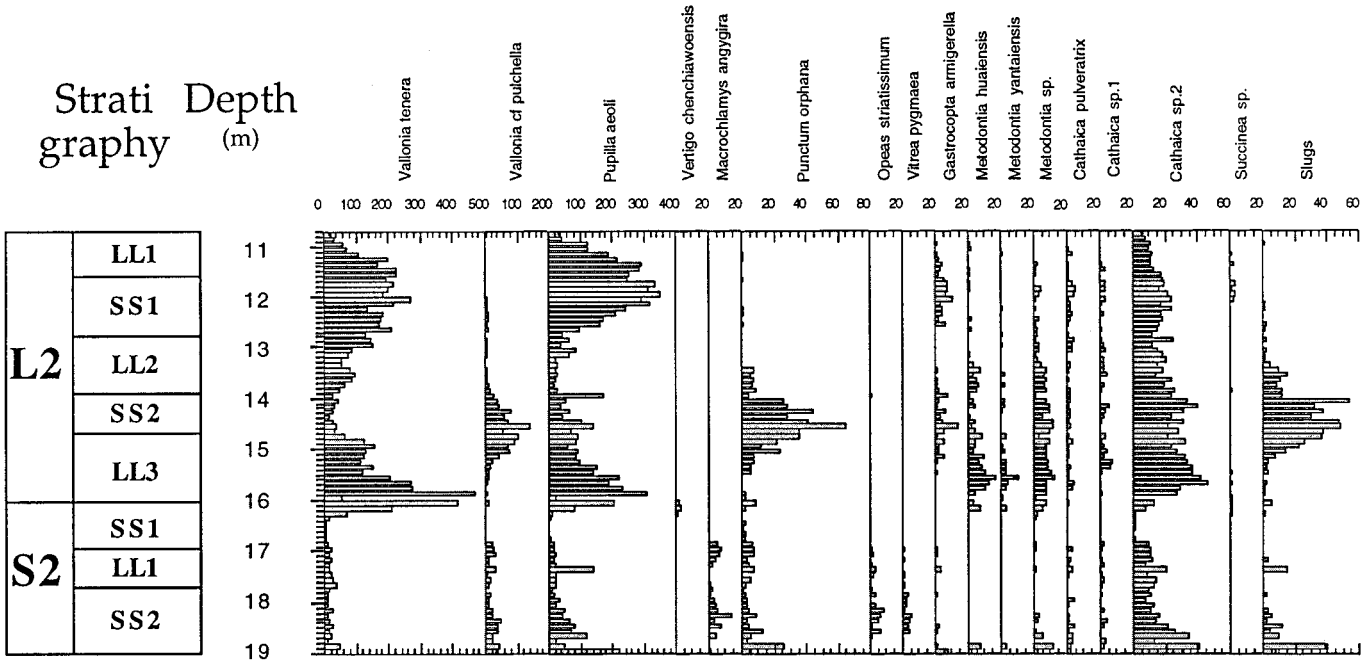

FIG. 2. Mollusk diagram of the late middle Pleistocene at Luochuan. The mollusk shells were picked under a binocular microscope. All the identifiable mollusk remains were considered in the total count of individuals (N_i) following the process described by Puisségur (1976), and the abundance was expressed as number of individuals per unit volume (10 liters of sediment).

magnitude, labeled 2, 3, and 4, during the interval 10,000–100,000 yr. However, the interval 130,000–244,000 yr is marked by a strong maximum centered at about 170,000 yr, with smaller peaks at about 140,000, 220,000, and 240,000 yr. The oriental and hygrophilous taxa indicate similar maxima between 244,000 and 130,000 yr though they differ during the S1–L1 cycle, especially during the deposition of the L1SS1 subunit (Fig. 4). Finally, the xerophilous species show two main maxima, with values (805 and 585) in the older sequence that are higher than the maximum determined at about 70,000 yr in the younger sequence. In contrast to those of the moist taxa, the maxima of these species do not exactly correspond to

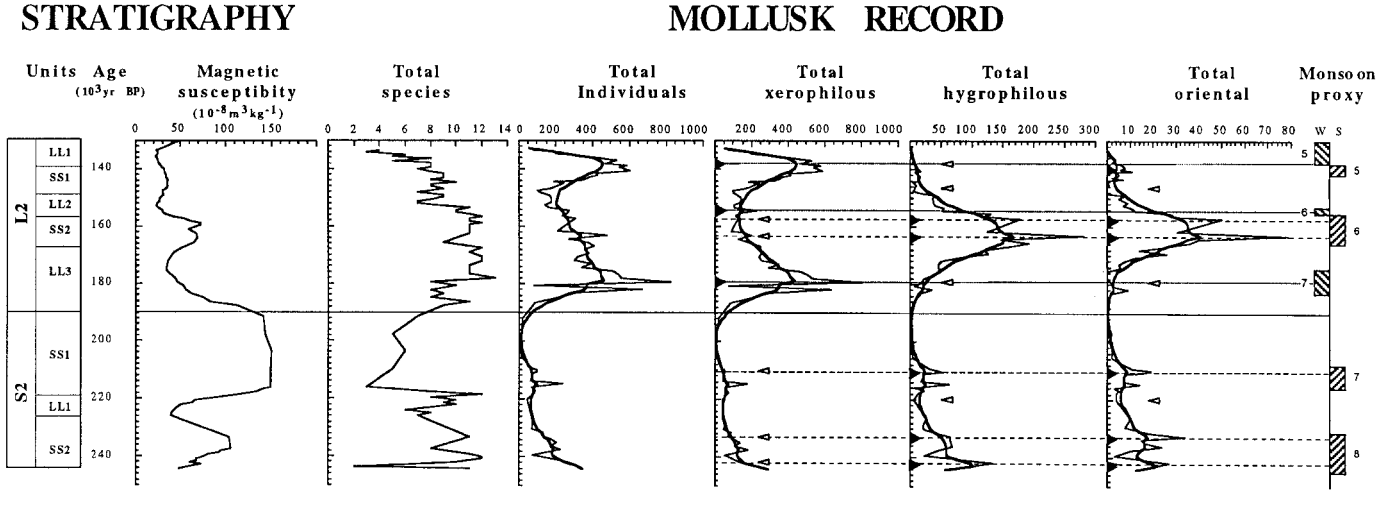

FIG. 3. Variation of magnetic susceptibility, total individuals, total species, total xerophilous, total hygrophilous, and total oriental identified for the studied sequence of the Luochuan section vs age. Counts are expressed in number per unit volume. Thick lines are smoothed curves (Stineman function). Arrows point to the maxima (solid) and the minima (open) in mollusk curves interpreted as indicating strengthened winter (W) or summer (S) monsoon intervals (Rousseau and Wu, 1997). The ages are based on the refined magnetic susceptibility model (Shackleton *et al.,* 1995).

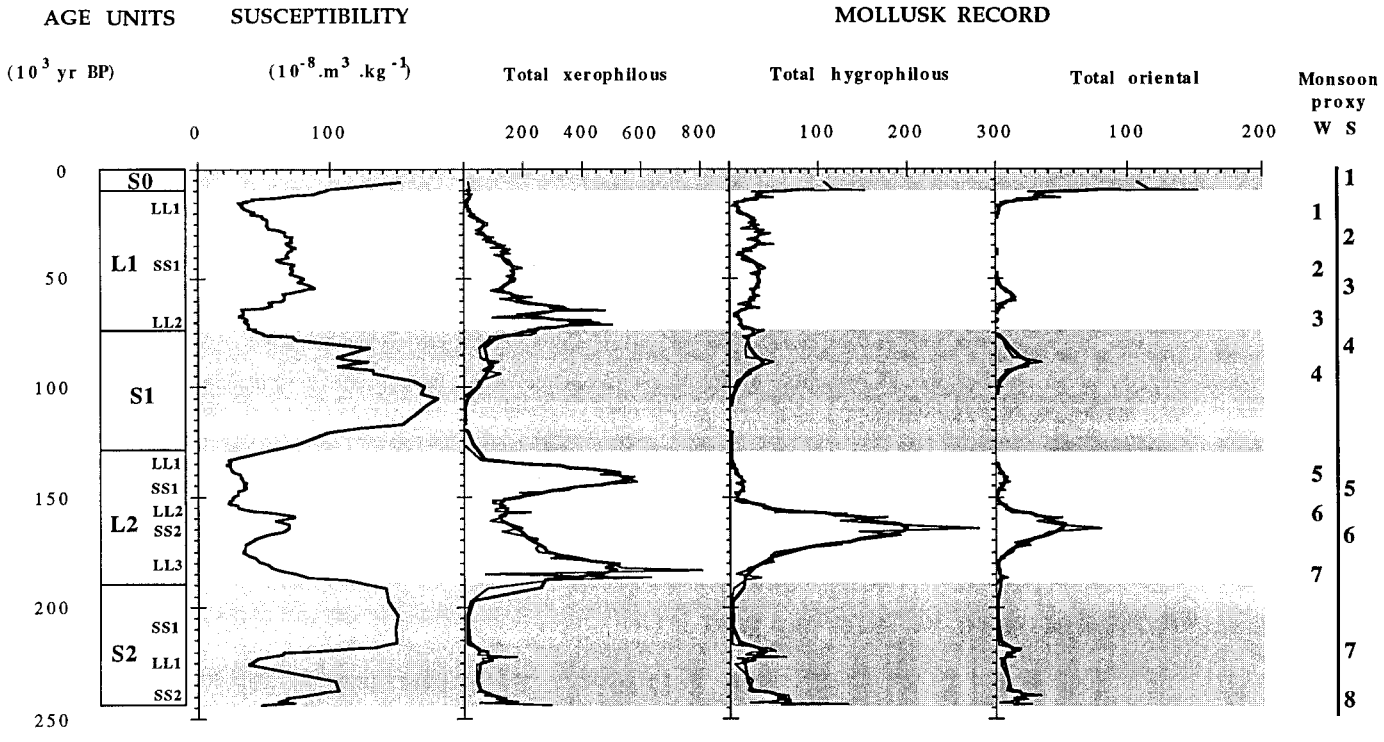

FIG. 4. Variations of the malacological record during the last two interglacial–glacial cycles as an index of the past monsoon variations against the magnetic susceptibility at Luochuan, central China (indicators are the same as in Fig. 3). The intervals of strengthened monsoon are labeled from top to bottom.

the minima read in the magnetic susceptibility record, which are interpreted to represent the coldest conditions. In both the S1–L1 and the S2–L2 sequences, changes in the xerophilous species show a lead of about 5,000 yr in the changes in the magnetic susceptibility signal in the loess deposits, in contrast to the moist species (Fig. 4).

One could object that these results, based on the classification of the identified mollusk species according to their ecological characteristics (Chen and Gao, 1987; Yen, 1939), would be oversimplified due to the authors' preclassification of the studied material. A reliable strategy to test such an assumption is to propose a comparison with other records of the monsoon variability. In the previous study, the mollusk results were compared with the Prell and Kutzbach precipitation index (Prell and Kutzbach, 1987), on one hand, and the pedological indices of Liu *et al.* (Liu *et al.*, 1995), on the other hand. The variations of the hygrophilous, oriental, and xerophilous groups were then in agreement with the other indices supporting a monsoonal interpretation of the mollusk record (Fig. 5). These independent indices, however, only concern the last climatic cycle and cannot be used to test the present results. Paleopedological and geochemical studies of the Changwu loess sequence, located about 100 km southwest from Luochuan, permit the determination of the Fe_d/Fe_t ratio record interpreted as a monsoon index (Guo *et al.*, 1998). Covering the last 600,000 yr this record appears to be accurate enough to test our interpretation. Figure 5 shows that variations in the hygrophilous and oriental groups fit the Fe_d/Fe_t maxima, supporting the interpretation of increased summer monsoons during these intervals. Variations in the xerophilous group show maxima during intervals of low values in the ratio, supporting winter monsoon dominance. If two independent indices of the paleomonsoon regime for the last climatic cycle and another one for the two last climatic cycles support the mollusk interpretation, then we can draw reliable conclusions about the direct relationship between monsoon variation and the mollusk evidence in Luochuan.

Despite these variations, the sampling protocol remained the same in both the S2–L2 and the S1–L1 sequences. The differences in the total number of individuals, and in the counts in the different groups, support the occurrence of different environmental conditions. It has been demonstrated in modern environments that unfavorable conditions permit low diversity and a reduced number in 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 to more unfavorable environmental conditions in the younger S1–L1 series. This would then agree with the Hovan *et al.* (1989) interpretation of increasing aridity over the area during the last 500,000 yr. Such an interpretation is nevertheless strictly hypothetical at present for two main reasons. These

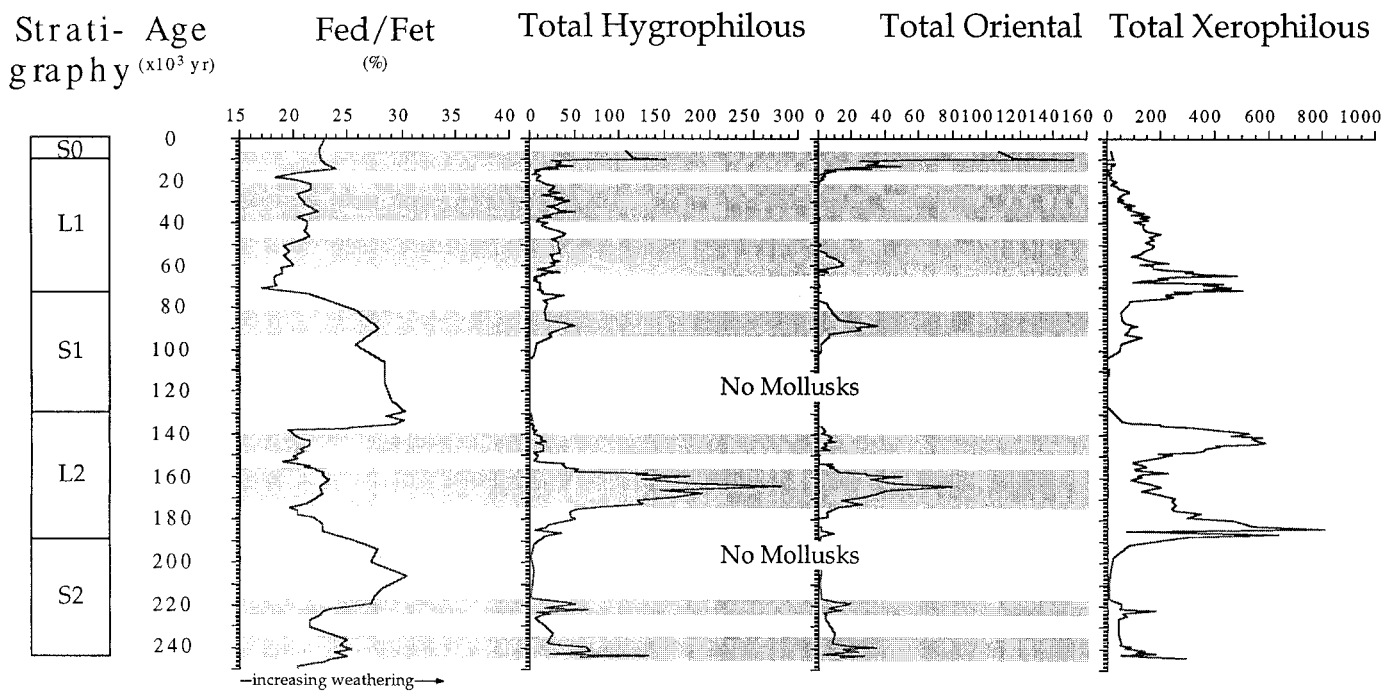

FIG. 5. Comparison between the malacological record in Luochuan and the Fe_d/Fe_t ratio at Changwu (Guo *et al.*, 1998) during the two last climatic cycles (S2–L2 and S1–L1). The gray areas indicate the intervals of strengthened summer monsoon.

results correspond only to the last two climatic cycles and would necessitate the analysis of older intervals to test the hypothesis of increasing aridity through time. The second point is that these results, even if they show possible correlations with other proxies, are only related to the Luochuan section. Other mollusk records exist elsewhere in the Chinese Loess Plateau (Keen *et al.*, 1995), but they (i) are not continuous and (ii) concern only the last climatic cycle (upper Pleistocene).

These new results, however, strongly emphasize that the snail assemblages at Luochuan, interpreted with xerophilous, hygrophilous, and oriental groups, record environmental changes related to the monsoon variations. The correspondence between the mollusk and pedological records could lead us to interpret their variations as representative of the Southeast Asia monsoonal regime during the last 244,000 yr, but more investigations are needed. Again, as for the S1–L1 sequence, the general decrease of both the xerophilous and the total mollusk content during L2LL1 is explained by the strengthening of the wind regime during dominant winter monsoons. The study of the eolian flux into the Pacific (Hovan *et al.*, 1989) shows the highest values during the deposition of this subunit inducing the strongest outflow of cold, dry continental air from central Asia over this area. More recently, Vandenberghe *et al.* (1997) showed that the grain size values were higher for L2LL1 and L2LL2 at Luochuan, supporting the Hovan *et al.* (1989) interpretation. The low values in the xerophilous taxa on top of the S2–L2 sequence must then be interpreted similarly to those in the last climatic cycle record. The climatic conditions were thus strong enough to limit severely (i) the growth of the individuals of species more tolerant of dryness, and (ii) the number of species itself (Rousseau, 1992; Rousseau *et al.*, 1994) (Figs. 4 and 5).

CONCLUSIONS

This study of new investigations of the mollusk assemblages in Chinese loess sequences provides indirect new data on the monsoon regime variations over Southeast Asia during the last two interglacial–glacial cycles.

The analysis of the S2–L2 sequence, i.e., between 244,000 and 130,000 yr, shows that conditions at least five times warmer and wetter occurred in the area due to a strengthened summer monsoon. Episodes of strengthened winter monsoon occurred at least four times. The comparison of the two last interglacial–glacial cycles, spanning the last 244,000 yr, indicates also different general conditions, expressed by the total number of individuals counted and by the number of individuals in the three ecological groups recognized. The older sequence provides higher N_I values than the youngest one, and this trend is hypothetically interpreted as a difference in the general environmental conditions within each individual interglacial–glacial cycle, in agreement with other proxies.

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