Response of mollusk assemblages from the Luochuan loess section to orbital forcing since the last 250 ka

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Abstract This note presents a new result of terrestrial mollusk study from the Luochuan loess section since the last 250 ka. A total of 213 samples, taken at intervals of 10 cm in the S_0-L_3 portion, were analyzed for fossil mollusks. Generally, 150—600 individuals were counted in each sample. According to the distribution of mollusk fossil assemblages in the loess section, 11 mollusk fossil zones have been recognized, representing different climatic and ecological conditions. Three main ecological groups were identified according to the temperature and moisture requirements of each taxon. The cold-aridiphilous group shows maxima at about 240—220, 190—182, 150—140 and 74—66 ka BP. The thermo-humidiphilous set has high abundances for at least 6 times in the section at about 246—240, 220—216, 170—158, 92—86, 60—44 and 10 kaBP. Our results show that variations in mollusk ecological groups are related with changes in the Earth orbital parameters at the 41 and 20 ka frequencies. Maxima in thermo-humidiphilous taxa are in phase with accretion intervals of obliquity (41 ka period), reflecting the East Asian summer monsoon with 41 ka period in controlling variations in terrestrial mollusk ecological groups. In addition, maxima in thermo-humidiphilous taxa appearing at about 246—240, 220—216, 60 and 10 kaBP, are consistent with procession (20 ka period) maxima, indicating that the procession period also plays an important role in adjusting the ecological pattern of mollusk groups.

Keywords: **mollusk assemblage, loess, orbital forcing.**

In the East Asian monsoon area, a major period of winter monsoon variations controlled by a 100-ka period of global ice-volume forcing has been clear since the past 800 kaBP[1—3]. But whether the variations in the East Asian summer monsoon with the same 100-ka period as winter monsoon or controlled by solar radiation is still controversial, due to the difference in knowing climatic proxies and their representing climatic significance[2, 4—6]. If the magnetic susceptibility of loess stratigraphy could be regarded as a proxy of pure summer monsoon (not a combined effect of winter and summer monsoons), it could be considered that the variations in the East Asian summer monsoon are surely simultaneously controlled by the global ice-volume forcing with the 100-ka period. However, recent studies indicated that the variations in the East Asian summer monsoon are in sensitive response to the changes in procession (20-ka period) and obliquity (41 ka)[7]. July precipitation since the last 150 kaBP in the Loess Plateau has correlated well with the variations of solar radiation in the low latitute area[8]. The key to interpreting the above-mentioned questions is to select the significant proxy index, such as biological remains to probe further the history and variability of the East Asian monsoon climate, and its relationship with orbital forcing. In this note, we study the characteristics of mollusk assemblages of the recent two glacial periods and investigate paleoenvironmental changes, based on the analysis of mollusk ecological groups and their response to the orbital forcing.

1 Materials and methods

The Luochuan loess section (35°45′ N, 109°25′ E) is located at about 200 km northeast of Xi'an. This area with an average elevation of 1 000 m lies in the north limit of the East Asian summer monsoon[9]. The stratigraphy of the loess profile consists of two formations with the upper 12.8 m called the Malan loess corresponding to the last climatic cycle and the lower 8.5 m which belongs to the Lishi loess to the penultimate cycle. 213 samples from 21.3 m loess deposits composed of interlayering loess and paleosol layers were analyzed for mollusk assemblages at sampling intervals of 10 cm. Each sample analyzed weighs about 10 kg, which was washed and sieved with a 0.5-mm mesh in the field. All mollusk species were counted, and broken shells were included following the method developed by

Puisségur[10]. Almost all the levels yielded shells of terrestrial mollusks except for the bottom of S_1 (12.3—11.5 m) and the upper part of S_{2-1} (11.6—11.4 m) with a few of fossil shells. Generally, 150—600 individuals can be counted from per sample and the maximum reaches 824 individuals in L_{2-5} formation. Parallel to our mollusk analysis, we measured the low field magnetic susceptibility every 10 cm in loess and every 5 cm in the paleosols down to the upper part of L_3, using a portable Bartington magnetometer, only 10 measurements at each level were averaged. The time series used in this note was composed of two parts; the age above S_1 obtained by the thermoluminescence dates[11] and the chronology of L_2-S_2 determined based on the age model of magnetic susceptibility established by Kukla[12,13].

2 Mollusk assemblages

In total, 25 species of terrestrial mollusks were identified for the Luochuan loess section of the last 250 ka. We divided these species into three main ecological groups according to the temperature and moisture requirements of each taxon[14,15]. (ⅰ) Cold-aridiphilous (taxa living in dry and relatively cold places) species consist of *Vallonia tenera, Pupilla aeoli, Cathaica richihofeni, C. pulveratrix* and *C. pulveraticula*. (ⅱ) Thermo-humidiphilous (warmth and moisture loving taxa) set includes *Macrochalamys angigyra, Vitrea pygmaea, Gestrocopta armigerella, Punctum orphana, Opeas striatissium, Metodontia yantaiensis, M. huaiensis, Kaliella lamprocystis,* and *Succinea* sp. Among this thermo-humidiphilous set, some species living in particularly warm and wet habitats, currently distributed in southeastern China are extracted to be the third group, named (ⅲ) Oriental group, including these species belonging to *Macrochalamys, Opeas, Vitrea, Gastrocopta* and *Punctum*. Their fossil occurrence in the studied section indicates particularly warm and humid conditions associated with strong summer monsoon.

According to distribution of mollusk fossil assemblages in the loess section, 11 mollusk fossil zones have been recognized, representing different climatic and ecological conditions (fig. 1). The composition of mollusk fauna and principal features of these zones are outlined below, along with

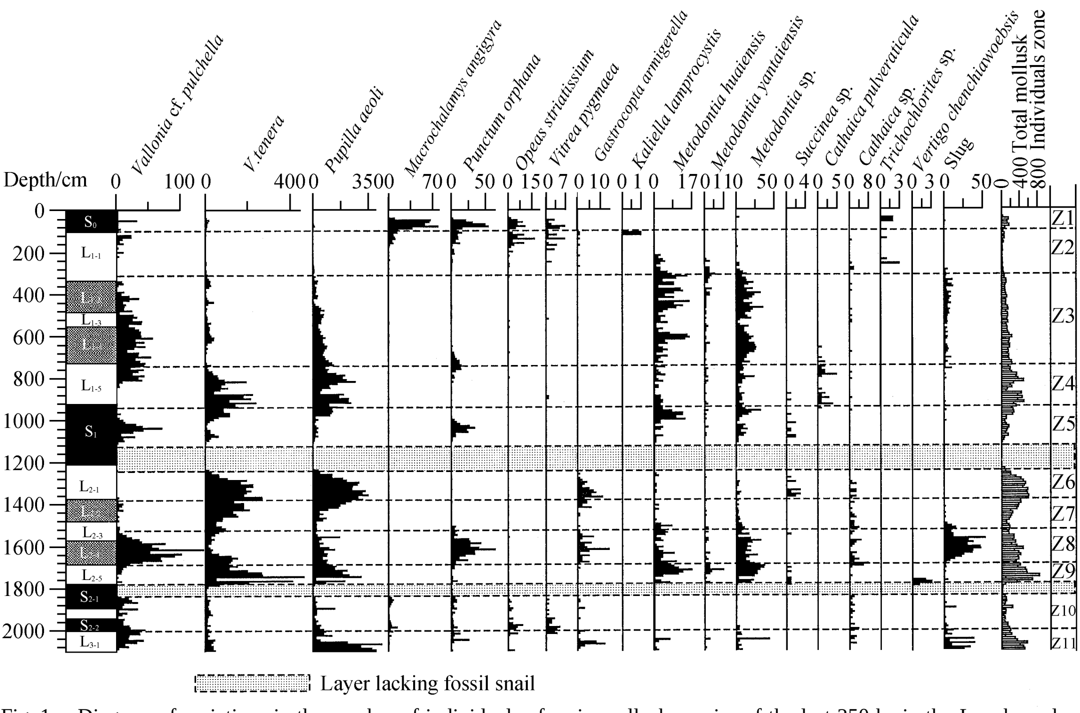

Fig. 1. Diagram of variations in the number of individuals of main mollusk species of the last 250 ka in the Luochuan loess section.

paleoenvironmental and paleoclimatic inferences.

Zone 11 (L_{3-1}, full glacial). This mollusk zone is characterized by dominant cold-aridiphilous species of *Pupilla aeoli, Vallonia tenera* and *V*. cf. *phuchella*. Thermo-humidiphilous species like *Punctum ophana* and *Gastrocopta armigerella* present certain amounts in this zone. This mollusk zone reflects a generally cold-dry condition with temporary impacts of warm-humid climates.

Zone 10 (S_{2-1}, S_{2-2}, the penultimate interglacials). This zone is prominently characterized by the abundant occurrence of thermo-humidiphilous species such as *Macrochalamys angigyra* and *Metodontia*. The number of cold-aridiphilous species like *Vallonia tenera* and *P. aeoli* decrease dramatically and even are absent completely from some levels. The composition of this mollusk zone represents particularlly warm and humid climate conditions. A temporary cooling period occurred between S_{2-1} and S_{2-2} paleosol units, indicative of abruptly rising and declining in the number of *P. aeoli* ranging from 20 to 138 and then down to 20 individuals in per 10 kg. In association with the changes in this cold-aridiphilous taxon, thermo-humidiphilous species reduce apparently and moreover a few warm and moist species disappear at the same time. This shortly cooling formed a thin loess deposit in stratigraphy. In the upper part of this zone, lower values of mollusk individuals presented, which may be explained by the dissolution of snail shells due to strong pedogenesis during soil developing.

Zone 9 (L_{2-5}, the early penultimate stadial). An obvious feature of this zone is the dominant occurrence of cold-aridiphilous species. *V. tenera* reaches its highest value of 469 individuals and secondary maximum of 415 at this period, while the amount of *P. aeoli* attains 308 in one sample. Warm and moist species appear sparsely in the section and even disappear completely from the assemblages. This mollusk zone reflects a rapid and large amplitude change in climate and environment during this period.

Zone 8 (L_{2-4}, the early penultimate interstadial). This zone is marked by a progressive decrease in cold-aridiphilous species and increase in thermo-humidiphilous components. Warm and moist species such as *Punctum orphana* and *Gastrocopta armigerella* show the maxima of 65 and 14 individuals respectively at this period, associated with the highest values of *V*. cf. *pulchella* and slugs about 130 and 54 individuals in per unit. The composition and abundance of mollusk fauna of this zone indicate a relatively warm and humid condition, in which temperature was not high, but moisture was high enough to support the thermo-humidiphilous species to survive.

Zone 7 (L_{2-3}-L_{2-2}, the middle penultimate to late penultimate interstadial). A small amount of thermo-humidiphilous species like *P. orphana* and *Metodontia* are placed by the rapid increase of cold-aridiphilous taxa. A few of *G. armigerella* only occur in L_{2-2} unit, a rather weakly developed soil layer. Mollusk assemblages of this zone show that the climate condition varied from the early relatively warm-wet stage to the late rather cold-arid one at this period.

Zone 6 (L_{2-1}, the late penultimate stadial). Mollusk assemblages in this zone are dominated again by cold-aridiphilous species of *V. tenera* and *P. aeoli*. Their abundances reach the peak values of 352 and 269 individuals per unit volume, respectively, reflecting a rather cold and dry ecological condition. Another striking feature of this zone is *Gastrocopta armigerella*, a species with narrow ecological tolerance to environmental change and presently living in cooler and wetter habitat, occurring continuously in the low part of this zone. Its appearance reflects a short-term cool-wet condition presented in the general trend of cold climate in this period. In the upper part of this zone, *G. armigerella* decreases rapidly, implying that a more deteriorated climatic conditon occurred.

Zone 5 (S_1, the last interglacial). Because intensive pedogenesis made a large number of mollusk shells lost in the lower part of the paleosol S_1, only a few of mollusk fossils were preserved, which caused the difficulty in interpreting paleoenvironment according to the mollusk assemblage. In the upper part of this zone, *P. orphana* and *Metodontia* are dominant together with a few occurrences of *Succinea*, representing quite warm and humid climate conditions. A high peak of the cool-wet speices of *V*. cf. *pulchella* appears in the later stage of this zone associated with progressively increased cold-dry species, showing the climatic condition changed from very warm-humid in the early period to cool-wet in the late period.

Zone 4 (L_{1-5}, the early stadial of the last glacial). The amounts of cold-aridiphilous species rise again in association with a small number of elements of *Cathaica*. *V. tenera* and *P. aeoli* reach another high values at this time, more than 200 and 150 individuals, respectively. *V*. cf. *pulchella* shows very low value at the beginning of this zone and gradually rises toward the upper part of the section, indicating that climate changed from the early dry-cold stage into the late cool-wet one.

Zone 3 ($L_{1\text{-}4}$-$L_{1\text{-}2}$, the early to late interstadials of the last glacial). This mollusk zone is characterized by a series of apparent fluctuations presented in the cold-aridiphilous taxa, which show gradually declined tendency toward the upper of this section. *Metodontia* is the principal component of thermo-humidiphilous species and appears two high values, corresponding to the intervals of two weakly developed soils. *V*. cf. *pulchella* and slugs show certain amounts in this zone. Mollusk assemblages in this zone reveal a series of climate fluctuations happening, alternating warm and cold conditions.

Zone 2 ($L_{1\text{-}1}$, the late stadial of the last glacial, the Last Glacial Maximum (LGM) period). The number of mollusk taxa is quite low in the whole zone. A small number of *V. tenera* appear at the low and middle parts of this section. *P. aeoli* disapppears completely from this zone. Mollusk assemblages in the LGM period show an extremely cold and dry climate condition. However, a prominent feature is that numerous thermo-humidiphilous species which are the elements of oriental group occurred discontinuously in the upper of the section together with the cold-aridiphilous species. The appearances of these species in the general tendency of extremely cold and dry period imply that the environmental condition changed dramatically and the large amplitude climate fluctuations happened. The seasonal warm-humid climates invaded to the central Loess Plateau, brought by temporarily strengthened summer monsoon, allowing these particularly warm and wet species to grow at this general cold and arid peroid[15].

Zone 1 (S_0, Holocene). This zone is marked evidently by abundant occurrence of the warm-humid species of *M. angigyra*, *P. orphana*, *O. striatissium* and *V. pygmaea*, representing the warm-humid interglacial climate conditions.

3 Variations in mollusk ecological groups during the last 250 ka and their relationship with the changes in orbital forcings

Fig. 2 shows variations in three main ecological groups in the studied Luochuan section vs. age. From this figure, we can see that the thermo-humidiphilous and oriental taxa have at least 6 times higher abundances in the section, focused on about 246—240, 220—216, 170—158, 92—86, 64—44 and 10 kaBP. Addtionally, one prominent phenomenon should be emphasized. During the periods of 216—202 and 124—116 kaBP, the number of mollusk shells and species is very low, even dropped to 1 individual at the bottom of S_1 and a few in the upper of S_2, which just correspond to the layers of the highest values in magnetic susceptibility and of the strongest developed soils. According to the characteristics of developed soils and high values of magnetic susceptibility of the two layers, they should represent peculiarly warm and wet conditions. Facturally, due to strong weathering and leaching actions during the process of pedogenesis, calcareous shells of snails dissoluted heavily to form the lack zones in the mollusk record. Although detailed studies on snail taphnomy are still few, we find that the number of snail shells in these sections did not reduce as the soils developed. In contrast, in most cases only when soil has developed to a certain degree, do the amounts of fossil snails begin to decrease suddenly, similar to the case of CCD formation in deep sea. Thus, the layers lacking snail fossils in paleosol stratigraphy should represent warmer and more humid environmental conditions and the periods of more strengthened summer monsoon.

Cold-aridiphilous taxa of the Luochuan loess sequence of the last 250 ka show at least four thriving periods, the maxima occurring at about 240—220, 190—182, 150—140 and 74—66 kaBP. At the LGM period, neither warm-humid taxa could stand nor a few cold-aridiphilous species lived. The climatic condition at this period became extreme deterioration, particularly the moisture lowered to the degree that even cold-aridiphilous species could not survive. Another explanation is that the climate at that time might fluctuate so rapidly that terrestrial mollusk was restrained from developing and breeding variously.

The Milankovitch theory considered that the Earth orbital variations are the major controlling factor of the Quaternary climate change. The record of mollusk assemblages from the Luochuan loess

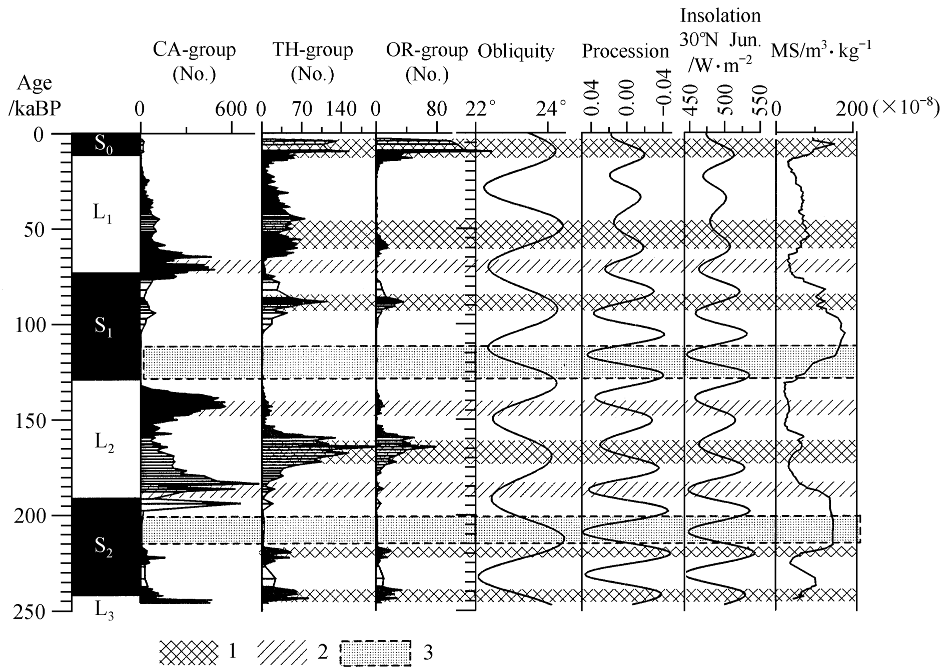

Fig. 2. Variations in three main ecological groups during the last two interglacial cycles and their relationship with orbital parameters and solar radiation at 30°N. 1, Thriving interval of thermo-humidiphilous taxa; 2, thriving interval of cold-aridphilous taxa; 3, layer lacking fossil snail.

section of the last 250 ka provides evidence for understanding the forcing factors that caused climate changes and the succession of biological community in the long time scale on the Loess Plateau. Fig. 2 shows that the maxima thriving periods of thermo-humidiphilous mollusk species (including 2 stronger weathered periods in soils) correspond to the accretion intervals of obliquity (41-ka period). However, the maxima thriving periods of cold-aridiphilous taxa (including the LGM period) are in phase with lessened intervals in obliquity. It has been known that the variations in obliquity have much higher effect in the high latitude than in the low latitude. When the obliquity becomes large, the annual isolation increases in the high latitude and decreases in the low latitude, causing increase in the difference of annual mean temperature (AMT) and the presence of hotter summer season. In contrast to this case, when the obliquity lessens, the annual isolation reduces in the high latitude, producing less difference in AMT favorable for accumulation of ice-sheet. The maxima thriving intervals of thermo-humidiphilous and oriental groups represent the intervals of summer monsoon strengthened, in which appropriate thermal and hydrological conditions were supplied by the strengthened summer monsoon for the growth and development of warm and moist species on the Loess Plateau. The maxima of cold-aridiphilous group reflect the strengths of winter monsoon. Each interval of summer monsoon strengthened is consistent with the accretion period of obliquity, and each interval of winter monsoon strengthened corresponds to the lessened period of obliquity.

However, it should be pointed out that the highest peak of thermo-humidiphilous taxa does not always strictly correspond to the maximum value of obliquity. Except for the error of time scale of stratigraphy, the effects of procession and solar isolation affected by the changes of orbital parameters are possibly the important forcing factors. The maxima of thermo-humidiphilous taxa at about 246—240, 220—216, 60 kaBP and the Holocene period are clearly consistent with the maximum values of procession and solar isolation at 30°N in June. However, it should be mentioned that not all the maxima of mollusk assemblages are correlated well to the maxima periods of procession.

Based on variations in mollusk ecological groups during the last 250 ka and their response to orbital changes, the obliquity plays a major role in controlling the ecological succession of terrestrial mollusk assemblages. In fact, variations in obliquity can change the climatic condition on the Earth, consequently, affecting the ecological succession of mollusk associations.

At the periods with similar variaitons in obliquity, the difference in the number of thermo-humidiphilous taxa cannot be explained simply by the obliquity, which might represent a gently developed trend overlapping on the background of great climatic changes.

4 Conclusion

This study clearly indicates that vairations in terrestrial mollusk associations are evidently related with changes in the Earth orbital parameters at 41 and 20 ka frequencies, reflecting the East Asian summer monsoon with 41-ka period in controlling variaitons in terrestrial mollusk ecological groups. In addition, the 20-ka period of procession also plays an important adjusting role in variations of ecological patterns of mollusk groups. The 100-ka period (eccentricity) is not a major controlling factor in the processes of ecological group successions, which might be a background factor controlling the variations in terrestrial ecological community.

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