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Climatic conditions recorded by terrestrial mollusc assemblages in the Chinese Loess Plateau during marine Oxygen Isotope Stages 12–10

Naiqin Wu[a,*], Xiaoyun Chen[a], D.D. Rousseau[b,c], Fengjiang Li[a], Yunpeng Pei[a,d], Bin Wu[a]

[a]*Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, PR China*
[b]*Institut des Sciences de l'Evolution, UMR CNRS 5554, Universite Montpellierll, Case 61, Place Eugene Bataillon, 34095 Montpellier Cedex 05, France*
[c]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[d]*School of the Earth Sciences and Resources, China University of Geosciences, Beijing 100083, PR China*

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Abstract

Past analogs for our present interglacial have been sought for better understanding of our present and future climate. Marine Isotope Stage 11 (MIS 11) has long been considered to be a good candidate and has gained increasing attention in recent studies of marine and terrestrial records. In the Chinese loess–paleosol sequences, S4 soil, interpreted as equivalent to MIS 11, yields a very precise terrestrial paleoclimate record of environmental changes that prevailed during this period. In this study, two high-resolution terrestrial mollusc records from the Loess Plateau have been analyzed to characterize climate variability during the periods of MIS 12–10. The changes in environment and climate, indicated by the variations in abundance of land mollusc species, are thus documented. Our mollusc results show that the L5 loess, equivalent of MIS 12, developed under relatively cold and dry conditions. Climate during this period was not as severe as indicated in the marine isotopic records. An episode of warmer and more humid condition occurred at the middle stage of the MIS 12, reflecting a summer monsoon strengthened during the glacial interval. A similar scenario has been observed in the middle part of MIS 10. In addition, our mollusc records provide insight into the climate conditions over the Loess Plateau during MIS 11, a general warm–humid climate dominated during the formation of S4 soil. But at least four fluctuations occurred at Xifeng region, reflecting unstable climate conditions and regional climate differences within the Loess Plateau during this period. Our study shows that the early part of S4, spanning over 30 ka, was very warm and humid, while the late part was characterized by mild-cool conditions. Comparison of mollusc species compositions of both MIS 11 and Holocene intervals reveals different climate conditions. The early part of MIS 11 was warmer and more humid than the Holocene optimum period, while the late part of MIS 11 was similar or cooler. Our study indicates that the extent of warming during the Holocene in the Loess Plateau might be significantly less than the conditions that prevailed during the MIS 11 interglacial period.

1. Introduction

Marine Isotopic Stage 11 (MIS 11) (~420–360 ka) is a unique interglacial period in Quaternary climate history. It has been suggested as a close analog to the Holocene climate because of the similar orbitally driven insolation (Droxler et al., 2003; Loutre and Berger, 2003) and comparable atmospheric greenhouse gas concentrations (Petit et al., 1999; EPICA Community Members, 2004). MIS 11 is characterized by the longest and the warmest interglacial interval of past 500 ka based on the study of marine isotopic records (Howard, 1997; Droxler et al., 1999). In contrast, MIS 12 (~470–420 ka) may indicate among the most extreme glacial climate conditions. The largest amplitude change in climate (deglacial warming) occurred at the MIS 12/11 boundary in the past 6 Ma, with about 160 m sea level rising at the termination of glacial stage 12 (Droxler and Farrell, 2000; Thunell et al., 2002). However, more recent studies indicated that lines of evidence about the degree of warming during MIS 11 and of cooling during MIS 12 from investigations of marine, terrestrial, and ice-core records remained complex (Droxler and Farrell, 2000). Thus, more detailed studies of

*Corresponding author. Tel.: +86 10 6200 8125; fax: +86 10 6201 0846.
E-mail address: nqwu@mail.iggcas.ac.cn (N. Wu).

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long-term and continuous geological records are urgently needed.

The Chinese loess–paleosol sequences have proven to be excellent paleoclimate archives, which yield one of the most complete and most sensitive terrestrial records of environmental changes for the past 2.6 Ma. The loess–paleosol sequences are commonly interpreted as an indication of alternating waxings and wanings of the paleomonsoons, with the soil-forming periods corresponding to strengthened summer monsoon and loess deposition to strengthened winter monsoon (An et al., 1991; Liu et al., 1995). In other words, the paleosols formed during interglacials and loess deposition prevailed during glacials. The present climate in the Loess Plateau is characterized by marked seasonal changes in dominant winds. In summer, the region is under the control of the warm–humid southeast summer Asian monsoon of tropical/subtropical origin, and it has high precipitation. In winter, the cold and dry northwest wind of sub-arctic origin prevails within the area. As a result, most of the annual rainfall is concentrated in the months between July and September (Zhang and Liu, 1992). Thus, the climate in this region is regarded as a semi-arid to semi-humid (Qian, 1991).

The alternating loess and paleosol layers of the last 500 ka are labeled downwards as S0, L1, S1, L2, S2, ..., and S5 according to Liu (1985). The stratigraphy of the loess–paleosol sequences is correlative across the whole Loess Plateau and can be well correlated with the marine isotopic stages (Kukla, 1987). S4 is commonly correlated to MIS 11, and L5 is equivalent to MIS 12. Both provide the best terrestrial records for the study of detailed climate changes and spatial pattern of the semi-arid and semi-humid area of the Loess Plateau. S4 soil has long been considered as one of the most strongly developed soil units in the Chinese loess–paleosol sequences of the last 2.5 Ma. It is used widely as a stratigraphic marker (Liu, 1985). It is commonly accepted that the S4 paleosol developed under extremely warm climate, representing a period of strengthened East Asian summer monsoon (An and Wei, 1980; Liu, 1985; Ding et al., 1995; Guo et al., 1996, 1998, 2000). Guo et al. (1998) conducted extensive studies on the properties of S4 soil layer based on palaeopedological, geochemical and magnetic susceptibility (MS) variations of three loess–paleosol sections from Xifeng, Changwu and Weinan located in the Loess Plateau. They concluded that S4 was formed under sub-tropical semi-humid climate. However, a recent study by Vidic et al. (2003) based on geochemical, sedimentologic and MS data from the Jiaodao section 30 km north of Luochuan sequence indicated that S4 is a relatively well-developed soil, but it is not an unusual warmth and stability of soil-forming interval. Apparently, it remains uncertain how the climate and environment changed during the S4 soil-forming interval in the Loess Plateau. The cause of the climate extreme is still a matter of debate. Moreover, there are many unanswered questions about the S4 paleosol and its L5 glacial predecessor. (1) What were the environmental and climatic conditions over the Loess Plateau during the development of S4 and the preceding L5 glacial deposit? (2) Was there any climatic stability at the peak interval of S4 development? (3) Was L5 an extremely cold glacial period? (4) How long did the characteristic interglacial condition last? (5) Was S4 climate warmer or colder than the climate in the Holocene? Was the climate of this episode less or more variable than the climate in the Holocene?

In the present study, we examine changes in climate and environment during the time interval of ~490–330 ka based on the analysis of land mollusc data from two loess–paleosol sequences at Xifeng and Luochuan in the central Loess Plateau. The period covers the so-called extreme glacial (MIS 12) and interglacial (MIS 11) climate changes of middle Pleistocene. Our study aims to: (1) address the pattern of ecological and environmental changes in the Loess Plateau during MIS 12–10; (2) characterize the changes in climate patterns at glacial and interglacial intervals; (3) compare the variations in intensity of summer monsoon climate between the MIS 11 and Holocene.

2. General setting and methods

The two studied loess sections of Xifeng (35°46′N, 107°41′E) and Luochuan (35°45′N, 109°25′E) are located in the central Loess Plateau (Fig. 1), and both are classical loess sections where numerous investigations have been performed (e.g., Heller and Liu, 1982; Liu, 1985; Kukla, 1987; Kukla and An, 1989; Kukla et al., 1990; Porter and An., 1995; Guo et al., 1996, 1998, 2000; Wu et al., 1996, 1999, 2000, 2001; Rousseau and Wu, 1997, 1999). The two sites are presently situated in the northern margin of the East Asian summer monsoon (Zhang and Liu, 1992). The modern mean annual temperature (MAT) and precipitation (MAP) are 8.3 °C and 560 mm in Xifeng, and 9.0–9.2 °C and 623–661 mm in Luochuan, respectively.

The MS has been found particularly useful in characterizing the stratigraphic boundaries of soil-loess sequences in Chinese loess studies (Heller and Liu, 1982; Kukla and An, 1989; Kukla et al., 1990). Its value is higher in soils than in the intervening loess layers (Liu, 1985; Kukla and An, 1989; Kukla et al., 1990; An et al., 1991). We measured the low-field MS of the Luochuan section every 10 cm in the loess layers and every 5 cm in the paleosols, using a portable Bartington magnetometer. Each MS is an average of 10 measurements on a sampling interval. The MS of the Xifeng section was measured at 10 cm intervals. The susceptibility signal is greater in soil than in loess (generally ranging between 190 and $20 \times 10^{-8}\,m^3\,kg^{-1}$). The stratigraphic correlation of the two sections is made according to some widely used stratigraphic markers. These are the top dark Holocene soil S0, the Last Interglacial soil S1 (corresponding with MIS 5), and the strongly developed rubified S4 and S5 (Fig. 2). The boundaries between loess and soil units are well reflected by MS. The correlation of MS records from the Xifeng and Luochuan loess-soil sequences of the last 500 ka with the SPECMAP $\delta^{18}O$

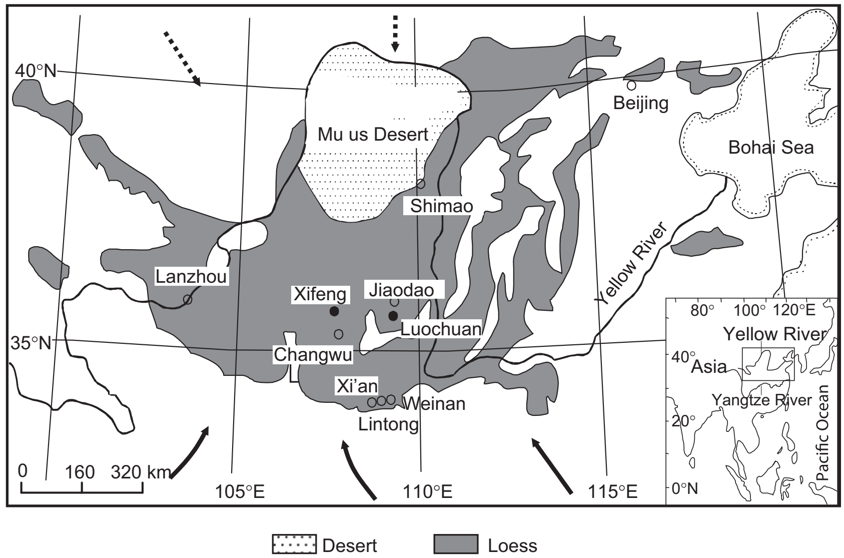

Fig. 1. Sketch map of the Central Chinese Loess Plateau and location of the studied sites mentioned in the text. The solid arrows indicate the direction of the East Asian summer monsoons, the dashed arrows the pathways of the East Asian winter monsoons (modified from Wu et al., 2002).

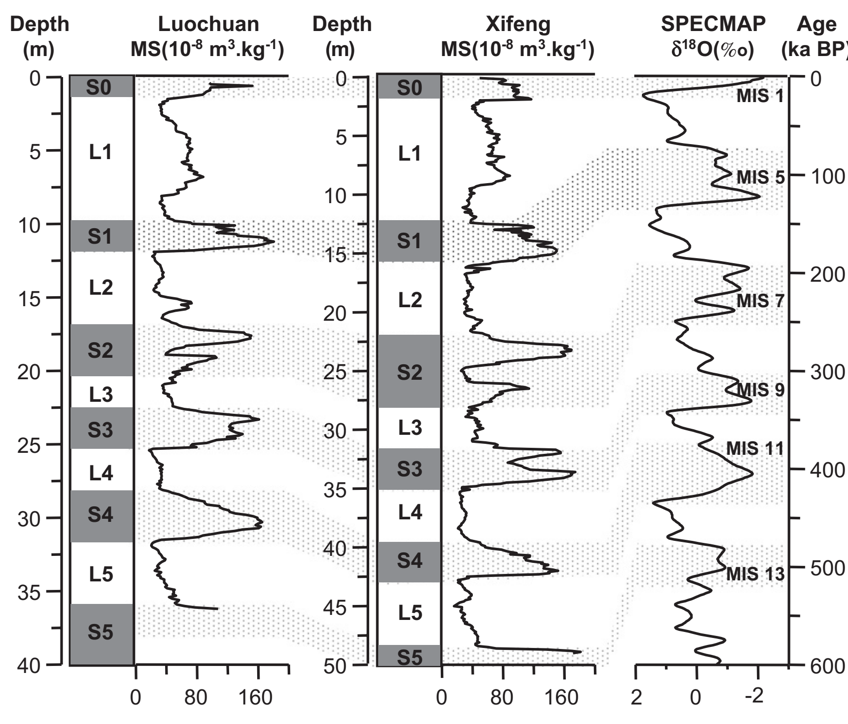

Fig. 2. Magnetic susceptibility (MS) records of the loess–soil sequence of the last 600 ka from Xifeng and Luochuan. Correlation with the SPECMAP $\delta^{18}O$ record (Imbrie et al., 1984). The soil and loess units and the marine Oxygen Isotope Stages are labeled following the literature. The land–sea correlation scheme follows Kukla (1987).

record (Imbrie et al., 1984) is shown in Fig. 2. The time series of these two loess sections are derived from Kukla et al. (1990).

In this study, we focus on the L5–L4 loess stratigraphies of the two loess–paleosol sequences, which were formed between MIS 12 and 10. The thickness of L5–L4 stratigraphy is ~13.2 m in the Xifeng loess section including L5 ~5.9, S4 ~3.0, and L4 ~4.3, and 11.0 m in Luochuan section composing L5 ~4.8, S4 ~2.6, and L4 ~3.6 m, respectively. A total of 242 samples for the mollusc study were taken from the L5–L4 strata of the two loess sections at 10 cm interval, which represents an approximate average temporal resolution per samples of ~800–1000 years for loess and ~2000–2300 years for soils, based on published chronostratigraphic studies (Kukla et al., 1990). Each sample weighs about 15 kg. All samples were washed and sieved in the field with a mesh diameter of 0.5 mm. The mollusc shells were sorted and identified under a binocular microscope. All identifiable mollusc remains were considered in the total count of individuals following the method developed by Puisségur (1976).

3. Results

Terrestrial mollusc shells are particularly abundant in the L5–L4 strata of the Xifeng and Luochuan sequences. Both sections show similar variations in the number of individuals and composition of species, reflected by the highest abundance in L5 loess unit and secondary abundance in L4 unit. All levels in the Xifeng loess section yielded mollusc shells; the minimum count is 11 individuals at the bottom of S4 at the depth of 42.8 m, and the maximum reaches 4083/15 kg shells at the depth of 46.1 m. The average number of individuals per sample in the Xifeng section is 1682 in L5 unit, 752 in L4, and 142 in S4. In Luochuan section, four samples did not yield mollusc shells at the bottom of S4. The highest value of mollusc shell individuals reaches 2276/15 kg in L5 unit at the depth of 32.6 m. The average number of individuals per sample in loess and soil layers is 1019 in L5 unit, 1128 in L4, and 144 in S4, respectively (Fig. 3).

Eighteen mollusc species were identified in the Xifeng loess section (Fig. 3a, Table 1). The dominant species include *Vallonia tenera*, *Pupilla aeoli*, *Pupilla muscorum*, *Gastrocopta armigerella*, and *Punctum orphana*. Fig. 4a shows the variability of these species during 490–330 ka interval. The percentages of both *V. tenera* and *P. muscorum* display their highest counts during MIS 12 and 10, the former shows two high maxima at MIS 12 and 10 (over 50%), and the latter exhibits a prominent maximum (close to 50%) in the earlier part of the MIS 12. *P. aeoli* shows high abundance at least six times during MIS 12–10, the maximum counts occurring at the middle part of MIS 12 (reach to 70%) and most of MIS 11 (average about 50%). *G. armigerella* dominates from the middle to late part of MIS 11 (about 30%), and in the middle part of MIS 12 (over 30%) and 10 (about 20%). *P. orphana* exhibits high values in the early and middle period of MIS 11 (reach 30%), the maximum abundance being in the middle of MIS 10, with a percentage close to 60%.

In the Luochuan sequence, 19 species have been identified from the L5 to L4 stratigraphy (Fig. 3b, Table 1). The predominant taxa are *V. tenera*, *P. aeoli*, *G. armigerella*, *Vertigo chenchiawoensis*, *P. orphana*, and slug (Fig. 4b). Among them, *V. chenchiawoensis* is the only fossil species with consequently its ecological characteristics yet unknown. Thus, we did not include it in our discussion in this study. Fig. 4b shows the variability in the counts of five main species during MIS 12–10. *V. tenera* exhibits its highest abundance (over 60%) in the early part of MIS 12 and secondary high value in the late part of MIS 12 and 10 (over 40%). *P. aeoli* displays a double maximum pattern (over 50%) in the middle part of MIS 12, and a sustained high abundance (about 40–50%) from the middle part of MIS 11–MIS 10. We should point out that the prominent maximum in the species *G. armigerella* at the bottom of MIS 11 does not reflect the real proportion of mollusc fauna during this period, as the strongly pedogenic dissolution caused the modification of faunal composition in both mollusc species and number of individuals. This species shows two notable maxima at the middle part of MIS 12 and 10, and a gradually decreased abundance from the middle of MIS 11–MIS 10. The slugs appear at the middle of MIS 11 and reach their highest values in early MIS 10. *P. orphana* has low abundance and sparely distribution in glacial periods of MIS 12 and 10, and its highest value (~20%) appears in the middle of MIS 11.

4. Discussion

4.1. Climate and ecological conditions in the Loess Plateau during MIS 12–10

The variations in the abundance of mollusc species provide information on paleoenvironmental changes in the Loess Plateau during MIS 12–10. The regular variability in the peak values of predominant taxa in the Xifeng and Luochuan loess sections clearly shows the ecological successions and climate changes during the deposition of L5–L4 (corresponding with MIS 12–10). As almost all of the identified taxa in both loess sections have modern analogs (Liu, 1985; Chen and Gao, 1987; Wu et al., 2001, 2002), we can use the modern ecological characteristics to infer paleoclimatic estimates during MIS 12–10 in the studied area. In this study, six species such as *V. tenera*, *P. aeoli*, *P. muscorum*, *G. armigerella*, *P. orphana*, and Slug have been selected to discuss the ecological and environmental changes during MIS 12–10.

As shown in Figs. 4a and b, mollusc fauna in the Xifeng and Luochuan loess sections was dominated by highly abundant cold-aridiphilous taxa such as *V. tenera*, *P. aeoli*, and *P. muscorum*, displaying a general cold and dry climate pattern during glacial periods of MIS 12 and 10. They also show some discrepancies in species abundance, reflecting the ecological and environmental contrast between the two sites during the loess deposited. *V. tenera* and *P. aeoli*, two typical cold-aridiphilous taxa present in the loess region, indicate however some ecological differences. *V. tenera* lives in drier conditions than *P. aeoli* (Wu et al., 2002), generally with a moisture range of ~200–350 mm (MAP). Conversely, *P. aeoli* adapts wider ecological conditions with MAT ranging from about 5.8–10.5 °C and MAP ~200–500 mm (Chen and Gao, 1987). The distribution of both species is restricted mainly to the NW continental interior, where the current summer monsoon hardly reaches, but where winter monsoon predominates for more than half the year (7–8 months) (Liu, 1985). The comparison of the variations in the high values of both *V. tenera* and *P. aeoli* in the Xifeng and Luochuan loess

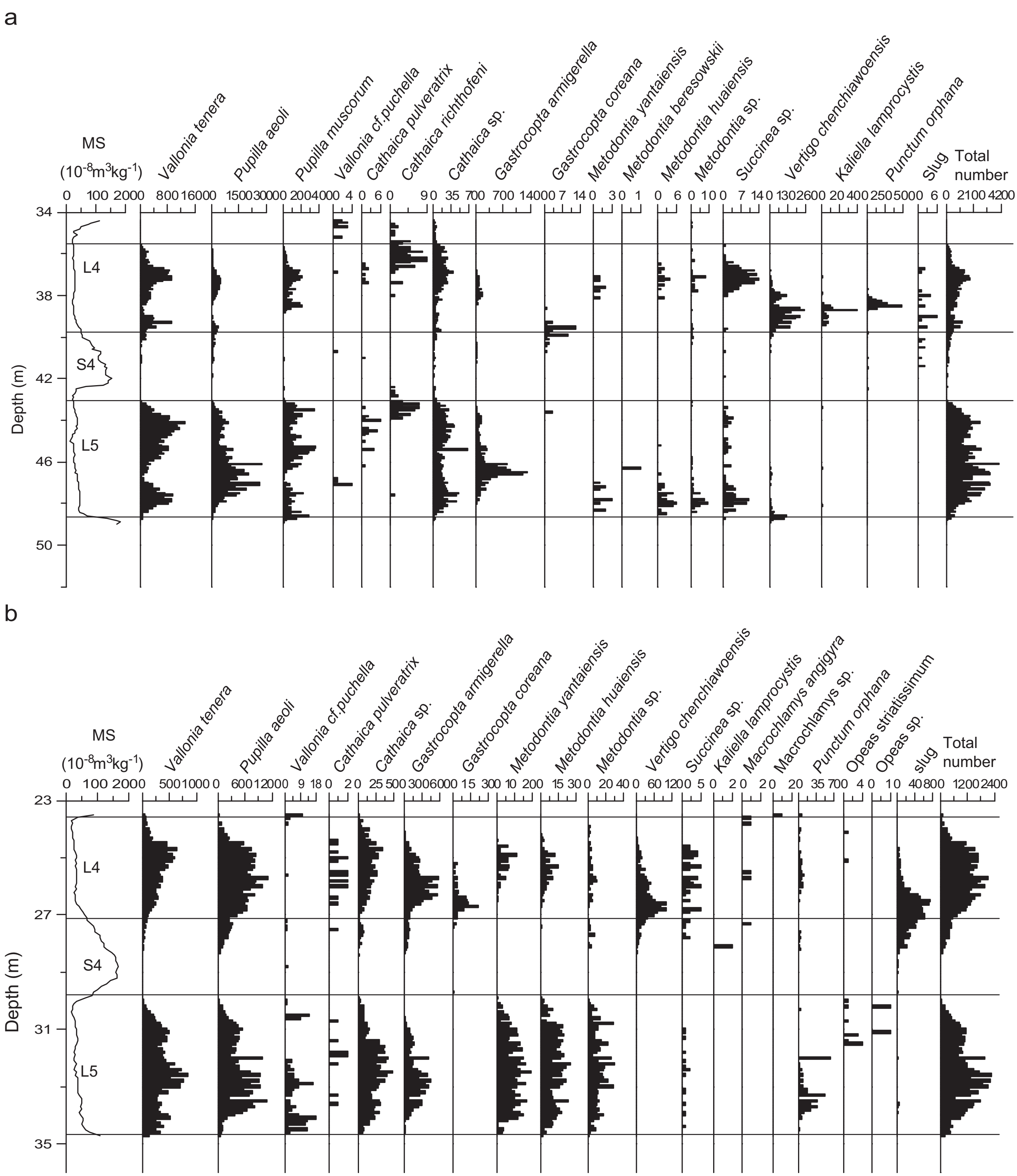

Fig. 3. Variations in mollusc species and magnetic susceptibility in the Xifeng (a) and Luochuan (b) L5–L4 sequences plotted versus depth. The mollusc species are expressed in the absolute abundance (total number of individuals counted per 15 kg).

sections, shows that the environmental conditions at Xifeng are more variable than at Luochuan during the studied interval. The ecological succession and climate changes can be outlined as follows:

4.2. The L5 unit, equivalent to MIS 12

During this period, the climate in the Xifeng region underwent several obvious changes. The beginning of this

Table 1
Mollusc species list from the studied sections of the Chinese Loess Plateau

Succineidae
Succinea sp.
Pupillidae
Pupilla aeoli (Hilber, 1883)
Pupilla muscorum (Linne, 1758)
Gastrocopta armigerella (Reinhardt, 1877)
Gastrocopta coreana Pilsbry, 1916
Vertigo chenchiawoensis Li, 1966
Valloniidae
Vallonia cf. *puchella* (Müller, 1774)
Vallonia tenera (Reinhardt, 1877)
Endodontidae
Punctum orphana (Heude, 1882)
Subulinidae
Opeas striatissimum (Gredler, 1882)
Opeas sp.
Ariophantidae
Kaliella lamprocystis Moellendorff, 1899
Macrochlamys angigyra Yen, 1939
Macrochlamys sp.
Bradybaenidae
Cathaica pulveratrix (Martens, 1882)
Cathaica richthofeni (Martens, 1873)
Cathaica sp.
Metodontia huaiensis (Crosse, 1882)
Metodontia yantaiensis (Crosse and Debeaux, 1863)
Metodontia beresowskii (Moellendorff, 1899)
Metodontia sp.
Limacidae
Slug

stage was dominated by a cool–humid climate as indicated by the high values of *P. muscorum* (Chen and Gao, 1987). Two drier periods appeared at Xifeng at about 430 and 450 ka, as reflected by two maxima of *V. tenera*. The modern analogs of this species with a similar abundance show that precipitation during these two periods was only about 200–350 mm, approximately corresponding to the modern precipitation conditions along the northwestern boundary of the Loess Plateau. In between these two dry periods, there was a relatively cold-wet interval as indicated by the highest abundance of *P. aeoli* and a noticeable amount of *G. armigerella* at about 445 ka. Modern populations, most similar to this glacial assemblage, are associated with the temperature of about 6–8 °C and the precipitation of about 300–500 mm (Wu et al., 2002). If the same fauna temperature and fauna precipitation relationships prevailed during the glacial period, it would indicate that the temperature and precipitation conditions in Xifeng region around 445 ka were a little lower than present day. The low temperature at glacial period made the soil more humid due to lower vapor evaporation, which favored *P. aeoli* growing prosperously. A warm–humid climate condition similar to that of today occurred at about 440 ka, marked by the highest abundance of *G. armigerella*. This species of *G. armigerella* is a typical thermo-humidiphilous representative in modern mollusc assemblages. It prefers a relatively warm–humid environment, with the most optimal temperature and humidity ranges being 5.8–10 °C, and 450–550 mm. Our modern investigation of land snail assemblages in the Loess Plateau shows that the highest abundance of this species was found at Xifeng and its surrounding area, to be one indicative species of summer monsoon impacting on the Loess Plateau. In summary, the climate changes at Xifeng during MIS 12 underwent an evolution of cool-wet, cold-dry, cold-wet, relatively warm-wet, to cold-dry conditions.

In Luochuan, climate conditions during the deposition of L5 were somewhat different from those in Xifeng. Apart from a dry-cold period characterized by the highest abundance of *V. tenera* in the earlier part of this stage, most of the glacial period is dominated by relatively cool-wet conditions, as shown in a broad maximum of *P. aeoli* and high abundance of *V. tenera* associated with small counts of thermo-humidiphilous species, *P. orphana*, *Opeas striatissimum*, and *G. armigerella*, as well as three species from *Metodontia* and one hygrophilous *Succinea* sp. (Figs. 3b and 4b). All of these thermo-humidiphilous species are characteristic of summer monsoon strengthening in the Loess Plateau at present. Their occurrence implied that the summer monsoon could persistently reach this region even during the glacial period, although the intensity of summer monsoon might have been weak. A period of intensified summer monsoon is observed between ~450 and 442 ka, reflected by distinct increase in the abundance of *G. armigerella*. The summer monsoon strengthening in Luochuan region is almost contemporaneous with that observed at Xifeng, which reveals a substantial, extensive intensified summer monsoon during the middle part of MIS 12 in the Loess Plateau. Our mollusc evidence suggests that the glacial of MIS 12 is not the most severe one, as documented in marine isotopic record (Mix et al., 1995; Pisias et al., 1995; Shackleton et al., 1995), and even far less than MIS 2 and MIS 6 in the Loess Plateau (Wu et al., 1996; Rousseau and Wu, 1997, 1999). It has been proposed that MIS 12 interval is a unique glacial in Quaternary climate history with extremely severe conditions and the largest amplitude change in oxygen isotopic composition in the MIS 12–11 transition and major ice-sheet expansion in the past 6 Ma (Droxler and Farrell, 2000), as evidenced by marine oxygen isotopic records (e.g., Mix et al., 1995; Pisias et al., 1995; Shackleton et al., 1995). The sea level was 20 m below the last glacial-minimum lowstand estimated at minus 120 m (Rohling et al., 1998). However, so far there has been no in-depth investigation done on the climate and environment condition during MIS 12 in the Chinese Loess Plateau. Some of the studies only briefly mentioned that it was a cold glacial period (Liu, 1985; Guo et al., 1993, 1998; Ding et al., 1994, 1995; Hao and Guo, 2005; Wu et al., 2005). There is not enough accurate and detailed discussion

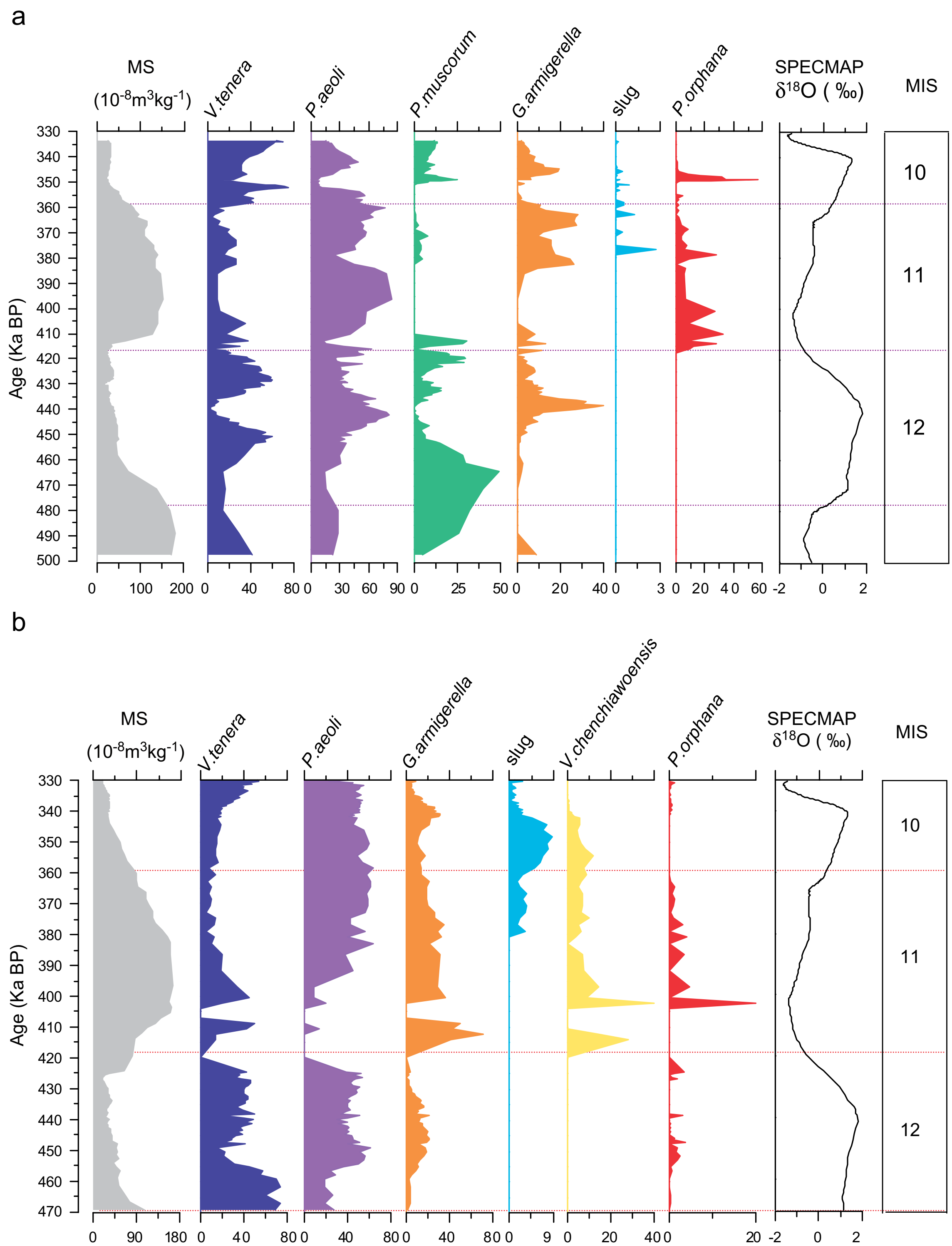

Fig. 4. Variations in the percentages of six mollusc species in the Xifeng (a) and Luochuan (b) loess sequences during MIS 12–10, compared with variations in magnetic susceptibility and SPECMAP $\delta^{18}O$ record (Imbrie et al., 1984).

about the environmental changes that prevailed during this period, especially the changes in the climate pattern. In this study, we present an attempt to reconstruct the processes of environmental changes based on the mollusc records from two loess sections in the central part of the Loess Plateau. Our result shows a distinct regional difference existed in this area under the circumstance of a general global cooling during this period.

4.3. The Interval of S4 paleosol, equivalent of MIS 11

Mollusc records during this period show that a general warm–humid climate condition prevailed over the Loess Plateau. A warm–humid optimum dominated in the early part of this period is reflected by strongly weathered soils in both loess sections. This resulted in the dissolution of a large number of mollusc shells. A mild climate condition similar to what we have today, however, prevailed later in this stage, as evidenced by higher values of *P. aeoli*. This moderate condition was not recognized in previous studies of S4 paleosol (Liu, 1985; Guo et al., 1998; Vidic et al., 2003). By comparing the mollusc records of both Xifeng and Luochuan sections, we found some evidence about some regional differences in ecological and climatic changes between these two sites during this period. A general climate condition at Xifeng is declined to cooler and more variable than that at Luochuan during MIS 11.

In Xifeng, a warm–humid climate prevailed during the early period of MIS 11 (~417–385 ka) characterized by higher counts of the thermo-humidiphilous *P. orphana* and strongly weathered soils. The paleopedological and geochemical studies by Guo et al. (1998) suggested subtropical semi-humid climates with an estimated MAT of at least 4–6 °C and MAP of 200–300 mm, higher than modern conditions, indicating a much strengthened summer monsoon period. During this warm–humid period, a cool fluctuation appeared at about 400 ka marked by the maximum abundance of *P. aeoil*. From about 385 ka, this area was influenced by a more moderate climate until the end of the whole MIS 11. The high abundance of *P. aeoli* and *G. armigerella* through the late part of the MIS 11 indicates that the environmental conditions were similar to what we have today. In the course of this mild climate, a short-term cooler fluctuation occurred at about 380 ka, reflected by higher values of *P. aeoli* and *V. tenera*, respectively. In short, the climate conditions in Xifeng during the whole MIS 11 were characterized by an early optimum warm and humid climate, followed by late mild conditions, and interrupted by several warm and cool fluctuations (Fig. 4a).

At Luochuan, a strongly weathered soil was developed at the lower part of the S4 unit as mentioned above. The strong pedogenesis resulted in totally decalcified layers and highly dissolved mollusc carbonate shells. Only a few shells remained after the strong soil weathering, and some levels were barren. The effect of dissolution in mollusk shells was particularly heavy at the bottom of S4 soil unit and decreased rapidly upwards. Mollusc individuals varied from zero at 30.0 m depth to 22 at 29.1 m (Fig. 3b). Thus, it is difficult to use mollusc assemblages to reconstruct paleoenvironmental conditions for this interval. In this study, we combined with the result of pedological study to infer paleoclimatic change. The strongly developed soil layer has been considered to be an indication of much warmer and more humid conditions than the present-day average (Guo et al., 1996, 1998). A large number of shells (over 100 individuals per sample) composed mainly of the predominant *P. aeoli* are noticed at about 380 ka, which implied that the extremely warm–humid climate ended at about that time. Thus, we assume that this warm–humid condition might have lasted over 30 ka (from ~417 to 385 ka) at Luochuan, almost the same length of time as the warm–humid period observed at Xifeng in the early part of S4 development. Starting from ~380 ka, climate in Luochuan began to gradually cool, as reflected by the progressive increase of *P. aeoli* and the decrease of *G. armigerella* and *P. orphana*. A generally mild climate condition dominated in the latter part of MIS 11. Paleopedological evidence also showed a weak pedogenesis during this period (Guo et al., 1996, 1998).

4.4. The interval of L4, equivalent of MIS 10

During this period, the climate in Xifeng area underwent once again several noticeable changes. Two cold and dry conditions indicated by the highest abundance of *V. tenera* occurred at the early and late parts of this stage. Conversely, in the middle part, an episode of strengthened summer monsoon (~345 ka) is reflected by the maximum abundance (close to 60%) of *P. orphana* and the scarcity of *P. aeoli* and *V. tenera*. Following this episode, a weakened summer monsoon phase appeared at ~340 ka, indicated by higher values of *G. armigerella* and *P. aeoli*.

In Luochuan, a cool-wet climate inherited from the late MIS 11 dominated the early part of MIS 10 interval, as documented by the high *P. aeoli* counts, associated with considerable individuals of *G. armigerella* and slugs. In the middle part of the MIS 10, a comparatively strong summer monsoon episode occurred at about 340 ka, indicated by the higher values of *G. arimigerella*. This warming episode was synchronous with that of the stronger summer monsoon observed at Xifeng, suggesting an intensifying summer monsoon phase at that time during the glacial MIS 10.

In summary, our high-resolution mollusc records of the Xifeng and Luochuan loess sections during MIS 12–10 indicate that the climate conditions were highly variable in the Loess Plateau in glacials as well as during the interglacial period.

5. The issues on MIS 11 climate condition in the Loess Plateau

5.1. Duration of the MIS 11 interglacial

As indicated by Kukla (2003), MIS 11 is somewhat different from the MIS 11 interglacial period. This stage lasted about 50–60 ka and covered approximately two and a half precessional cycles, which is much longer than the interglacial MIS 5e, MIS 9, or even the elapsed part of the Holocene. In the Chinese loess sequence, S4 is a single paleosol in the central part of the Loess Plateau as shown by the single susceptibility peak, contrary to clearly distinguishable multiple peaks in S2 and S5. In previous studies, S4 was considered an individual paleosol representing the entire MIS 11 interglacial. Thus, the estimated duration of the whole S4 varied from ~30 to 60 ka according to different authors based on the correlation with the odd numbered marine isotope stages and astronomical calibration of Chinese loess paleoclimatic records (Bassinot et al., 1994; Lu et al., 1999; Heslop et al., 2000; Ding et al., 2002). In our study, we used the age estimates proposed by Kukla et al. (1990), based on MS-age model using magnetostratigraphic boundaries as age controls, and correlated to the SPECMAP marine isotopic stages (Fig. 2) and other time scales by orbital tuning (Bassinot et al., 1994; Lu et al., 1999; Heslop et al., 2000; Ding et al., 2002). As an independent timescale for Chinese loess sequence, the age model by Kukla et al. (1990) remains valid as a working model although some assumptions of the model are contested in part by rock magnetism studies (Guo et al., 1998, 2000). Thus, according to this age model, the duration of S4 is up to 60 ka.

Our mollusc records from Xifeng and Luochuan loess sections indicate that S4 paleosol was not developed under a uniform climate condition. It was formed under two different climate regimes. Firstly, the early part, from ~417 to 385 ka, shows very warm and humid climate conditions reflected by thermo-humidiphilous molluscs, strongly weathered soil, and the highest MS values. This represents the true interglacial period. This warm interglacial condition lasted over 30 ka at Xifeng and Luochuan regions, largely exceeding the interglacial conditions observed in the Loess Plateau during MIS 5e, 7e and 9e. Secondly, the latter part from 385 ka to the end of MIS 11 is characterized by a mild climate, particularly clearly expressed in the Xifeng mollusc record. The early warm optimum conditions of MIS 11 are also recorded in the diatom records retrieved from Lake Baikal, farther north from the Loess Plateau, suggesting a long period of uninterrupted warmth in continental Asia between 385 and 450 ka (Karabanov et al., 2003).

5.2. *Climate stability of MIS 11 in the Loess Plateau*

The variability in maximum values of mollusc taxa of the Xifeng and Luochuan loess sequences reflects an unstable climate during MIS 11. Furthermore, it is documented that the Xifeng section underwent stronger instability (Fig. 4a). As shown in Fig. 4a, apparent climate changes occurred at least four times during MIS 11, at about 410, 400, 390, and 370 ka, respectively. The climate in this region underwent periods: extremely warm–humid, briefly cooling, warmer and more humid, and relatively cool period. It should be noted that a brief cooling spell is observed at ~400 ka at the maximum interval of warm–humid MIS 11 interglacial period indicated by the highest MS peak values. Such result is an artifact but documents substantially that climate fluctuation existed even in the optimum period of MIS 11 interglacial. This cooling spell has also been recorded in the Shimao loess section located at the northern edge of the Loess Plateau, where two S4 soils separated by a layer of loess material were described (Sun et al., 1999), indicating a cooling and drying episode. We found that the regions close to the transition between desert and loess deposits or to the northwestern part of the Loess Plateau have more sensitive reflections on climate changes, especially indicative of summer monsoon intensity, because of their location to the potential source of the dust located in the different northern deserts (Ding et al., 1999; Yang and Ding, 2004).

5.3. *Climate pattern of MIS 11 in the Loess Plateau*

Comparison of mollusc records from the Xifeng and Luochuan loess sections indicate cooler and drier conditions at Xifeng than at Luochuan during the MIS 11 as indicated above. A similar conclusion was proposed from previous pedological and geochemical studies. Indeed, Guo et al. (1998) found that the pedological features in the field of S4 paleosol at Xifeng was less developed than those of S4 paleosols at Changwu (located 100 km south of Xifeng) and at Weinan (at the southern-most part of the Loess Plateau) (Fig. 1). This is mainly reflected by lower MS and Fed/Fet ratios, suggesting weaker weathering intensity due to a drier climate condition at Xifeng. Vidic et al. (2003) studied the properties of the five recent paleosols (S5–S1) of the Jiaodao loess section (~30 km north of Luochuan). This study showed that S4 paleosol did not indicate an unusual warm condition during the development of S4. The cooling spell revealed by the mollusc record at the peak interval of MIS 11 interglacial in the Xifeng sequence, and the intervening loess layer in two S4 soils in the Shimao section have not been recorded in the Luochuan section and other southward loess sections of similar age. This shows an obvious regional climate difference at that time in the Loess Plateau. Hao and Guo (2005) suggested that spatial variations in climate pattern, similar to present-day, prevailed during the development of S4 paleosol based on the study of MS of 50 loess sequences. Thus, we could speculate that extreme warm–humid climate was present in the southeastern part of the Loess Plateau during the peak interval of MIS 11 interglacial. This might correspond to subtropical monsoon climates with higher precipitation and temperature (Guo et al., 1998), which caused strong leaching of soil carbonates and dissolution of mollusc shells in that region. Conversely, in the northwestern part of the Plateau including Xifeng and Jiaodao regions, relatively warm and humid climate prevailed at the same time, inducing weaker soil developments (Guo et al., 1998; Vidic et al., 2003) and better preservation of mollusc carbonate shells. Therefore, greater gradients in MAT and MAP could have existed in the Loess Plateau during MIS 11 interglacial, as supported by spatial variations of MS values at this period (Hao and Guo, 2005).

Both Xifeng and Luochuan mollusc records indicate relatively moderate climates dominated in late part of MIS 11, as analyzed above. Not enough paleoclimate data are yet available to infer changes in the climate pattern over the Loess Plateau during this time interval, but it seems that less regional differences prevailed according to the variations in mollusc assemblages of both loess sections.

5.4. Comparison of climate warmth between MIS 11 and the Holocene

MIS 11, at about 400 ka, has been interpreted as an analog for the Holocene and future climate under the natural forcing due to the similar conditions of orbitally driven insolation (Droxler et al., 2003; Loutre and Berger, 2003). Until now, there have been many studies investigating unusual MIS 11 climatic conditions as recorded in different marine and continental records. In land, paleoclimatic records reveal that the interglacial conditions were not identical in different terrestrial studies. At some localities, the interglacial interval equivalent to MIS 11 was warmer than the Holocene (Karabanov et al., 2003; Rousseau, 2003), where, as at other localities, the estimated temperatures were only similar to or even cooler than the Holocene (Kukla, 2003; Vidic et al., 2003; EPICA Community Members, 2004). In the Chinese loess–paleosol sequences, almost all paleoclimatic reconstructions of S4 paleosol resulted from the studies of pedological and geochemical properties of the sediment. For example, based on the morphological comparison of paleosols and loess units with present-day soils in different climatic regimes in China, Liu et al. (1985) interpreted that the MAT and MAP were of about 13 °C and 650 mm, respectively, at Luochuan during the S4 paleosol development. Han et al. (1997) proposed estimates of ~11.3 °C (MAT) and ~670 mm (MAP) based on the stable isotope composition of carbonate concretions in the Luochuan sequence. Guo et al. (1998) assumed that S4 formed under extreme warm climate conditions, with an estimated MAT of at least 4–6 °C higher and MAP of 200–300 mm higher than modern values based on soil morphology, geochemistry, and MS of three loess sequences distributed along a southeast to northwest transect in the Loess Plateau. Vidic et al. (2003) recently considered that the climatic conditions during the formation of S4 were relatively warm and humid based on the pedogenic intensity and other proxy properties in the Jiaodao sequence.

Our mollusc records from both the Xifeng and Luochuan loess sequences reveal clearly different climate conditions presented in the early and late parts of the S4 formation. The early part spanning over 30 ka was a true interglacial. Climate conditions during this interval should

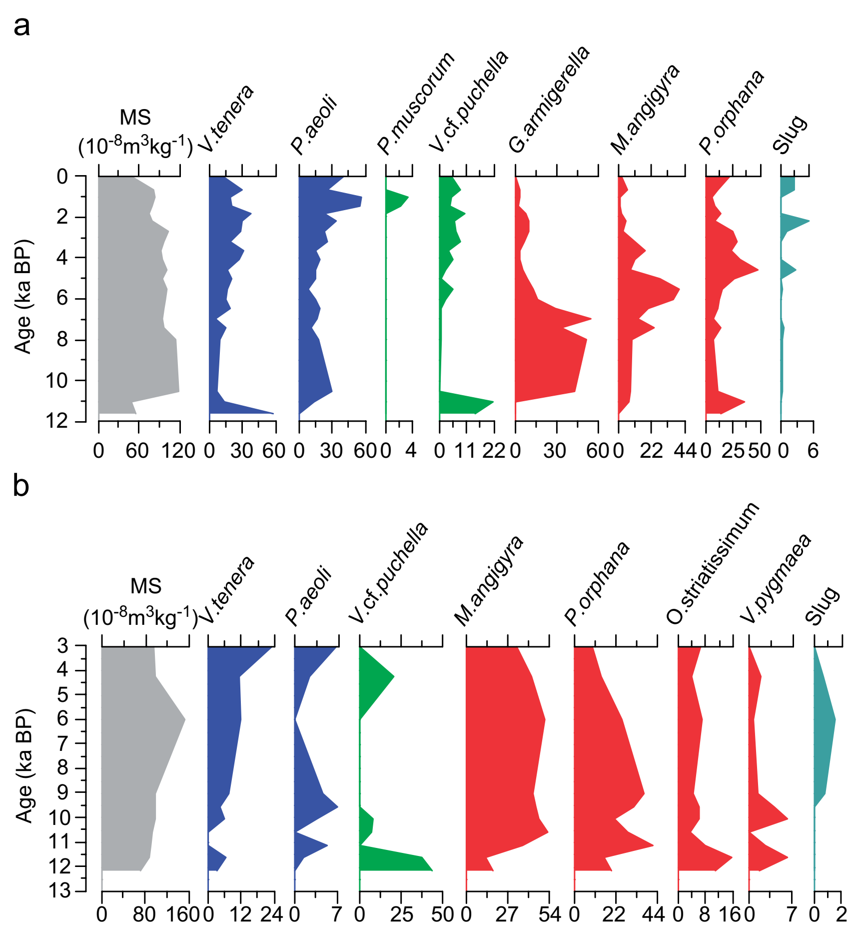

Fig. 5. Variations in the percentages of mollusc fossil species from Holocene (S0) records in Xifeng (a) and Luochuan (b) loess sequences.

be very warm and humid, which caused strong soil pedogenesis and the dissolution of most mollusc shells. A similar phenomenon was found in the Holocene soil (S0) of the Weinan (Wu et al., 2002) and Lintong loess sequences at the southern-most part of the Loess Plateau, showing a certain extent of dissolution in mollusc assemblages. Presently, both Weinan and Lintong regions have a MAT of 11.3–13.6 °C and a MAP of 529–650 mm. Thus, we can estimate that the temperature conditions at Xifeng and Luochuan regions during the early 30 ka of MIS 11 might have been similar to the modern ones in the southeastern part of the Loess Plateau, but with higher precipitation. It might be expected to correspond to the climate conditions of Weinan and Lintong regions at the Holocene optimum period with a MAT of ~11–14 °C and a MAP of ~600–800 mm (Wu et al., 1995).

Our mollusc records also indicate that warm–humid climate of the early part of MIS 11 in the Loess Plateau changed from mild to cool condition at about 385 ka. Comparison of mollusc assemblages of the late part of MIS 11 with those of the Holocene shows differences. The Holocene mollusc assemblages presented more thermo-humidiphilous species (6 of total 11 taxa) such as *Macrochalmys angigyra*, *P. orphana*, *Opeas stratissimum*, *Vitrea pygmaea*, *G. armigerella*, *Kaliella lamprocystis*, etc. Moreover, the abundance of thermo-humidiphilous species is higher in the Holocene record, for example, *M. angigyra* and *P. orphana* reach their highest values of 54% and 37% at Luochuan and 40% and 48% at Xifeng, respectively (Fig. 5a and b). While in the late part of MIS 11, the thermo-humidiphilous species has only two representatives of *P. orphana* and *G. armigerella* and their abundance falls to less than 30% (Fig. 4a and b). This indicates that climate conditions during this period were less warm than during the Holocene in Luochuan and Xifeng regions.

6. Conclusion

Land snails are the most widespread fossil remains in the Chinese loess sequences, which have long been regarded as a useful indicator of environmental changes (Liu, 1985). The study of MIS 12–10 land snail records from two loess sequences of the Chinese Loess Plateau allowed us to precisely reconstruct the climate changes that prevailed during this interval. A series of climate fluctuations, characterized by the variations in abundance of land mollusc species, have been documented in the corresponding loess and paleosol successions. Our mollusc study showed that L5 loess, equivalent of MIS 12, formed under relatively cold and dry conditions. Climate at this period was not as severe as indicated by the marine isotopic records (e.g., Mix et al., 1995; Pisias et al., 1995; Shackleton et al., 1995). However, an episode of warmer and more humid condition occurred at the middle part of the MIS 12, reflecting a strengthened summer monsoon during this glacial interval. A similar scenario has been evidenced in the middle part of MIS 10.

Our mollusc records also provide insight into the climate conditions in the Loess Plateau during the MIS 11, interpreted as the closest analog to the present interglacial. S4 paleosol, equivalent of MIS 11, developed under two major different climate regimes: ranging from the very warm–humid early phase to the mild-cool late interval. Furthermore, a cooling spell has been documented at the interglacial optimum, reflecting unstable climate conditions. The early warm–humid conditions lasted over 30 ka, supporting that MIS 11 is a unique long interglacial in the Quaternary climate history. Moreover, obvious regional differences in climate patterns prevailed over the Loess Plateau during the interglacial period of MIS 11. The extreme warm–humid climate only occurred in the southeastern part of the Loess Plateau.

Comparison of MIS 11 and Holocene climates based on the mollusc species compositions indicates major differences. The climate at the early part of MIS 11 was warmer and more humid than during the Holocene optimum period, but the conditions during late part of MIS 11 were similar to or cooler than late Holocene. Our study indicates that the extent of warming during the Holocene might be significantly less than the conditions that prevailed during the MIS 11 interglacial period.

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