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Climate of the Past Discussions

Terrestrial mollusc records from Xifeng and Luochuan L9 loess strata and their implications for paleoclimatic evolution in the Chinese Loess Plateau during marine oxygen isotope stages 24–22

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Abstract

Marine Isotope Stages 24–22 is a key period of the Mid-Pleistocene Transition, however, its climate variability is still unclear. The coarse-grained loess unit L9, one of the most prominent units in the Chinese loess stratigraphy, yields a high potential terrestrial record of paleoclimatic and paleoenvironmental changes during this period. In this study, two high-resolution terrestrial mollusc records of L9 loess strata from the Xifeng and Luochuan sequences in the Chinese Loess Plateau were analyzed. Our mollusc results show that the MIS 24, the early and late parts of MIS 22 were dominated by cold and dry climate. Relatively mild-humid climate occurred in MIS 23 and the middle part of MIS 22. The climatic conditions at Xifeng region were cooler and more unstable compared to Luochuan region. A comparison of mollusc species composition and other proxies of L9 strata (MIS 24–22) with those of L1 loess units (MIS 4–2) reveals that the L9 loess was not deposited under the most severe glacial conditions in Quaternary climate history as suggested by previous studies. Our study shows that climatic conditions in the Loess Plateau during the L9 loess forming period were like that of gentle glacials (MIS 24 and MIS 22) and interglacial (MIS 23), as suggested by marine δ^{18}O record. Three cooling fluctuations occurred at ~940–923 ka, 905–895 ka and 885–875 ka, which might be hints of the global "900 ka cooling event". The "900-ka event" in the Loess Plateau seems not a simple long glaciation but a complex of several climatic fluctuations superposed on a general cooling trend. The uplift of Tibetan Plateau and its adjacent regions during this period resulted in a rapid increase in source materials of desert and loess and an enhancement of winter monsoon, which would have amplified the effects of cooling climate on dust production and transport during MIS 24–22, as indicated by increased grain size and mass accumulation rate of L9 loess.

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1 Introduction

The Chinese loess sequences have continuously documented the climatic and environmental changes of the past 2.6 Ma (Liu, 1985; Kukla, 1987; Ding et al., 2002). L9 loess, one of the most prominent units among the loess-paleosol sequences, is commonly used as a stratigraphic marker due to its pale color, coarse texture, loose cementation and huge thickness (Liu, 1985). L9 loess unit is composed of two loess layers and one interbedded paleosol layer, which commonly corresponds to Marine Isotope Stages 24–22 (~940–860 ka) (Kukla, 1987; Liu et al., 1999; Ding et al., 2002). Previous studies emphasized on field observation and analyses of physical and chemical proxies, and considered L9 as an indicator of the severest glacial conditions (Liu, 1985; Guo et al.,1998; Lu et al., 2000). Guo et al. (1998) conducted extensive investigations on the properties of L9 loess layer based on paleopedological, geochemical and magnetic susceptibility (MS) variations of three loess-paleosol sections from Xifeng, Changwu and Weinan in the Loess Plateau. Their study suggested that L9 was formed under a semi-desertic climate with strengthened aeolian deposition and the summer monsoon rarely penetrated into Loess Plateau region. However, marine δ^{18}O records show that global ice volume during MIS 24–22 was not as high as those glacials in middle and late Pleistocene and the amplitude of glacial-interglacial was relatively small, indicating a weak glacial (Lisiecki and Raymo, 2005). Thus, it has long been considered that a distinct difference existed in climatic conditions revealed by terrestrial aeolian records and marine δ^{18}O signals during the L9 loess forming period. However, the cause of extreme climate in the Loess Plateau remains unclear.

As mentioned above, the L9 loess stratigraphy, equivalent to MIS 24–22, was formed at a unique period in Quaternary climate history. It deposited in a transition when the dominant periodicity of global climate changed from ~41-kyr to ~100-kyr (i.e. Middle Pleistocene Transition) (Ruddiman et al., 1989; Mudelsee and Schulz, 1997; Raymo et al., 1997; Clark et al., 2006). In addition, the first long glaciation (~80 kyr) of the Pleistocene occurred at ~900 ka, when a global cooling event called "900-ka event" was

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documented in both marine and terrestrial records (Ruddiman et al., 1989; Williams et al., 1997; Schefuss et al., 2004; Zheng et al., 2005; Clark et al., 2006; Bintanja and van de Wal, 2008). However, the amplitude and temporal pattern of this cooling event are different in these records. More investigations are needed to develop a detailed picture of this cooling event so that we may understand the temporal and spatial patterns and mechanisms for this event. The thick L9 stratigraphy as a unique terrestrial record provides us an opportunity to study the behavior of 900-ka event in East Asia. It not only can provide information about detailed climate change and spatial pattern of the semi-arid and semi-humid area in the Loess Plateau, but also can reveal the response of the East Asian monsoon system during this period. In this study, we analyzed terrestrial mollusc assemblages from two well-known loess-paleosol sequences at Xifeng and Luochuan in the central Loess Plateau to emphasize the following questions: (1) Was the L9 formed under an extremely cold glacial period? (2) Do the climatic conditions indicated by L9 loess imply the feature of a regional event or the response of regional climate to a global event? (3) If the latter, how did the loess depositions respond to the global 900 ka cooling event? and (4) How was the exceptionally thick loess deposition formed?

2 General setting and methods

The Xifeng (35°46′ N, 107°41′ E) and Luochuan (35°45′ N, 109°25′ E) loess sequences are located in the central Loess Plateau (Fig. 1). Climate in this study area is characterized by seasonal alternation of the East Asian summer and winter monsoons (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 620–660 mm in Luochuan, respectively.

These two classical loess sections have been intensively investigated (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, 2007;

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Rousseau and Wu, 1997, 1999; Lu et al., 2000). In this study, we focus on the L9 loess stratigraphies of the two loess-paleosol sequences, which were formed during MIS 24–22. Figure 2 shows the correlation of magnetic susceptibility (MS) records from the Xifeng and Luochuan loess-paleosol sequences of the last 1000 ka with the newly compiled LR04 δ^{18}O record. The L9 stratigraphy in the Xifeng section is ~10.7 m in thickness with three layers, i.e. L9LL1 loess, L9SS1 paleosol, and L9LL2 loess from the top down (Kukla and An, 1989; Kukla et al., 1990). The L9 stratigraphy in the Luochan section is ~7.5 m in thickness with the same three layers as the Xifeng section. The L9LL1 and L9LL2 loess are corresponded to MIS 22 and 24 (Fig. 2), respectively, whereas the L9SS1 paleosol is equivalent to MIS 23 (Liu, 1985; Liu et al., 1999; Ding et al., 2002). The age of the studied two loess sequence was obtained by using boundaries ages of loess-paleosol sequences (Ding et al., 2002) as age controls, and then interpolation between age controls using magnetic susceptibility model of Kukla et al. (1990). Although this model was based on some assumptions that are still somewhat contentious (Heller et al., 1993), it remains a working model for obtaining an independent timescale, having been widely used in many long-term loess dating studies (Kukla and An, 1989; Kukla et al., 1990; Liu et al., 1995; Guo et al., 1998, 2000).

A total of 196 samples for mollusc study were taken from the L9 strata of the two loess sections at 10 cm interval, which represents an approximate average temporal resolution per sample of ~500–800 years for loess and ~700–1300 years for soil in Xifeng, and ~700–900 years for loess and ~700–1300 years for soil in Luochuan. 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 picked and identified under a binocular microscope. All identifiable remains were considered in the total count of individuals following the method developed by Puisségur (1976).

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3 Results

3.1 Fossil mollusc assemblages

Terrestrial mollusc shells are particularly abundant in the L9 strata of the Xifeng and Luochuan sequences (Fig. 3). All levels in both sections contain shells. In Xifeng section, the maximum count (2151/15 kg shells) is at the bottom of L9SS1 (80.6 m at the depth) whereas the minimum (only 1 individual) is at the top of L9LL1 (74.5 m at the depth). The average numbers of individuals per sample in the Xifeng section are 529, 1285, and 352 in L9LL2, L9SS1, and L9LL1 units, respectively. In Luochuan section, the highest value of mollusc shell individuals reaches 4156/15 kg in L9SS1 (59.3 m at the depth), and the top of L9LL1 (55.3 m at the depth) just contains one individual (the minimum). Again, more individuals are found in soil layer (2313/15 kg in L9SS1) than loess layers (473/15 kg in L9LL2 and 558/15 kg in L9LL1) at the Luochuan section (Fig. 3). A total of 140 461 individuals were identified for the L9 strata of the Xifeng and Luochuan sections.

14 mollusc species were identified in the Xifeng loess section (Fig. 3a). The dominant species includes *Vallonia tenera*, *Vallonia* cf. *pulchella*, *Pupilla aeoli*, *Pupilla cupa*, *Gastrocopta armigerella*, and *Punctum orphana*. Figure 4a shows percentage variations of these species during the interval of MIS 24–22. High percentages of both *V. tenera* and *P. cupa* exhibit during MIS 24 and 22. Three peaks in the percentages of *V. tenera* (over 50%) occur at MIS 24, early and late parts of MIS 22. *P. aeoli* dominates at the most of MIS 23 (over 60%) and the middle part of MIS 22 (over 70%). *G. armigerella* exhibits maximum counts at the early part of MIS 23 (38%) and the middle part of MIS 22 (39%). Both *V*. cf. *pulchella* and *P. orphana* show high abundance during MIS 23.

In the Luochuan loess section, 15 mollusc species were identified from the L9 stratigraphy (Fig. 3b). The predominant taxa are *V. tenera*, *V*. cf. *pulchella*, *P. aeoli*, *P. cupa*, *G. armigerella* and *P. orphana*, similar to Xifeng section. The percentage variations of these six species are shown in Fig. 4b. *V. tenera* exhibits two main peaks at MIS 24 (over 40%) and the early part of MIS 22 (over 30%), and *P. cupa* reaches its highest value at the early part of MIS 22. High percentages of *P. aeoli* (over 50%) mainly occur at the early part of MIS 24, MIS 23, and the middle part of MIS 22. *G. armigerella* and *V*. cf. *pulchella* show relatively sustained abundance during MIS 24–22 except for the boundary of MIS 23 and MIS 22. *G. armigerella* maintains its high values (over 30%) during the late part of MIS 24 to the early part of MIS 23, and the most part of MIS 22. *P. orphana* has low abundance and exhibits its main peak at MIS 23 and the middle part of MIS 22.

It should be pointed out that a large number of mollusc shells were dissolved at the upper part of L9LL1 due to strong carbonate dissolution as the upper S8 soil formed. This dissolution process largely modified the mollusk faunal compositions in species and individuals. However, the mollusc remains could still provide some information about environmental changes.

The mollusc assemblages of the Xifeng and Luochuan L9 strata can be divided into three ecological groups according to the ecological requirements of those taxa for temperature and moisture (Chen and Gao, 1987; Wu et al., 1996, 1999, 2001; Rousseau and Wu, 1997, 1999). The first one is the cold-aridiphilous group, consisting of *V. tenera*, *P. aeoli*, and *P. cupa*. These taxa live in dry and relatively cold regions presently dominated by winter monsoon, and their fossil species are thus used as an indicator of winter monsoon (Liu, 1985; Wu et al., 1996; Rousseau and Wu, 1997, 1999). The second one is the thermo-humidiphilous group. The species of this group including *G. armigerella* and *P. orphana* favor warm and moist conditions. They are presently distributed in the regions dominated by summer monsoon, and their appearance in the loess stratigraphy indicates a penetration of the summer monsoon into Loess Plateau region (Wu et al., 2000, 2002). The third one is cool-humidiphilous group. It just contains one species, *V*. cf. *pulchella*. This taxon lives in relatively cool and wet regions (Chen and Gao, 1987; Wu et al., 1996).

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3.2 Climatic conditions inferred from fossil mollusc assemblages

The abundant mollusc individuals preserved in the L9 strata in the Xifeng and Luochuan loess sections provide us an opportunity to detailedly investigate climatic and environmental conditions in the Loess Plateau during MIS 24–22. Since most of the identified taxa in both sections have their modern analogs (Liu, 1985; Chen and Gao, 1987; Wu et al., 2002, 2007), we can use modern observation data to infer paleoclimatic conditions in the studied area.

As shown in Fig. 4a and b, mollusc fauna in both Xifeng and Luochuan sections were dominated by cold-aridiphilous taxa during MIS 24. Among them, *V. tenera* is a dominant species. It presently prefer drier and colder ecological environments than other species in the continental interior of northwest China, with optimal ranges of MAT (5.8–10.5 °C) and MAP (200–350 mm) (Chen and Gao, 1987; Wu et al., 2001, 2002, 2007). Its high percentages at MIS 24 (over 67%) together with abundant *P. aeoli* and *P. cupa* in the Xifeng section indicate a cold-arid climatic condition, implying a strengthened winter monsoon. Few thermo-humidiphilous taxa such as *G. armigerella* and *P. orphana* during this interval reflect a weak influence of summer monsoon on this region. Meanwhile, the Luochuan region was also dominated by a cold-arid climate, as indicated by a peak value of *V. tenera* (reaches 47%). However, the abundance of thermo-humidiphilous *G. armigerella* shows an increasing trend after the middle part of MIS 24 and reaches 40% at the end, indicating warmer and wetter conditions in the Luochuan than in the Xifeng region.

During the interglacial of MIS 23, relatively warm-humid conditions prevailed over the Loess Plateau, as evidenced by high values of *G. armigerella* and *P. orphana*. *G. armigerella* is a typical thermo-humidiphilous species in modern mollusc assemblages. It prefers a relatively warm-humid environment with MAT and MAP ranges being 5.8–10 °C and 450–550 mm (Wu et al., 2007). *P. orphana* has higher requirements for thermal-hydrologic conditions than *G. armigerella*. It now is mainly distributed in the southeast of China with MAT of 13–17.5 °C and MAP of 615–1124 mm (Chen and

Gao, 1987; Wu et al., 2001). The abundance of these two species indicates that the precipitation during MIS 23 was approximately close to modern precipitation conditions in the southeast part of the Loess Plateau, however, the temperature was lower than the present. Moreover, the numbers of snail individuals per sample at this interval reach their highest values through MIS 24–22 period (Fig. 3), indicating a distinct amelioration of thermal-hydrologic conditions in the Loess Plateau during the interglacial of MIS 23. However, cold-aridiphilous species *P. aeoli* with MAT and MAP ranges of 5–10 °C and ~200–500 mm (Chen and Gao, 1987) also shows high abundance at this interval. This suggests that the climatic conditions in the Loess Plateau might be generally mild. At the late part of MIS 23, a rapid cooling trend happened, as indicated by a quick increase in values of *V. tenera* and *P. cupa* in two sections. Meanwhile, *G. armigerella* and *P. orphana*, the thermo-humidiphilous species, decreased rapidly and even vanished.

During MIS 22, the Loess Plateau underwent two obvious cold-dry/warm-wet cycles. Climatic conditions were extremely cold-dry in the early part of MIS 22 (around ~900 ka), as evidenced by remarkably high abundance of *V. tenera* and *P. cupa*. The modern analog of this assemblage exists near the northwestern boundary of the Loess Plateau where MAT is ~4–7 °C and MAP ~200–300 mm (Chen and Gao, 1987). This indicates that both temperature and precipitation in Xifeng and Luochuan regions at about 900 ka were much lower than the present day. Moreover, the numbers of individuals per sample drop to very low values during this interval, also reflecting severe climatic conditions. In the middle part of MIS 22 (around 890 ka), climatic conditions tended to be moderate, as shown by marked increases of *G. armigerella* in the Xifeng section and *P. orphana* in the Luochuan section. However, the high peak of *P. aeoli* at this period indicates cool conditions somewhat like that in MIS 23. Another cold-dry/warm-wet cycle happened in the late part of MIS 22 (~885–860 ka). Since strong carbonate dissolution dissolved a large number of mollusc shells, the mollusk faunal compositions during this interval were largely modified. However, the remained mollusc individuals can still provide enough information about climate changes. A notable

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change in mollusc fauna is that the high abundance of *V. tenera* is replaced by high *G. armigerella*, reflecting that climatic conditions changed from cold-dry to warm-wet. This change is more evident in the Xifeng section than in the Luochuan section (Fig. 4a and b).

In summary, the high-resolution mollusc records from the Xifeng and Luochuan L9 loess stratigraphy reveal that the climatic conditions were highly variable in the Loess Plateau during MIS 24–22. The climate in this region at this interval experienced a series of changes from cold-dry, mild, shortly cold-dry, cool-wet, cold-dry, to relatively warm-wet conditions.

However, climatic conditions show somewhat different between the Xifeng and Luochuan sections. First, the number of mollusc individuals and the abundance of thermo-humidiphilous species in the L9 loess stratigraphy are higher in the Luochuan section than the Xifeng section, indicating warmer and wetter climatic conditions at Luochuan. Second, a continuous occurrence of *G. armigerella* at Luochuan suggests that the East Asian summer monsoon could affect this region during whole period of MIS 24–22, but it was absent at Xifeng in three coldest stages (~940–923 ka, 900–895 ka, and 885–875 ka) of MIS 24 and MIS 22. Thus a bigger climate gradient might exist in the Loess Plateau at these cold periods than warm ones. The environmental conditions at Xifeng were more instable and variable than at Luochuan.

4 Discussions

4.1 Climatic implications of L9 loess

In previous studies, L9 loess was suggested as a representative of extremely cold and dry climatic conditions (e.g. Liu, 1985; Guo et al., 1998; Lu et al., 2000). However, marine isotope records show that MIS 24 and 22 are not the most severe glacials in the Quaternary history. Therefore, it has long been argued that loess records might reveal a quite different climatic condition from that indicated by marine isotope records. L9

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loess was thus ascribed to regional rather than global climate changes (Liu, 1985; Sun et al., 2000). Our new mollusc records reveal that severe climatic conditions recorded by L9 loess only occurred at three stages in the Loess Plateau, i.e. at ∼940–923 ka, 905–895 ka and 885–875 ka. Climatic conditions during other intervals of MIS 24–22 apart from these three cold periods were relatively mild, suggesting that L9 loess was not formed under a uniform condition with extremely cold and dry climate.

Clark et al. (2006) indicated that the climate of MIS 24–22 has a pattern similar to that of the last glacial (MIS 4–2). Both have long glaciations consisting of two stadials separated by an interstadial period. A comparison of the L9 and L1 (corresponding to MIS 4–2) loess shows somewhat similarity between them. For example, they are composed of two loess layers and a subdued paleosol layer, and both of them have great thickness (in Xifeng the thickness of L9 is 10.7 m and L1 is 10.2 m; in Luochuan L9 is 7.5 m and L1 is 8.5 m in thickness) and high sedimentation rates (in Xifeng are 13.85 cm/kyr in L9 and 17.12 cm/kyr in L1; in Luochuan are 9.62 cm/kyr in L9 and 14.91 cm/kyr in L1). However, our mollusk records do reveal a significant difference between them. Mollusc assemblages from L9 loess are remarkably different from those of the L1 loess (Wu et al., 1996; Chen and Wu, 2008) (Fig. 5). The former contains less cool-humidiphilous species and more thermo-humidiphilous mollusc species. For example, the mean values of *G. armigerella* are 1.2% at Xifeng and 0.2% at Luochuan during MIS 4–2, whereas they reach 11% at Xifeng and 26.5% at Luochuan during MIS 24–22 (Fig. 4). The mollusc assemblages during the last glacial indicate that climatic conditions were colder and drier than the MIS 24–22 in the Loess Plateau. Figure 6 shows variations in mollusc biomass (mollusc biomass = number of individuals in each sample/(sample vol./sampling thickness)/sedimentation time) during MIS 24–22 and MIS 4–2. Obviously, the mollusc biomass during MIS 24–22 is much higher than that of MIS 4–2, indicating the same fact as revealed by mollusc assemblages. Furthermore, the sedimentation rates are much lower in L9 than L1 at the Xifeng and Luochuan sections (Fig. 7), supporting mollusc results. Additionally, the weathering intensity revealed by FeD/FeT ratio of loess deposits indicates that the

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L9 loess experienced stronger pedogenesis than L1 (Guo et al., 2000), and a pollen record from Chaona loess sequence in the central Loess Plateau shows that the vegetation during MIS 24–22 was a forest-steppe instead of steppe during the last glacial (Wu et al., 2004). Overall, all these lines of evidence indicate that climatic conditions during L9 loess formation were less severe than those of the last glacial. Therefore, it can be concluded that the L9 loess was not a production of extremely cold glacial period as suggested by previous studies. In spite of the occurrence of some short cold fluctuations, the climatic conditions recorded by L9 loess are similar to that indicated by marine isotope records. It is characterized by gentle glacials (MIS 24 and 22) and interglacial (MIS 23).

4.2 The response of 900-ka cooling event in the Loess Plateau

As mentioned above, a series of significant changes in global climate happened during MIS 24–22. For example, global ice volume during this period increased by 15% compared to former glacials (Lisiecki and Raymo, 2005), thus the first long glaciation (~80 kyr) of the Pleistocene occurred around 900 ka (Jansen et al., 2000; John and Krissek, 2002; Bintanja and van de Wal, 2008). And the sea level reached its lowest at MIS 22 during the interval from MIS 28 to MIS 22 (Kitamura and Kawagoe, 2006). Clark et al. (2006) referred to such cold-dry global climatic conditions as "900-ka event". This global cooling event has been documented in many records (Ruddiman et al., 1989; Clemens et al., 1996; Hodell et al., 2003; Liu and Herbert, 2004; Raymo et al., 2004; Schefuss et al., 2004; McClymont and Rosell-Mele, 2005; Jin et al., 2009). All records with different resolution indicated that the cooling mainly happened at MIS 24 and 22. However, the timing and amplitude of major temperature drop are significantly different in various records. For example, North Atlantic SSTs dropped to the lowest value at MIS 22 with an amplitude of ~10 °C (Ruddiman et al., 1989), while in eastern equatorial Pacific SSTs fell only by ~2 °C at MIS 22 and 4 °C at MIS 24 (Liu and Herbert, 2004). Although work to date has revealed many strong hints of this event in both marine and terrestrial records, its pattern and regional responses have not been well understood.

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In East Asia, biological records from the Lake Baikal and South China Sea indicated an intensified East Asian winter monsoon and remarkable decreases in temperature at ~900 ka (Williams et al., 1997; Jian et al., 2003; Zheng et al., 2005), apparently implying a prominent response of regional climate to the 900-ka cooling event. In the Chinese Loess Plateau, the thick L9 loess itself, which indicated a strengthened winter monsoon and increased Asia aridity (Liu, 1985; Guo et al., 1998; Lu et al., 2000; Sun et al., 2006), was suggested to be linked to this event. In previous studies, the L9 loess as a whole was correlated to the "900-ka event" (e.g. Clark et al., 2006). However, our mollusc records from the Xifeng and Luochuan loess sequences reveal that climatic conditions in the Loess Plateau were not stable during this interval (MIS 24–22). This interval generally with cold conditions together with strong winter monsoon, suggested by dominant cold-aridiphilous mollusc taxa in both sections, was interrupted by two warm episodes associated with strengthened summer monsoon. These two obvious warm episodes occurred at ~923 ka and ~895 ka. It is evident that the 900-ka cooling event in the Loess Plateau started at ~940 ka and experienced three cooling fluctuations at ~940–923 ka, 905–895 ka, and 885–875 ka. Among them, the one at ~905–895 ka (the boundary of MIS 23 and 22) was the toughest in both intensity and extent, but its duration is the shortest (Fig. 4). This cold stage started with a fast cooling and ended with a rapid warming, and it is characterized by extremely cold-dry climatic conditions, as mentioned above. The unstable climatic conditions during MIS 24–22 suggest that the 900-ka event in the Loess Plateau is not a simple long glaciation but a complex of several fluctuations in temperature superposed on a general cooling trend.

4.3 Possible causes of the formation of exceptionally thick and coarse-grained L9 loess

The grain size variations in numerous loess sections show that the loess unit L9 and L15 represent the coarsest loess of the last 2.5 Ma (Liu and Ding, 1993). Question here is why the exceptionally thick and coarse loess deposition of L9 was accumulated during the gentle glaciation of MIS 24–22. One reason is that abundant dust sources

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and fast dust accumulation occurred during this period. It is commonly considered that desertic lands in northwestern China and central Asia are the source areas of loess, and the dust is transported by northwesterly winter monsoon winds (Liu, 1985; An et al., 1991). A number of studies demonstrate that a tectonic movement of Tibetan Plateau named "Kunlun-Huanghe" happened during the depositing time of L9 loess (Li, 1991; Cui et al., 1998). The uplift of Tibetan Plateau and its adjacent regions greatly favored the production of aeolian dust through its control on the glacial erosion and mountain denudation (Amano and Taira, 1992; Cui et al., 1998; Sun and Liu, 2000), thus resulting in a rapid increase of source materials of desert and loess. Besides, its climatic effects may have aggravated ice sheet expanding and cooling of the Northern Hemisphere (Birchfield and Wertman, 1983; Raymo and Ruddiman, 1992; Rea et al., 1998; Li and Fang, 1999), which would have intensified East Asian winter monsoon to carry more particles from deserts to the Loess Plateau. Therefore, we speculate that the uplifted Tibetan Plateau would have amplified the effects of climate cooling during MIS 24–22 on both dust production and transport. This explains why both grain size and mass accumulation rate increased during the deposition of L9 loess.

Another reason is the climatic conditions of the subdued interglacial of MIS 23. The preservation and assemblages of mollusc fossil together with other proxies (Kukla and An, 1989; Guo et al., 2000; Sun et al., 2006) all indicate mild climatic conditions during MIS 23. Relatively cool climatic conditions of MIS 23 brought about relatively weak pedogenic characteristic of L9SS1 paleosol. This is why the paleosol unit of L9SS1 and two typical loess units of L9LL1 and L9LL2 are usually incorporated into a complex unit of L9 loess in field work, leading to the prominent thickness of L9.

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5 Conclusions

The study of land snail records from two loess sequences of the Chinese Loess Plateau provides reliable and detailed information about climatic implications of L9 loess. Our results show that the L9 loess developed under variable climatic conditions. Generally cold and dry climate dominated the main stage of MIS 24 and early and late parts of MIS 22. Episodes of relatively mild-humid climate occurred during MIS 23 and middle part of MIS 22. Climatic conditions at Xifeng were more severe and instable than at Luochuan, reflecting an obvious regional difference in the impacts of East Asian summer monsoon on the Loess Plateau.

Comparisons of L9 and L1 loess layers based on mollusc assemblages and other climate proxies show that the climatic conditions recorded by L9 loess were not the most severe in the Quaternary history, similar to those indicated by marine isotope records. Therefore, climatic changes revealed by L9 loess not only have regional signals but also have a global comparable significance. Our mollusc records also reveal the pattern of climatic response in Loess Plateau to the 900-ka global cooling event. It is characterized by three major cooling fluctuations occurring at ~940–923 ka, 905–895 ka and 885–875 ka. Our study suggests that the 900-ka event is not a simple long glaciation but a complex of several fluctuations with a generally cooling trend. The increase in dust source for loess associated with the uplift of Tibetan Plateau and its adjacent regions, the strengthening of East Asian winter monsoon, and mild climatic conditions of the subdued interglacial of MIS 23 are potential causes for the formation of the unique thick L9 loess deposition.

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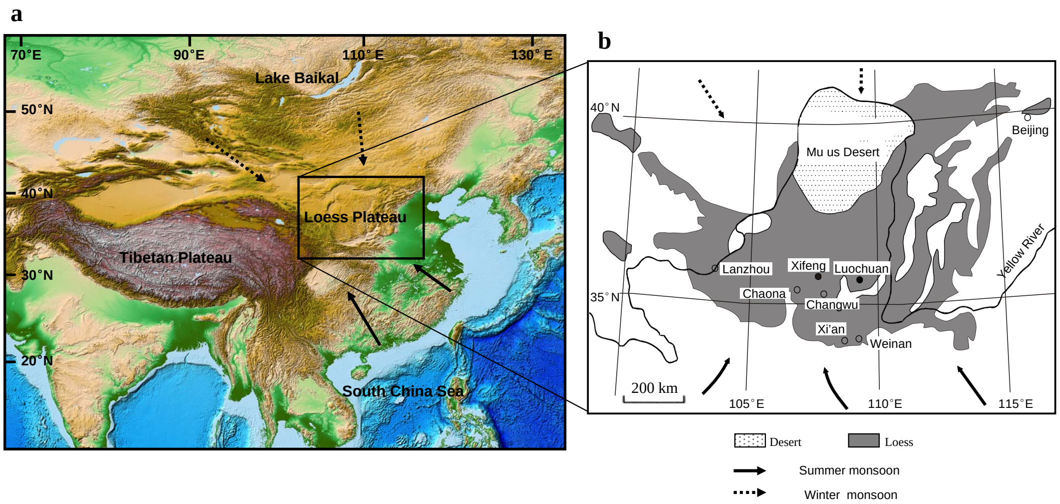

Fig. 1. **(a)** Map showing the Loess Plateau in the region of High Asia (map modified from NOAA; http://www.ngdc.noaa.gov/mgg/global/global.html). **(b)** Sketch map of the Central Chinese Loess Plateau and location of the studied sites mentioned in the text. The solid arrows indicate the direction of the East Asian summer monsoons, the dashed arrows indicate the pathways of the East Asian winter monsoons.

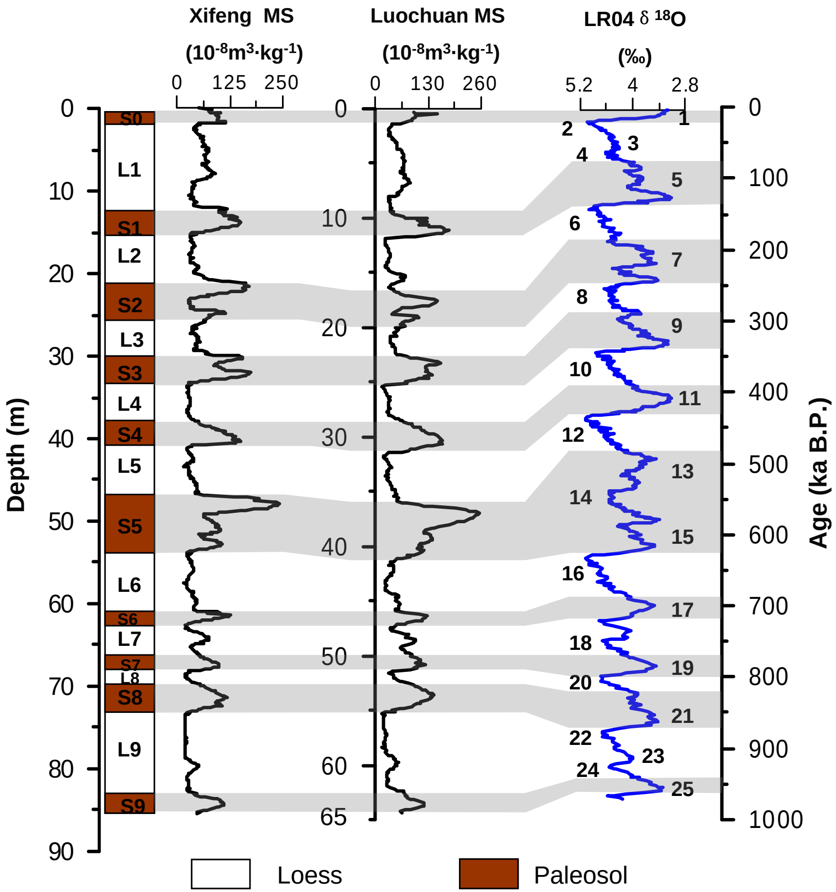

Fig. 2. Magnetic susceptibility (MS) records of the loess-soil sequence of the last 1000 ka from Xifeng and Luochuan and correlation with the LR04 δ^{18}O record (Lisiecki and Raymo, 2005). The soil and loess units are labeled following Liu (1985). The land-sea correlation scheme follows Kukla (1987) and Liu et al. (1999).

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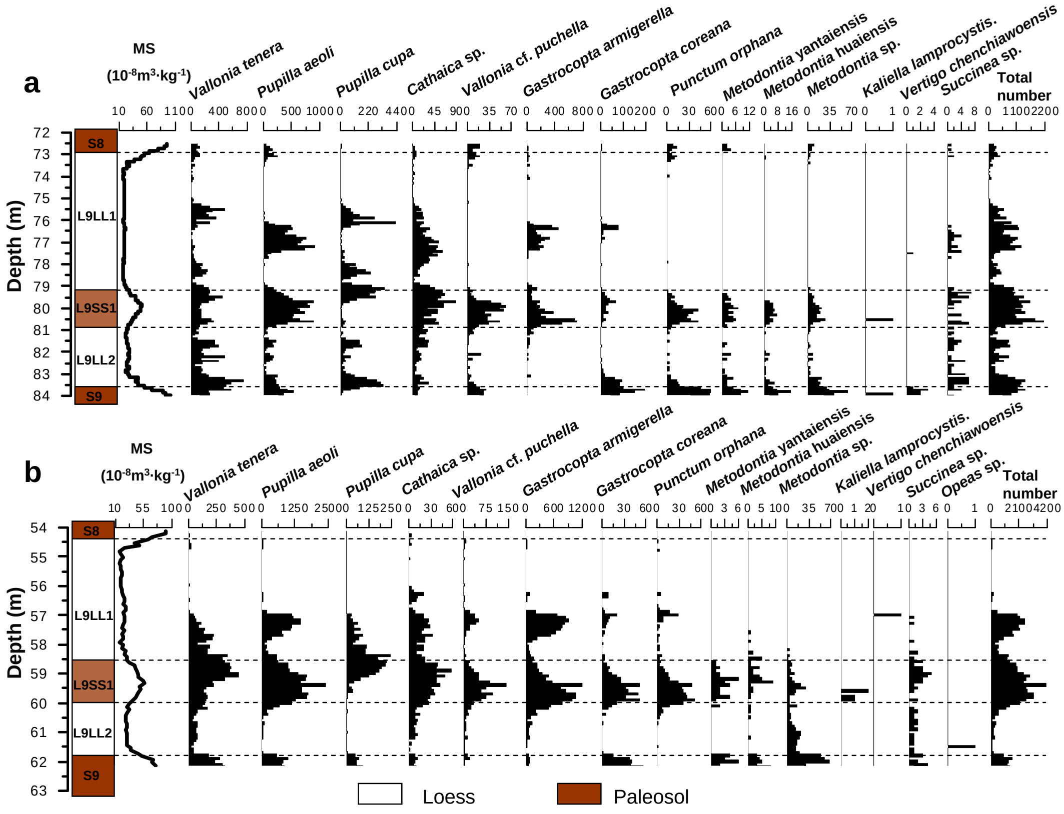

Fig. 3. Variations in mollusc species and magnetic susceptibility in the Xifeng **(a)** and Luochuan **(b)** L9 stratigraphies plotted versus depth. The mollusc species are expressed in the absolute abundance (total number of individuals counted per 15 kg).

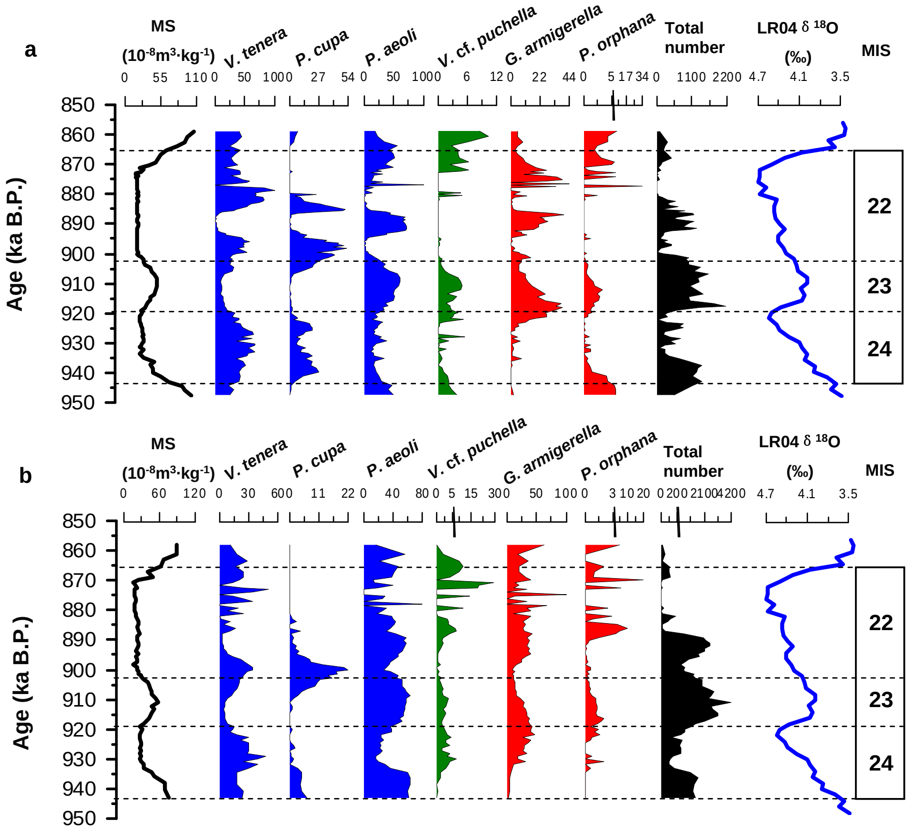

Fig. 4. Variations in the percentages of six mollusc species in the Xifeng **(a)** and Luochuan **(b)** loess sequences during MIS 24–22, compared with variations in magnetic susceptibility and LR04 δ^{18}O record (Lisiecki and Raymo, 2005). The three ecological groups are distinguished by colors (blue for cold-aridiphilous, green for cool-humidiphilous and red for thermo-humidiphilous).

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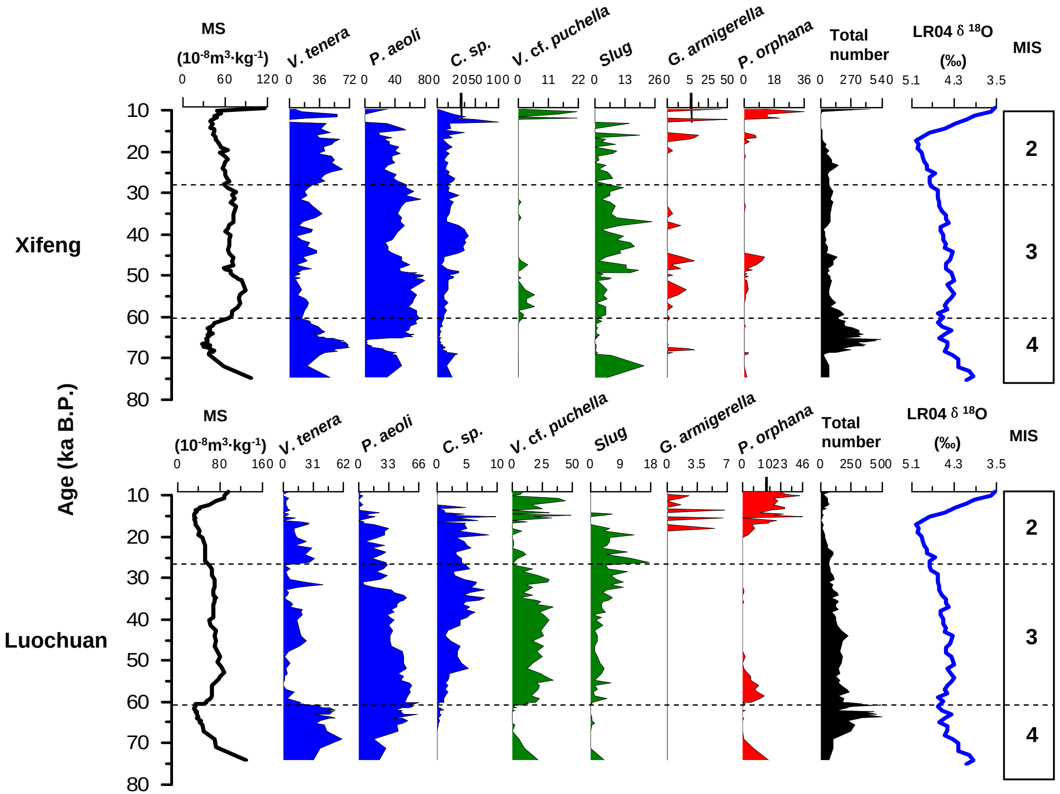

Fig. 5. Variations in percentages of mollusc fossil species from last glacial (L1) records in the Xifeng (Chen and Wu, 2008) and Luochuan (Wu et al., 1996) loess sequences. The three ecological groups are distinguished by colors (blue for cold-aridiphilous, green for cool-humidiphilous and red for thermo-humidiphilous).

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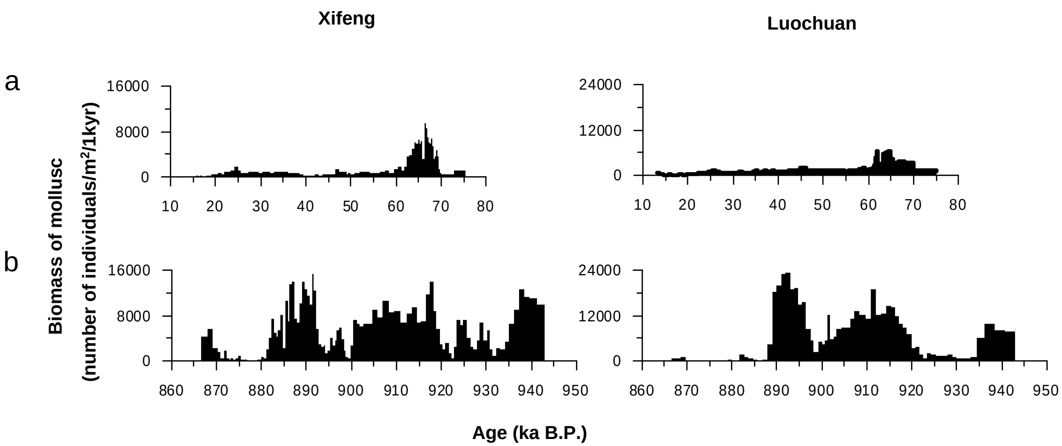

Fig. 6. Comparison of biomass of mollusc fossils from L1 **(a)** and L9 **(b)** records in the Xifeng and Luochuan loess sequences.

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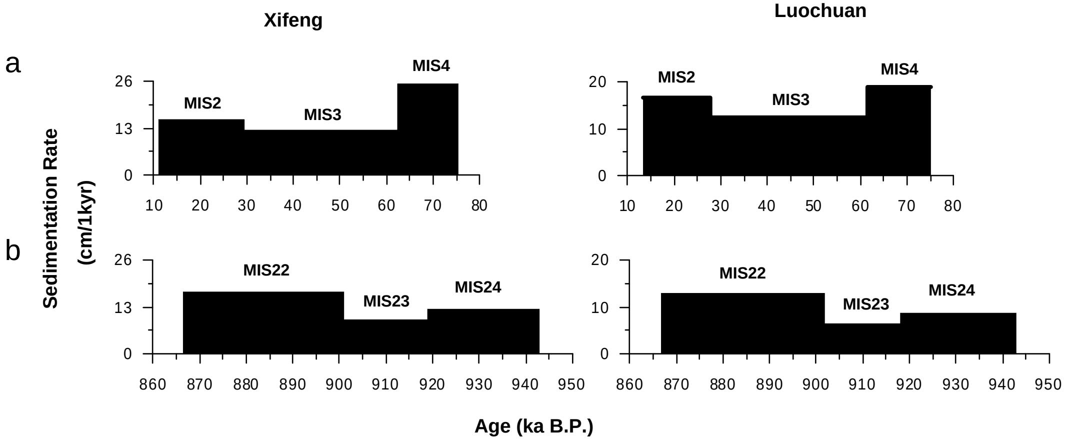

Fig. 7. Comparison of sedimentation rates from L1 **(a)** and L9 **(b)** records in the Xifeng and Luochuan loess sequences.

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