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Terrestrial mollusk records from Chinese loess sequences and changes in the East Asian monsoonal environment

Naiqin Wu[a,b,c,*], Fengjiang Li[a,b], Denis-Didier Rousseau[d,e]

[a] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China
[c] College of Earth Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Laboratoire de Meteorologie Dynamique, UMR INSU-CNRS 8539 & CERES-ERTI, Ecole Normale Superieure, Paris Cedex 05, France
[e] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

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A B S T R A C T

The terrestrial mollusk fossils found in Chinese loess strata have been studied for over one hundred years. However, the greatest progress in these studies has been made only in the last two decades. In this paper, we review the advancements, advantages and limitations of terrestrial mollusk studies in Chinese loess deposits. Improvements in research methods and approaches have allowed the extraction of more detailed paleoenvironmental and paleoclimatic information from mollusk assemblages. The broadened research scope and content have yielded many new findings and results. The mollusk record has thus become one of the most important proxies in the paleoenvironmental and paleoclimatic reconstruction of loess-paleosol sequences in China. The greatest progress in the studies of terrestrial mollusks in Chinese loess sequences can be summarized as follows: (1) modern mollusk assemblages can be classified into four ecotypes, based on their temperature and humidity requirements, including eurytopic, semi-aridiphilous and sub-humidiphilous, cold-aridiphilous, and thermo-humidiphilous types; (2) Quaternary mollusk assemblages can be modified into the following three ecological types: glacial loess, interglacial paleosol, and interstadial weakly-developed paleosol assemblages; (3) mollusk records successfully reveal long-term climatic and environmental changes reflective of the history of East Asian monsoonal variations since the Late Cenozoic, and the succession of mollusk species also indicate short-term environmental changes such as millennial climate variability during Last Glacial Maximum and unstable climatic fluctuations during glacial and interglacial periods; and (4) more recently, new analytical approaches have offered increased research potential in areas such as paleotemperature reconstruction using the isotopic compositions of modern and fossil mollusk shells, combined with higher accuracy ^{14}C dating of Quaternary loess deposits, which will greatly improve future loess paleoenvironmental research.

1. Introduction

The widespread fossil remains preserved in Quaternary loess-paleosol sequences represent an important record for the study of geological evolution and climate change. Terrestrial mollusks, taxonomically classified into the *Gastropoda* of *Mollusca*, are the most common biological remains identified in Quaternary loess deposits. They are highly sensitive to environmental, and therefore climatic changes, and can thus be considered typical 'index animals' for loess-based paleoenvironmental research (Liu, 1985). During the early years of loess research, Richthofen proposed in his initial research that the Chinese loess deposits contained fossil gastropods which were all terrestrial species sparsely distributed throughout the stratigraphic sequence, demonstrating that these loess deposits had not been reworked by water flow. This provided the most direct biological evidence for his hypothesis that the loess deposits in China had been transported there by the wind (Richthofen, 1877, 1882). Recently, international Quaternary studies have developed rapidly, using new methods and techniques, leading to an increasing importance being placed on the paleoenvironmental studies of terrestrial mollusk fossils found in Quaternary loess and Late Cenozoic wind-blown dust deposits. Especially in recent decades, the study of the loess snail in the world has made great progresses, including snail's ecological distribution, high resolution fossil record and stable isotopes analysis of terrestrial snail shell *etc*. (e.g. Metref et al., 2003; Balakrishnan et al., 2005; Zanchetta et al., 2005; Antoine et al., 2009; Yanes et al., 2009; Kehrwald et al., 2010; Zaarur et al.,

* Corresponding author.
E-mail address: nqwu@mail.iggcas.ac.cn (N. Wu).

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2011; Huang et al., 2012; Colonese et al., 2013; Eagle et al., 2013; Yanes and Romanek, 2013; Horsák et al., 2015).

Important research activity was conducted in China between the 1920s and 1980s into the terrestrial mollusk fossils found in loess. Liu (1985), in 'Loess and the Environment', put forward a detailed compilation of the research conducted into terrestrial mollusk fossils during this period. It can be concluded that this period's body of work could be subdivided into: (1) the period prior to the 1950s, when the focus was placed on descriptions of the genus and species of terrestrial mollusks (Yen, 1939, 1943); (2) the period from the 1950s to the 1980s, when the emphasis was still on the collection of terrestrial mollusk data, apart from some detailed work on the taxonomic identification and classification of terrestrial mollusks. A focus was placed on stratigraphic records and the ages of the strata in which the fossils were found (Yu et al., 1963; Li, 1966). Some research was also begun into the relation between the composition of terrestrial mollusks and their living environment during the period from the 1950s to the 1980s (Lu and An, 1979; Chen et al., 1982). All of this previous work lay the biological foundations for the subsequent subdivision and differentiation of loess strata, and therefore of past paleoenvironments and paleoclimates. Liu (1985), in 'Loess and the Environment', explicitly suggested that the terrestrial mollusk fossils preserved in the loess strata could be used as 'indicator animals' of the paleoenvironment and paleoclimate recorded in loess-paleosol sequences, pointing toward their potential for future studies of the paleoclimate and paleoenvironment of China's loess regions. However, due to the lack of much basic work on the relation between the composition of modern terrestrial gastropods and climatological parameters, research into this field of science in China came more or less to a full stop between the mid-1980s and the early 1990s. Internationally, this period saw a rapid development of research into terrestrial mollusk fossils, allowing paleoenvironmental and paleoclimatic research to progress from a state of qualitative analysis state toward a semi-quantitative or quantitative stage (Rousseau, 1991).

From the beginning of the 1990s, research on the terrestrial mollusk fossils found in Chinese loess entered a new phase. Research methods and fields of terrestrial mollusk fossils made remarkable headway, gradually being used as new and vital indices in loess paleoenvironmental research. Major advances in research approaches were reached in terms of: (1) the employment of an internationally-used washing and sieving of snail samples using water became the preferred method for collecting fossil terrestrial mollusks from Chinese Quaternary loess. For example, in our study, mollusk samples were taken from loess sections at 3, 5 and 10 cm intervals (Wu et al., 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997, 1999; Chen and Wu, 2008). Each sample was approximately $60 \times 45 \times 20\,cm^3$ in size, or weighed ~15 kg to 20 kg. All samples were washed and sieved in the field using a mesh of diameter 0.5 mm. The mollusk shells were sorted and identified under a binocular microscope. All identifiable mollusk fragments were considered in the total count of individuals following the method developed by Puisségur (1976). This new method of sampling and collecting mollusks has since been used in sampling of the Quaternary loess sequence in China, yielding a great abundance of terrestrial mollusk fossils. This meets the requirements of quantitative statistics and improves the reliability of any environmental analysis and interpretation, and also greatly reduces the transportation difficulties caused by the vast quantities of sediments in all the samples; (2) a wide variety of multivariate statistical methods have been used to handle and process the terrestrial mollusk fossil data and to establish the statistical relation between terrestrial mollusk species and/or its assemblages, and climatic factors. Of these methods, the use of transfer functions based on terrestrial mollusks can quantitatively or semi-quantitatively reconstruct paleoclimatic parameters (Rousseau, 1991; Wu et al., 1997); and (3) the introduction of geochemical methods, especially stable isotope analysis, into the research of the relation between terrestrial mollusk shell stable isotopes and climatic or environmental factors, has been able to produce remarkable results, and can therefore be considered a vital research tool for investigating the evolution of the East Asian monsoonal environment.

Apart from the use of the new methods reviewed above, the studies of loess terrestrial mollusks has focused especially on paleoclimatic and paleoenvironmental studies related to the evolution of the monsoonal environment, and on investigations into the ecological requirements of modern terrestrial mollusk assemblages, thus: (1) paleoclimatic and paleoenvironmental studies have focused on different timescales, including climatic conditions during typical time intervals such as marine isotope stages (MIS) 24–22, 15–13, and 11 (Wu and Wu, 2008, 2011; Wu et al., 2007), climate instability and asynchronous changes in temperature and precipitation (Wu et al., 1999, 2002), and climatic periodicities and the response to orbital forcing as recorded by terrestrial mollusk fossils (Wu et al., 2000, 2001; Pei and Wu, 2005; Chen and Wu, 2008; Li et al., 2008; Rousseau et al., 2009; Li and Wu, 2010); and (2) investigations into the ecological requirements of modern terrestrial mollusk assemblages. This has included a survey of the habitats of modern terrestrial mollusks, and in particular their appearance, distribution and abundance within these habitats, the optimum conditions for survival, reproduction, and growth rates *etc.*, and the relation between terrestrial mollusk assemblages and their relevant environmental factors. These basic investigations are the key to using terrestrial mollusks to quantitatively reconstruct paleoclimatic and paleoenvironmental evolution. Recently, several studies have provided promising results. For example, experiment and observation of the survival, activity and feeding habits of *Bradybaena similaris* in environments with different relative humidities has provided reliable information for the interpretation of paleoenvironments (Xu et al., 2002).

Looking back on the progress of research in terrestrial mollusks found in loess since the publication of the seminal monograph 'Loess and the Environment' in 1985, such research can be seen to have entered a new phase. There have been comprehensive and systematic studies of terrestrial mollusk assemblages in loess. Additionally, considerable progress has been made in establishing the origins of loess and paleoclimatic evolution at different timescales, based on the analysis of terrestrial mollusk fossils preserved in Quaternary loess strata (e.g., Keen, 1995; Wu et al., 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997,1999; Chen and Zhang, 1998; Chen and Wu, 2008; Wu and Wu, 2008, 2011; Rousseau et al., 2000, 2009) and Late Miocene–Pliocene red clay strata (e.g., Pei et al., 2004; Wu et al., 2006), as well as Miocene–Pliocene loess strata (e.g., Li et al., 2006a, 2006b, 2008; Li and Wu, 2010).

2. The geographical distribution and ecological environments of extant terrestrial mollusks on the Chinese Loess Plateau

Information on the ecological requirements of modern terrestrial mollusk species, whose fossil species are found in loess, can provide a base for interpreting the paleoenvironment. The growth and reproductive rates of modern terrestrial mollusks are intimately related to the environments within which they live and develop. The type of vegetation, air temperature and relative humidity (RH), the degree to which the soil has been enriched with organic matter, soil moisture content, sunlight and habitat substrate, all greatly influence the diversity of terrestrial mollusk communities, the composition, distribution and abundance of mollusk species. Of these numerous environmental factors, temperature and RH appear to be the key factors controlling the growth and development of terrestrial mollusks. Nonetheless, there are marked differences in the sensitivities to changes in temperature and RH displayed by different terrestrial mollusk species (Li et al., 2016).

Yen (1939) conducted an outstanding piece of mollusk research, producing a systematic survey and classification of modern Chinese terrestrial mollusks. This remains a seminal point of reference when identifying terrestrial mollusk species. During the 1980s, Chen and Gao (1987) conducted a systematic identification and classification of the

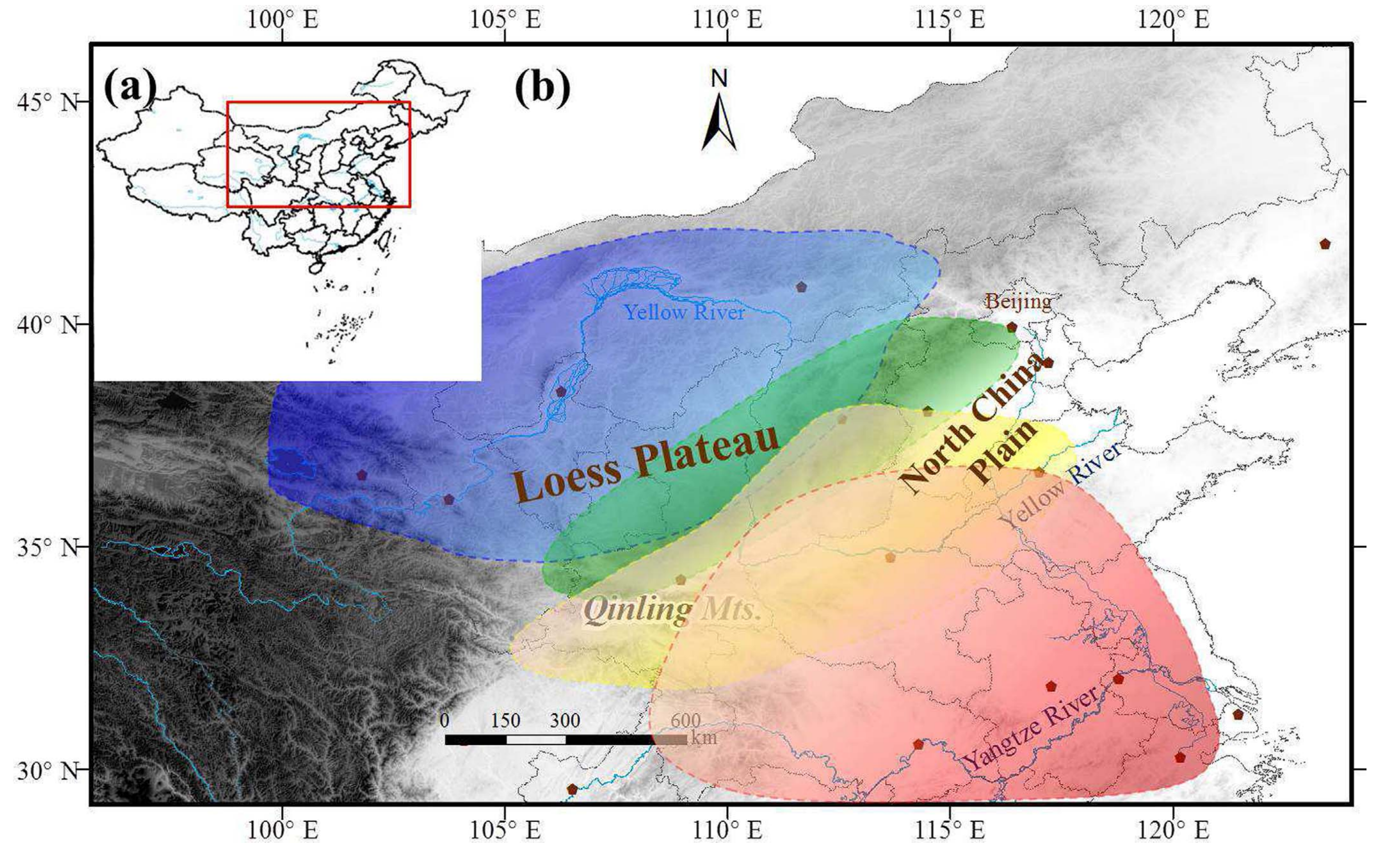

Fig. 1. Sketch map showing the location of the Chinese Loess Plateau (CLP) and surrounding regions (a), and the predominant geographical distribution of the eurytopic (indicated in yellow), semi-aridiphilous and sub-humidiphilous (indicated in light green), cold-aridiphilous (indicated in blue), and thermo-humidiphilous (indicated in red) ecological groups of extant terrestrial mollusks on the CLP and surrounding regions (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

modern terrestrial mollusks frequently found in China. In addition to species identification, Chen and Gao (1987) presented in their monograph the ecological habitats, and geographical and geological distributions, of different species. Since the turn of the 21st Century, successive publications have focused on the shell morphology, geographical distribution and ecological habitats of modern terrestrial mollusks (e.g., Chen and Zhang, 2004; Qian, 2008; Wang and Chen, 2011; Qian and Zhou, 2014). Research on Chinese modern terrestrial mollusks has made substantive progress, providing a foundation for the ecological classification of the terrestrial mollusk fossils found in loess. Using previously published data on the geographical distribution and habitats of modern terrestrial mollusks (Yen, 1939; Chen and Gao, 1987; Chen and Zhang, 2004; Qian, 2008; Wang and Chen, 2011; Qian and Zhou, 2014), and combining with our investigations into the geographical distribution of modern terrestrial mollusks, we subdivided modern terrestrial mollusks from the Chinese Loess Plateau (CLP) into four ecological groups, *i.e.* terrestrial mollusks which are: (1) eurytopic group; (2) semi-aridiphilous and sub-humidiphilous group; (3) cold-aridiphilous group; and (4) thermo-humidiphilous group (Fig. 1).

(1) The eurytopic group includes species which exhibit a strong ability to adapt to ecological environments. They are widely distributed in different ecological habitats found in the humid areas of the northern subtropics-temperate zone where the mean annual temperature (MAT) is ~6 to 15 °C, and the mean annual precipitation (MAP) is ~400 to 800 mm. The optimum temperature for growth and development is ~20 to 25 °C, with a corresponding RH of ~90% (Chen and Gao, 1987; Xu et al., 2002). Our research into modern terrestrial mollusk communities on the CLP and its surrounding regions has shown that this group of terrestrial mollusks was most abundantly distributed in the southeastern CLP. Typical species in this group include *Bradybaena similaris*, and species of *Cathaica* such as *Cathaica fasciola* and *Cathaica pulveratrix etc.*
(2) The semi-aridiphilous and sub-humidiphilous group prefers semi-arid and sub-humid environments. This group of terrestrial mollusks is widely distributed in the semi-arid, sub-humid zones of central eastern, northern and western China in regions where the MAT is ~8 to 14 °C, and the MAP is ~300 to 600 mm. They are most abundantly found in northern China, central China, and the southeastern CLP. Typical species in this group include *Cochlicopa lubrica* and species of *Succinea* and *Vallonia*, such as *Succinea erythrophana* and *Vallonia* cf. *pulchella etc*.
(3) The cold-aridiphilous group prefers cold and dry environments. These are widely distributed in the semi-arid and arid continental zones of northwestern China in regions where the MAT is ~5 to 10.5 °C, and the MAP is ~ 200 to 450 mm. They are also found in the high and cold regions (> 4000 m above sea level) of the Tibetan Plateau (TP), but are most abundant in the central northern CLP, where the MAT is ~6 to 9°C, and the MAP is ~200 to 400 mm. Typical species in this group include species of *Pupilla*, *Vallonia* and *Cathaica*, such as *Pupilla aeoli*, *Vallonia tenera* and *Cathaica pulveratricula etc.*
(4) The thermo-humidiphilous group prefers warm and humid environments. These are found in subtropical and temperate zones. In our investigations into the geographical ranges of modern terrestrial mollusk communities, we found that this group of terrestrial mollusks is distributed in regions to the south of the Yellow River where the MAT is ~13 to 17.5 °C, and the MAP is ~620 to 1120 mm. Within this group are some species which have adapted to particularly warm and humid environments, such as those found in southeastern China where the MAT is > 14 °C and the MAP is > 800 mm. The optimum growing season temperature is ~25

to 27 °C, and the preferred precipitation is ∼330 to 440 mm. Typical species in this group include species of *Cyclophorus*, *Macrochlamys*, *Euphaedusa*, *Opeas*, *Kaliella* and *Metodontia etc.*

Our most recent research of modern terrestrial mollusk assemblages, based on 356 samples collected from the surface soils of the CLP and its surrounding regions, has allowed the characterization of the quantitative distribution and the optimum ecological factors of *Metodontia*. In the studied region, *Metodontia* with an abundance of > 20% appears to occur mainly in regions where the MAT is > 11 °C, and the MAP lies between 550 mm and 850 mm. The optimum MAT is ∼10.2 to 14.1 °C for *Metodontia huaiensis*, and ∼8.9 to 14.0 °C for *Metodontia yantaiensis*; the optimum MAP is ∼530 to 800 mm for *Metodontia huaiensis*, and ∼470 to 750 mm for *Metodontia yantaiensis*. These results provide the quantitative evidence required for using *Metodontia* species as indicators of changes in the East Asian summer monsoon (EASM).

3. Modification of the ecological composition of terrestrial mollusk groups in Quaternary loess deposits

The species composition and distribution of terrestrial mollusk assemblages in Quaternary loess sequences are comparatively different from those of modern terrestrial mollusk assemblages. In 'Loess and the Environment' (Liu, 1985), based on the terrestrial mollusk assemblages from the Luochuan loess sequence, Quaternary terrestrial mollusk assemblages from the CLP were subdivided into two groups, *i.e. Cathaica-Pupilla* and *Metodontia-Cyclophorus*. The former represents the dominant species found in glacial loess deposits, while the latter is the main species observed in interglacial paleosol layers (Liu, 1985). However, our recent systematic and statistically quantitative research of terrestrial mollusk fossils collected from numerous loess sequences such as the Luochuan, Xifeng, Weinan and Changwu sections on the CLP, implies that the dominant species in these two assemblages needs to be amended. In accordance with the composition and/or abundance of the dominant species found in the loess and paleosol strata, and the characteristics of the ecological environments that they represent, we subdivided the groups of terrestrial mollusk fossils found in CLP loess-paleosol sequences into three groups:

(1) **Terrestrial mollusk assemblages found in loess**
Pupilla-Vallonia-Cathaica. This assemblage is mainly composed of the following species:
Pupilla aeoli (Hilber, 1883) (Fig. 2a, b)
Pupilla muscorum (Linne, 1758) (Fig. 2c, d)
Vallonia tenera (Reinhardt, 1877) (Fig. 2e–g)
Vallonia cf. *pulchella* (Müller, 1774) (Fig. 2 h–j)
Cathaica pulveratrix (Martens, 1882) (Fig. 2 k–m)
Cathaica pulveratricula (Martens, 1882) (Fig. 2n–p)
Cathaica fasciola (Draparnaud, 1801)

This assemblage occurs principally in thick loess layers, such as the L1, L2, L3, L4 and L5 loess layers at the Luochuan and Xifeng sections, and contains terrestrial mollusk species which correspond with the cold-aridiphilous ecological group of modern terrestrial mollusks. *Pupilla* and *Vallonia* are most abundant in this assemblage, at usual > 90% of the total. Between three and five species of *Cathaica* are also often observed in this assemblage, but their abundance is relatively low at, usually, < 10%. Small numbers of other species which prefer cool and wet and/or thermo-humid environments are also present, reflective of a comparatively dry and cold steppe and/or desert steppe environment.

(2) **Terrestrial mollusk assemblages found in interglacial paleosols**
Punctum-Macrochlamys-Metodontia. This assemblage is mainly composed of the following species:
Punctum orphana (Heude, 1882) (Fig. 3a–c)
Macrochlamys angigyra Yen, 1939 (Fig. 3d–f)
Gastrocopta armigerella (Reinhardt, 1877) (Fig. 3 g, h)
Opeas striatissimum (Gredler, 1882) (Fig. 3 k)
Metodontia yantaiensis (Crosse and Debeaux, 1863) (Fig. 3 l–n)
Metodontia huaiensis (Crosse, 1882) (Fig. 3o–q)
Metodontia beresowskii (Moellendorff, 1899)

This assemblage is often observed in mid and upper paleosol layers, *e.g.* in S0, S1, S2, S3 and S4 paleosol strata at the Luochuan and Xifeng sections, and in the Qin'an Miocene paleosols. These are correspondent with those modern terrestrial mollusk species that prefer warm and wet/humid environments. This terrestrial mollusk fossil assemblage is represented by the species *Macrochlamys angigyra*. This is an important species which prefers warm and wet/humid environments, and thus indicates a warm and humid climatic regime. Another important member of this assemblage is *Punctum orphana*. This species has a comparatively lower ecological dependence upon temperature and humidity than does *Macrochlamys angigyra.* A comparatively large number of *Metodontia* are also observed in this assemblage, although their abundance is often no higher than 20% (Wu et al., 1996, 2000, 2001; Rousseau and Wu, 1997). Further, this assemblage also includes a certain number of species which thrive in cold and dry, and/or cool and wet, environments, but these are few, and their abundance is low. As a whole, this assemblage reflects the presence of relatively warm and wet/humid climatic conditions indicative of a forest-steppe environment. The strong carbonate leaching which occurred during the soil development process has led to the dissolution of terrestrial mollusk shells, especially in the lower part of strongly-developed paleosols, creating a non-fossilized 'barren bed'. This non-fossilized bed, with its characteristics indicative of strongly-developed paleosols, is indicative of those extremely warm and wet/humid climatic conditions found throughout geological history that are known to have occurred in forest and/or forest-steppe environments.

(3) **Terrestrial mollusk assemblages found in weakly-developed paleosols**
Vallonia-Metodontia-slugs. This assemblage is composed mainly of the following species:
Vallonia cf. *pulchella* (Müller, 1774) (Fig. 2 h–j)
Metodontia yantaiensis (Crosse and Debeaux, 1863) (Fig. 3 l–n)
Metodontia huaiensis (Crosse, 1882) (Fig. 3o–q)
Gastrocopta armigerella (Reinhardt, 1877) (Fig. 3 g, h)
Gastrocopta coreana Pilsbry, 1916 (Fig. 3i, j)
Slug

This assemblage is often found in weakly-developed paleosol layers, such as the last glacial L1-2 and L1-4 layers at the Luochuan and Xifeng loess sections (Wu et al., 1996, 1999, 2000, 2001; Chen and Wu, 2008). They correspond to modern terrestrial mollusk group which thrive in semi-arid, semi-humid conditions. This assemblage is characterized by considerable numbers and abundant species which include many cold-aridiphilous and thermo-humidiphilous mollusks, and as well cool and humid/wet species are present. The total mollusk individuals exceeds 2000 in some strata (*e.g.* in the weakly-developed paleosols within loess units L4 and L5) (Wu et al., 2007). The thermo-humidiphilous *Metodontia* is relatively abundant, and populations of *Gastrocopta* often form peaks. This is reflective of comparatively warm and humid periods within an overall cold glacial environment, and indicates the existence of relatively lush steppe.

4. Changes in the monsoonal environment as recorded by terrestrial mollusk fossils on the CLP

Terrestrial mollusks are sensitive indicators of climate change and have certain unique advantage in differentiating terrestrial and aqueous

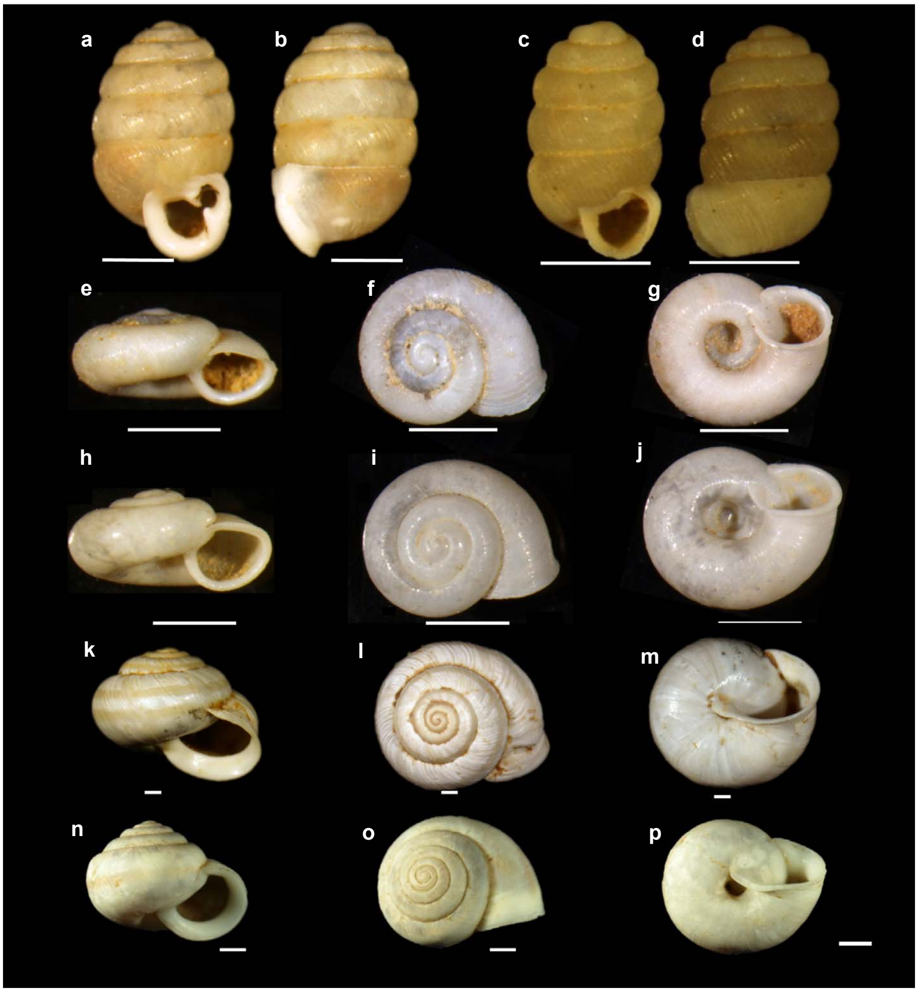

Fig. 2. Photographs of some typical cold-aridiphilous terrestrial mollusk species found in the Chinese loess-paleosol sequences. (a, b) *Pupilla aeoli*; (c, d) *Pupilla muscorum*; (e–g) *Vallonia tenera*; (h–j) *Vallonia* cf. *pulchella*; (k–m) *Cathaica pulveratrix*; (n–p) *Cathaica pulveratricula*.

sedimentary environments. Research on the terrestrial mollusk fossils found in Chinese loess over the last 20 years has allowed the reconstruction of changes in the long-term evolution of the East Asian winter monsoon (EAWM) and EASM during the Neogene and Quaternary (Liu, 1985; Wu et al., 1995, 1996, 1997, 2000, 2001; Keen, 1995; Rousseau and Wu, 1997, 1999; Rousseau et al., 2000; Li et al., 2008). Terrestrial mollusk fossils are also sensitive to short-term changes in the monsoonal environment (Wu et al., 1999, 2002). In this paper, we address the ecological succession and evolution of the monsoonal environment of the CLP since the Late Cenozoic, based on the species composition, ecological group, abundance, and changes in the isotopic composition of the shells of terrestrial mollusk fossils found in wind-blown loess sequences on the CLP.

4.1. Wind-blown origin of the late Miocene-Pliocene loess-paleosol and red clay sequences as documented by terrestrial mollusk records

Terrestrial mollusk fossil research has made significant contributions to many different aspects of geology, including the continental drift hypothesis. More particularly, in the early years of loess studies such research provided key evidence for the wind-blown origins of the Quaternary loess (Richthofen, 1882). Recent research about the Neogene terrestrial mollusk fossils has provided crucial paleontological evidence for the wind-blown origin of the Neogene loess sequences in the western CLP and the red clay deposits in the eastern CLP (Pei et al., 2004; Li et al., 2006a, 2006b). In the past decades, the Miocene (22–6.2 Ma) and late Miocene-Pliocene (7.1–3.5 Ma) loess-paleosol deposits were reported from the western CLP (Guo et al., 2002; Hao and Guo, 2004). Although there are numerous lines of sedimentological and geochemical evidence proving that these deposits are of wind-blown origin (e.g., Guo et al., 2002; Hao and Guo, 2004), more evidence, especially concerning the character of the original sedimentary environment, is necessary to clarify the initial conditions of deposition. Among those, biological approaches are of particular values. Li et al. (2006a, 2006b) analyzed the composition and preservation of mollusk assemblages in the Dongwan and QA-I sections, and found that all mollusk fossil individuals were preserved in perfect condition, without exhibiting any signs of reworking. The terrestrial mollusk fossils discovered were all terrestrial species, with no aquatic species present, and were mostly identical to the species often collected in Quaternary loess and paleosol sequences from the CLP. Generally, cold-aridiphilous species were dominant in the loess layers, while thermo-humidiphilous species were mostly encountered in the paleosols. These terrestrial mollusk fossil characteristics support the suggestion that the Miocene-Pliocene loess-paleosol deposits in the western CLP are typical loess-paleosol sequences of wind-blown origin. Similar analytical research has also been conducted into the Neogene red clay formation at Xifeng (6.2–2.4 Ma) on the eastern CLP (Pei et al., 2004). These research results have strongly corroborated the non-aquatic environmental conditions known to have accompanied dust deposition during the late Miocene to Pliocene.

Fig. 3. Photographs of some typical thermo-humidiphilous terrestrial mollusk species in the Chinese loess-paleosol sequences. (a–c) *Punctum orphana*; (d–f) *Macrochlamys angigyra*; (g, h) *Gastrocopta armigerella*; (i, j) *Gastrocopta coreana*; (k) *Opeas striatissimum*; (l–n) *Metodontia yantaiensis*; (o–q) *Metodontia huaiensis*.

4.2. Paleoclimatic and paleoenvironmental evolution over different timescales

4.2.1. Late Neogene changes in the monsoonal environment as evidenced by the terrestrial mollusk fossil record on the CLP

The large quantities of terrestrial mollusk fossils preserved in the eolian deposits on the CLP from the Neogene to the present represent a record of the evolution/history of the East Asian monsoon over this long period (e.g., Liu, 1985; Wu et al., 1996, 1997, 1999, 2000, 2001, 2002, 2006, 2007; Rousseau and Wu, 1997, 1999; Rousseau et al., 2000, 2009; Pei et al., 2004; Chen and Wu, 2008; Li et al., 2008; Li and Wu, 2010; Wu and Wu, 2008, 2011). The analysis of terrestrial mollusk fossil assemblages in the Xifeng red clay sequence (6.2–2.4 Ma) has identified three ecological groups. The cold- and dry-loving *Cathaica* has been used to identify changes in the EAWM; the warmth- and wet-loving *Metodontia* represents changes in the EASM; and the eurytopic species, including *Bradybaena similaris*, and some species of *Cathaica* genus, such as *C. fasciola* and *C. pulveratrix*, indicate a relatively mild climate, with moderate temperature and humidity within a moderate EAWM and EASM regime. Therefore, the evolution of the monsoonal environment from 6.2 to 2.4 Ma in the Xifeng area can be subdivided into the following periods based on the succession of these three ecological groups of terrestrial mollusks: 6.2–5.4 Ma, when the EAWM predominated, the climate was relatively cold and dry; 5.4–4.5 Ma, when the EASM strengthened, the climate was warm and wet; 4.5–3.4 Ma, when the climate was moderately mild, the EAWM and EASM exerted the equivalent impact on the studied region; and 3.4–2.4 Ma as the EAWM predominated, the climate quickly cooled (Fig. 4). Climatic changes in this region are characterized by a stepwise cooling from 5.4 to 2.4 Ma, with a 1 Ma rhythmicity. The cooling trend is in good agreement with the general global cooling trend during this period, as documented by marine $\delta^{18}O$ records (Wu et al., 2006).

Changes in the three terrestrial mollusk fossil ecological groups found in the Xifeng red clay sequence spanning the time interval from 6.2 to 2.4 Ma have revealed three major eco-environmental shifts that occurred at ~5.4, 4.5 and 3.4 Ma (Fig. 4). The 5.4 Ma shift towards a strengthened EASM is consistent in age with the change in vegetation in Lingtai from completely dominant desert or desert-steppe vegetation to coniferous and broadleaved forest, with a small quantity of subtropical vegetation types (Wu, 2001). The shift that occurred at 4.5 Ma towards milder conditions is coincident with the reduction in C3 plants and the expansion in C4 plants, as shown in the stable isotope records at Xifeng and Lingtai during the 4.5–4 Ma (Ding and Yang, 2000; Jiang et al., 2002) (Fig. 4). Analysis of these records shows that the ecological shift that occurred at ~5.4 Ma may be related to the global climate change that happened at that time. The ecological shifts which occurred at ~4.5 Ma and ~3.4 Ma may be closely related to the uplift of the TP, and the shoaling of the central American seaway (Nie et al., 2014), *i.e.* they could correspond to the indirect response of terrestrial ecosystems to tectonic movement, although the ultimate causes for the climatic

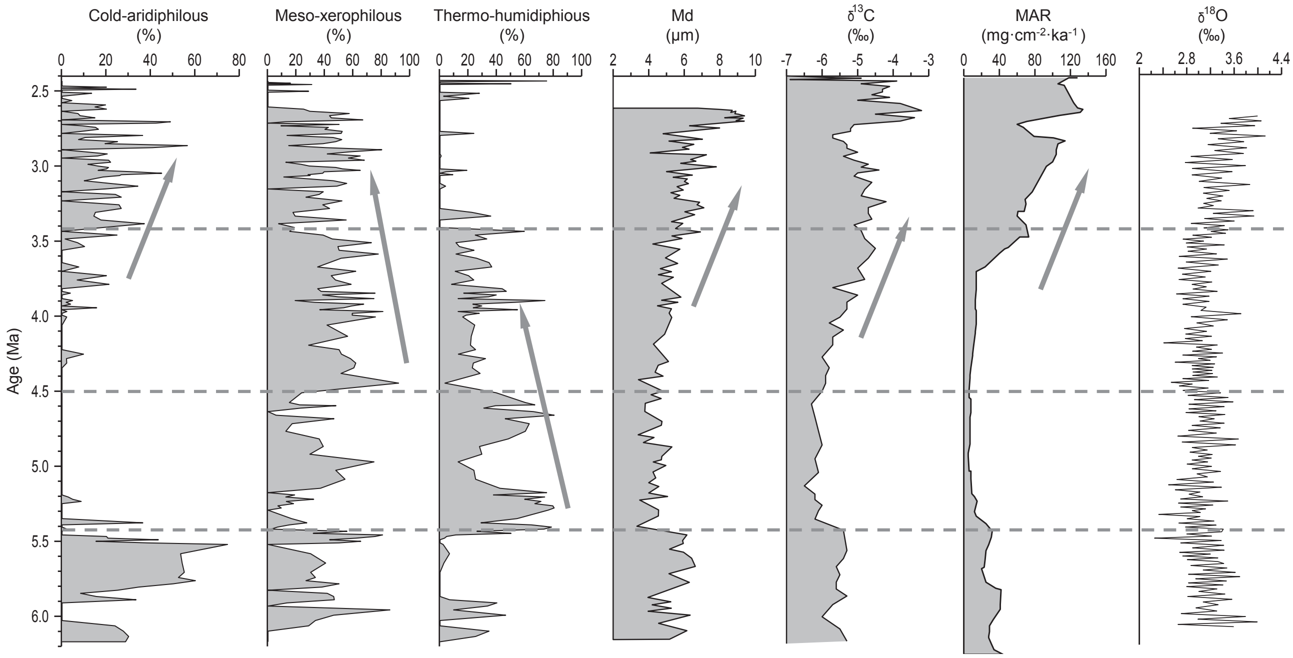

Fig. 4. Variations in the percentages of three terrestrial mollusk fossil ecological groups from the Xifeng red clay sequence, compared with median grain size (MD) (Guo et al., 2001), $\delta^{13}C$ (Jiang et al., 2002), mass accumulation rate (MAR) from the North Pacific ODP Site 885/886 (Rea et al., 1998), and the marine $\delta^{18}O$ record from ODP Site 846 (Shackleton et al., 1995). Solid arrows indicate the major changes in terrestrial mollusk fossil ecological groups (modified from Wu et al. (2006)).

transition are still under debate. They may also share an intimate relation with the development of the Northern Hemisphere ice sheet during this period (Wu et al., 2006).

4.2.2. Quaternary changes in the monsoonal environment over different timescales as evidenced by the terrestrial mollusk fossil record on the CLP

Over the past 20 years or more, the majority of loess terrestrial mollusk fossil research has focused on paleoenvironmental and paleoclimatic changes over different timescales during the Quaternary (e.g., Liu, 1985; Wu et al., 1996, 1997, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997, 1999; Rousseau et al., 2000, 2009; Chen and Wu, 2008; Wu and Wu, 2008, 2011). Here, we use two case studies to review the Quaternary paleoclimatic changes on orbital timescale.

Case 1 concerns terrestrial mollusk fossil assemblages from the L5–L4 loess stratigraphy (correlated with MIS 12–10) in the Xifeng and Luochuan Quaternary loess-paleosol sections (Wu et al., 2007). A total of 25 terrestrial mollusk fossil species were identified, from which six dominant species were selected. Based on changes in the peak abundance of these six dominant species, Wu et al. (2007) reconstructed the environmental and climatic changes during the MIS 12–10 period on the CLP (Fig. 5), when climatic conditions over the CLP appear unstable. Fluctuations in the glacial and/or interglacial ecological environment appear much more frequently at Xifeng than at Luochuan. Furthermore, climatic fluctuations seem much stronger during MIS 12 (corresponding in age to loess unit L5) than during MIS 10 (comparable in age with loess unit L4). This would indicate that the influence of the EAWM on the CLP strengthened significantly during MIS12, although these two glacial periods also experienced sub-stages during which the EASM was stronger, as exemplified by peaks in the abundance of *Gastrocopta armigerella*. The particular compositional and ecological characteristics of terrestrial mollusk fossil assemblages show that cold climatic conditions were prevalent during MIS12 (glacial stages) on the CLP. Overall, the climate during MIS11 (comparable in age with paleosol S4) on the CLP appears to have been warm and wet, although, in comparison to the relatively stable record yielded at Luochuan, the ecological environment seems to have experienced at least three or four unstable fluctuations at Xifeng. In the early stages of MIS11 (with a duration of ~ 30 ka), the CLP's climate appears to have been considerably warm and wet, epitomized by the significant dissolution of terrestrial mollusk shells during sustained and heavy leaching of the soil. This leaching appears to have been more marked at Luochuan than at Xifeng. The CLP's climate during the late MIS11 was comparatively mild, cool and wet. Overall climatic conditions on the CLP during MIS11 experienced extreme warmth and humidity, short-term cooling, relative warmth and humidity, and relatively cool and wet sub-stages (Wu et al., 2007).

Case 2 is a study of the paleoclimate during the deposition of the L9 unit on the CLP, corresponding to MIS 24–22. The extremely thick and visually distinguished L9 strata at Xifeng and Luochuan on the CLP contain a rich and continuous abundance of terrestrial mollusk fossils. The study of these terrestrial mollusk fossil assemblages reveals a dominant abundance of cold-aridiphilous terrestrial mollusk group, with two notable peaks in abundances of thermo-humidiphilous terrestrial mollusk group. This would suggest that during the period during which L9 was deposited (comparable with MIS 24–22), the CLP's climate, as opposed to the extremely cold and dry climate apparently reflected by field observations and other physical and chemical indicators, was comparatively cool overall. The general climatic changes experienced appear to have followed a pattern of cold and dry, comparatively warm and wet, short-term cooling, cold and wet, cold and dry, and warming periods. During MIS 24–22, the EASM still exerted some influence on the CLP, but a clear spatial difference is evident. This can be seen in the weakness of the influence of the EASM at Xifeng, relative to Luochuan. The two sub-stages during which the EASM strengthened occurred at 922–910 ka and 893–885 ka. The mollusk fossil record shows that the climatic conditions on the CLP during the formation of L9 were similar to those indicative of gentle glacial (MIS 24 and MIS 22) and interglacial (MIS 23) periods, as suggested by the marine $\delta^{18}O$ record, indicating that the climate prevalent during the depositional stages of the L9 loess layer is globally comparable (Wu and Wu, 2011). The above two cases show that terrestrial mollusk records can clearly reveal the long-term characteristics of changes in the glacial/interglacial monsoonal environment, and especially glacial climate characteristics; this is because glacial periods are characterized by weaker soil leaching than interglacial periods, conditions which are more suited to the preservation of snail fossils.

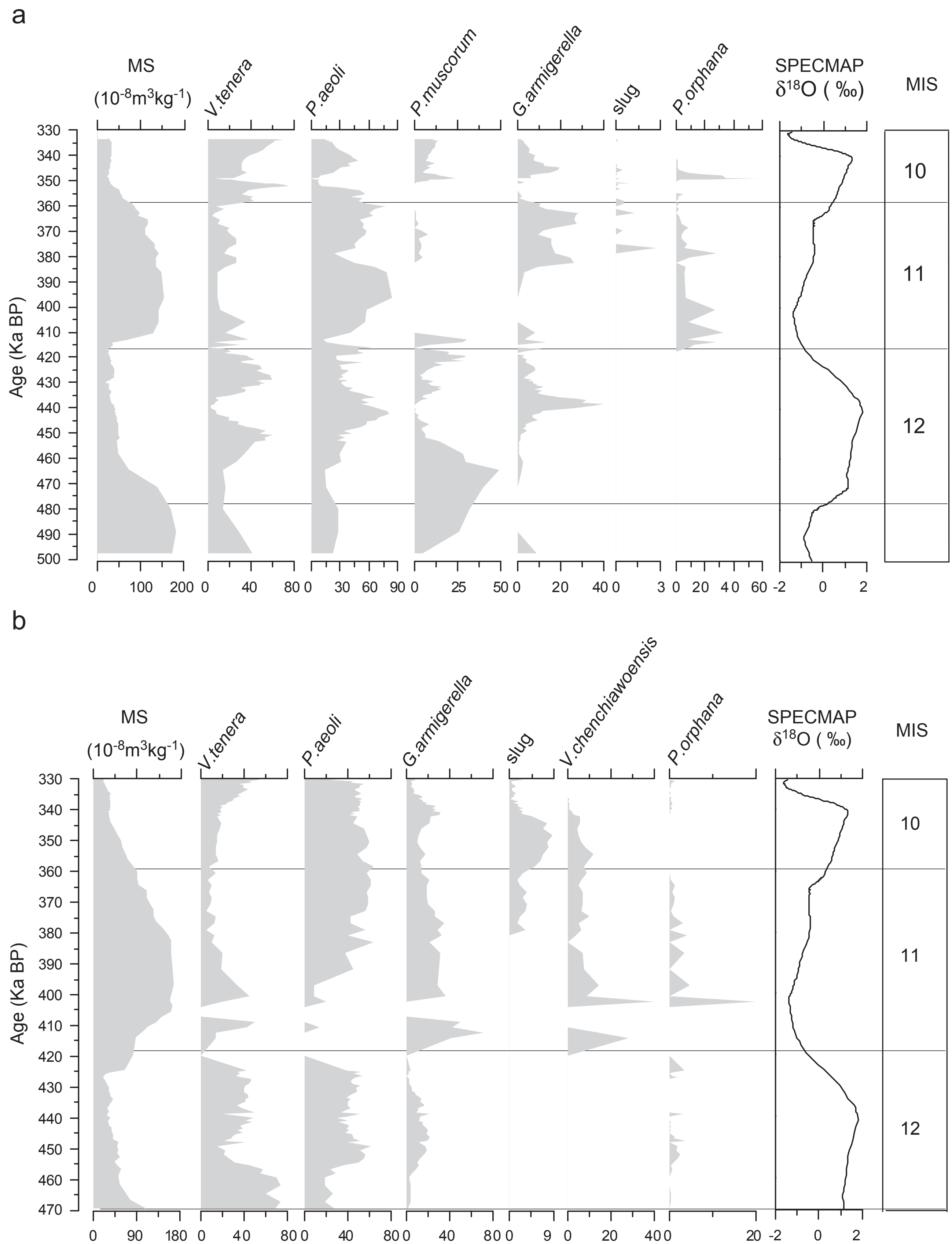

Fig. 5. Variations in the percentages of six terrestrial mollusk species in the Xifeng (a) and Luochuan (b) loess sequences during MIS 12–10, compared with variations in magnetic susceptibility (MS) and the SPECMAP $\delta^{18}O$ record (Imbrie et al., 1984) (modified from Wu et al. (2007)).

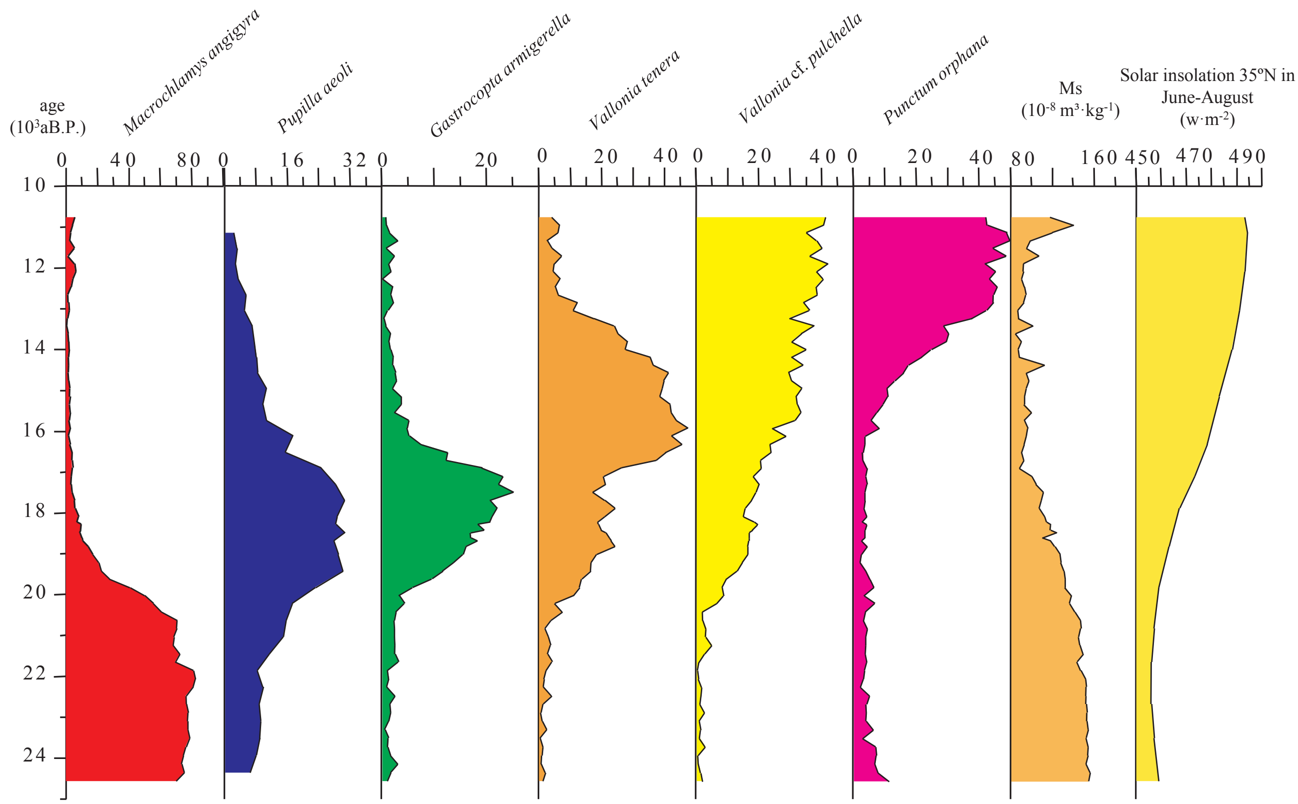

Fig. 6. Rapid variation in the peak abundances of the six terrestrial mollusk species from the Weinan loess sequence in the southern CLP during the Last Glacial Maximum (LGM), compared with variations in magnetic susceptibility (MS) and summer (June to August) insolation in the Northern Hemisphere (35°N) (modified from Wu et al. (2002)).

The climatic sensitivity of terrestrial mollusks has also proved them to be a reliable environmental proxy of climatic instability on the millennial timescale (e.g., Wu et al., 1996, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997, 1999; Chen and Wu, 2008; Wu and Wu, 2008, 2011; Rousseau et al., 2009). The study of the relatively high-resolution (using a 3 cm sampling interval, equivalent to a time resolution of ~200 yr) terrestrial mollusk fossil record of the Last Glacial Maximum (LGM) at the Weinan loess section has revealed a millennial climatic variability. A succession of peak abundances in six typical terrestrial mollusk species shows millennial climatic fluctuations, and an asynchronous variation in temperature and precipitation, showing that changes in temperature clearly predate those in humidity by 1–2 ka (Fig. 6). This study has suggested that the reason for this particular climatic pattern was the interaction between the EAWM and the EASM. The EASM could have reached the southeastern parts of the CLP for the whole LGM, as shown by the presence of thermo-humidiphilous mollusks. The intensification of the EAWM during the LGM shortened the duration of the EASM, impacting the CLP on an annual basis, but the EASM maintained its inherent strength, thus providing quantities of water and warmth suited to the continuous growth and development of thermo-humidiphilous mollusks during a glacial age (Wu et al., 2002).

Terrestrial mollusk assemblages from the past 500 ka in the Luochuan loess-paleosol sequence reveal that there were three exceptionally strong EASM events, as indicated by the exceptionally high abundance of thermo-humidiphilous terrestrial mollusks during the glacial periods concurrent with the L5, L4 and L2 loess depositional stages (Fig. 7). It can be seen that the glacial environment experienced three anomalous periods of EASM strengthening, occurring at ~470 ka, ~360 ka and ~170 ka. The reason for the occurrence of these three events could be related to orbital parameters, the reorganization of atmospheric and oceanic circulations, the difference in the temperature gradient between high and low latitudes, and changes in Northern Hemisphere ice volumes (Rousseau et al., 2009).

Studies of terrestrial mollusk fossil assemblages since the last glacial at the four loess sections of Xifeng, Changwu, Luochuan and Weinan have revealed the unstable climatic conditions that prevailed on the CLP during glacial periods, with clear millennial fluctuations which correlate well with the Greenland Ice Core Project 2 ice core oxygen isotope record. Such climatic instability during glacial periods might be related to the unstable nature of lower atmospheric circulation patterns in the Northern Hemisphere (Wu et al., 1999; Chen and Wu, 2008). Changes in the abundances of terrestrial mollusk fossils seen in the L9 loess strata (comparable with MIS 24–22) at Luochuan and Xifeng reveal a '900 ka event' on the CLP; it can be seen that the overall trend towards climate cooling during this period experienced a number of climatic fluctuations, with three periods during which the EAWM strengthened, at ~930 ka, ~900 ka and ~880 ka. Of these, the sharpest cooling occurred at ~900 ka. Periods experiencing a relative strengthening of the EASM occurred at ~920 ka and ~890 ka. Analysis suggests that the unstable cold/warm fluctuations of these periods are related to the expansion of Northern Hemisphere ice volumes and the strengthening of solar radiation, leading to enhanced thermodynamic differences between the land and sea, and a consequent strengthening of both the EAWM and EASM, and subsequent climatic instability (Wu and Wu, 2011). Generally speaking, these unstable climates, as revealed by the above mentioned terrestrial mollusk records, have occurred at different timescales during the Quaternary. As for their causes, there is a variety of possible explanations resulting from different dynamic mechanisms.

4.2.3. Climatic periodicities and orbital forcing as revealed by terrestrial mollusk fossils

Previous paleoclimatic studies based on physical, chemical and biological records from the loess-paleosol sequences of the CLP have indicated that changes in the East Asian monsoon circulation patterns appear closely related to global climatic drivers such as the Earth's orbital parameters, solar radiation and global ice volumes (e.g., Liu, 1985; Kukla, 1987; Ding et al., 1994, 1995; Xiao et al., 1995; Liu and

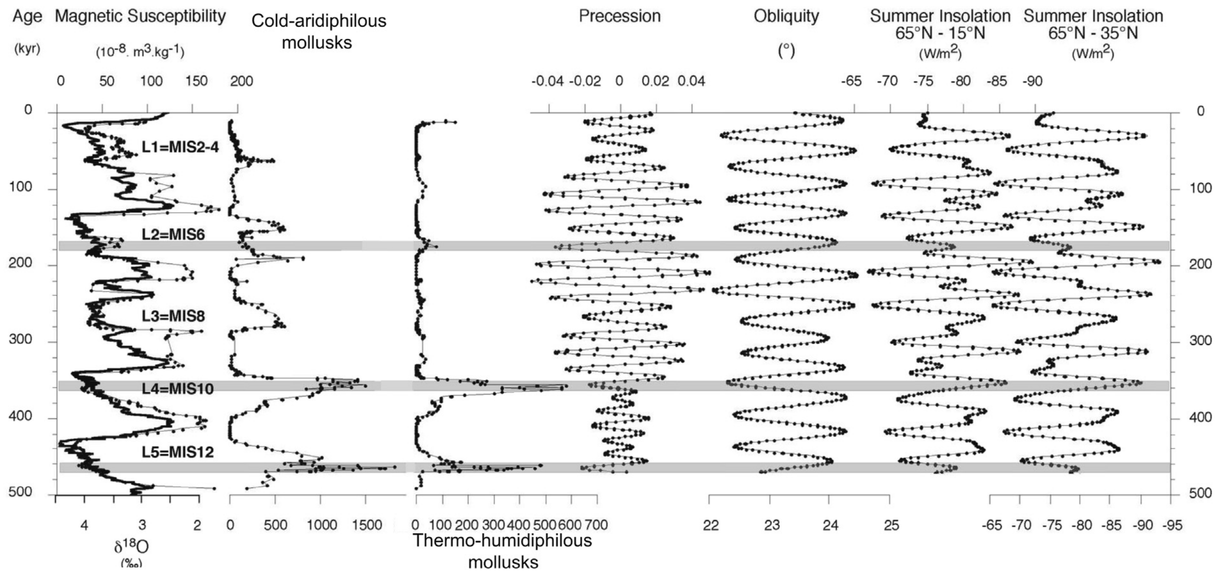

Fig. 7. Variations in the cold-aridiphilous mollusks (indicators of the EAWM) and thermo-humidiphilous mollusks (indicators of the EASM) from the Luochuan loess-paleosol sequence, compared with orbital parameters and insolation gradients (modified from Rousseau et al., 2009). The stacked $\delta^{18}O$ (bold curve) is from Lisiecki and Raymo (2005). The computed climatic precession and obliquity is from Laskar et al. (2004), and the differences in the mean summer and winter insolation values at 65°N and 15°N represent the insolation gradient between high latitudes and the tropics. The gray bands characterize exceptional glacial summer monsoon intervals. L1 to L5: loess units; MIS 2 to MIS 12: marine isotope stages.

Ding, 1998; An, 2000; Guo et al., 2000, 2002; Rousseau et al., 2000, 2009; Wu et al., 2000, 2001; Wu and Wu, 2008, 2011; Li et al., 2008; Li and Wu, 2010). High-resolution studies of terrestrial mollusk fossils from the Luochuan and Changwu loess-paleosol sequences on the CLP, covering the last 350 ka, show different responses of typical thermo-humidiphilous and cold-aridiphilous terrestrial mollusk species to orbital forcing. The thermo-humidiphilous *Punctum orphana* shows predominant periodicities centered on 41 ka and 23 ka cycles, indicating that the strength of the EASM is sensitive to orbital forcing at obliquity and precession frequency bands; in contrast, the cold-aridiphilous *Vallonia tenera* and *Pupilla aeoli* show a different pattern, with predominant periodicities concentrating on the ~100 ka and ~41 ka bands, indicating thereby the impact of global ice volumes on changes in the EAWM. The terrestrial mollusk fossil record also indicates that changes in the EAWM and EASM both show a ~41 ka periodicity at the obliquity band. This would indicate the relatively stronger impact of obliquity on climate change in mid and high latitudes (Berger and Pestiaux, 1984). As the obliquity increases, the solar radiation received by mid and high latitudes also increases significantly (Harrison et al., 1995; Colman et al., 1995), leading to a reduction in atmospheric pressure over land surfaces, a strengthening of the EASM, and conditions beneficial to the growth and development of thermo-humidiphilous terrestrial mollusks on the CLP. When the obliquity decreases, the solar radiation in mid and high latitudes decreases, providing favorable conditions for ice sheet growth, and allowing a strengthening of the EAWM, leading to an abundance of cold-aridiphilous terrestrial mollusk species on the CLP (Wu et al., 2000, 2001). On an orbital timescale, the relation between changes in the EAWM and EASM is highly complex, and there is no single model indicative of the 'seesaw' pattern outlined above (Wu et al., 2001).

Rousseau et al. (2000) analyzed terrestrial mollusk fossil assemblages from the Luochuan loess strata of the last glacial and discovered different periods during which the EAWM and the EASM predominated. Climate change as documented by the abundances of different ecological groups of terrestrial mollusk fossils is in good agreement with variations in the summer and winter solar radiation values at 30°N. Wu and Wu (2008) studied terrestrial mollusk fossil assemblages in the S5 paleosol layer (corresponding in age to MIS 15–13) and showed through power spectrum analysis that the thermo-humidiphilous terrestrial mollusk species *Gastrocopta coreana* exhibited a cyclic change of ~23 ka, indicating that precession-driven low-latitude solar radiation was the principal controller of changes in the EASM on the CLP; the changes in the cold- and dry-loving species *Pupilla aeoli* indicated, on the contrary, a clear periodicity of ~100 ka, and a weak periodicity of ~43 ka, indicating that the EAWM was still affected by global ice volumes under overall warm and humid climate conditions. Based principally on evidence derived from terrestrial mollusk assemblages, Wu and Wu (2008) proposed that global ice volumes and Northern Hemisphere solar radiation were the most important factors in the evolution of the CLP's climatic environment and the growth and decline of the EAWM and EASM during MIS15–13.

Systematic research into terrestrial mollusk fossil assemblages taken from the Dongwan loess section in the western CLP, spanning the late Miocene-Pliocene (~7.1 to 3.5 Ma), has found a new transitional pattern of climatic change from ~100 ka to ~41 ka (Fig. 8), contrary to that experienced during the Middle Pleistocene Transition (MPT). The variations in the cold-aridiphilous and thermo-humidiphilous ecological groups of terrestrial mollusks in the Dongwan section indicate two different monsoon-dominated periods during 7.1–3.5 Ma (Fig. 8). Between 7.1 and 5.5 Ma, the EAWM, with a ~100 ka periodicity, was dominant. Between 5.1 and 4 Ma, the EASM dominated, with a ~41 ka periodicity. Between these two periods is a transitional period of ~400 ka. Li et al. (2008) analyzed the possible reasons for such a climatic transition. The period characterized by a strengthening EAWM is coeval with orbital-scale changes in global ice volumes. The dominant EASM with 41 ka frequency may be related to the changes in oceanic circulations caused by the closure of the Panama and Indonesian seaways, as well as the formation/enlargement of the Western Pacific Warm Pool, and changes in solar radiation caused by changes in obliquity; all these factors would have led to the increased transportation of water vapor to mid and high latitudes (Li et al., 2008). The significance of this study may be the discovery of a new climatic transition mode hitherto neglected in long-term terrestrial and marine paleoclimatic studies.

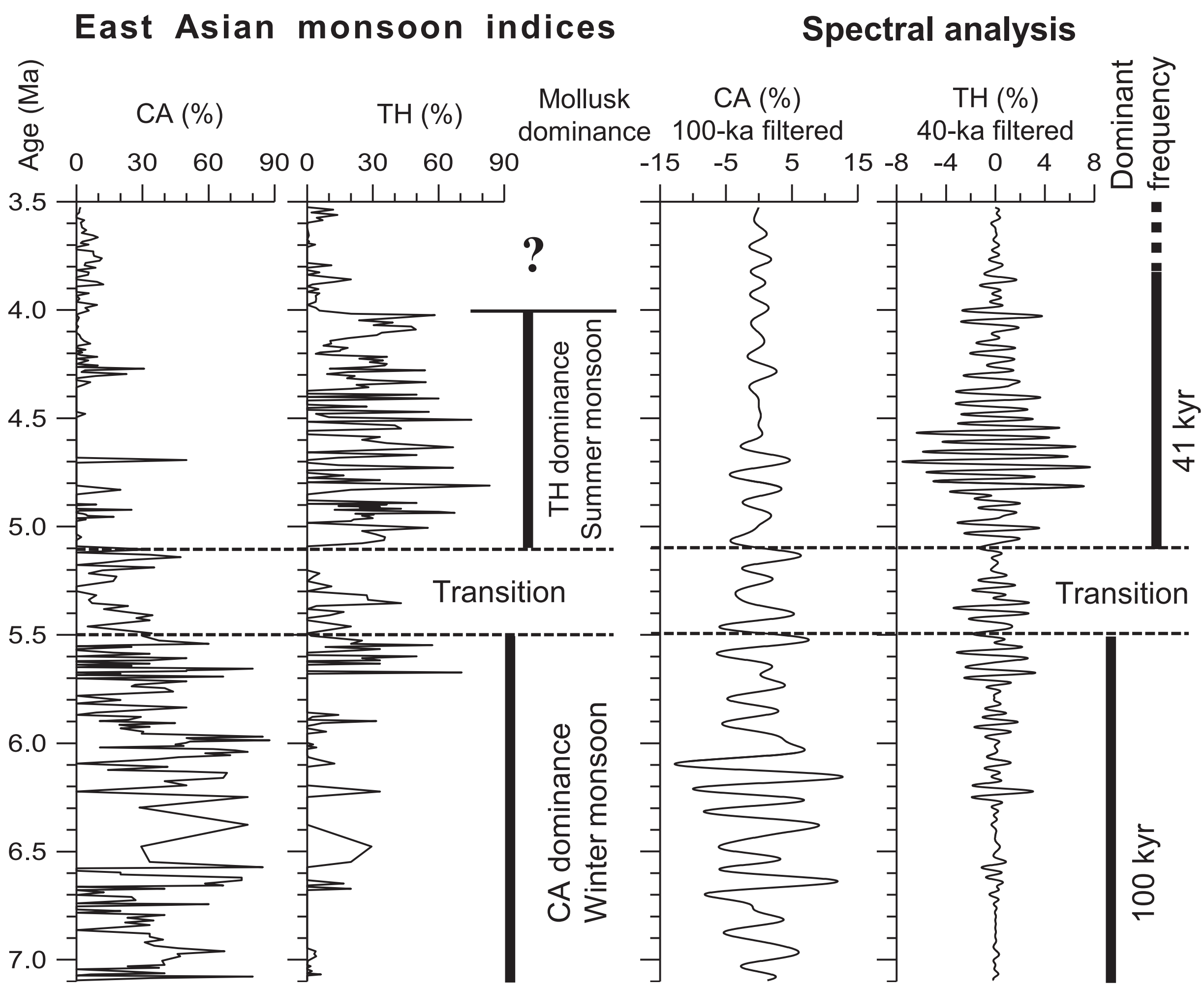

Fig. 8. Changes in the percentages and band-pass filtered curves of cold-aridiphilous (CA) and thermo-humidiphilous (TH) terrestrial mollusk records from the late Miocene-Pliocene Dongwan loess sequence on the western CLP, indicating different monsoonal and periodicity-dominated periods (modified from Li et al. (2008)).

4.3. The evolution of the monsoonal environment as revealed by the stable isotopes of loess terrestrial mollusk shells

Numerous studies have confirmed that the stable isotopes of the calcium carbonate shells of terrestrial mollusks can effectively record an isotopic signal corresponding to their diet (vegetation) and precipitation (monsoonal) isotopes during the relevant terrestrial mollusk growing season (e.g., Yapp, 1979; Lécolle, 1985; Goodfriend and Magaritz, 1987; Goodfriend et al., 1989; Leng et al., 1998; Stott, 2002; Metref et al., 2003; Balakrishnan et al., 2005; Zanchetta et al., 2005; Liu et al., 2006, 2007; Gu et al., 2009; Sun et al., 2009; Yanes et al., 2009; Kehrwald et al., 2010; Huang et al., 2012). These studies have demonstrated that the stable isotopes of terrestrial mollusk shells can act as a good climatic proxy for paleoenvironmental changes, and especially for seasonal climate change at different timescales (e.g., Leng et al., 1998; Sun et al., 2009; Huang et al., 2012). Liu et al. (2007) studied, from modern terrestrial mollusks on the CLP and its surrounding regions, the carbon isotopic composition of organic carbon from the soft bodies and of inorganic carbon from the aragonite shells. They found a significant correlation between shell aragonite inorganic carbon isotopes and the corresponding soft body organic carbon isotopes. Their result indicated dietary controls on the carbon isotopic composition of terrestrial mollusk shell carbonates, as previous studies have proved that the bodies of snails possessed the same carbon isotopic composition as the food those snails consumed. Thus, the carbon isotopic composition of the carbonate shell can be used as a proxy to estimate carbon isotopic abundance in the diet of terrestrial mollusks (Liu et al., 2007). The oxygen isotopic composition of the aragonite shells of modern terrestrial mollusks appears to be related principally to the $\delta^{18}O$ values of summer monsoonal precipitation, which potentially allows the reconstruction of the history of the EASM on the CLP (Liu et al., 2006).

Gu et al. (2009) studied the stable carbon isotopic compositions of the calcium carbonate shells of *Cathaica pulveratrix*, and of soil organic matter (SOM) from the Mangshan loess section since the last glacial. They showed that changes in the $\delta^{13}C$ values of the carbon isotopic composition of terrestrial mollusk shell aragonite, an indication of the isotopic compositions of the mollusks' diet, did not correlate significantly with the carbon isotopic composition of the SOM ($\delta^{13}C_{SOM}$), an indicator of paleovegetation. Terrestrial mollusk shell $\delta^{13}C$ values do not accurately reflect the relative biomasses of C3 and C4 plants in local vegetative environments, whereas the oxygen isotopic composition of terrestrial mollusk shells depends principally on the isotopic composition of the precipitation which falls during the terrestrial mollusk shell's growing season, with temperature and humidity being only secondary factors; this would indicate that the oxygen isotopic composition of mollusk shells can reflect changes in the strength of the paleo-EASM.

The stable isotopic compositions of terrestrial mollusk shells provide the potential to reveal seasonal climatic features. Based on stable carbon and oxygen isotopic analysis of modern terrestrial mollusk assemblages from different climatic zones across the CLP, Huang et al. (2012) attempted to construct a statistical relation between the isotopic compositions of terrestrial mollusk shells and the length of the growing season. Their results indicated that differences between the isotopic compositions of cold-aridiphilous *Pupilla aeoli* and thermo-humidiphilous *Punctum orphana* roughly reflected changes in the length of the growing season on the CLP, from east to west. Both $\delta^{13}C$ and $\delta^{18}O$ values decreased by 1‰ with a 15-day and 19-day shortening of the growing season, respectively. This relation was then used to study changes in the length of the growing season at different stages of the last glacial from 70 ka onwards. The result revealed the length of the growing season during the Holocene to be ~200 ± 10 days, ~40 days longer than that observed during the last glacial. This research opened up new pathways into the study of the seasonal climatic changes in the monsoon regions of China.

In recent years, research into the clumped isotopes (Δ_{47}) found in terrestrial mollusk shells has allowed new approaches to the quantitative reconstruction of paleotemperatures (e.g., Zaarur et al., 2011; Eagle et al., 2013; Wang et al., 2016). Zaarur et al. (2011) were the first to report on the clumped isotopes (Δ_{47}) found in the shells of modern terrestrial mollusks collected from different climate zones. They discovered that the temperatures at which the carbonates formed in terrestrial mollusk shells were notably higher than the site-specific annual and growing season temperatures. They therefore suggested that the Δ_{47} temperatures could not be directly used to reconstruct air temperatures. However, Wang et al. (2016) recently reported on the Δ_{47} values found in the shells of the two terrestrial mollusk species *Cathaica* sp. and *Bradybaena* sp. at 24 sites in northern China, including the CLP. They discovered that the temperatures obtained through an analysis of the Δ_{47} values of these two species exhibited a relatively good relation with the temperatures extant during the terrestrial mollusks' growing season. The temperatures thus gained might therefore act as a possible temperature gauge for monsoonal regions. Eagle et al. (2013) tentatively studied the Δ_{47} values of 32 modern terrestrial mollusk shells and of 37 LGM loess terrestrial mollusk shells from Puxian County in Shanxi Province. They reconstructed changes in temperature since the LGM, and determined that summer temperatures during the last glacial changed by 6–7 °C. It must, however, be pointed out that although using the Δ_{47} values of loess terrestrial mollusk shells to reconstruct accurately changes in paleotemperatures seems very promising, there are still multiple environmental factors to consider, such as the terrestrial mollusks' physiology, ecology *etc.*, which would have affected the Δ_{47} levels of calcium carbonate in the shells of terrestrial mollusks during the growing season. Therefore, it is now necessary to develop a deeper understanding of the Δ_{47} values of terrestrial mollusk shells, in particular through the study of modern processes, in order to obtain more accurate paleotemperatures.

5. Questions and future prospects for terrestrial mollusk fossil research

Terrestrial mollusks have great potential for the study of paleoclimate and paleoenvironmental changes from the late Cenozoic to the present. The 22 Ma old Chinese loess has preserved abundant terrestrial mollusk fossils, providing a unique material for the study of terrestrial mollusk successions since the Miocene (Guo et al., 2002; Li et al., 2006b). The study of the terrestrial mollusks found in Chinese loess has already established an initial biological succession from the Late Miocene to the Quaternary, providing a key record for the study of the relation between biological evolution and environmental change. With the development of a high-resolution terrestrial mollusk fossil sequence and spatial pattern for particular periods (*e.g.*, MIS 11, MIS 3 and the Holocene *etc.*), it is now possible to explore the evolution of the monsoonal environment on a millennial scale, and compare these results with modeling experiments. Surveys on the growing season of modern terrestrial mollusks and their relation to the climate and environment could establish the hydrothermal configurations of the paleoclimate and paleoenvironment, providing new pathways, and more abundant data, into the quantitative study of loess paleoclimates (Li et al., 2016). The high-resolution analysis of terrestrial mollusk shell stable isotopes and clumped isotopes (Δ_{47}), and in particular of the continuous stable isotopic analyses along the growth axis of a terrestrial mollusk shell, can supply more detailed information concerning seasonal environmental differences and vegetation types (Leng et al., 1998; Liu et al., 2006, 2007; Huang et al., 2012; Eagle et al., 2013; Wang et al., 2016). Improvements in dating methods and techniques could lead to terrestrial mollusk shells being used to produce highly accurate dating results (Xu et al., 2010, 2011). The study of the taphonomy of terrestrial mollusk fossil shells is crucial for the accurate reconstruction of the paleoenvironment, especially for paleosols, and has also become an important area of research. The introduction and application of new research methods have opened up new fields of research into the terrestrial mollusk fossils preserved in loess, rejuvenating this long-established academic discipline.

It should be pointed out that, regardless of terrestrial mollusks being more directly sensitive to climatic, environmental and ecological processes, compared to some chemical and physical proxies, there are still certain limitations to, and uncertainties in the interpretation of the paleoenvironment, due largely to the insufficient number of studies into the taphonomy of fossil mollusks, and into ecological surveys of modern terrestrial mollusks. These current deficiencies can be enumerated as follows: (1) there is a lack of physiological and ecological investigations into modern terrestrial mollusk species and individuals, as well as a lack of observational data about their biological growth processes and environmental parameters under laboratory controlled conditions, resulting in possible deviations, including mistakes/errors in explanations of the paleoenvironment and paleoclimate using terrestrial mollusk fossil assemblages and shell isotopic data; (2) problems concomitant with the differential preservation of terrestrial mollusk fossil species, where it can be generally stated that terrestrial mollusk fossils in loess units are well-preserved, and shell dissolution rarely occurs, but that within paleosol layers, terrestrial mollusk shell dissolution can occur to a greater or lesser extent, exemplified especially by the fewer terrestrial mollusk fossils preserved in strongly developed paleosol units such as the lower parts of S1, S4 and S5 layers, implying any extremely difficult explanation of the paleoenvironment; (3) regional differences in the stratigraphic distribution of terrestrial mollusk ecological groups. When using terrestrial mollusk fossil ecological groups to explain paleoenvironments, we must consider regional differences, as identical terrestrial mollusk ecological group may exhibit a different, even quite contrary, stratigraphic distribution in different climatic regions. For example, the *Pupilla-Vallonia* assemblage, frequently seen in the last glacial loess units of the sections at Weinan, Luochuan and Xifeng on the central and southern CLP (Wu et al., 1996, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997; Chen and Wu, 2008), is dominant in paleosols of the last interglacial and Holocene at the Lanzhou loess section on the northwestern CLP (Keen, 1995); and the high abundance of the thermo-humidiphilous *Punctum orphana* found in the Holocene paleosol layers of the loess sections at Luochuan, Changwu and Xifeng (Wu et al., 1995, 2001, 2002; Rousseau and Wu, 1997; Chen and Wu, 2008), shows a comparable abundance in last glacial terrestrial mollusk assemblages at the Mangshan section on the southeastern CLP. Therefore, when using terrestrial mollusk fossil assemblages to interpret paleoenvironments, and in particular when reconstructing paleoenvironmental spatial patterns, it is imperative that the regional differences in the stratigraphic distributions of terrestrial mollusk ecological groups from different climatic and environmental conditions should be carefully considered, so as to avoid discrepancies in paleoenvironmental interpretations; and (4) with regard to the increasing quantities of paleoenvironmental information being extracted, *e.g.* concerning the ecological significance of extinct species, and the biological evolution of terrestrial mollusk species in relation to the climate and the environment, it is crucial that more systematic research should be developed in order to improve gradually the accuracy of any interpretations of the paleoenvironment recorded by terrestrial mollusk fossils.

Acknowledgments

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References

An, Z.S., 2000. The history and variability of the East Asian paleomonsoon climate. Quatern. Sci. Rev. 19, 171–187.
Antoine, P., Rousseau, D.D., Moine, O., Kunesch, S., Hatté, C., Lang, A., Tissoux, H., Zöller, L., 2009. Rapid and cyclic aeolian deposition during the Last Glacial in European loess: a high-resolution record from Nussloch, Germany. Quatern. Sci. Rev. 28, 2955–2973.
Balakrishnan, M., Yapp, C.J., Theler, J.L., 2005. Environmental significance of $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios of modern land-snail shells from the southern great plains of North America. Quatern. Res. 63, 15–30.
Berger, A.L., Pestiaux, P., 1984. Accuracy and stability of quaternary terrestrial insolation. In: Berger, A.L., Imbrie, J., Hags, J., Kukla, G., Saltzman, B. (Eds.), Milankovitch and Climate, Part 1. Reidel, Dordrecht, Netherlands, pp. 83–111.
Chen, D.N., Gao, J.X., 1987. Economic Fauna Sinica of China: Terrestrial Mollusca. Science Press, Beijing, pp. 186 (in Chinese with English abstract).
Chen, D.N., Lu, Y.C., An, Z.S., 1982. Snail assemblages in loess strata and their environmental implication. In: Chinese Association for Quaternary Research eds. Proceedings of the 3rd National Quaternary Conference of China. Science Press, Beijing, 7–15 (in Chinese with English abstract).
Chen, D.N., Zhang, G.Q., 1998. A study of the fossil land snails contained and signicance from mount Tomor of xinjiang uygur zizhiqu, china. Acta Zootaxon. Sin. 23, 235–244 (in Chinese with English abstract).
Chen, D.N., Zhang, G.Q., 2004. Fauna Sinica (Invertebrata, vol. 37) (Mollusca: Gastropoda: Stylommatophora: Bradybaenidae). Science Press, Beijing, pp. 482.
Chen, X.Y., Wu, N.Q., 2008. Relatively warm-humid climate recorded by mollusk species in the Chinese Loess Plateau during MIS 3 and its possible forcing mechanism. Quatern. Sci. 28, 154–161 (in Chinese with English abstract).
Colman, S.M., Peck, J.A., Karabanov, E.B., Carter, S.J., Bradbury, J.P., King, J.W., Williams, D.F., 1995. Continental climate response to orbital forcing from biogenic silica records in Lake Baikal. Nature 378, 769–771.
Colonese, A.C., Zanchetta, G., Fallick, A.E., Manganelli, G., Saña, M., Alcade, G., Nebot, J., 2013. Holocene snail shell isotopic record of millennial-scale hydrological conditions in western Mediterranean: data from Bauma del Serrat del Pont (NE Iberian Peninsula). Quatern. Int. 303, 43–53.
Ding, Z.L., Yu, Z.W., Rutter, N., Liu, T.S., 1994. Towards an orbital time scale for Chinese loess deposits. Quatern. Sci. Rev. 13, 39–70.
Ding, Z.L., Liu, T.S., Rutter, N.W., Yu, Z.W., Guo, Z.T., Zhu, R.X., 1995. Ice-volume forcing of East Asian winter monsoon variations in the past 800,000 years. Quatern. Res. 44, 149–159.
Ding, Z.L., Yang, S.L., 2000. C3/C4 vegetation evolution over the last 7.0 Myr in the Chinese Loess Plateau: evidence from pedogenic carbonate $\delta^{13}C$. Palaeogeogr. Palaeoclimatol. Palaeoecol. 160, 291–299.
Eagle, R.A., Risi, C., Mitchell, J.L., Eiler, J.M., Seibt, U., Neelin, J.D., Li, G.J., Tripati, A.K., 2013. High regional climate sensitivity over continental China constrained by glacial-recent changes in temperature and the hydrological cycle. Proc. Natl. Acad. Sci. U.S.A. 110, 8813–8818.
Goodfriend, G.A., Magaritz, M., 1987. Carbon and oxygen isotope composition of shell carbonate of desert land snails. Earth Planet. Sci. Lett. 86, 377–388.
Goodfriend, G.A., Magaritz, M., Gat, J.R., 1989. Stable isotope composition of land snail body water and its relation to environmental water and shell carbonate. Geochim. Cosmochim. Acta 53, 3215–3221.
Gu, Z.Y., Liu, Z.X., Xu, B., Wu, N.Q., 2009. Stable carbon and oxygen isotopes in land snail carbonate shells from a last glacial loess sequence and their implications of environmental changes. Quatern. Sci. 29, 13–22 (in Chinese with English abstract).
Guo, Z.T., Biscaye, P., Wei, L.Y., Chen, X.H., Peng, S.Z., Liu, T.S., 2000. Summer monsoon variations over the last 1.2 Ma from the weathering of loess-soil sequences in China. Geophys. Res. Lett. 27, 1751–1754.
Guo, Z.T., Peng, S.Z., Hao, Q.Z., Biscaye, P.E., Liu, T.S., 2001. Origin of the Miocene-Pliocene Red-Earth Formation at Xifeng in Northern China and implications for paleoenvironments. Palaeogeogr. Palaeoclimatol. Palaeoecol. 170, 11–26.
Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., Liu, T.S., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416, 159–163.
Hao, Q.Z., Guo, Z.T., 2004. Magnetostratigraphy of a late Miocene-Pliocene loess-soil sequence in the western Loess Plateau in China. Geophys. Res. Lett. 31, L09209. http://dx.doi.org/10.1029/2003GL019392.
Harrison, S.P., Kutzbach, J.E., Prentice, I.C., Behling, P.J., Sykes, M.T., 1995. The response of Northern Hemisphere extratropical climate and vegetation to orbitally induced changes in insolation during the last interglaciation. Quatern. Res. 43, 174–184.
Horsák, M., Chytrý, M., Hájková, P., Hájek, M., Danihelka, J., Horsáková, V., Ermakov, N., German, D.A., Kočí, M., Lustyk, P., Nekola, J.C., Preislerová, Z., Valachovič, M., 2015. European glacial relict snails and plants: environmental context of their modern refugial occurrence in southern Siberia. Boreas 44, 638–657.
Huang, L.P., Wu, N.Q., Gu, Z.Y., Chen, X.Y., 2012. Variability of snail growing season at the Chinese Loess Plateau during the last 75 ka. Chin. Sci. Bull. 57, 1036–1045.
Imbrie, J., Hays, J.D., Martinson, D.G., Mcintype, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., Shackleton, N.J., 1984. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record. In: Berger, A., Imbrie, J., Hays, J., Kukla, G., Saltzman, B. (Eds.), Milankovitch and Climate, Part 1. Reidel, Dordrecht, Netherlands, pp. 269–305.
Jiang, W., Peng, S., Hao, Q., Liu, T., 2002. Carbon isotopic records in paleosols over the Pliocene in Northern China: implication on vegetation development and Tibetan uplift. Chin. Sci. Bull. 47, 687–690.
Keen, D.H., 1995. Molluscan assemblages from the loess of North Central China. Quatern. Sci. Rev. 14, 699–706.
Kehrwald, N.M., McCoy, W.D., Thibeault, J., Burns, S.J., Oches, E.A., 2010. Paleoclimatic implications of the spatial patterns of modern and LGM European land-snail shell $\delta^{18}O$. Quatern. Res. 74, 166–176.
Kukla, G., 1987. Loess stratigraphy in Central China. Quatern. Sci. Rev. 6, 191–219.
Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B.A., 2004. Long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428, 261–285.
Lécolle, P., 1985. The oxygen isotope composition of land snail shells as a climatic indicator: applications to hydrogeology and paleoclimatology. Chem. Geol. (Isotope Geosci. Section) 58, 157–181.
Leng, M.J., Heaton, T.H., Lamb, H.F., Naggs, F., 1998. Carbon and Oxygen isotope variations within the shell of an African land snail (*Limicolaria kambeul chudeaui* Germain): a high-resolution record of climate seasonality? The Holocene 8, 407–412.
Li, F.J., Wu, N.Q., 2010. Pliocene land snail record from western Chinese Loess Plateau and implications for impacts of summer insolation gradient between middle and low latitudes on the East Asian summer monsoon. Global Planet. Change 72, 73–78.
Li, F.J., Wu, N.Q., Pei, Y.P., Hao, Q.Z., Rousseau, D.D., 2006a. Wind-blown origin of Dongwan late Miocene-Pliocene dust sequence documented by land snail record in western Chinese Loess Plateau. Geology 34, 405–408.
Li, F.J., Wu, N.Q., Rousseau, D.D., 2006b. Preliminary study of mollusk fossils in the Qinan Miocene loess-soil sequence in western Chinese Loess Plateau. Sci. China, Ser. D Earth Sci. 49, 724–730.
Li, F.J., Rousseau, D.D., Wu, N.Q., Hao, Q.Z., Pei, Y.P., 2008. Late Neogene evolution of the East Asian monsoon revealed by terrestrial mollusk record in western Chinese Loess Plateau: from winter to summer dominated sub-regime. Earth Planet. Sci. Lett. 274, 439–447.
Li, F.J., Wu, N.Q., Dong, Y.J., Lu, H.Y., Chen, X.Y., Zhang, D., Zhang, Y.T., Huang, L.P., Wu, B., 2016. Quantitative distribution and calculation of ecological amplitude of land snail *Metodontia* in the Chinese Loess Plateau and adjacent regions. Quatern. Sci. 36, 564–574 (in Chinese with English abstract).
Li, Y.T., 1966. Cenozoic Gasteropod fossils in Lantian and Weinan and their stratigraphic significance. In: Proceedings of the Cenozoic in Lantian, Shaanxi province. Science Popularization Press, Beijing, pp. 225–254 (in Chinese with English abstract).
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20, PA1003. http://dx.doi.org/10.1029/2004PA001071.
Liu, T.S., 1985. Loess and the Environment. China Ocean Press, Beijing, pp. 251.
Liu, T.S., Ding, Z.L., 1998. Chinese loess and the paleomonsoon. Annu. Rev. Earth Planet. Sci. 26, 111–145.
Liu, Z.X., Gu, Z.Y., Xu, B., Wu, N.Q., 2006. Monsoon precipitation effect on oxygen isotope composition of land snail shell carbonate from the loess plateau. Quatern. Sci. 26, 643–648 (in Chinese with English abstract).
Liu, Z.X., Gu, Z.Y., Wu, N.Q., Xu, B., 2007. Diet control on carbon isotopic composition of land snail shell carbonate. Chin. Sci. Bull. 52, 388–394.
Lu, Y.C., An, Z.S., 1979. Discussion on paleoenvironmental changes in the Loess Plateau since about 700 ka. Chin. Sci. Bull. 24, 221–224 (in Chinese with English abstract).
Metref, S., Rousseau, D.D., Bentaleb, I., Labonne, M., Vianey-Liaud, M., 2003. Study of the diet effect on $\delta^{13}C$ of shell carbonate of the land snail *Helix aspersa* in experimental conditions. Earth Planet. Sci. Lett. 211, 381–393.
Nie, J.S., Stevens, T., Song, Y.G., King, J.W., Zhang, R., Ji, S.C., Gong, L., Cares, D., 2014. Pacific freshening drives Pliocene cooling and Asian monsoon intensification. Sci. Rep. 4 (5474), 1–8.
Pei, Y.P., Wu, N.Q., 2005. Orbit-related climate cycle revealed in mollusk fossil record from Xifeng Red Clay formation in the Chinese Loess Plateau. Quatern. Sci. 25, 663 (in Chinese with English abstract).
Pei, Y.P., Wu, N.Q., Li, F.J., 2004. Terrestrial mollusk evidence for the origin and sedimentary environment of the Late Tertiary Red Clay Formation in the Loess Plateau, China. Chin. Sci. Bull. 49, 1072–1076.
Puisségur, J.J., 1976. Mollusques continentaux quaternaires de Bourgogne. Significations stratigraphiques et climatiques. Rapports avec d'autres faunes boréales de France: Université de Dijon Mémoires Géologiques, vol. 3, pp. 241.
Qian, Z.X., 2008. Farmland Molluscs from Zhejiang Province, China. Hangzhou Press, Hangzhou, pp. 425 (in Chinese with English abstract).

Qian, Z.X., Zhou, W.C., 2014. Illustrated Handbook of Common Terrestrial Mollusks in China. Zhejiang People's Art Press, Hangzhou, pp. 228.
Rea, D.K., Snoeckx, H., Joseph, L.H., 1998. Late Cenozoic eolian deposition in the North Pacific: Asian drying, Tibetan uplift, and cooling of the northern hemisphere. Paleoceanography 13, 215–224.
Richthofen, F.V., 1877. China, vol. 1. Verlag von Dietrich Reimer, Berlin, pp. 758.
Richthofen, F.V., 1882. On the mode of origin of the loess. Geol. Mag. 9, 293–305.
Rousseau, D.D., 1991. Climatic transfer function from Quanteranry molluscs in European loess deposits. Quatern. Res. 36, 195–209.
Rousseau, D.D., Wu, N.Q., 1997. A new molluscan record of the monsoon variability over the past 130,000 yr in the Luochuan loess sequence, China. Geology 25, 275–278.
Rousseau, D.D., Wu, N.Q., 1999. Mollusk record of monsoon variability during the L2–S2 cycle in the Luochuan loess sequence, China. Quatern. Res. 52, 286–292.
Rousseau, D.D., Wu, N.Q., Guo, Z.T., 2000. The terrestrial mollusks as new indices of the Asian paleomonsoons in the Chinese Loess Plateau. Global Planet. Change 26, 199–206.
Rousseau, D.D., Wu, N.Q., Pei, Y.P., Li, F.J., 2009. Three exceptionally strong East-Asian summer monsoon events during glacial times in the past 470 kyr. Climate Past 5, 157–169.
Shackleton, N.J., Hall, M.A., Pate, D., 1995. Pliocene stable isotope stratigraphy of ODP Site 846. Proc. ODP Sci. Results 138, 337–355.
Stott, L.D., 2002. The influence of diet on the δ^{13}C of shell carbon in the pulmonate snail *Helix aspersa*. Earth Planet. Sci. Lett. 195, 249–259.
Sun, X.H., Gu, Z.Y., Wang, X., 2009. Oxygen isotopic variations in the shells collected monthly from a live species of land snails at a locale in Zhenjiang, Jiangsu province, China. Quatern. Sci. 29, 976–980 (in Chinese with English abstract).
Wang, H.J., Chen, D.N., 2011. Terrestrial Mollusca of Important Region from China. Gansu Science and Technology Press, Lanzhou, pp. 527 (in Chinese with English abstract).
Wang, X., Cui, L., Zhai, J., Ding, Z., 2016. Stable and clumped isotopes in shell carbonates of land snails *Cathaica* sp. and *Bradybaena* sp. in north China and implications for ecophysiological characteristics and paleoclimate studies. Geochem. Geophys. Geosyst. 17, 219–231.
Wu, B., Wu, N.Q., 2008. Paleoenvironmental study of S5 paleosol formation: based on mollusk fossil evidence. Quatern. Sci. 28, 901–908 (in Chinese with English abstract).
Wu, B., Wu, N.Q., 2011. Terrestrial mollusk 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. Climate Past 7, 349–359.
Wu, N.Q., Lu, H.Y., Chen, D.N., Gao, F.Q., 1995. Late glaciation paleoenvironment in Weinan, Shaanxi: evidence based on snail fossils. Quatern. Sci. 2, 139–149 (in Chinese with English abstract).
Wu, N.Q., Rousseau, D.D., Liu, T.S., 1996. Land mollusk records from the Luochuan loess sequence and their paleoenvironmental significance. Sci. China, Ser. D Earth Sci. 39, 494–502.
Wu, N.Q., Lu, H.Y., Guo, Z.T., 1997. Reconstruction of paleoclimate in the Loess Plateau using nonlinear mathematical methods. Chin. Sci. Bull. 42, 1014–1016.
Wu, N.Q., Rousseau, D.D., Liu, T.S., 1999. Climate instability recorded by mollusk assemblages from the late glacial loess deposits in China. Chin. Sci. Bull. 44, 1238–1242.
Wu, N.Q., Rousseau, D.D., Liu, X.P., 2000. Response of mollusk assemblages from the Luochuan loess section to orbital forcing since the last 250 ka. Chin. Sci. Bull. 45, 1617–1622.
Wu, N.Q., Rousseau, D.D., Liu, T.S., Lu, H.Y., Gu, Z.Y., Guo, Z.T., Jiang, W.Y., 2001. Orbital forcing of terrestrial mollusks and climatic changes from the Loess Plateau of China during the past 350 ka. J. Geophys. Res. 106, 20045–20054.
Wu, N.Q., Liu, T.S., Liu, X.P., Gu, Z.Y., 2002. Mollusk record of millennial climate variability in the Loess Plateau during the last glacial maximum. Boreas 31, 20–27.
Wu, N.Q., Pei, Y.P., Lu, H.Y., Guo, Z.T., Li, F.J., Liu, T.S., 2006. Marked ecological shifts during 6.2–2.4 Ma revealed by a terrestrial molluscan record from the Chinese Red Clay Formation and implication for palaeoclimatic evolution. Palaeogeogr. Palaeoclimatol. Palaeoecol. 233, 287–299.
Wu, N.Q., Chen, X.Y., Rousseau, D.D., Li, F.J., Pei, Y.P., Wu, B., 2007. Climatic conditions recorded by terrestrial mollusc assemblages in the Chinese Loess Plateau during marine Oxygen Isotope Stages 12–10. Quatern. Sci. Rev. 26, 1884–1896.
Wu, Y.S., 2001. Palynoflora at late Miocene-early Pliocene from Leijiahe of Lingtai, Gansu Province, China. Acta Botan. Sin. 43, 750–756 (in Chinese with English abstract).
Xiao, J.L., Porter, S.C., An, Z.S., Kumai, H., Yoshikawa, H., 1995. Grain size of quartz as an indicator of winter monsoon strength on the Loess Plateau of central China during the last 130,000 yr. Quatern. Res. 43, 22–29.
Xu, W.H., Zhou, J.C., Zhang, E., Chen, Y.X., Yan, K.H., Wang, R.M., 2002. Effects of temperature and humidity on *Bradybeana similaris*. Jiangsu J. Agric. Sci. 18, 99–102 (in Chinese with English abstract).
Xu, B., Gu, Z.Y., Han, J.T., Liu, Z.X., Pei, Y.P., Lu, Y.W., Wu, N.Q., Chen, Y.F., 2010. Radiocarbon and stable carbon isotopes analyses of land snails from the Chinese Loess Plateau: environmental and chronological implications. Radiocarbon 52, 149–156.
Xu, B., Gu, Z.Y., Han, J.T., Hao, Q.Z., Lu, Y.W., Wang, L., Wu, N.Q., Pei, Y.P., 2011. Radiocarbon age anomalies of the land snail shells in Chinese Loess Plateau. Quat. Geochronol. 6, 383–389.
Yanes, Y., Romanek, C.S., 2013. Quaternary interglacial environmental stability in San Salvador Island (Bahamas): a land snail isotopic approach. Palaeogeogr. Palaeoclimatol. Palaeoecol. 369, 28–40.
Yanes, Y., Romanek, C.S., Delgado, A., Brant, H.A., Noakes, J.E., Alonso, M.R., Ibanez, M., 2009. Oxygen and carbon stable isotopes of modern land snail shells as environmental indicators from a low-latitude oceanic island. Geochim. Cosmochim. Acta 73, 4077–4099.
Yapp, C.J., 1979. Oxygen and carbon isotope measurements of land snail shell carbonate. Geochim. Cosmochim. Acta 43, 629–633.
Yen, T.C., 1939. Die Chinesischen Land-und Süsswasser Gastropoden des Natur-Museums Senckenberg. Abhandlumgen der Senckenbergischen Naturforschenden Gesellschaft, vol. 444, pp. 235.
Yen, T.C., 1943. Review and summary of Tertiary and Quaternary non-marine mollusks of China. Proc. Acad. Nat. Sci. Philadelphia 95, 267–309.
Yu, W., Wang, H.J., Li, Z.S., 1963. Gastropod Fossils in China. Science Press, Beijing, pp. 361 (in Chinese with English abstract).
Zaarur, S., Olack, G., Affek, H.P., 2011. Paleo-environmental implication of clumped isotopes in land snail shells. Geochim. Cosmochim. Acta 75, 6859–6869.
Zanchetta, G., Leone, G., Fallick, A.E., Bonadonnaa, F.P., 2005. Oxygen isotope composition of living land snail shells: data from Italy. Palaeogeogr. Palaeoclimatol. Palaeoecol. 223, 20–33.