Pliocene land snail record from western Chinese Loess Plateau and implications for impacts of the summer insolation gradient between middle and low latitudes on the East Asian summer monsoon

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A R T I C L E   I N F O
Article history:
Received 3 October 2009
Accepted 16 April 2010
Available online 28 April 2010

Keywords:
terrestrial mollusk
loess–palaeosol sequence
East Asian monsoon
insolation gradient
Pliocene

A B S T R A C T
The East Asian monsoon probably existed as early as at the Palaeogene/Neogene boundary. However, its evolutionary process is still less well known owing mainly to the lack of long, continuous palaeoenvironmental records. The recently reported Miocene (22–6.2 Ma) and late Miocene–Pliocene (7.1–3.5 Ma) loess–palaeosol sequences from the western Chinese Loess Plateau (CLP) provide new insights into the evolution of the monsoon system. However, reports on the bioclimatic indicators from these deposits and the subsequent reconstruction of the palaeomonsoon are rare. Here we present a Pliocene terrestrial mollusk record from the western CLP and discuss the possible impact of isolation gradients on the East Asian summer monsoon. Our results show that most peak values of the dominant thermo-humidiphilous mollusk taxa, Metodontia and Punctum, a proxy of the East Asian summer monsoon, approximately correspond to maxima of mean summer insolation-gradient variations between middle and low latitudes over this geological period, providing further evidence for such a causal relationship. Mean summer insolation gradient between middle and low latitudes could influence atmospheric circulation (in the present condition the East Asian summer monsoon). Any elevated mean summer insolation gradients between middle and low latitudes would have intensified the East Asian summer monsoon and the flux of moisture and heat over the oceans to the interior region including the CLP, creating favorable conditions for the expansion of the mollusk fauna. As such, the mollusk record from the loess–palaeosol deposits in the western CLP provides evidence for insolation-gradient impacts on the development of the East Asian monsoon system in the Pliocene.

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1. Introduction

Since the early 1980s, many lines of evidence have been obtained to suggest that the East Asian monsoon was probably established as early as at the Palaeogene/Neogene boundary, i.e., the Oligocene/Miocene boundary (Zhou, 1982; Wang, 1990; Liu and Guo, 1997; Sun and Wang, 2005). However, the evolutionary process and possible driving forces remain less well understood due largely to the lack of long, continuous palaeoenvironmental records. Miocene (22–6.2 Ma) and late Miocene–Pliocene (7.1–3.5 Ma) loess–palaeosol deposits were recently reported from the western Chinese Loess Plateau (CLP) (Guo et al., 2002; Hao and Guo, 2004). These Neogene deposits are of eolian origin and can stratigraphically be correlated across the region, providing further evidence supporting that the onset of the East Asian monsoon took place no later than the early Miocene (Guo et al., 2002; Hao and Guo, 2004; Liu et al., 2005, 2006; Li et al., 2006a,b; Qiao et al., 2006; Hao and Guo, 2007; Guo et al., 2008). The subsequent numerous studies on them have provided new insights into the evolution of the East Asian monsoon and possible forcing factors. Although studies on sedimentology, geomagnetism, and geochemistry of these sequences have contributed greatly to our understanding of the palaeomonsoon variability at a tectonic scale (Guo et al., 2002; Qiao et al., 2006; Hao et al., 2008a,b; Liang et al., 2009), the evolution of the palaeomonsoon and possible forcing factors at an orbital time scale remain poorly understood. Furthermore, palaeomonsoon reconstruction using bioclimatic indicators from these deposits has rarely been reported.

Fossil land snails are the most common and abundant fossil remains in the eolian deposits in the CLP. They are very sensitive to environmental changes and have long been used as ‘indicator animals’ in palaeo-climatic studies (Liu, 1985). Mollusk fossils have provided important clues for understanding of the origin of the Quaternary loess–palaeosol deposits and for the palaeoenvironmental
reconstructions (Braun, 1847; Richthofen, 1882; Liu, 1985; Wu et al., 1996; Rousseau and Wu, 1997, 1999; Wu et al., 2000, 2001, 2002, 2007). Recently, such fossil records have been used to obtain the key biological evidence for a wind-blown origin of the Miocene–Pliocene loess deposits on the western CLP (Li et al., 2006a,b). However, little study has been conducted on the development of the Neogene palaeomonsoon as reflected by the terrestrial mollusks.

In the present study, terrestrial mollusks preserved in the upper part of the Dongwan section on the western CLP were collected and examined for a better understanding of the East Asian summer monsoon at an orbital time scale and the possible driving factors in the Pliocene. Our study shows that a causal link probably exists between the summer monsoon system and the mean summer insolation gradient between middle and low latitudes and the 35°N insolation during the Pliocene.

2. Geological settings and methods

The Dongwan loess–palaeosol section used in this study is located at 105°47′E, 34°58′N in Qinan County on the western CLP (Fig. 1). This is a semi-arid region with a mean annual precipitation of 400 mm and a mean annual temperature of 10.4 °C with a July mean temperature of 22.7 °C (cf. Guo et al., 2002). In summer, the East Asian summer monsoon carries warm, moist air mass to the CLP, bringing heavy rainfalls across this region. Accordingly, more than half of the annual precipitation occurs in July to September. In winter, the winter monsoon winds from the Siberian High prevail over the CLP, resulting in a dry, cold climate.

The Dongwan loess section, which is 73.7 m thick, is exposed in a northeast-aligned, deep and narrow valley at an elevation of about 1880 m above sea level. This section contains 84 distinguishable loess–palaeosol couplets. Hao and Guo (2004) had established, based on 319 oriented samples collected at 20, 25 cm intervals, the chronology of the Dongwan section using palaeomagnetic reversals as age controls and then interpolation based on the susceptibility model developed by Kukla et al. (1990). With a reasonable assumption that the precipitation of natural magnetic dust from higher atmospheric levels occurs at a quasi-constant rate, this model weighted the thickness of each measured layer by its magnetic susceptibility, took into account of the accumulated values, and then calculated the apparent age of a given level by linear interpolation of the weighted values between palaeomagnetic reversals (Kukla et al., 1990). The time series based on this model correlates well with those of the deep sea oxygen isotope records. Although some assumptions used in this model are debated by some on the basis of rock magnetism, such a model has remained as an important method in obtaining an independent time scale for the loess–palaeosol succession and has been widely used in the research of the Quaternary loess and late Neogene Red Clay deposits (Kukla et al., 1990; Guo et al., 2000; Wu et al., 2001; Guo et al., 2001, 2002; Wei and Guo, 2003). This age model returned a geochronology for the Dongwan loess–palaeosol succession ranging from 7.1 to 3.5 Ma (Hao and Guo, 2004). The upper part of this succession used for this study spans from 5.1 to 3.5 Ma, and the calculated linear sedimentation rates for this part of section are 0.90 to 4.44 cm/ka (Hao and Guo, 2004). The sampling intervals of 10 to 40 cm thus correspond to a rough temporal resolution of 4.7 to 13 ka.

The upper 31.4 m of the section, corresponding to the time span of 5.1 to 3.5 Ma as already mentioned, was examined and sampled for the present study. A total of 152 samples each weighting about 30 kg were collected at an interval of 20 cm. Where prominent lithological changes exist, sampling took place between 10 and 40 cm at several locations. To reduce the cost on transportation of such a large amount of material, the samples were processed in the field. Because of the lithification or semi-lithification of the loess and soil layers, the regular washing and sieving for unconsolidated Quaternary deposits

Fig. 1. Map showing location of the Dongwan loess sequence and the studied area.
3. Results

Mollusk fossils are abundant through the Dongwan section, and they all are terrestrial taxa with excellent preservation conditions, containing both adults and juveniles (Li et al., 2006a). Of the 152 samples collected from the upper 31.4 m of the Dongwan section, 147 contain fossil mollusks, yielding a total of 9504 individuals with an average of over 64 shells per sample. Only 5 samples were found barren. The maximum count reaches 440/30 kg at 10.8 m depth. Of the 22 mollusk species identified (Fig. 2), 21 have been found in the Chinese Quaternary loess–paleosol deposits, and most have their modern representatives. Thus, the mollusk species in the upper part of the Dongwan section can be grouped into cold-aridiphilous (species living in dry and relatively cold places) and thermo-humidiphilous (warmth and moisture-loving species) ecological groups, as previously defined in the Quaternary loess–paleosol sequences (e.g., Liu, 1985; Wu et al., 1996; Rousseau and Wu, 1997, 1999; Rousseau et al., 2000; Wu et al., 2000, 2001, 2002, 2006, 2007). The thermo-humidiphilous group includes species belonging to genera of Metodontia huaiensis, Cathaica pulveraticula, Cathaica schensiensis, Cathaica placenta, Pupilla aeoli, Pupilla sp., Vallonia sp., and Pupopsis retrodens. They were mainly found at depths ranging from 0 to 17 m with a heterogeneous and discontinuous occurrence except Cathaica sp. (Fig. 2). It has long been suggested that the occurrence of these snails is closely related to a strong winter monsoon over the CLP (Wu et al., 1996; Rousseau and Wu, 1997, 1999; Rousseau et al., 2000; Wu et al., 2000, 2001, 2002, 2006, 2007).

Fig. 3 shows changes in the sum of Metodontia and Punctum, the two dominant thermo-humidiphilous taxa in the Dongwan section. They predominate in the early Pliocene from 5.1 to 4.0 Ma, suggesting the prevalence of warm, moist conditions under a strong summer monsoon during this geological episode. There are 36 to 39 high or low peaks in the abundance of the two taxa through the section from 5.1 to 3.5 Ma, indicating changes on orbital bands, among which 32 to 35 peak values can be correlated with the oscillations of the obliquity and mean summer insolation gradient between middle and low latitudes (35°-0°N), high percentages approximately corresponding to maxima in both obliquity and insolation gradient between middle and low latitudes, suggesting a possible causal link between the summer monsoon and the insolation gradient. In addition, more than 20 peaks of these two mollusk genera match the maximum values of the 35°N insolation, indicating that local insolation may also have played a role in the expansion of the mollusk fauna (Fig. 3).

Spectrum analysis of the sum of Metodontia and Punctum shows that the variations lie within the orbital frequency, concentrated on obliquity and precession bands although another frequency at 29 ka is also noticeable (Fig. 4A), similar to the oscillations of the mean summer insolation gradient between middle and low latitudes that concentrated in obliquity (41 ka) and precession (23 and 19 ka) frequencies over this geological period (Fig. 4B), indicating again that, on the obliquity band, insolation gradient between middle and low latitude is an important factor contributing to the evolution of the East Asian summer monsoon during the early Pliocene, whereas local insolation or/and insolation gradient between middle and low latitude may both exert controls on the evolution of monsoon on the precession band. However, it is noteworthy that the sample thickness of 20 cm in the present study is not detailed enough to discuss the precession variations and higher density sampling is not possible. Instead, the samples were progressively broken into particles of about 0.5 mm size and the snails and any visible shell fragments picked up. This was a slow and painstaking procedure that involved in a large amount of work in the field, and only half to one sample was processed by one worker in one day. In the laboratory, the mollusk remains were repaired, identified and counted under a set of Leica binocular microscopes. The shell fragments were considered in the total count of individuals following the method developed by Puisségur (1976).
needed in the future in order to detect this frequency. In fact, it is possible that a record with increased temporal resolution would show that the spectral density at the precession band might exceed that at the obliquity band. However, the spectral analysis of the magnetic susceptibility record at 20 cm sampling interval from the Dongwan loess–palaeosol sequence indicates 57 ka and 34 ka frequencies, as well as mean summer insolation at 35°N. Obliquity and insolation data are from Laskar et al. (2004).

4. Discussion

The CLP is located in a middle-latitude region where the East Asian winter and summer monsoons prevail, causing this region very sensitive to changes in both the high and low latitudes in the Northern Hemisphere. The winter monsoon carries cold, dry air from the high latitude, whereas summer monsoon brings warm, moist air over the low-latitude oceans into this region. Therefore, the thick eolian deposits in the CLP have great potentials of preserving the footprints of these two monsoons since the early Miocene (Liu, 1985; An et al., 2001; Guo et al., 2002; Hao and Guo, 2004). In the present study, the focus is placed on the development of the summer monsoon over the Pliocene warm period.

The mollusk record appears to suggest that the mean summer insolation gradient between middle and low latitudes has played an important role in shaping the East Asian summer monsoon at an orbital time scale. Obliquity is an important factor in controlling the latitudinal distribution of insolation (Berger, 1984). When this factor is large, the summer insolation increases at middle latitudes and decreases at low latitudes, strengthening the meridional mean summer insolation gradient. Meridional insolation gradients can exert controls on the atmospheric circulation (Berger, 1976; Young and Bradley, 1984; Johnson, 1991). Elevated such mean summer insolation gradients raises the air pressure gradient from low to middle latitudes and enhances the summer monsoon circulation, amplifying the moisture and heat transport over the low-latitude oceans to the middle-latitude CLP. In addition, local insolation is also an important factor impacting the East Asian summer monsoon as indicated by correlations between the two thermo-humidiphilous mollusk genera and the maximum values of the 35°N insolation. Therefore, both effects, increases of insolation gradient between middle and low latitudes and local insolation, remains as the likely driving forces behind the intensified summer monsoon and the expansion of thermo-humidiphilous mollusks during the Pliocene. A similar mechanism has also been proposed for the development of the late Quaternary East Asian summer monsoon on the basis of thermo-humidiphilous terrestrial mollusks in the CLP (Chen and Wu, 2008; Rousseau et al., 2009). However, in the present paper we cannot give any evidence supporting that which factor, local insolation or insolation gradient, is more predominant on the precession bands at the present temporal resolution. Higher resolution studies are needed to focus on this issue.

The idea that insolation gradients can influence the climate at an orbital time scale has long been proposed. Early in the 1960s, Kutzbach et al. (1968) argued that changes in insolation gradient are
great enough to impact climate. Later, Young and Bradley (1984) suggested that the hemispheric insolation gradients have played an important role in driving the global atmospheric circulation during the past 150 ka, and may have modulated the transport of moisture to high latitudes. Similarly, Johnson (1991) concluded that changes in insolation gradient can greatly amplify and alter the climatic effects of insolation variations. Recently, Raymo and Nisancioglu (2003) suggested that variations in the mean summer insolation gradient between high and low latitudes may exert a dominant control on the high-latitude climate between 3 and 0.8 Ma. However, little is known from the pre-Pleistocene geological archives. The Pliocene terrestrial mollusk record from the western CLP suggests a possible causal link between the East Asian summer monsoon and the insolation gradient between middle and low latitudes. An increased such meridional mean summer insolation gradient strengthened the atmospheric circulation including the East Asian summer monsoon (Trenberth and Caron, 2001) and amplified the moisture and heat transport to the middle-latitude regions including CLP, triggering the rapid expansion of the warmth- and moisture-loving mollusk taxa in the studied region during the Pliocene. Our study on the Pliocene mollusk fauna thus provides further evidence for insolation-gradient impacts on the development of the monsoon system at an orbital time scale. It should be pointed out that, although the growth and development of the Pliocene thermo-humidiphilous mollusks in the CLP was clearly related to the insolation gradient between middle and low latitudes and the local insolation, other possible influences cannot be excluded, such as the insolation gradient between high and low latitudes which may exert a dominant control on high-latitude atmospheric meridional transport of moisture and heat (Raymo and Nisancioglu, 2003), and thus may also have probable moisture input to the middle-latitude regions.

Apart from the insolation gradients and local insolation, another factor also probably played an active role in the development of the East Asian summer monsoon in the Pliocene. The closure of the Panama and Indonesian seaways changed the heat distribution in the Pacific and Atlantic, causing reorganization of the global climate patterns (e.g., Haug and Tiedemann, 1998; Cane and Molnar, 2001). For instance, this event altered the atmospheric moisture flux from a latitudinal to meridional transport, resulting in an increase in moisture at middle and high latitudes (Young and Bradley, 1984; Raymo and Nisancioglu, 2003). The closure of these seaways probably strengthened and enlarged the western Pacific warm pool, an important source of water vapor and latent heat for the higher latitudes (Maier-Reimer et al., 1990; Yan et al., 1992; Mikolajewicz et al., 1993; Mikolajewicz and Crowley, 1997; Haug and Tiedemann, 1998; Chaissen and Ravelo, 2000; Li et al., 2004). As such, an enlarged warm pool would have resulted in a strengthened summer monsoon and, subsequently, increased precipitations over the CLP, creating favorable conditions for the thermo-humidiphilous mollusk fauna.

It has been suggested that prior to 2.75 Ma, the East Asian summer and winter monsoon indicators, i.e., magnetic susceptibility and grain size, respectively, are in phase with one another whereas after 2.75 Ma, the summer and winter monsoon indicators are out of phase with one another (Clemens et al., 2008). In our study, the cross spectral analysis of the thermo-humidiphilous mollusk time series relative to cold-aridiphilous time series shows that they are not in phase with one another from 5.1 Ma to 3.5 Ma at the obliquity bands, differing from the findings by Clemens et al. (2008). There may be at least two reasons for this difference. First, the result from the cross spectral analysis may contain some deviations because the cold-aridiphilous snails are not continuous in distribution in the section during the Pliocene warm period due probably to a weak winter monsoon during this period. Therefore, the cold-aridiphilous terrestrial mollusks are not suitable for cross spectral analysis. Second, climatic conditions inferred from different climatic proxy indicators, such as grain size, magnetic susceptibility, and terrestrial mollusks, may differ because of their different sensitivity to climate change. For instance, the grain size, a proxy of winter monsoon, shows a dominant 100 ka cycle and a weak 41 ka frequency during the late Pleistocene, similar to the cycle as reflected by lithologic characters in the loess–paleosol succession (Ding et al., 1995), whereas the cold-aridiphilous mollusk fossils, another winter monsoon proxy, shows a dominant 100 kyr and a strong 41 ka cycle in the past 350 ka (Wu et al., 2000, 2001).

5. Conclusions

The Pliocene terrestrial mollusk record from the western Chinese Loess Plateau (CLP) shows that thermo-humidiphilous taxa predominate during 5.1 to 3.5 Ma, indicating the prevalence of warm, moist conditions with intensified summer monsoons. The peak values of the sum of Metodontia and Punctum, the two typical thermo-humidiphilous mollusk taxa, correspond approximately to the maxima of the mean summer insolation gradient between middle and low latitudes and some maximum values of the 35°N insolation. Furthermore, the dominant orbital frequencies obtained from these two warmth- and moisture-loving taxa match those obtained from the meridional mean summer insolation-gradient variability, thus suggesting a possible causal link between the summer monsoon and the insolation gradient. The mean summer insolation gradient exerts controls on atmospheric circulations of the summer monsoon and, subsequently, the moisture and heat transport to the CLP located at middle-latitude regions, thus affecting the expansion or shrinkage of the thermo-humidiphilous mollusk fauna in this region. Spectrum analysis of the faunal record suggests that local insolation may be also important for the faunal abundance and the development of the summer monsoon during the Pliocene. As such, the mollusk record from the Pliocene loess–paleosol deposits in the western CLP not only provides further evidence for insolation-gradient impacts on the evolution of the East Asian monsoon in the Pliocene, extending the validity of the insolation-gradient hypothesis on orbital time scales to the early Pliocene, but also may provide an impetus for model tests of the relationship between the East Asian monsoon and insolation gradient.

Acknowledgements

This study is supported by the Chinese Academy of Sciences (KZCX2-YW-117), the National Natural Science Foundation of China (Projects 40730104, 40972119, and 40702030), the president excellent prize of Chinese Academy of Sciences, and China Postdoctoral Science Foundation (200801110 and 20070420066). Drs. Qingzhao Hao and Yunpeng Pei provided valuable field assistance and spectral analysis. The cross spectral analysis and calculation of the insolation were conducted by Drs. Guangshan Chen and Li Qin, respectively. Suggestions and comments by Drs. Steven Clemens and Slobodan Markovic greatly improved the quality of the manuscript. Special thanks go to Dr. George Gao from the Ontario Geological Survey for careful improvement of English. Useful discussion was also made with Dr. Denis-Didier Rousseau.

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