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# 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

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ABSTRACT

More and more evidence indicates that the onset of the East Asian (EA) monsoon can be traced back to the Oligocene–Miocene boundary (at about 23 Ma). However, the process of its evolution is still less well-known until now. Here we investigate its late Neogene evolution by analyzing a terrestrial mollusk sequence, from the Chinese Loess Plateau (CLP), covering the period between 7.1 and 3.5 Ma. Considering the modern ecological requirements of these organisms, we were able to define two groups of cold-aridiphilous (CA) and thermo-humidiphilous (TH) species, representing the EA winter and summer monsoon variations, respectively, as previously defined in the Quaternary glacial–interglacial cycles. Variations in these two groups indicate two different monsoon dominated periods during 7.1–3.5 Ma. First, between 7.1 and 5.5 Ma, the EA winter monsoon, with a 100-kyr periodicity, was dominant. Second, between 5.1 and 4 Ma, the EA summer monsoon dominated, with a 41-kyr periodicity. Furthermore, our mollusk record yields valuable evidence for a late Miocene–Pliocene transition of about 400 kyr from winter monsoon dominated towards summer monsoon dominated, associated with a periodicity transition from weak 100 kyr to 41 kyr. The strengthened winter monsoon interval, with a 100-kyr periodicity, is coeval with orbital-scale global ice-volume changes, in conjunction with the uplift of the Tibetan Plateau which probably reinforced the winter monsoon sub-regime. Conversely, closures of the Panama and Indonesian seaways, associated with changes in obliquity between 5.1 and 4 Ma, are probably major forcing factors for the observed dominant summer monsoon with 41-kyr frequency, favoring heat and moisture transports between low and high latitudes to allow TH mollusks to grow and develop in the CLP.

## 1. Introduction

Since the warm phase of the mid-Miocene climatic optimum, marine benthic foraminiferal $\delta^{18}O$ indicates a general cooling trend punctuated by numerous events such as the expansions of the East Antarctic ice sheet, followed later by the development of its western counterpart, the occurrence of glaciers or ice caps in the Northern Hemisphere from late Miocene and large expansion by about 3.6 Ma, and the closures of the Panama and Indonesian seaways, preceded by uplifts of both Tibetan and Colorado Plateaus (e.g., Zachos et al., 2001). All these events strongly impacted the climatic variations including the Asian monsoon towards the better known Quaternary oscillations. However, although some sedimentological and geochemical studies focused on the evolution of the East Asian (EA) monsoon and its possible correlation with these above events during the time interval preceding the settlement of the major Northern Hemisphere ice sheets (e.g., Sun et al., 1998; Ding et al., 1998; An et al., 2001; Guo et al., 2004), it is still necessary to further investigate and characterize this issue and complement its characterization, especially through various approaches including biological analyses.

The Chinese Loess Plateau (CLP) is a key continental region for reconstructing the EA monsoon variations. This region is located in the middle latitudes of the Northern Hemisphere, in a climatic zone presently characterized by seasonal alternations of the EA summer and winter monsoon sub-regimes. In the summer, the EA summer monsoon carries warm, moist air masses towards the Loess Plateau from tropical low-latitude areas, causing heavy rainfall. In the winter, the winter monsoon winds from the Siberian High of the high latitudes prevail, resulting in dry, cold climate conditions. The well-known loess–paleosol sequences of the past 2.6 Ma here yield valuable information about the Quaternary EA monsoon evolution (e.g., Liu, 1985). The Red Clay sequences underlying the loess–paleosol sequences have great potential for deciphering late Neogene evolution of the EA monsoon. Paleomagnetic measurements date their lower boundary in the eastern CLP to about 7–8 Ma (Sun et al., 1998; Ding et al., 1998). In the western

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CLP, however, the time coverage of loess–paleosol sequences is significantly different from the east. The basal age of these sequences is dated to early Miocene, about 22 Ma, at the QA-I sequence (Guo et al., 2002), and the upper limit is about 3.5 Ma at the Dongwan sequence (Hao and Guo, 2004). Thus, the Neogene loess–paleosol sequences in the western CLP cover the time interval of 22–3.5 Ma. These records are particularly valuable and informative because they show clear alternations between loess and paleosol units, preserve terrestrial proxies of past climate, and may thus record orbital-scale variations of the EA monsoon (Guo et al., 2002; Hao and Guo, 2004). In this study, we analyze terrestrial mollusks from the Dongwan loess–paleosol sequence in the western CLP with objectives to investigate the orbital-scale evolution of the EA monsoon during the late Miocene–Pliocene and the possible driving factors of these changes.

## 2. Materials and methods

Among all the investigated late Miocene–Pliocene eolian series in the CLP, the studied Dongwan loess–paleosol sequence (105°47′E, 34°58′N) (Hao and Guo, 2004) (Fig. 1) is the first one from the western CLP. It is located about 30 km east of the Miocene eolian sequences (QA-I) (Guo et al., 2002) (Fig. 1). It is exposed on the slope of a narrow valley with high-elongated hilly flanks that extend northeastward at an elevation of about 1880 m above sea level. This section is about 73.7 m thick, and composed of 84 distinguishable loess–paleosol couplets. The time series of the Dongwan section was established by Hao and Guo (2004) using paleomagnetic reversals as age controls and then interpolation based on the susceptibility model (Kukla et al., 1990), yielding an age ranging from 7.1 to 3.5 Ma ago (Fig. 2). Although some assumptions of the model are partly debated by rock magnetism studies, it remains valid to obtain an independent time scale for Chinese loess (Kukla et al., 1990), having been extensively applied to numerous studies of Quaternary loess and late Neogene Red Clay sequences (e.g., Guo et al., 2000, 2001, 2002; Wu et al., 2001; Wei and Guo, 2003). The average linear sedimentation rate of the Dongwan section is 2.09 cm/kyr (Hao and Guo, 2004). Thus, the sampling thickness of 20 cm corresponds to a rough temporal resolution of 9.6 kyr.

A total of 310 mollusk fossil assemblages were collected using a 20-cm sampling thickness, except some parts where it varied between 10 and 50 cm according to the lithological changes. Each sample weighs about 30 kg. In the field, we broke all samples progressively into small pieces of about 0.5 mm in diameter, collecting all available individual shells and visible broken pieces. In the laboratory, all the identifiable mollusk

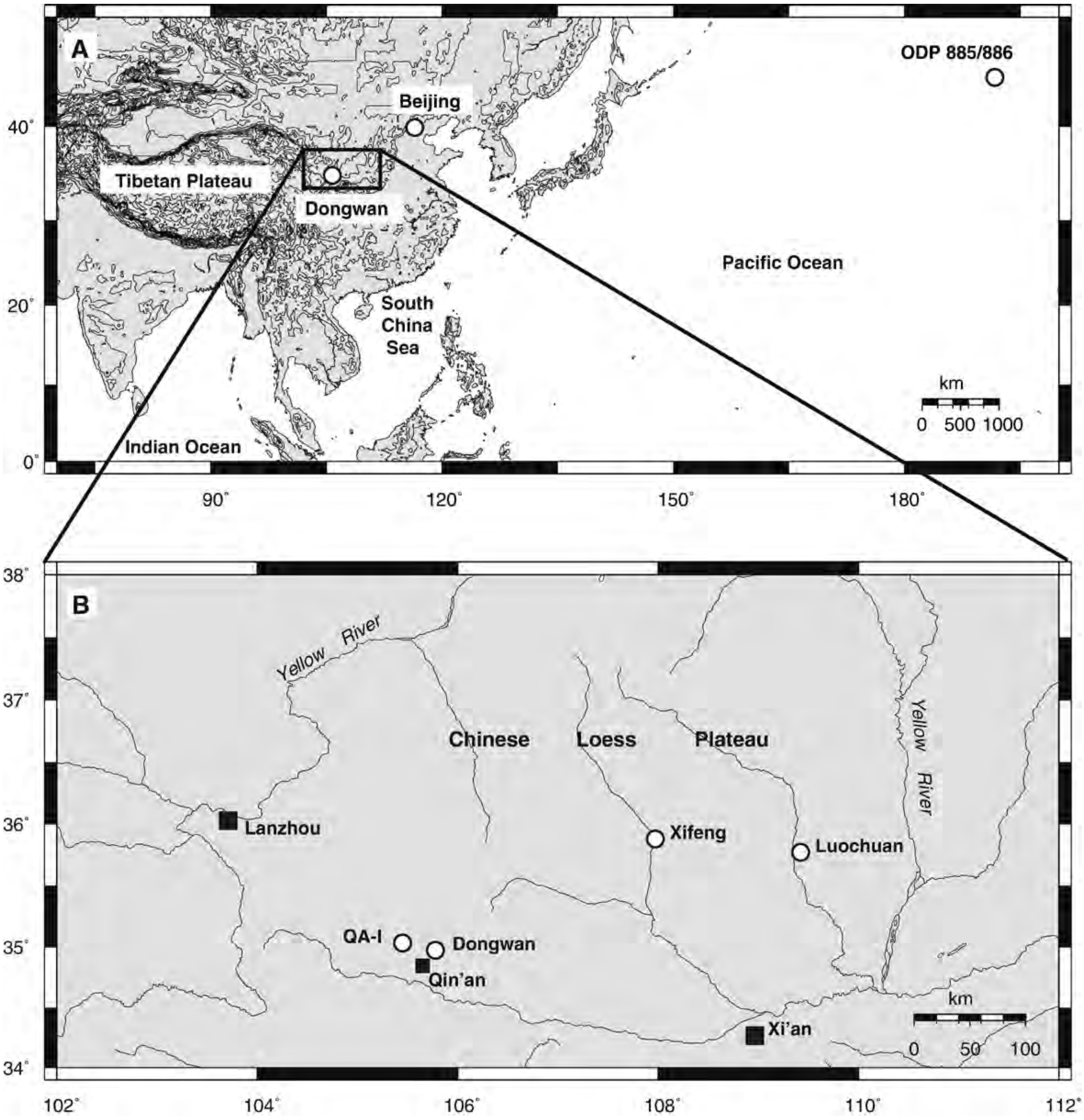

**Fig. 1.** Location of the Dongwan loess sequence. A. Map showing the study area in Asia. B. Location of the Dongwan section, other sections mentioned in the text (white circles), and main cities (black squares) in the Chinese Loess Plateau (CLP).

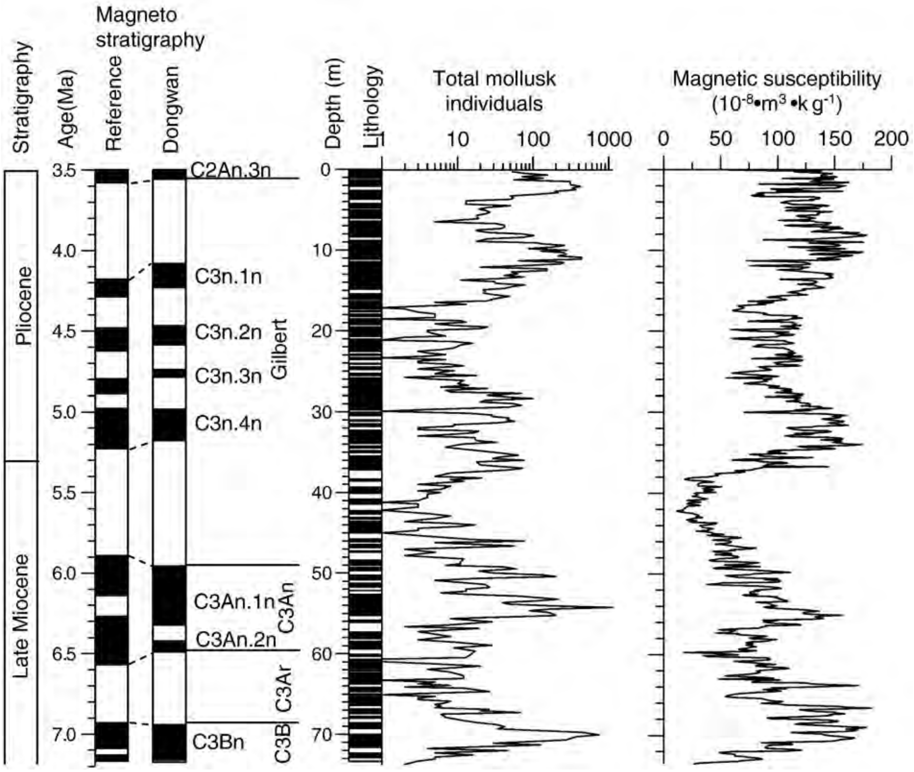

**Fig. 2.** The Dongwan loess–paleosol sequence. From left to right, stratigraphy, correlation of Dongwan with the reference (Cande and Kent, 1995) magnetostratigraphies (Hao and Guo, 2004), lithology showing the alternation of paleosols (black) and loess (white) units, total mollusk individuals (this study) and magnetic susceptibility (Hao and Guo, 2004).

remains were further repaired and considered in the total count of individuals following the method developed by Puisségur (1976). The mollusk time series was interpolated to a constant 1-kyr interval before spectral analysis. Maximum entropy spectral analysis and band-pass filter were performed using the PPPHALOS software (Guiot and Goeury, 1996).

## 3. Results

Mollusk fossils are abundant in the Dongwan sequence. All mollusk fossil shells show an excellent preservation, well dispersed in the section and furthermore showing both adults and juveniles (Li et al., 2006). The maximum count reaches 1121/30 kg at 54 m depth (Fig. 2). The variation in total mollusk individuals parallels the fluctuations of the low field magnetic susceptibility (MS) values (Fig. 2). This indicates that the post-pedogenic processes, such as carbonate dissolution, did not affect the mollusk assemblages preserved (Li et al., 2006). Thus, mollusk assemblages in the late Miocene–Pliocene loess–paleosol sequence are assumed to record original ecological conditions.

Twenty-four mollusk species have been identified in the Dongwan section and have been previously described by Li et al. (2006). Among these species, 22 have been identified in the Chinese Quaternary loess–paleosol sequences, and most have modern representatives. Thus, the mollusk species in the loess and paleosol layers of the Dongwan section can be grouped within the same cold-aridiphilous (CA) and thermo-humidiphilous (TH) ecological groups as previously defined in the Quaternary glacial–interglacial cycles (e.g., Liu, 1985; Rousseau and Wu, 1997, 1999; Wu et al., 1996, 2000, 2001, 2002, 2006, 2007; Rousseau et al., 2000), both representing distinctly different climatic and environmental conditions. The CA group includes species living in dry and relatively cold places. Conversely, the TH group gathers warmth and moisture loving species. Their occurrences in the studied sequence imply the impact of winter and summer monsoon on that location of the CLP, respectively (Rousseau and Wu, 1997, 1999; Wu et al., 1996, 2000, 2001, 2002, 2006, 2007; Rousseau et al., 2000).

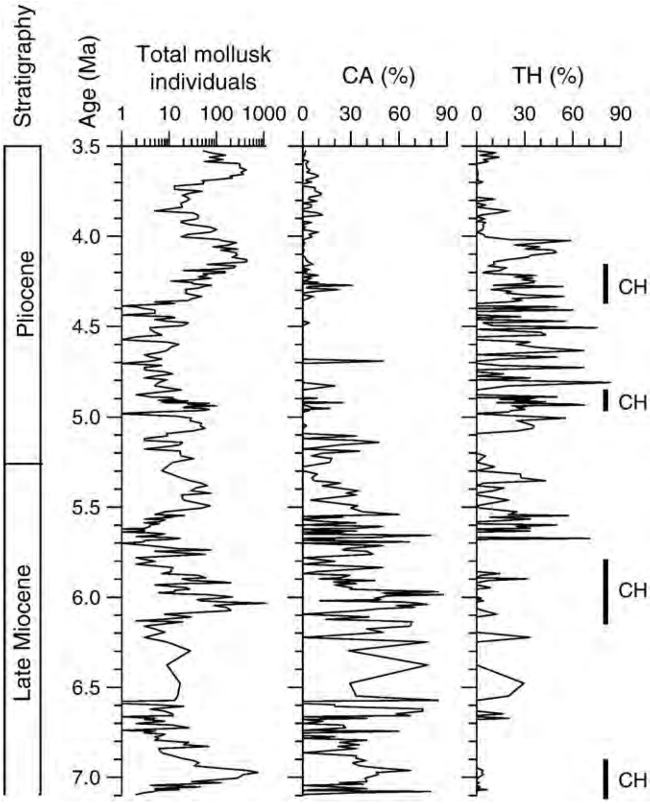

**Fig. 3.** Variations of terrestrial mollusk record during the late Miocene to Pliocene in the Dongwan loess sequence. From left to right, total mollusk individuals, percentages of cold-aridiphilous (CA) mollusk group, and thermo-humidiphilous (TH) mollusk group. Vertical lines labeled CH characterize the occurrence of cool-humidiphilous species.

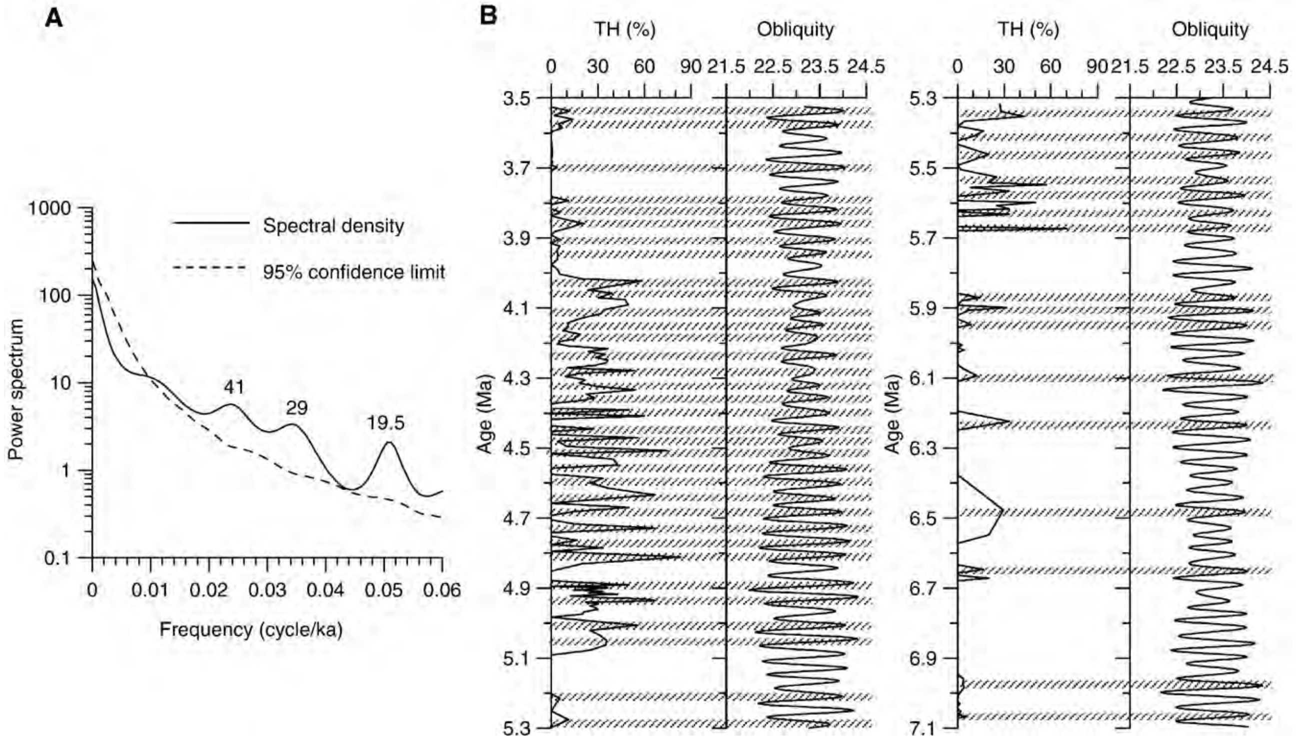

**Fig. 4.** Time series of thermo-humidiphilous (TH) mollusk percentages in the Dongwan loess sequence. A. Spectral analysis using the Maximum Entropy method. B. Variations in thermo-humidiphilous mollusks compared with obliquity (Laskar, 1990). Maximum entropy spectral analysis was performed using the PPPHALOS software (Guiot and Goeury, 1996).

Within the TH group, *Gastrocopta* prefers living in relatively cool and moister conditions (Wu et al., 2007), and has been abundantly found in the gullies of Luochuan and Xifeng, where moisture is higher. Thus, in this study, we subdivided it into another group named cool-humidiphilous (CH) species. Its distribution in the section is not continuous. It is strongly concentrated around the depths of about 10 m, 30 m, 50 m, and 70 m with about 1-Myr rhythmicity (Fig. 3). Consequently, the changes in this species are not at orbital time scales and will be reported in detail elsewhere.

Variations in CA and TH mollusk species in the Dongwan sequence show that key climate changes occurred between 7.1 and 3.5 Ma in this particular area (Fig. 3). CA mollusk species are dominant in the

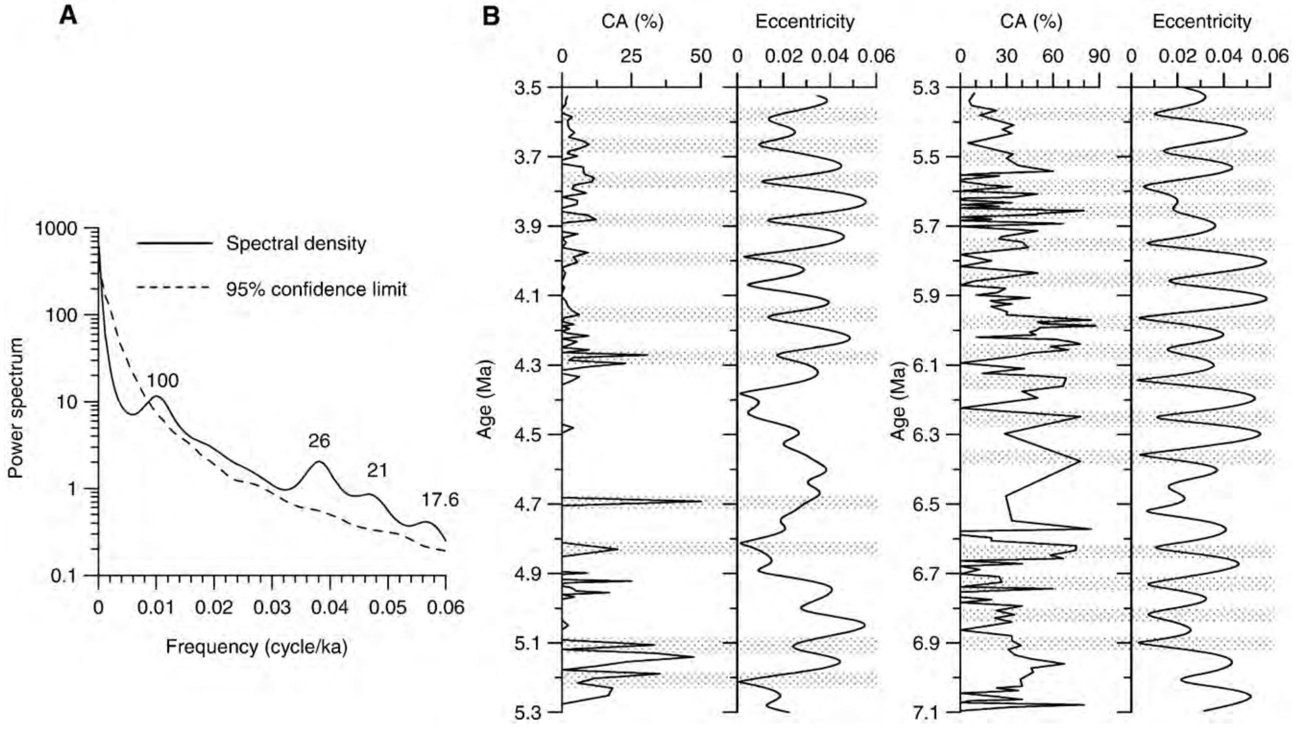

**Fig. 5.** Time series of cold-aridiphilous (CA) mollusk percentages in the Dongwan loess sequence. A. Spectral analysis using the Maximum Entropy method. B. Variations in cold-aridiphilous mollusks compared with eccentricity (Laskar, 1990). Maximum entropy spectral analysis was performed using the PPPHALOS software (Guiot and Goeury, 1996).

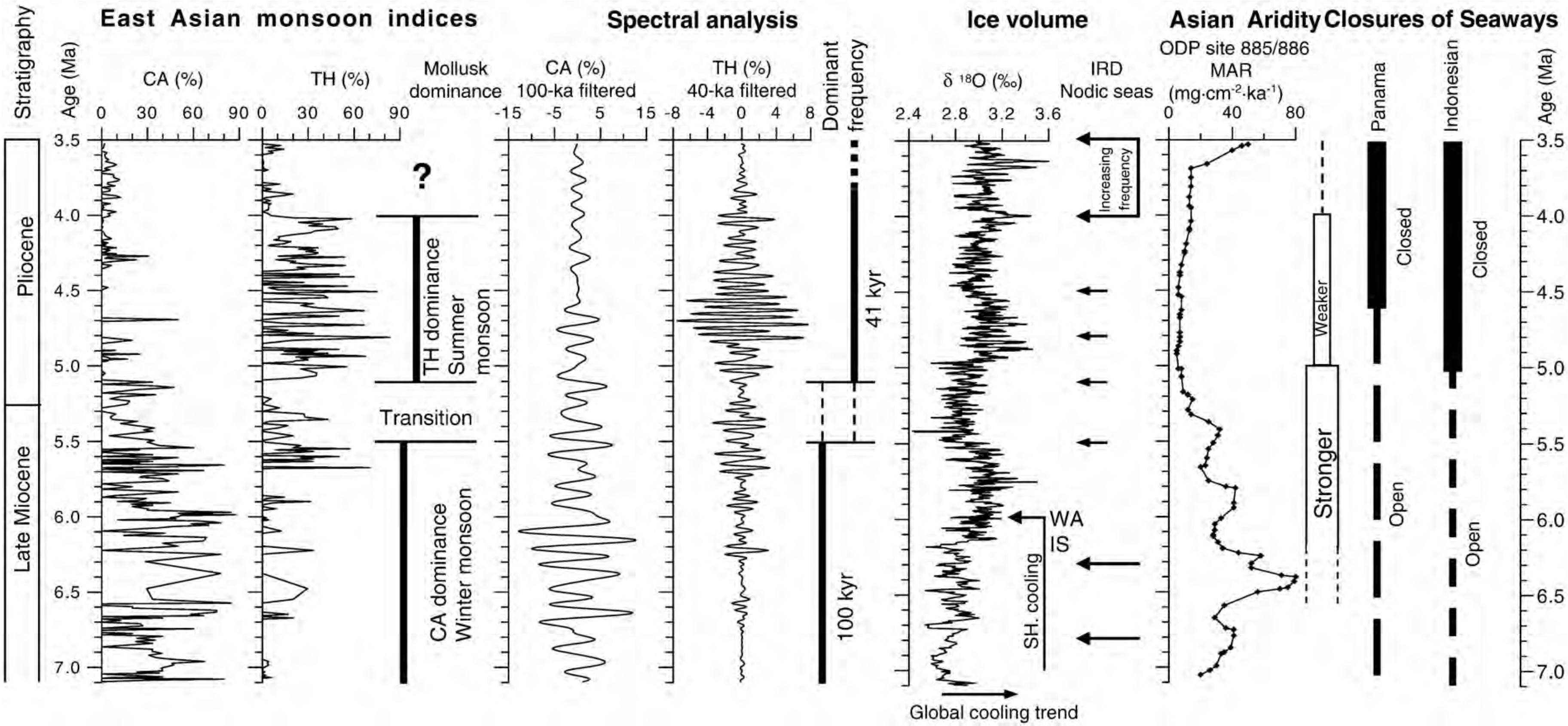

**Fig. 6.** Climate history of East Asian monsoon from the Dongwan sequence between 7.1 and 3.5 Ma. Changes and band-pass filtered curves of cold-aridiphilous (CA) and thermo-humidiphilous (TH) terrestrial mollusk records, ice volume deduced from benthic foraminiferal $\delta^{18}$O record (Zachos et al., 2001) with indication of West Antarctica ice sheet (WAIS) buildup, indication of main ice-rafted detritus (IRD) from Northern Hemisphere high latitude (Jansen and Sjøholm, 1991; deMenocal, 1993; Wolf-Welling et al., 1996; Thiede et al., 1998; St. John and Krissek, 2002), continental aridity inferred from mass accumulation rate of eolian dust at ODP Site 885/886 (Rea et al., 1998), and timing of Panama and Indonesian seaway closures (Haug and Tiedemann, 1998; Cane and Molnar, 2001). Band-pass filter was performed using the PPPHALOS software (Guiot and Goeury, 1996).

late Miocene, from 7.1 to 5.5 Ma, with the highest percentage close to 90%, indicating that cold, dry climate conditions prevailed during this period. Numerous fluctuations can be noticed in the changes in CA mollusks, and they are stronger between 7.1 and 6 Ma except in the time interval of about 6.5–6.4 Ma where the loose sampling interval may not provide detailed information. Conversely, TH species, less abundant before about 5.5 Ma, apart from a relatively high occurrence between 5.7 and 5.5 Ma, are rather dominant in the early Pliocene from 5.1 to 4.0 Ma. They show numerous high magnitude fluctuations indicating the prevalence of warm, wet climate conditions during this period. A transition from a CA dominated period towards a TH dominated one lasted about 400 kyr between 5.5 and 5.1 Ma.

In terms of frequency, the TH record is concentrated in the obliquity (41 kyr) and precession (19.5 kyr) bands, while another frequency at 29 kyr is noticed (Fig. 4A). TH variations appear to match with the oscillations of obliquity, high percentages of TH corresponding to maxima in tilt (Fig. 4B). CA signal conversely shows a power residing in the eccentricity band (100 kyr), precession band (21 and 17.6 kyr), and a frequency at 26 kyr (Fig. 5A). CA variations show maximum values corresponding to minima in eccentricity (Fig. 5B). However, we would like to point out that our sample resolution is far less enough to discuss the precession variation at present and higher resolution studies are needed in the future about this power. Thus, the studied interval reveals a particular result: while the 7.1- to 5.5-Ma interval appears to be dominated by 100-kyr eccentricity frequency, the 5.5- to 5.1-Ma interval shows a transition towards the younger interval of 5.1 to 4 Ma, which is dominated conversely by obliquity frequency (41 kyr) (Fig. 6).

## 4. Discussion

### *4.1. East Asian monsoon evolution during late Miocene–Pliocene inferred from terrestrial mollusk sequence*

As mentioned above, variations in the CA and TH groups reveal the processes of climatic changes and the evolution of the EA paleomonsoon sub-regimes during the late Miocene–Pliocene in the CLP. Two climatic patterns with different dominated periods can be distinctly witnessed during 7.1–3.5 Ma. First, during late Miocene between 7.1 and 5.5 Ma, the CA mollusk group is abundant, indicating dominance of a cold, dry climate and prevailing EA winter monsoon. Contemporaneous to the CA dominated interval is the enhancement of the continental aridity in the Asian inland. This is characterized by coarser eolian grain size in Red Clay sequence in the CLP and higher dust accumulation rate in eolian deposits in northwest Pacific, respectively (Rea et al., 1998; Guo et al., 2004) (Fig. 6). Moreover, the CA dominance is coincident with a global cooling trend deduced from the variation of the stacked benthic foraminiferal $\delta^{18}$O record for the same period (Zachos et al., 2001) (Fig. 6). Maximum entropy spectral analysis and band-pass filter of the CA record reveal dominance of 100-kyr periodicity during 7.1–5.5 Ma, especially during about 7–6 Ma. The higher percentages correspond to minima in eccentricity (Fig. 5B), showing CA variations with a strong eccentricity frequency, a similar scenario being noticed in late Quaternary CA mollusks in the CLP (Wu et al., 2001), however, in a different climate context.

It is noteworthy that the 100-kyr signal observed in the late Miocene mollusk record does not show any sawtooth shape like those occurred in the middle to late Pleistocene. The simultaneous marine benthic foraminiferal $\delta^{18}$O record compiled by Zachos et al. (2001) also lacks a sawtooth shape during the same period. This might be related to the variation in the Southern Hemisphere ice volumes, which is quite different from the status of two polar ice sheet developments during the Pleistocene. In addition, we cannot rule out other possible mechanisms for the late Miocene 100-kyr signal, such as clipping of one side of an eccentricity-modulated precession response. Another phenomenon is that the 41-kyr signal does not appear in the late Miocene CA mollusk group, but it is obvious in the late Pleistocene CA mollusk record (Wu et al., 2001). A similar result has been observed in benthic foraminiferal oxygen isotope record for the same interval (Zachos et al., 2001). We speculate that different ice-volume conditions in the Northern Hemisphere during the late Pleistocene and late Miocene could probably induce a different climate response mechanism in paleoenvironmental records.

Second, during the early Pliocene from 5.1 to 4.0 Ma, TH species show high percentages, and they almost replace CA species, characterizing a summer monsoon dominated interval. The dominant frequency at this period changes to 41 kyr, and high percentages of TH correspond to maxima in tilt (Fig. 4B), as mentioned above. Variations in the TH group approximately match the alternation of loess and paleosol layers. Each paleosol–loess couplet in the Dongwan section shows an average frequency of 42.6 kyr, considered to be attributed to variations in Earth's obliquity (Hao and Guo, 2004). The mean grain size and BiSiO$_2$ content in Lake Baikal revealed that obliquity-related frequency occurred in the Pliocene in the deep continental interior (Kashiwaya et al., 2003), although later than our record. This rhythm is consistent with a previous finding in the Pliocene benthic foraminiferal $\delta^{18}$O record (Shackleton et al., 1995). It should be noted that the 41-kyr frequency has been found in many Quaternary summer monsoon proxies such as TH mollusk group, magnetic susceptibility, and FeD/FeT ratio in the CLP (Wu et al., 2000, 2001; Guo et al., 2000; Wei and Guo, 2003; Chen and Wu, 2008), and in the tropical upwelling region of the South China Sea (e.g., Jian et al., 2001).

During an approximate 400-kyr transition period, between 5.5 and 5.1 Ma, the CA group markedly reduced but remained still relatively dominant compared with the TH group, except at about 5.3 Ma. The occurrence of this transition coincides with a fast and severe decrease in benthic foraminiferal $\delta^{18}$O record (Fig. 6), associated with a distinct increase in the total count of individuals which followed a decreasing trend between about 6.1 and 5.6 Ma (Fig. 3).

Therefore, our terrestrial mollusks recorded a transition characterized by a periodicity transition from 100-kyr to 41-kyr frequency in the western CLP, that is, from dominant winter monsoon to dominant summer monsoon, during late Miocene to early Pliocene. This is opposite to that observed during the Quaternary, in which the climatic signal shifted from 41-kyr dominant frequency towards 100 kyr at about 950 ka named mid-Pleistocene transition (MPT) (e.g., Prell, 1982; Berger et al., 1993). The shift observed between the two ecological groups in the Dongwan sequence approximately corresponds to the onset of Pliocene, and the shift towards warmer conditions has been observed in numerous terrestrial and marine records (e.g., Rea et al., 1998; Sun et al., 1998; Kashiwaya et al., 2001; Guo et al., 2004; Wang et al., 2003; Jian et al., 2003; Wu et al., 2006), indicating a global warming period. The terrestrial mollusk record from the Xifeng Red Clay sequence, for example, also indicates contemporaneous transition between an interval with predominant CA mollusk group and some meso-xerophilous species towards a period characterized by high values of TH group (Wu et al., 2006). The continental aridity, which is considered as driving the origin of loess material in north-central China and eolian deposits in northwest Pacific, became weaker during this time interval as indicated by a finer grain size in the CLP and a lower dust accumulation rate in northwest Pacific (Rea et al., 1998; Guo et al., 2004) (Fig. 6). This is further supported by a contemporaneous pollen record from northwest China, indicating a warm, humid assemblage with high percentages in *Quercus* and *Juglans* temperate deciduous trees, and even the occurrence of subtropical evergreen tree pollen of *Carya* as well as aquatic taxa of *Typha* and Cyperaceae (Sun et al., 2007).

### *4.2. Possible causes of mollusk succession and East Asian monsoon evolution during late Miocene–Pliocene*

As mentioned previously, high percentages of the Dongwan CA mollusk fossils during the 7.1 to 5.5 Ma indicate prevailing cold, arid climate conditions in the studied area. This parallels a global cooling trend indicated by the compiled benthic foraminiferal $\delta^{18}$O record (Zachos et al., 2001), the increase in ice-rafted detritus (IRD) flux in the Northern Hemisphere, and the buildup of the Western Antarctica ice sheet showing a weak 100-kyr frequency. This would imply that global cooling, including the buildup of ice in both the Northern Hemisphere and Antarctica, could have impacted or contributed to the global climate affecting then the EA winter monsoon and therefore permitting the development of CA mollusks in the CLP.

General circulation model experiments indicate that the wind regime in the middle and high latitudes is very sensitive to changes in high-latitude surface conditions especially in ice development (Manabe and Broccoli, 1985; Kutzbach and Wright, 1985; COHMAP, 1988). The extended ice sheets in the Northern Hemisphere can reinforce the southward movement of cold air and thereby enhance the Siberia High. This high pressure cell controls the EA winter monsoon wind system which is presently impacted by polar air surges (Chang et al., 2006). Thus, the CLP is particularly sensitive to high-latitude changes that affect the EA winter monsoon winds. However, climatic conditions were very different during the late Miocene and Quaternary and present day. In fact, numerous studies indicated that ice volume increased in the Northern Hemisphere during the late Miocene. IRD pulses have been noticed between 7.2 and 6 Ma with several relatively strong events around about 7.2, 6.8, and 6.3 Ma (Jansen and Sjøholm, 1991; deMenocal, 1993; Wolf-Welling et al., 1996; Thiede et al., 1998; St. John and Krissek, 2002) (Fig. 6). They even reached 51°N during 6- to 5-Ma interval (deMenocal, 1993). Prior to these findings, Mudle and Helgason (1983) had reported evidence for a cooling and the occurrence of possible mountain glaciations in the late Miocene in Iceland. All these lines of evidence support a further increase in Northern Hemispheric high-latitude cooling in the late Miocene, contributing to the presence of middle-sized glaciations in this area (e.g., Jansen and Sjøholm, 1991). Thus, a significant proportion of the variability observed in the late Miocene benthic foraminiferal $\delta^{18}$O record should be sought elsewhere.

Jansen and Sjøholm (1991) and Grutzner et al. (2003) suggested that Antarctic ice-volume changes could have impacted the global climate during this period. Indeed, in Antarctica, small ice masses were present in the Eocene, and initiation of large ice sheets took place at about the Eocene/Oligocene boundary at about 34 Ma. Further intensifications occurred in the middle Miocene and late Pliocene, indicated firstly by the building up of East Antarctic ice sheet (EAIS), and then by its western smaller counterpart (e.g., Zachos et al., 2001). Most importantly, the late Miocene witnessed ice sheet growth in Antarctica at orbital frequencies (Grutzner et al., 2003, 2005). Therefore, the increasing ice volume in both Antarctica and Northern Hemisphere high latitude may have modified the global climate, amplifying the EA winter monsoon regime characterized in Dongwan by the dominance of the CA mollusk species between 7.1 and 5.5 Ma. As reviewed above, cooling in the Northern Hemisphere can impact the EA winter monsoon by enhancing the Siberian High. However, the mechanism, if any, explaining how the Antarctic ice masses could influence the EA winter monsoon, cannot be addressed by the present study. A coincident observation that the EAIS underwent large size variations at orbital time scales during late Miocene (Grutzner et al., 2003, 2005) may support our speculation, but it still remains to be tested by climate models and more geological evidence.

Ice sheet influence on past climate observed between 7.1 and 5.5 Ma is not the only factor to be considered to interpret our results. Climate models suggest that the EA monsoon is closely linked to the uplift of the Himalaya and Tibetan Plateau (e.g., Kutzbach et al., 1989; Ruddiman and Kutzbach, 1990; An et al., 2001; Liu and Yin, 2002; Liu et al., 2003), whose effects on the EA winter monsoon are more significant than on the summer monsoon (Liu and Yin, 2002). Although the timing and height of the Tibetan Plateau uplift are still controversial, more evidence from both the interior of the Tibetan Plateau and surrounding basins indicates that large amplitude uplift occurred at about 8 Ma (e.g., Harrison et al., 1992; An et al., 2001; Clark et al., 2005). More recent studies of a detailed late Miocene and younger magnetostratigraphy by Fang et al. (2005) place much improved time constraints on the deformation and, hence, uplift of northeastern Tibet, which is the part located nearest the CLP, at about 8 Ma. Such tectonic activity was not only thought to trigger the enhancement of the EA monsoon, but also considered to be driving factors of general cooling through the consequential increase in the chemical weathering rate, thus accelerating ice expansion in Northern Hemisphere high latitudes (Raymo et al., 1988; Ruddiman and Kutzbach, 1990; Raymo and Ruddiman, 1992) and further favoring the strengthening of EA winter monsoon. However, presently there appears to be no evidence indicating major uplifts of the Tibetan Plateau during the time interval of 7.1–5.5 Ma, although youthful uplift existed (e.g., Royden et al., 1997; Sun et al., 2008). It can thus be speculated that uplift of the Tibetan Plateau had not directly contributed to the transition in the EA monsoon observed in the Dongwan terrestrial mollusk record. However, if it reached a significant height at about 8 Ma, the Tibetan Plateau could accelerate climate cooling and strengthen the formation of winter monsoon from Northern Hemisphere high latitudes during late Miocene, as indicated by the geological records and model results (e.g., Kutzbach et al., 1989; Ruddiman and Kutzbach, 1990; Harrison et al., 1992; An et al., 2001; Liu and Yin, 2002; Liu et al., 2003), showing a combined effect with the growing climate amplifiers located at high latitudes in both hemispheres.

Enhancement of the EA summer monsoon between 5.1 and 4 Ma is near synchronous to closures of the Panama and Indonesian seaways, and maximum values of TH mollusks closely correspond to obliquity maxima. Closures of the Panama and Indonesian seaways occurred respectively during latest Miocene and early Pliocene and may have greatly participated in changes of the distribution of heat between the Pacific and Atlantic basins, causing reorganization of global climate patterns (e.g., Haug and Tiedemann, 1998; Cane and Molnar, 2001; Hall, 2002). This could have impacted the atmospheric moisture flux between high and low latitudes, changing from a latitudinal to meridional transport, resulting in an increase of moisture at high latitude (Young and Bradley, 1984; Raymo and Nisancioglu, 2003).

Obliquity is an important factor in controlling the insolation distribution in middle and high latitudes (Berger, 1984), and also controls the gradient in summer insolation between high and low latitudes, which drives the poleward atmospheric heat and moisture transport (Young and Bradley, 1984; Raymo and Nisancioglu, 2003). When the obliquity becomes large, the annual insolation increases in the high latitude and decreases in the low latitude, causing an increase in the difference in annual mean temperature and the occurrence of hotter summers (e.g., Wu et al., 2000). Thus, the middle and high latitudes would receive more heat and moisture at obliquity maxima, causing a strong summer monsoon and abundant occurrence of TH mollusks in the CLP.

Moreover, the closure of the seaways likely played important roles in the strengthening and enlargement of the western Pacific warm pool (WPWP) indicated by both geological records and modeling studies (Maier-Reimer et al., 1990; Mikolajewicz et al., 1993; Mikolajewicz and Crowley, 1997; Haug and Tiedemann, 1998; Chaisson and Ravelo, 2000; Li et al., 2004). As the moisture in the CLP mainly originates from the western Pacific area transported mainly by the EA summer monsoon, the hydrology of WPWP including the South China Sea is crucial. Recent study shows that the local hydrography in the western Pacific evolved towards modern "warm pool" conditions after 6.6 Ma as revealed by the deepening of the thermocline (Li et al., 2004). The warm pool is an important source of water vapor and latent heat for the higher latitudes (Yan et al., 1992), and thus can provide more precipitation to the CLP through summer monsoon, and therefore favorable conditions for the growth and development of the TH group in the CLP during this studied interval. Therefore the reorganization of the ocean circulation linked to closures of the Panama and Indonesian seaways, associated to obliquity changes, contributed to the occurrence of climate conditions yielding the dominance of the summer monsoon and abundant occurrence of TH mollusk species in the CLP.

## 5. Conclusion

Our Dongwan terrestrial mollusk record indicates that two periods corresponding to different EA monsoon sub-regimes dominated during the late Miocene–Pliocene. Between 7.1 and 5.5 Ma, the EA winter monsoon characterized by cold-aridiphilous mollusks dominated with a 100-kyr periodicity. Conversely, between 5.1 and 4 Ma, the EA summer monsoon characterized by thermo-humidiphilous mollusks dominated with a 41-kyr periodicity. A transition of approximate 400 kyr existed in between. The winter monsoon during 7.1–5.5 Ma coincides with the expansion and decay of middle-sized glaciations in the Northern Hemisphere and the building up of the Antarctic ice sheet. Uplift of the Tibetan Plateau may have contributed to the cooling trend and the strength of the intensity and frequency of the EA winter monsoon. The dominant summer monsoon between 5.1 and 4 Ma coincides with ocean reorganization imposed by the closures of Panama and Indonesian seaways, and insolation variations modulated by obliquity reinforcing meridional heat transport between low and high latitudes. The transition from a 100-kyr dominated interval towards a 41-kyr dominated one is contrary to that observed in the mid-Pleistocene, which corresponds to ice-volume expansion at high latitude and show a shift in the periodicity from 41 kyr to 100 kyr. It also corresponds to the early Pliocene warming interval. Thus, our results suggest that the late Miocene to Pliocene climate transition may be related to ice-volume growth and decay associated with tectonic events such as uplift of the Tibetan Plateau and closures of Panama and Indonesian seaways, although the ultimate mechanisms for climate transition are still under debate. Such results and interpretations allow us to integrate the climatic history of the CLP within a much more global prospective.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.07.038.

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