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Palynological evidence for Late Miocene–Pliocene vegetation evolution recorded in the red clay sequence of the central Chinese Loess Plateau and implication for palaeoenvironmental change

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Abstract

In northern China, the Late Miocene–Pliocene red clay in the eastern Loess Plateau fills a gap of climate records between the well-known loess-soil sequences of the last 2.6 Ma and the Miocene loess-soil sequences from the western Loess Plateau. Previous studies indicate that the red clay is also of wind-blown origin, covering the period from ~7–8 to ~2.6 Ma. The red clay therefore provides a good archive to reconstruct paleoecological succession and paleoclimate change. In this study, a palynological investigation was conducted on the late Miocene–Pliocene red clay sequence at Xifeng, central Loess Plateau, which provides new insights into the nature of the evolution of vegetation and climate change from ~6.2 to ~2.4 Ma. Our results show that during this period the central Loess Plateau region was covered mainly by a steppe vegetation, indicating long lasting dry climatic condition. Three vegetational zones were recognized during this period. Zone A (~6.2 to ~5.8 Ma) is characterized by a steppe ecosystem; Zone B (~5.8 to ~4.2 Ma) is characterized by a significant increase of temperate forest plants, indicating a relatively humid regional climate; Zone C (~4.2 to ~2.4 Ma) indicates a typical steppe ecosystem. The vegetation shift at about 4.5–3.7 Ma, when the temperate forest plants decrease, the vegetation gradually changed to typical grassland and even to desert steppe. This is interpreted to represent a drying event. The uplift of the Tibetan Plateau at about 4.5 Ma that resulted in the intensification of the monsoon reversal is thought to have played an important role in this significant ecological change. High-latitude cooling may have partially contributed to the climate shift during ~4.5 to ~3.7 Ma in the Loess Plateau region, and most likely was the driving force for the ecological shift at about 3.7 Ma.

Keywords: Red clay; Pollen; Paleovegetation; Late Miocene–Pliocene; Chinese Loess Plateau

1. Introduction

The Loess Plateau of China contain a long eolian loess deposition archive suitable for tracing past environment changes in Asian (Liu, 1985; Ding et al., 1998; Sun et al., 1998; Ding et al., 2001; Guo et al., 2002; Lu

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et al., 2004). The composition of loess sediment can be separated into three portions. One portion is Quaternary loess-soil sequence (Liu, 1985), the second portion is the Late Miocene–Pliocene red clay (Ding et al., 1998; Sun et al., 1998; Ding et al., 2001; Lu et al., 2004), the third portion is Miocene Qin'an loess sequence (Guo et al., 2002). Recently much research has focused on late Miocene–Pliocene red clay. Some researchers have argued that the red clay is of eolian origin by using sedimentary proxies (Ding et al., 1998; Guo et al., 2001; Lu et al., 2001; Yang and Ding, 2004) and geochemical methods (Gu et al., 1999; Ding et al., 2001; Guo et al., 2004). Further researches try to reconstruct the paleoclimate changes and the Asian monsoon evolution by using various proxies during late Miocene and Pliocene (Sun et al., 1998; Ding et al., 1999; Gu et al., 1999; Yang et al., 1999; Guo et al., 2001; Xiong et al., 2002; Sun, 2004). However, the nature and process of the regional climate and ecological changes from the late Miocene to the Pliocene have not been well documented because of the complexity of the processes involved (Han et al., 1998; Ding et al., 1999; Liu et al., 2005). Although the study of $\delta^{13}C$ ratio has provided some useful information of vegetation changes (Yang et al., 1999; Ding and Yang, 2000; Jiang et al., 2002; Gu et al., 2003; Vidic and Montanez, 2004), this technique tracks only changes in the proportion of C_3/C_4 vegetation. This isotope technique completely fails to discriminate the different types of C_3 vegetation (trees, shrubs, cool season grasses) and how the different types of C_3 vegetation might have changed as C_4 grasses expanded.

Pollen analysis can provide direct evidence for paleovegetation change, thus yielding a far more complete picture of paleovegetation change in the Loess Plateau region. Some authors have fruitfully addressed the paleovegetation record of the Chinese loess/paleosol sequences over the last 1.2 Ma (e.g. Sun et al., 1996a; Li et al., 2003; Lü et al., 2003; Wu et al., 2004; Jiang and Ding, 2005), however, systematic palynological data from the red clay remains very sparse because of the difficulty in extracting sufficient numbers of pollen grains from this sediment. In this study, we present a new pollen record from the late Miocene to the Pliocene red clay sequence at Xifeng, central Loess Plateau, to reconstruct the change in the paleoflora assemblage, and we also compare our new pollen record with the isotope record for the expansion of C_4 grasses at about 4.5 Ma. The paleovegetation records contribute to improving our understanding of the processes of climate and ecological changes, the causes of the major Northern Hemisphere cooling and the environmental effects the Tibetan Plateau uplift had on adjacent areas.

2. Geography

The Chinese Loess Plateau lies within the Eastern Asian monsoon zone. The present climate is characterized by prominent seasonal gradients in wind direction, precipitation and air temperature between winter (cold and dry) and summer (hot and wet) (Qian, 1991). In the summer season, the East Asian summer monsoon brings warm, moist air masses from the tropical oceans to the

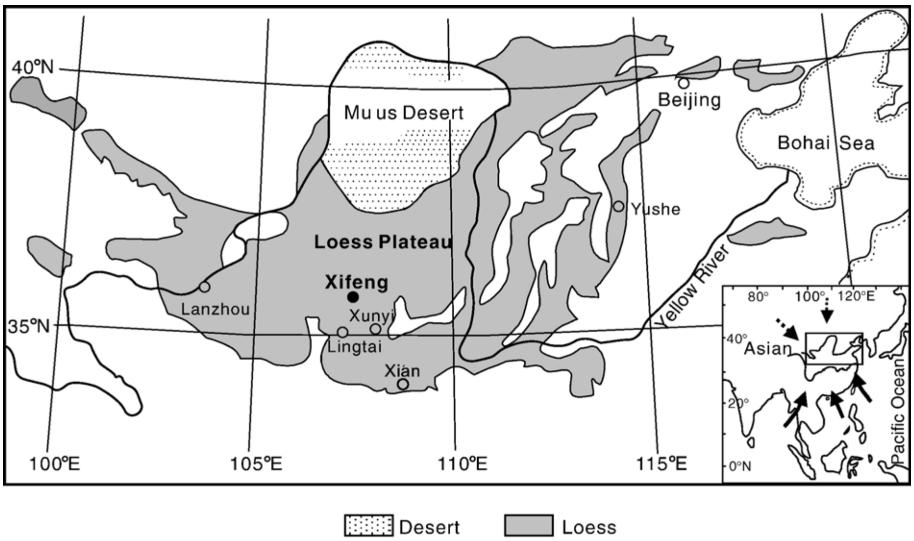

Fig. 1. Schematic map showing the Chinese Loess Plateau and the location of the studied Xifeng section as well as some sections mentioned in the text. The solid and dashed arrows respectively show summer and winter monsoon directions.

plateau, resulting in heavy rainfall in the region. In the winter season, the winter monsoon winds blowing from the Siberian region prevail across the plateau, leading to a dry and cold climate. Across the plateau, the mean annual precipitation (MAP) and mean annual temperature (MAT) decrease from ∼650 mm and ∼14 °C in the southeast to ∼300 mm and ∼8 °C in the northwest (Qian, 1991). Therefore, there is a strong climatic gradient over this region. The present-day gradient is from semi-humid through semi-arid to arid from the southeastern plateau close to the northern Qinling Mountains, across the central plateau, to the northwestern plateau close to the southern Mu Us Desert (Deng et al., 2005).

The Xifeng (107°58′E, 35°53′N) section is situated in the central Loess Plateau (Fig. 1). The region is dominated by a semi-arid continental climate and has a MAP of 580–590 mm and a MAT of 8.9–9.1 °C. The mean July temperature is 22.3 °C, and the mean January temperature −5.3 °C.

The modern vegetation in Loess plateau is characterized by a semi-arid temperate meadow steppe and steppe communities with *Bothriochloa ischaemum*, *Artemisia gmelinii*, *A. girldii*, *Stipa bungeana*, *Lespedeza dauricum* as the dominant species. Some trees and shrubs grow in some gullies where soil water is available due to the topography, but no successive natural forests exist in the lowlands. These trees and shrubs usually include *Ostryopsis davidiana*, *Populus davidiana, P. simonii. P. hopeinsis, Ulmus pumila, Pyrus betulaefolia, Platycladus orientalis, Prunus armeniaca* var. *ansu, Hippophae rhamnoides, Sophora viciifolia, Spiraea pubescens, Rosa xanthia.* Most areas on top of the Loess plateaus have been cultivated for crops (Hou, 1983; Liang, 2003).

The warm-temperate forest steppe is just distributed in Liupan Mountains to the southwest of this study area at an average altitude of about 2500–2700 m with the highest peak at 2942 m. Patches of forest are found on the northern slope of the Liupan Mountains, which consists largely of *Quercus liaotungensis*, *Pinus tabulaeformis*, *P. armandii* and *P. orientalis*. Many shrubs like *Zizyphus sativa*, *S. viciifolia*, *O. davidiana* and *Forsythia suspense* appear on small mountain foothills (Hou, 1994). The patched mixed forest on the southern slope is mainly composed of *Q. liaotungensis*, *P. davidiana* and *Betula platyphylla*. *Rosa*, *Spiraea*, *H. rhamnoides* usually grow under an upper canopy of other trees (Feng, 1987).

3. Material and methods

The Xifeng section consists, from top to bottom, of Quaternary loess-paleosols, late Tertiary red clay, and fluviolacustrine strata (Sun et al., 1998; Guo et al., 2000, 2001, 2004). The red clay sequence has a thickness of 56 m. Previous magnetostratigraphic investigations have provided robust age control for the studied sequence. The Gauss-Matuyama boundary (∼2.6 Ma) was identified near the contact between loess-soil sequence and the red clay (Sun et al., 1998) and the lower boundary of the red clay sequence was dated at ∼7.6 Ma (Sun et al., 1998). The fact that the red clay sequence records the major magnetostratigraphic units from ∼7.6 to ∼2.6 Ma indicates that it contains a nearly continuous record of paleoclimate over that time interval.

Recently, the section was systematically studied using various proxies (Guo et al., 2001), that show the lower section older than ∼6.2 Ma is a reworked deposit due to alluvial and slope processes (Guo et al., 2001). In this study, only the eolian part of the section was analyzed. All our samples come from the 53.2-m-thick stratigraphic interval starting from the overlying Quaternary paleosol layer S32 up to a calcareous nodule horizon in the lower part of the red clay formation. 532 samples were taken at 10-cm intervals for magnetic susceptibility measurements that were performed on a Bartington magnetic susceptibility meter. The depth–age transformation was performed based on the magnetostratigraphic results (Sun et al., 1998) by using the magnetic susceptibility curve as a correlation, which suggests that the studied sequence covers the period of 6.2–2.4 Ma. 107 samples at about 50-cm intervals were selected for pollen analysis. The samples were treated with 10% HCl to remove carbonate, and then were treated with HF to digest silica. The treated samples were then washed with distilled water, sieved through a 5-μm screen to remove silica gel and fine particles, and dehydrated with glacial acetic acid. An acid with nine parts acetic acid to one part sulfuric acid was used to remove organic materials. Finally, the samples were washed, centrifuged, and mounted in silicone oil for microscopic analysis. All the samples contain pollen. The pollen sum counted of 5 samples among 107 samples is less than 100, but the pollen sum counted of the other 102 samples is more than 100 (Fig. 2). The total pollen was used to construct a plot of pollen spectra (percentages and concentration) versus age (Figs. 2 and 3). In general, the state of preservation of pollen was poor because of the oxidation of the eolian sediments, thus, pollen concentrations are influenced by weathering. For example, the concentration of paleosol in the Quaternary loess-soil sequence is less than that of loess (Sun et al., 1996a). In addition, pollen with selective preservation probably influences on the assemblages. However, recent studies of pollen from eolian deposition show that the assemblage of pollen in Chinese loess is very similar to the plants that

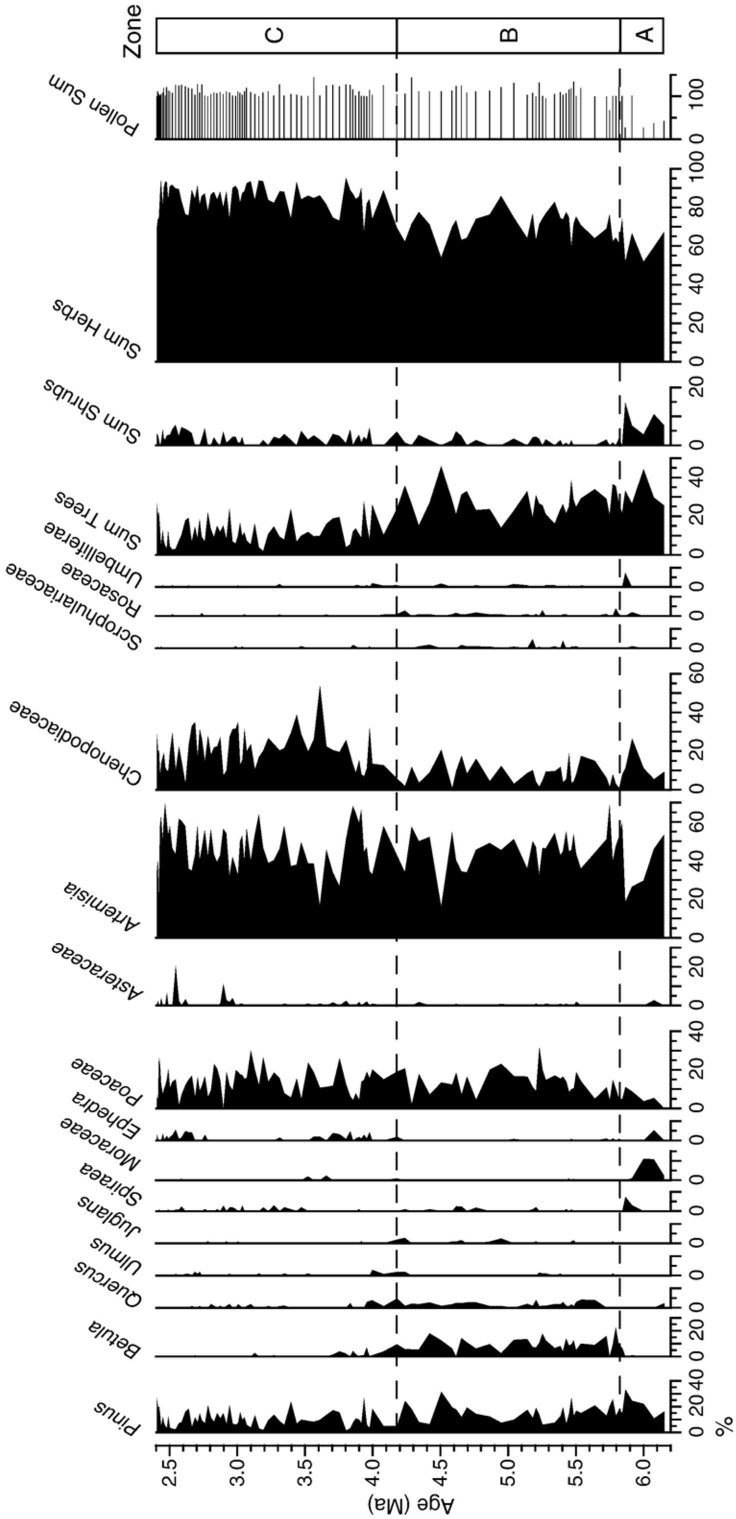

Fig. 2. Age diagram of pollen percentage of the Xifeng Red Clay sequence.

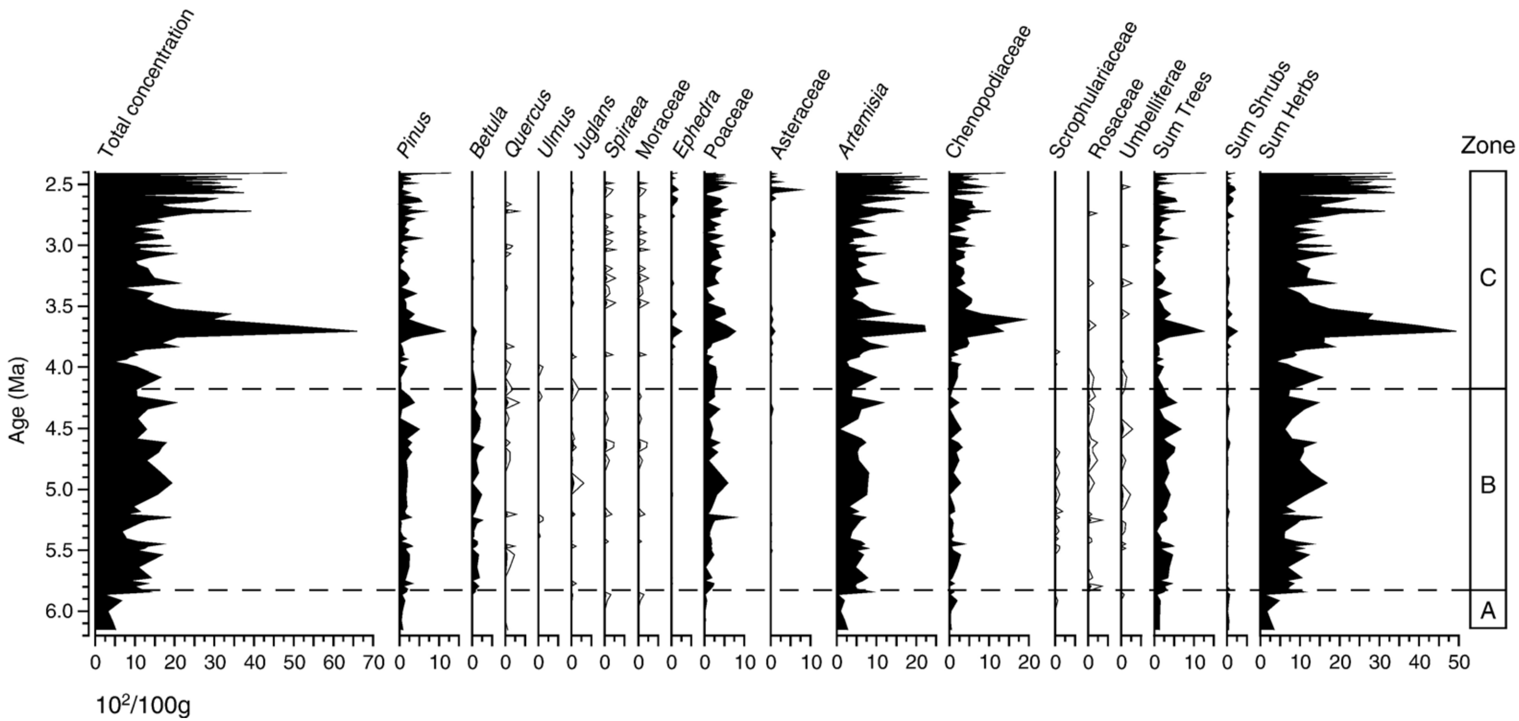

Fig. 3. Age diagram of pollen concentration of the Xifeng Red Clay sequence. Shaded areas with Fine lines represent 5* exaggeration for visual effect.

were growing the Loess Plateau region during the Quaternary (e.g. Sun et al., 1996a; Lü et al., 2003; Wu et al., 2004; Jiang and Ding, 2005), therefore, here we discuss the ecological change by using mainly pollen assemblage and percentage.

4. Results of the palynological study

More than 40 families and genera of sporopollen were identified from all of the samples. A high percentage of grassland taxa and a low percentage of temperate forest taxa characterize the pollen assemblage. Those sporopollen includes arboreal taxa (such as *Pinus*, *Betula*, *Juglans*, *Quercus*, *Ulmus* and Moraceae,), shrub taxa (such as *Ephedra*, Oleaceae, *Sambucus* and *Spiraea*), and herbaceous taxa which are mainly Chenopodiaceae, *Artemisia*, Asteraceae, Poaceae, Scrophulariaceae, Rosaceae, and Umbelliferae. According to the pollen assemblage and the percentage of those taxa, three ecological zones are recognized in the Xifeng red clay sequence: A (53–51 m), B (51–33 m) and C (33–0 m) (Figs. 2 and 3), which are described bellow.

4.1. Zone A: 53–51 m, 6.2–5.8 Ma

This zone displays a higher percentage of shrub taxa (0–15%, average 7%), low concentrations of pollen and no occurrence of *Betula*, *Ulmus* and *Juglans* (Figs. 2 and 3). The shrub taxa are *Sambucus*, Oleaceae and *Spiraea*. Grassland taxa (51–72%, average 62%) and a low percentage of temperate forest taxa (22–44%, average 26%) characterize this zone. The main species of steppe taxa are Chenopodiaceae (1–26%, average 10%), *Artemisia* (19–59%, average 41%) and Poaceae (0–11%, average 6%), and the main forest taxon is *Pinus* (11–33%, average 20%).

4.2. Zone B: 51–33 m, 5.8–4.2 Ma

This zone shows a sudden appearance and increase of *Betula* (0–23%), accompanied by the appearance of *Ulums*, *Quercus* and *Juglans*, and a decrease in shrubs (Fig. 2), and a increase in the concentration of temperate forest plants (Fig. 3). In this zone grassland taxa (54–85%, average 71%) are dominant and temperate forest taxa make up a low percentage (14–46%, average 27%) of the assemblage. Among the grassland taxa, *Artemisia* (16–69%, average 45%), Poaceae (2–32%, average 14%), and Chenopodiaceae (0–21%, average 8%) are the most common elements, accompanied by Asteraceae, Rosaceae and Umbelliferae. Among the temperate forest taxa, *Pinus* (6–32%, average 15%) is the most common element, accompanied by *Betula* (0–23%, average 10%), *Quercus* (0–4%), *Juglans* (0–3%) and minor percentage of *Ulmus*. The shrubs decrease from 7% to 1%, and only a few spores occur.

4.3. Zone C: 33–0 m, 4.2–2.4 Ma

This zone is characterized by a steady increase of grassland taxa (herbs, 67–95%, average 85%) and a decrease in temperate forest types (27–2%, average 12%), and especially an increase in the percentage of and concentration of steppe taxa, such as Chenopodiaceae (3–54%, average 20%) and *Ephedra* (Figs. 2 and 3). This is particularly noticeable in the *Betula* curve decrease (10–0%, average 0.6%), accompanied by a decrease of *Pinus* and *Quercus* and coinciding with the disappearance in *Juglans* and *Ulmus* (Fig. 2). In this zone *Artemisia*, Poaceae and Chenopodiaceae are dominant (Fig. 2).

5. Discussion

5.1. Paleovegetation history

Palynological analyses show that from ~6.2 to ~5.8 Ma herbs are dominant, and arbores are few (Fig. 2), *Pinus* is the main component of arbores. *Pinus* is usually over-represented because of its high pollen production and long distance dispersion (Denton and Karlen, 1973; Wang and Wang, 1983; Sun and Wu, 1988; Li and Yao, 1990; Tong et al., 1996). Therefore, they are generally regarded as being exotic. In the Xifeng section, although *Pinus* pollen averages 20% and has a peak at 33% in Zone A of the Xifeng section, other arboreal pollens are rare (Fig. 2). Therefore the arboreal *Pinus* pollen in Zone A (~6.2 to ~5.8 Ma) is exotic, and probably is sourced from the Liupan Mountains. The pollen assemblage in Zone A suggests a steppe environment during the period from ~6.2 to ~5.8 Ma.

The pollen assemblage between 5.8 and 4.2 Ma suggests that the vegetation was still dominated by herbs but had a significant arboreal component made up of *Betula, Quercus, Juglans* and *Ulmus* (Fig. 2). The pollen assemblage indicated that there are some temperate forest plants in the vegetation community on the Loess Plateau during this time. The study of pollen-climate response surface of *Pinus*, *Betula* and *Quercus* shows that these taxa are very sensitive to humidity and their pollen contents increase with rainfall (Sun et al., 1996b; Wang et al., 1997). Therefore the pollen data between ~5.8 and ~4.2 Ma indicates that the temperate forest increased significantly, implying a relatively humid climate.

The percentages of herbaceous vegetation increases at ~4.2 Ma. Herbs indicative as arid climate such as Chenopodiaceae significantly increase and the presence of *Ephedra* indicating extreme aridity frequently appears after ~4.2 Ma (Fig. 2). Among the arboreal types, the main pollen is *Pinus* while the others have almost disappeared, indicating that *Pinus* pollen is exotic in this interval and that the climate after ~4.2 Ma is significantly drier than before. In addition, during the period from ~3.7 to ~3.3 Ma the average content of Chenopodiaceae is over 28% with a peak value of 54%, implying the ecosystem was desert steppe during ~3.7 to ~3.3 Ma.

To sum up, the pollen assemblage implies that the main vegetation type in the Xifeng area was grassland during ~6.2 to ~2.4 Ma, indicating a long lasting dry climatic condition on the Loess Plateau from the late Miocene to the late Pliocene. The aridification may have started earlier, as evidenced by the onset of dust accumulation in the east-central Loess Plateau since ~7–8 Ma (Sun et al., 1998; Ding et al., 1998, 2001; Lu et al., 2004).

5.2. Paleoclimate significance of the paleovegetation shift during 4.5–3.7 Ma

Although the pollen assemblage indicates a significant shift towards drier climate at about 4.2 Ma, the smoothed data (5 point running average) clearly shows that the shift towards a drier climate started at about 4.5 Ma and lasted to ~3.7 Ma (Fig. 4). During this period, the vegetation changed significantly. Firstly, the mean percent arboreal pollen decreases from 27% to 12% (Fig. 4A) and some arboreal taxa disappeared (Fig. 2). The mean percentage of birch pollen decreases from 10% to 0.6% (Fig. 4C); *Quercus*, from 1.6% to 0.5%; *Pinus*, from 15% to 10% (Fig. 2). Secondly, there is an apparent increase of herbaceous vegetation, whose mean percentage increases from 70% to 85% (Fig. 4B). For instance, the mean percentage of Chenopodiaceae increases from 8% to 20% with a peak value of 54% (Fig. 4D). The extremely drought-tolerant species *Ephedra* occurs frequently during this time, with a sudden increase in its mean percentage (from 0.1% to 1.0%) (Fig. 2). Thirdly, the ratios of Chenopodiaceae/*Artemisia* and *Betula*/*Artemisia*, which are good indices for moisture (El-Moslimary, 1990; Liu et al., 1999; Mensing et al., 2004), exhibit a significant increase and a sudden decrease from ~4.5 to ~3.7 Ma, respectively (Fig. 4E,F). These characteristics suggest an expansion of drought-tolerant species, such as Chenopodiaceae and *Ephedra*, signaling a prominent drying event during that period.

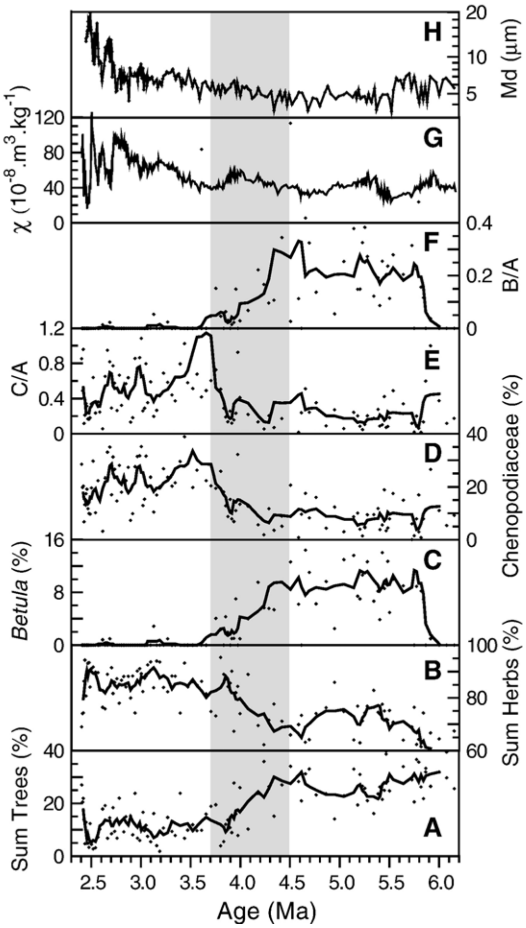

Fig. 4. Comparison of the records of (A) trees, (B) herbs, (C) *Betula*, (D) Chenopodiaceae, (E) Chenopodiaceae/*Artemisia*, (F) *Betula*/*Artemisia*, (G) magnetic susceptibility (χ), (H) median grain size (Md). The median grain size data are after Guo et al. (2001).

Previous researchers have focused on two main aridification events in Asian at ~8 Ma and ~3.6 Ma, and argue that the two events were related to the uplift of the Tibetan Plateau (Ruddiman and Kutzbach, 1989; Manabe and Broccoli, 1990; An et al., 2001; Guo et al., 2004; Zheng et al., 2004) and the expansion of Arctic ice-sheet associated with ongoing global cooling (Ruddiman and Kutzbach, 1989; Guo et al., 2004). Recent researches also suggest that the aridification event at about 4.5 Ma is important for the evolution of terrestrial ecosystems in the middle latitude areas (Janecek and Rea, 1983; Rea et al., 1998; Guo et al., 1999; Gu et al., 1999; Xue and Zhao, 2003; Guo et al., 2004; Pei et al., 2004). In the studied Xifeng red clay sequence, the dust grain size begins to increase gradually from ~4.5 Ma (Guo et al., 1999, 2004) (Fig. 4H), suggesting an intensification of winter monsoon and aridification in Asia. Terrestrial snail fossil assemblages suggest that the climate became increasingly drier at ~4.5 Ma (Pei et al., 2004). This climate shift is also suggested in other sections of the Loess Plateau. In the Lingtai red clay sequence a general increase in the ratios of Na/Al and Fe^{2+}/Fe^{3+} at ~4.5 Ma indicate a decrease in chemical weathering intensity (Gu et al., 1999). In the Xunyi red clay sequence soil micromorphology features suggest an apparent decrease in the degree of pedogenesis at ~4.2 Ma (Xue and Zhao, 2003). The north Pacific dust flux as a proxy for the aridification of Asia gradually increased from ~4.5 Ma, and the dust grain size shows a prominent coarsening trend from ~4.6 Ma (see Figs. 3 and 4 of Rea et al., 1998, p. 219; Janecek and Rea, 1983; Rea et al., 1998). All above evidence indicates the ubiquitous occurrence of this drought episode.

In our data there is a significant increase in herbaceous Chenopodiaceae (Fig. 4D), coinciding with the shift in $\delta^{13}C$ ratios of pedogenic carbonates from the red clay (Yang et al., 1999; Ding and Yang, 2000; Jiang et al., 2002). This implies an expansion of C_4 vegetation. Studies of present day plant distribution indicate that the strongly seasonal distribution of rainfall was favorable for C_4 vegetation growth (Doliner and Jolliffe, 1979; Collins and Jones, 1985; Wang et al., 2004). The dramatic ecological shift during the latest Miocene in northern Pakistan (Quade et al., 1989; Quade and Cerling, 1995) and in central Nepal (Hoorn et al., 2000) may mark this strengthening of the monsoon system. Therefore, the paleovegetation shift indicates that the seasonal reversal was intensified during ~4.5 to ~3.7 Ma.

This climate shift during about ~4.5 to ~3.7 Ma is reflected in the marine $\delta^{18}O$ records (e.g., Shackleton et al., 1995), and ice-rafting information from the North Atlantic (Jansen and Sjøholm, 1991) and the North Pacific (De Menocal, 1993). However, the $\delta^{18}O$ records from the East Atlantic, East Pacific and Caribbean Sea show that there may have been several failed attempts of the climate system to develop the Northern Hemisphere glaciation during ~4.1 to ~3.9 Ma and ~3.5 to ~3.3 Ma (Haug and Tiedemann, 1998). In addition, it is noted that the ice-rafting events in the North Atlantic (Jansen and Sjøholm, 1991) and the North Pacific (De Menocal, 1993) show low-amplitude fluctuations at ~5 to ~3 Ma, and are significantly enhanced after ~2.6 Ma. Therefore, high-latitude cooling may have partially contribute to the climate shift during ~4.5 to ~3.7 Ma in the Loess Plateau region.

Recent study suggests that an episode of Tibetan uplift occurred at about 4.5 Ma (Zheng et al., 2000). The uplift of the Tibetan Plateau may play an important role in Asian aridification, thus contributing to the climate shift during ~4.5 to ~3.7 Ma suggested by our pollen data. The uplift of the Tibetan Plateau could exert a profound effect upon atmospheric circulation and environmental changes of Eastern Asia (Ruddiman and Kutzbach, 1989; An et al., 2001; Guo et al., 2002, 2004; Wang et al., 2005). It would form a water vapor barrier, so that the water vapor carried by the South West monsoon could not reach the northern part of the Tibetan Plateau (Ruddiman and Kutzbach, 1989), leading to the decrease of rainfall and gradual vegetational change to arid grasslands in the Asian interior. At the same time, the plateau uplift probably strengthens the seasonal reversal (An et al., 2001).

In addition, some important tectonic changes may have contributed to the climate shift during ~4.5 to ~3.7 Ma. The closing of the Panamanian Isthmus at ~4.5 Ma and the Indonesia Seaway before 4 Ma may have caused reorganization of global climate patterns (Janecek and Rea, 1983; Haug and Tiedemann, 1998, Driscoll and Haug, 1998; Rea et al., 1998), thus stimulating global cooling and the eventual growth of ice sheets (Cane and Molnar, 2001).

Another prominent feature of our pollen data is the indication of the ecological shift at ~3.7 Ma. The Chenopodiaceae/*Artemisia* ratio, a useful proxy of moisture, increases abruptly at ~3.7 Ma, and Chenopodiaceae increases quickly to an average of 28% during ~3.7 to ~3.3 Ma, indicating that a significant ecological shift from steppe to desert steppe occurred at around 3.7 Ma (Fig. 4D,E). The climate shift has been extensively documented in terrestrial and marine records (e.g., Shackleton et al., 1995; Rea et al., 1998; An et al., 2001; Guo et al., 2004). For example, an abrupt increase of mass accumulation of eolian dust in the North Pacific at ~3.6 Ma indicates a significant strengthening of Asian aridity (Rea et al., 1998). An episode of Tibetan uplift at ~3.6 Ma may have significantly contributed to the development of Asian aridification (Li et al., 1997; An et al., 2001; Guo et al., 2004). Therefore, this abrupt ecological shift at ~3.7 Ma possibly results from the strengthening of East Asian monsoon reversal, which was closely linked to the phased uplift of the Tibetan Plateau and the development of the Northern Hemisphere glaciation (Prell and Kutzbach, 1992; An et al., 2001; Guo et al., 2004).

6. Conclusions

The pollen record of the Xifeng red clay sequence presents a continuous terrestrial ecological archive of the late Miocene–Pliocene times. The pollen assemblage suggests that the vegetation between 6.2 and

2.4 Ma in the Xifeng area was dominated by grassland, indicating a long lasting dry climate in the Loess Plateau during that period. The ecological shift occurred during ~4.5 to ~3.7 Ma, when the temperate forest plants decrease gradually, the vegetation changed to typical steppe, even to desert steppe, indicative of a prominent drying event. This vegetation shift coincided with long changes recorded by different proxies at numerous aeolian dust records in China and in the North Pacific, especially with vegetation variations revealed by $\delta^{13}C$ ratios. The uplift of the Tibetan Plateau at about 4.5 Ma was probably the main driving force, although the ultimate causes for the climatic changes are still under debate.

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