ASTRONOMICAL SIGNALS IN DIFFERENT CLIMATE PROXIES FROM THE QUATERNARY LOESS-SOIL SEQUENCES IN CHINA

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Abstract. In the study of loess-soil sequences from monsoonal northern China, magnetic susceptibility (MS) and chemical weathering indexes (such as the ratio of free Fe_2O_3 versus total Fe_2O_3, FeD/FeT) are usually used as proxies of the summer monsoon, and grain-size of bulk samples as a proxy of the winter monsoon. In this report, orbital signals recorded in these climate proxies are compared, showing that they all yield frequency patterns essentially similar to that of the marine $\delta^{18}O$ record. This is attributable to the interactive effects of the winter (dust accumulation intensity and winter monsoon) and summer (summer monsoon) forcings, and particularly to the predominance of the winter signals in the frequency patterns of these proxies. Loess deposition in northern China and the resulting stratigraphic structure, as is reflected by the alternations between loess and soil layers, were primarily controlled by ice-boundary conditions through influencing dust accumulation intensity. We also developed a geochemical proxy (SiO_2/Al_2O_3) to reflect the changes of original eolian grain-size prior to post-depositional weathering, and compare the orbital signals with those recorded in the grain-size of bulk samples. The results reveal a near-lack of the ~100-ka cycle and a predominance of ~40-ka and ~23-ka cycles in the variations of original eolian grain-size. These indicate a relative independent dynamic link between dust grain-size and ice-boundary conditions. Rather, the combination of the moderate ~40-ka obliquity signals and the strong ~23-ka precessional signals suggests a factor relative to low-latitude insolation changes. We thus believe that original eolian grain-size bears strong summer signals, probably through the influence of summer moisture on the conditions of the southern margins of the deserts. The clear orbital signals in all of these climate proxies from Chinese loess greatly support the Milankovitch theory of paleoclimate.

Key words: Milankovitch cycles, loess, paleoclimate, monsoon.

Introduction

During the late Cenozoic, thick eolian deposits have been formed at the middle reaches of the Yellow River in northern China within an area referred to as Loess Plateau (Fig. 1). These include the well-known loess-soil sequences of the last 2.6 Ma (LIU, 1985; KUKLA and AN, 1989; AN *et al*., 1990), the *Hipparion Red-Earth Formation* (HREF, or *Red-Clay*) in the eastern Loess Plateau from ~8 to 2.6 Ma BP (SUN *et al*., 1998; DING *et al*., 2001; QIANG *et al*., 2001), the Pliocene loess-soil sequence in the western Loess Plateau (HAO and GUO, 2004), and the Miocene loess-soil sequences in the western Loess Plateau (GUO *et al*., 2002). Combination of these eolian deposits provides a near-complete terrestrial climate record of the past 22 Ma.

Complete loess-soil sequences of the last 2.6 Ma are mostly more than 150 m in thickness, which recorded more than fifty soil-forming intervals intercalated with dust deposition intervals (GUO *et al.*, 1996a). Major interglacial soils and glacial loess units are labeled S0, L1, S1, L2, S2... from the top to the bottom (LIU, 1985). The stratigraphy is well correlative with that of the marine $\delta^{18}O$ record (KUKLA, 1987) and the correlation pattern since the middle Pleistocene was also confirmed by an eolian record in the North Pacific (HOVEN *et al.*, 1989), which appears to be a direct link between the Chinese loess and marine $\delta^{18}O$ stratigraphy.

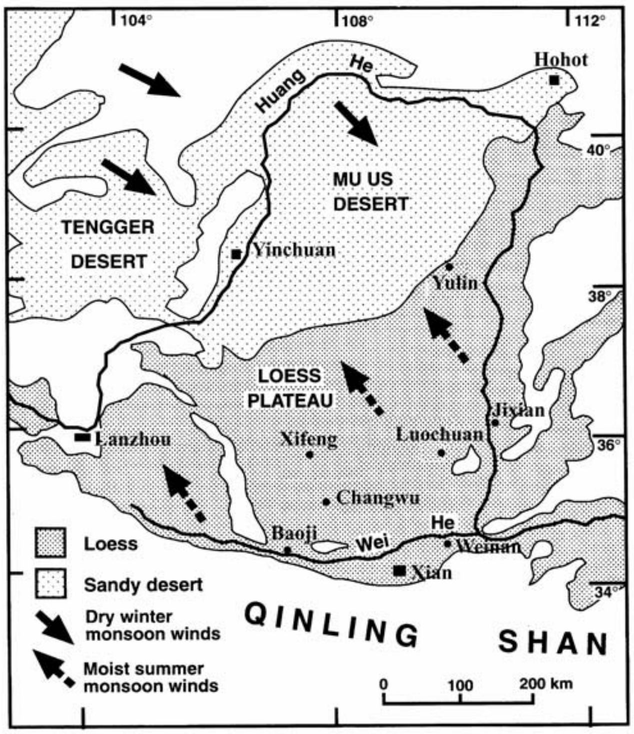

Fig. 1. Map showing the Chinese Loess Plateau, the locations of the sites mentioned in the text, and the modern East-Asian summer and winter monsoon circulations (modified after AN and PORTER, 1997)

The Loess Plateau is located in the East-Asian monsoon zone. Cyclical climate changes are expressed by the alternations of loess and soil layers (AN *et al.*, 1990; LIU *et al.*, 1995). Soils were formed in warm-humid periods corresponding to stronger effects of summer monsoon while loess was formed under relatively dry-cold conditions with strengthened effects of winter monsoon (AN *et al.*, 1990; LIU *et al.*, 1995). The alternations between loess and soils indicate cyclical changes in the effects of winter and summer monsoons (AN *et al.*, 1990; LIU *et al.*, 1995). Eolian deposition and pedogenesis are, indeed, competing processes at all times, and the presence of a soil simply indicates that the latter process was predominant (AN *et al.*, 1990; GUO *et al.*, 1991).

Various climate proxies have been used to explore the climate signals from the loess-soil sequences (AN *et al.*, 1990,1991; HELLER *et al.*, 1993; DING *et al.*, 1994, 2002; LIU *et al.*, 1995; PORTER and AN, 1995; GUO *et al.*, 1996b, 1998, 1999, 2000; LU *et al.*, 1996; ROUSSEAU and WU, 1997; SUN *et al.*, 1997). Most frequently used proxies include magnetic susceptibility (*An et al.*, 1990; HELLER *et al.*, 1993), grain-size (AN *et al.*, 1991; DING *et al.*, 1994; PORTER and AN, 1995), paleo-weathering intensity (GUO *et al.*, 1996b, 1999, 2000) etc. In this report, we attempt to summarize and compare the orbital signals in these different climate proxies with a new climate proxy developed for the last 1.27 Ma. The significance of these orbital signals on the dynamics of the monsoon climate is also discussed.

Climate proxies and timescales

Magnetic susceptibility has been proven particularly useful in characterizing the alternations of loess and soils in the Loess Plateau and is hence widely used as a climate proxy (AN *et al.*, 1990; HELLER *et al.*, 1993). Because its value is higher in soils than in the surrounding loess layers, it is usually used to reflect the effects of summer monsoon (AN *et al.*, 1990). Rock magnetic studies suggested that fine-grained ferrimagnetic minerals of pedogenic origin are primarily responsible for the higher susceptibility values in soils (ZHOU *et al.*, 1990; MAHER and THOMPSON, 1991). Magnetic susceptibility is also usually regarded as an indication of pedogenic intensity. The close correlation between susceptibility and lithostratigraphy (KUKLA and AN, 1989), as characterized by the alternations between loess and soil layers, indicates that it is a reliable indicator reflecting the cyclical changes of loess deposition and soil formation.

Climate significance of magnetic susceptibility has been extensively reviewed (HELLER *et al.,* 1993; HAN *et al.,* 1996). Its relationship with climate seems to be sometimes non-linear (HAN *et al.,* 1996) in that some climate changes, which are clearly documented by other proxies, such as the pedological indicators (LIU *et al.,* 1995; GUO *et al.,* 1998) and the malacological population (ROUSSEAU and WU, 1997), are not necessarily recorded by magnetic susceptibility. In this case, the ratio of CBD (citrate-bicarbonate-dithionite)-extractable free Fe_2O_3 (FeD) and total Fe_2O_3 (FeT), an index widely used by pedologists (DUCHAUFOUR, 1983), was used to assess paleoweathering intensity (GUO *et al.*, 1996b, 1998, 1999, 2000). The ratio, which is expressed as a percentage, is a measurement of the quantity of iron liberated from iron-bearing silicate minerals by chemical weathering relative to the total iron available. The CBD-extractable Fe_2O_3 is, mainly of pedological origin (SINGER *et al.*, 1992). Since the soils in the region are frozen from late autumn to early spring (Institute of Soil Sciences, 1978), chemical weathering mainly depends upon the summer temperature and precipitation, which are closely linked with the strength of the summer monsoon. Thus, the FeD/FeT paleo-weathering index (Fig. 2) primarily reflects the effects of the East-Asian summer monsoon on the loess materials. It has documented a series of summer monsoon changes of global significance, which are not necessarily recorded by magnetic susceptibility (GUO *et al.*, 2000). However, dust deposition intensity would have also affected chemical weathering intensity because quicker accumulation rate would lead to weaker weathering.

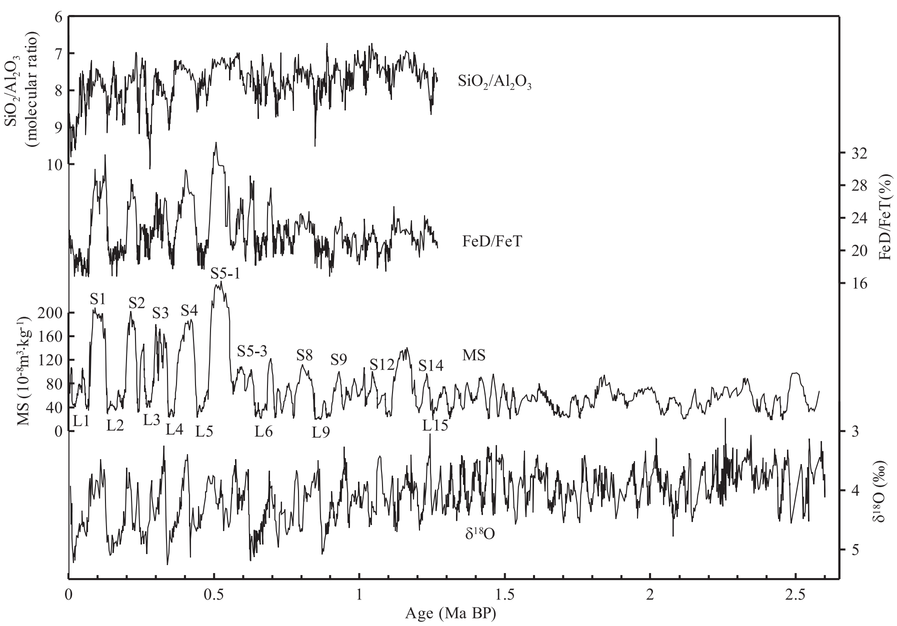

Fig. 2. SiO_2/Al_2O_3 molecular ratio, FeD/FeT and magnetic susceptibility (MS) of the Xifeng loess-soil sequence compared with marine $\delta^{18}O$ record. Loess and soil stratigraphic units are labeled. SiO_2/Al_2O_3 are based on samples at 10-cm intervals. Chemical analyses were made using wet chemical method for SiO_2 and ICP method for Al_2O_3, with an analytical precision of 1.7% for SiO_2 and 3.7% for Al_2O_3. Susceptibility data used here are based on samples from the Xifeng type section at 10-cm intervals, measured using a Batington MS2 susceptibility meter. FeD/FeT data are from GUO *et al.* (2000). Timescale was developed using the magnetic susceptibility model of KUKLA *et al.* (1990) revised by new geomagnetic polarity timescale (CANDE and KENT, 1995). Marine $\delta^{18}O$ data are from SHACKLETON *et al.* (1990)

Grain-size of the loess-soil sequences is another widely used climate proxy in Chinese loess (AN *et al.*, 1991; DING *et al.*, 1994; PORTER and AN, 1995; AN and PORTER, 1997). It is usually interpreted as an indication of the strength of the transporting winds (HOVAN *et al.*, 1989; PORTER and AN, 1995; AN and PORTER, 1997; REA *et al.*, 1998) and the distance from the source area to the depositional site (REN *et al.*, 1996; DING *et al.*, 1999). However, grain-size of bulk samples from the loess-soil sequences is also affected by syn- and post-depositional weathering and pedogenesis during warm and humid periods (GUO *et al.*, 1996b, 2000). In order to address the original eolian grain-size changes, grain-size of quartz obtained by chemical extraction from bulk samples (PORTER and AN, 1995; XIAO *et al.,* 1995) was analyzed. Some geochemical indicators of eolian grain-size (such as the SiO_2/Al_2O_3 and SiO_2/TiO_2 molecular ratio) have also been developed to address the pre-weathering grain-size changes (LIU *et al.*, 1995; PENG and GUO, 2001; WEI and GUO, 2003; GUO *et al.,* 2004). The SiO_2/Al_2O_3 for the fractions <76 μm is positively correlated with grain-size (Fig 3a). Although a negative correlation is found for the fraction >76 μm, the influence on the SiO_2/Al_2O_3 ratio of the total sample is negligible because the cumulative weight for the fractions >76 μm represents only a proportion of less than 3% by weight of the total sample (GUO *et al.*, 2004). Si and Al are insoluble elememts during the weathering of loess in the semi-arid Loess Plateau region, and their ratio remained stable during post-deposition weathering and was controlled by origin eolian grain-size. The SiO_2/Al_2O_3 ratio of the bulk sample can therefore be used as a suitable indicator for addressing original eolian grain-size changes (PENG and GUO 2001; GUO *et al.*, 2004). On the contrary, the FeD/FeT ratio is basically independent of grain-size changes (Fig. 3b) and mainly reflects weathering intensity (GUO *et al.*, 2000).

Several kinds of timescales have been constructed for the loess-soil sequences of the past 2.6 Ma, all using geomagnetic boundaries as primary age controls. Radiocarbon and luminescence dating provided additional age controls for late Quaternary sequences (LU *et al.*, 1988; FORMAN, 1991; ZHOU *et al.*, 1991; LIU *et al.*, 1994; GUO *et al.*, 1996b). The methods include land-sea correlation (BLOEMENDAL *et al.*, 1995), interpolations

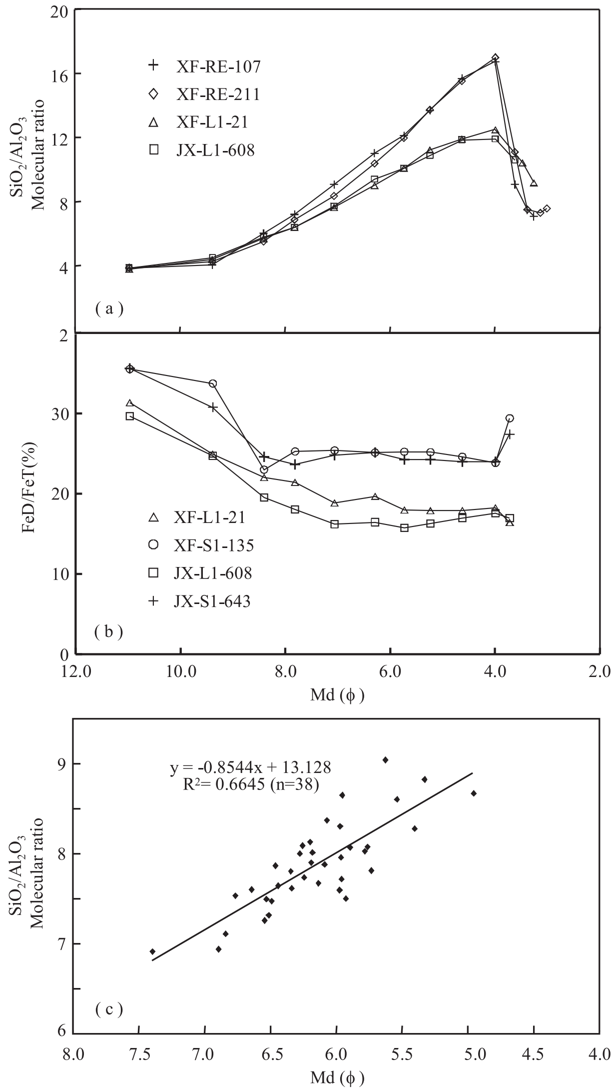

Fig. 3. Relationships between the chemical components and eolian grain size. (a) SiO_2/Al_2O_3 molecular ratio in different grain-size fractions for two typical loess samples and two weakly weathered Red-Earth samples of Pliocene age (GUO *et al*., 2004), (b) FeD/FeT in different grain-size fractions for two typical loess samples and two soils samples, respectively. The two loess and two soil samples are from Quaternary loess L1 and soil S1 in the Xifeng (XF) and Jixian (JX) sections, respectively, and the two Red-Earth (RE) samples are from the Pliocene Red-Earth of eolian origin at Xifeng. SiO_2 and Al_2O_3 were analyzed by X-Ray fluorescence with analytical uncertainties of ±2%. (c) Linear correlation between SiO_2/Al_2O_3 and median grain-size of thirty-eight bulk samples from different loess units at Xifeng (GUO *et al*., 2004)

between known age controls weighted by climate proxies, such as magnetic susceptibility (KUKLA *et al*., 1990) and grain-size (PORTER and AN, 1995; VANDENBERGHE *et al*., 1997; LU *et al*., 2002, 2004), orbital tuning (e.g. DING *et al*., 1994; LU *et al*., 1999; HESLOP *et al*., 2000). Among these methods, interpolations of weighted climate proxies provide independent timescales. A comparison of different astronomical timescales was made by HESLOP *et al*. (2000). Several lines of uncertainty may affect the accuracy of the timescales. These includes at least the possible 'lock-in' effect of geomagnetic boundaries (TAUXE *et al*., 1996), non-linearity of dust accumulation rate, temporal resolution of the record, and potential phase differences of climate changes in China relative to those of the orbital parameters and marine changes. A prominent difficulty arises from the fact that only few independent age controls are available for the sequences with more than 150 m thickness.

Orbital signals in different proxies and the implications

Climate cycles reflected by magnetic susceptibility of the loess-soil sequences in China have been addressed in a number of earlier studies (e.g. HUA *et al*., 1990; KUKLA *et al*., 1990; BLOEMENDAL *et al*., 1995). Fig. 4a shows an evolutive spectrum of the Xifeng susceptibility timeseries of the last 2.6 Ma that essentially confirms the earlier results. We use here the timescales of KUKLA *et al.* (1990) revised by new geomagnetic polarity timescale (CANDE and KENT, 1995) for spectral analyses of magnetic susceptibility. The results of the model (KUKLA and AN, 1989; KUKLA *et al*., 1990) have demonstrated that it is a valuable working model for obtaining an independent timescale, because the susceptibility signal, whatever its origin, is generally in inverse proportion to the sedimentation rate. Prior to 1.0 Ma BP, a period at ~ 41-ka was dominant, attributable to an obliquity band (BERGER, 1977). A ~100-ka period relative to eccentricity (BERGER, 1977) started since ~1.3 Ma and became dominant since 1.0 Ma (Fig. 5a). The ~ 41-ka obliquity period significantly weakened since 1.0 Ma. Over the last 0.7–0.8 Ma, a precessional cycle at ~23-ka is also clear. The spectral evolution of magnetic susceptibility is, thus, essentially in parallel with that of the marine $\delta^{18}O$ record (SHACKLETON *et al*., 1990). The shift of dominant period from the 41-ka obliquity band to the ~100-ka eccentricity one matches well the mid-Pleistocene transition (RUDDIMAN*, et al*., 1989; IMBRIE*, et al*., 1993). However, the onset of the ~100-ka period at ~1.3 Ma BP appears to be earlier than in most of the marine $\delta^{18}O$ records. This is also expressed on the band-pass filtered curves (Fig. 5) and has also been documented by the paleo-weathering index FeD/FeT (GUO *et al*., 2000). An early onset of the ~100-ka signals in the Quaternary was

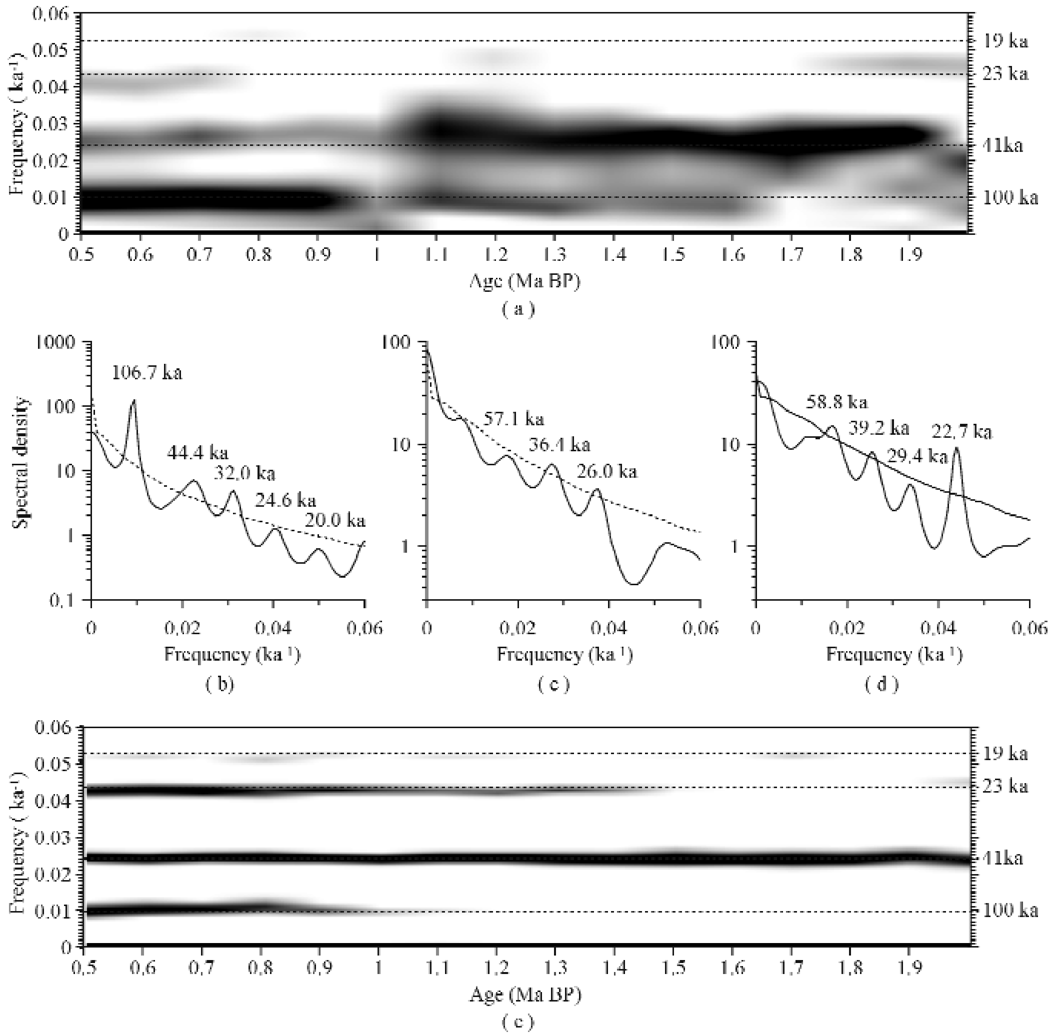

Fig. 4. Spectral analyses of magnetic susceptibility, FeD/FeT and SiO_2/Al_2O_3 from the Xifeng section compared with those of the marine $\delta^{18}O$ record. (a) Evolutive spectra for magnetic susceptibility of the last 2.58 Ma. Timescale is from KUKLA *et al.* (1990) revised by new geomagnetic polarity timescale (CANDE and KENT, 1995). (b)–(c) Maximum entropy spectral analyses for FeD/FeT and SiO_2/Al_2O_3 timeseries of the last 1.27 Ma, respectively. Timescale same as in (a). (d) Maximum entropy spectral analysis for SiO_2/Al_2O_3 timeseries of the last 1.27 Ma plotted on an alternative timescale obtained through a correlation with the orbitally-tuned timescale (HESLOP *et al*., 2000) from Luochuan. The solid lines refer to power spectral density (PSD) and dash lines to 90% confidence limit. (e) Evolutive spectra for marine $\delta^{18}O$ record of the last 2.60 Ma (data from SHACKLETON *et al.,* 1990). Evolutive spectra analyses for (a) and (e) are made using Maximum entropy method with a sliding window length of 1000 ka and a sliding step of 100 ka. PSD over the 90% confidence limit is shown on logarithm scales. Dark areas represent higher PSD values and white areas represent low values. Samples were taken at 10-cm intervals, representing an average temporal resolution of 1.17 ka. All the timeseries were interpolated to a constant 1-kyr interval before spectral analysis. Maximum entropy spectral analyses are made using PPPhalose program (GUIOT, 1990)

also observed from the tropical Atlantic Ocean (RUTHERFORD and D'HONDT, 2000).

The FeD/FeT ratio, a measurement of loess weathering intensity, is only available for the last 1.27 Ma at Xifeng (Fig. 2). Its fluctuations generally match those of magnetic susceptibility (Fig. 2). However, several extreme interglacials corresponding to the S1, S4, S5-1 and S5-3 soils, clearly expressed in the FeD/FeT values and soil morphological indicators (GUO *et al.*, 1998), are not necessarily recorded by magnetic susceptibility (e.x. S4 and S5-3). The increases in weathering intensity at ~ 800-ka and ~650-ka (corresponding to the lower boundary of S5-3) are not observed in the magnetic susceptibility timeseries. The latter indicates a major shift in amplitude at ~ 550 ka, corresponding to the lower boundary of S5-1, which is not consistent with the traditional pedological indicators (GUO *et al.,* 1998) or with FeD/FeT. Spectral analysis (Fig. 4b) of the Xifeng FeD/FeT timeseries of the last 1.27 Ma shows clear 106.7-ka, 44.4-ka , 24.6-ka and 20.0-ka periods roughly corresponding to the dominant periods of the Earth's eccentricity, obliquity and precession, respectively. The spectral pattern of the FeD/FeT ratio (Fig. 4b) is essentially consistent with that of magnetic susceptibility (Fig. 4a).

Several authors (DING *et al*., 1994, 2002; LU *et al*., 2002, 2004) have addressed the orbital signals in the grain-size timeseries of bulk samples, each using their own timescale. DING *et al.* (1994), using the <2?m />10?m grain-size ratio and an orbitally-tuned timescale from Baoji (Fig. 1), revealed three different frequency patterns for the past 2.5 Ma, a combination of 400-ka and 55-ka periods from 2.5 to 1.6 Ma, the dominance of 40-ka obliquity period from 1.6 to 0.8 Ma, and that of the 100-ka period for the last 0.9 Ma. This frequency evolution is essentially similar to that of magnetic susceptibility in spite of the small disagreements and the patterns of the last 1.6 Ma are in parallel with the marine $\delta^{18}O$ record (LIU *et al*., 1999). Based on an independent timescale developed by a grain-size model and the content of the fraction >30 µm for the sequence of the last 1.0 Ma from Luochuan, LU *et al.* (2002) revealed a shift from dominantly quasi-200 to quasi-100-ka cycle at around 500 ka BP, a relatively weak and varying 60–50-ka cycle during some intervals, and a 25–18-ka cycle over the entire timeseries. However, the 41-ka obliquity signal is not evident in this record (LU *et al*., 2002). Their efforts on the sequences at Luochuan and Xifeng of the last 2.6 Ma (LU *et al*., 2004) showed that only the longer cycles of ~400 and ~100-ka cycles are well recorded while the theoretically 41-ka and 22-ka cycles are episodically missing, probably due to the time-resolution of paleosol units or the unstable depositional process. They also observed ~66, 56, 33 and 27-ka cycles, which may related to harmonic-interaction cycles and an unstable dust deposition process (LU *et al*., 2004).

Fig. 3a shows that SiO_2/Al_2O_3 molecular ratio can be used as a suitable proxy of original eolian grain-size prior to post-depositional weathering (PENG and GUO, 2001; GUO *et al*., 2004). The fluctuations of SiO_2/Al_2O_3 do not generally correspond to the changes of magnetic susceptibility; rather it exhibits much higher frequency oscillations (Fig. 2). Their values in some parts of the loess units are similar to those in soil units. This fluctuation pattern greatly differs from the timeseries of grain-size obtained from bulk samples.

The spectra calculated for SiO_2/Al_2O_3 of the Xifeng section (Fig. 4c and 4d) are quite different from those of magnetic susceptibility (Fig. 4a) and those of the previously mentioned grain-size timeseries of bulk samples (DING *et al*., 1994, 2002; LU *et al*., 2002, 2004). Using the timescale of KUKLA *et al*. (1990), periods centered at 36.4-ka and 26-ka are clear. Within the accuracy of this independent timescale, the 36.4-ka cycle is attributable to the 40-ka obliquity cycle and the 26-ka peak amy be attributable to the 23-ka precessional one (Fig. 4c). This appears to be confirmed by a spectral analyze (Fig. 4d) using the orbitally-tuned timescale of Heslop et al (2000). A prominent feature is that the eccentricity period, centered at ~100-ka (BERGER and LOUTRE, 1991), is nearly undetectable in SiO_2/Al_2O_3. The larger amplitudes of the ~100-ka signals during the last 1.0 Ma in magnetic susceptibility (Fig. 5a), FeD/FeT (Fig. 5b) and in gain-size of bulk samples (e.g. DING *et al*., 1994) are not observed in the SiO_2/Al_2O_3 ratio (Fig. 5c).

The differences between the proxies closely related with the stratigraphic structure (magnetic susceptibility, FeD/FeT and grain-size changes of bulk samples) and the geochemical proxy of original eolian grain-size (SiO_2/Al_2O_3) are helpful for understanding the climate dynamics in northern China. The temporal changes of susceptibility, FeD/FeT and grain-size of bulk samples resulted indeed from the interaction and mixed effects of the winter forcing (primarily dust accumulation intensity) and the summer forcing (moisture and temperature related to the summer monsoon). Their frequency patterns essentially parallel that of the marine $\delta^{18}O$ records (SHACKLETON *et al*., 1990), indicating a dominant control of the ice-boundary conditions on loess deposition through modulating the aridity of the source areas, the strength of the winter monsoon winds, and hence the intensity of dust accumulation rate. The clear Milankovitch cycles in these proxies indicate strong orbital controls on loess deposition and soil formation. Because of the negligible effect of eccentricity in modulating the solar insolation budget (BERGER and LOUTRE, 1991), the ~100-ka period in geological records posterior to 1.0 Ma is usually interpreted as the signals of global ice-volume variations (IMBRIE *et al*., 1984). The strong ~100-ka period of these proxies for the last 1.0 Ma indicates a strong impact of glacial-interglacial cycles on Asian climate.

The behavior and frequency differences between the grain-size of bulk samples and the original eolian grain-size indicate that post-depositional weathering and soil-forming processes did have led to much finer grain-size in soils, leading to greater contrasts between loess and soil units. A most interesting feature is the near lack of the ~100-ka period in the SiO_2/Al_2O_3 timeseries, indicating a rather weak dynamic link between original eolian grain-size and global ice-volume variations. Rather, the precessional ~23-ka and the obliquity ~41-ka periods suggest a strong control of solar insolation, and the strong ~23-ka period (Fig. 4c, 4d) suggest an insolation-forced factor of low latitude origin.

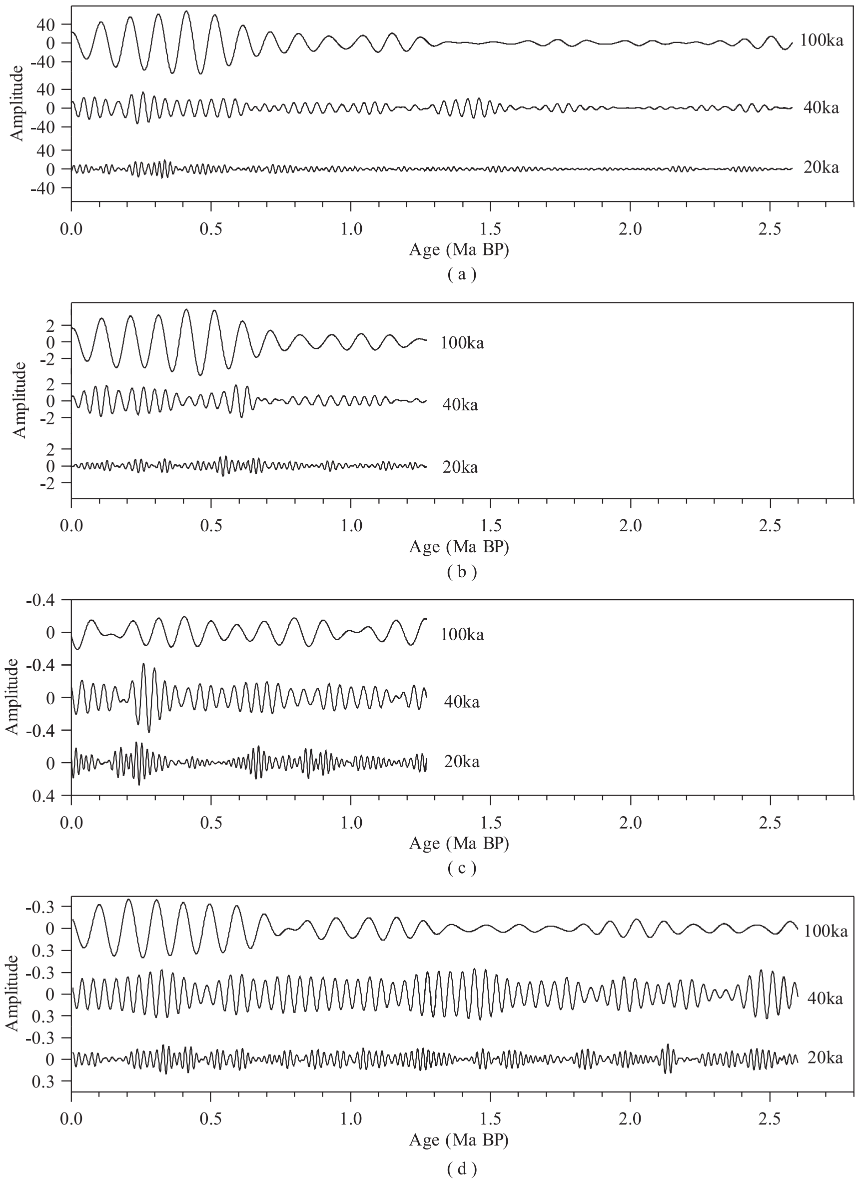

Fig. 5. Band-pass filtered curves at ~100, ~40 and 20-ka bands of (a) magnetic susceptibility, (b) FeD/FeT and (c) SiO_2/Al_2O_3 from the Xifeng loess-soil sequence, compared with those of (d) the marine $\delta^{18}O$ record. Band-pass filters of 0.010±0.002, 0.025±0.005 and 0.050±0.002 are used respectively. $\delta^{18}O$ data are from SHACKLETON *et al.* (1990). Timescale for Xifeng is the same as in Fig. 1

The exact mechanisms through which the original eolian grain-size was more strongly influenced by insolation, but was relatively independent of global ice-volume variations are not yet totally clear, and need additional studies. These features are helpful to further understand the processes related to eolian deflation, transportation and deposition. In view of the strong ~23-ka period that suggests an insolation-forced factor of low latitude origin, these signals should be generated by the summer forcing from the low-latitude (PRELL and KUTZBACH, 1987, 1992; CLEMENS *et al.*, 1991).

The eolian dust forming the loess deposits in northern China was originated from the deserts north and northwest to the Loess Plateau (LIU, 1985; ZHANG *et al.*, 1997). The distance between the deserts and a given loess deposition site has strong impacts on controlling eolian grain-size changes (LIU, 1985; REN *et al.*, 1996). A number of studies have demonstrated that the south margins of the deserts have experienced drastic south-north oscillations following the strength of the summer monsoon (DONG *et al.*, 1996; SUN *et al.*, 1998; DING *et al.*, 1999). These mechanisms provide a possible explanation for the combination of a moderate ~40-ka cycle and a strong ~23-ka cycle in the original eolian grain-size timeseries: higher low-latitude insolation values would lead to more moisture from the low-latitudes through summer circulations (PRELL and KUTZBACH, 1992; CLEMENS *et al.*, 1991), of which the front would penetrate more deeply into the desert lands in northern China. Consequently, the surface conditions (such as the vegetation situation) in the south margins of the deserts would oscillate following the fluctuations of the strength of these summer circulations, leading to eolian grain-size changes for a given site at the rhythms of insolation. If these were the cases, the variations of original eolian grain-size would bear strong signals of summer moisture.

It is well known that eolian dust was transported by the Asian winter monsoon to the Loess Plateau region (LIU, 1985; AN *et al.*, 1991), of which the strength would be significantly controlled by the intensity of the Siberian High (CHEN *et al.*, 1991). If eolian grain-size is more dependent on the strength of winter monsoon, we would expect to find strong ~100-ka signals, the dominant rhythm of ice-volume changes for the last one millions years (RUDDIMAN, *et al*., 1989; IMBRIE *et al*., 1993) since larger ice coverage in the north pole would significantly enhance the Siberian High (KUTZBACH and WRIGHT, 1985). However, we clearly find that original eolian grain-size timeseries are characterized by moderate ~40-ka and strong ~23-ka signals and a near-lack of the ~100-ka cycle, suggesting a strong dependence on the summer forcing, probably through modulating the amount of summer moisture to the drylands north to the Loess Plateau.

Conclusive remarks

Our comparative study on the frequency patterns of various climate proxies from the Quaternary loess--soil sequences therefore provides several interesting aspects about the orbital signals in these records.

(1) The clear orbital signals in the frequently used climate proxies from Chinese loess-soil sequences indicate the strong effects of Earth's orbital changes on the East-Asian monsoon climate, and therefore greatly support the Milankovitch theory of paleoclimate (MILANKOVITCH, 1941; BERGER, 1977). However, efforts are needed in exploring new climate proxies with special emphasis to distinguish the summer and winter signals.

(2) The rough-similar spectral patterns of magnetic susceptibility, some chemical weathering proxies and gain-size of bulk samples with that of the marine $\delta^{18}O$ record indicate that the basic stratigraphy structure of the Quaternary loess-soil sequences is primarily modulated by the winter forcing, through modulating the rhythm of dust accumulation intensity and probably also the strength of winter monsoon. In terms of frequency, the summer signals in these proxies were significantly marked by the predominance of the winter signals. However, these proxies bear also some significant characteristics the summer monsoon changes, especially within the paleosol units. For example, the warm-humid extremes corresponding to marine stage 11, 13 and 15 are clearly documented by these proxies (GUO *et al*., 1998, 2000). The onset of the 100-ka signals in these proxies at ~1.3 Ma BP, earlier than for marine records (IMBRIE *et al.,* 1984, 1993; RUDDIMAN *et al.,* 1989), may also originated from a summer effect.

(3) Our new geochemical proxy (SiO_2/Al_2O_3 molecular ratio), which rules out the effects of post-depositional weathering modification, shows a near-independence of the original eolian grain-size on the glacial-interglacial changes. Original eolian grain-size fluctuated over the past 1.27 Ma with a clear ~40-ka period, a strong ~23-ka period and a near-lack of the ~100-ka period, suggesting a predominance of a summer forcing relative to low-latitude insolation changes. These are likely attributable to the effects of the summer moisture through modulating the land surface conditions of the desert margins. The similarity of spectral pattern between bulk sample grain-size and marine $\delta^{18}O$ record is attributable to post-depositional weathering during interglacial times, leading to a significantly fining of grain-size in soils, and thus to greater contrasts between loess and soil units

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