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Periodicities of palaeoclimatic variations recorded by loess-paleosol sequences in China

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Abstract

Palaeoclimatic periodicity recorded by Chinese loess-paleosol sequence has been investigated for a number of years. However, conclusions from previous investigations are still controversial, and interpretation of cycle evolution is quite equivocal. In this study, two typical loess-paleosol sequences (148 and 191 m in thickness, respectively) in the central Chinese Loess Plateau are sampled (3872 samples total) and measured for grain size distribution and magnetic susceptibility in order to reconstruct the palaeoclimatic changes over the past three million years. On the basis of a new, sensitive proxy indicator of palaeoclimate and a newly developed independent time scale (not orbitally-tuned), two time series of Asian dust storm variations, which are highly related to the palaeoclimate system changes, are obtained. Wavelet and spectrum analyses indicate that there are approximately 400, 200, 100, 66, 57, 41, 31, 27 and 22 kyr cycles in these typical loess-paleosol records. Some orbital-driven cycles are weak and are not well presented in the new time series while some non-orbital cycles are found. Since the eccentricity frequencies of the solar irradiance of approximately 400 and 100 kyr are preserved in these palaeoclimatic sequences, the lack of relatively short-time orbital cycles of 41-kyr-obliquity and 22-kyr-precession cycles in part of the two time series may be explained by the relatively low time-resolution of the loess-paleosol deposits. Through an astronomical estimate, the obliquity and precession cycles should leave stronger footprints on records of palaeoclimatic variations at the middle latitudes of the northern hemisphere. The presence of non-orbital cycles may be explained by unstable dust deposition processes and pedogenic processes in the paleosol units, which could misrepresent or obliterate the imprint of the solar irradiance frequency. This conclusion may indicate that one should be cautious when investigating specific palaeoclimatic changes (e.g., at sub-orbital time scales) recorded in loess deposits, especially in the paleosol units.

1. Introduction

Chinese loess is regarded as one of the best continental archives of palaeoclimatic and palaeoenvironmental changes of the Late Cenozoic era (Liu, 1985; Kukla and An, 1989; An et al., 1990; Liu and Ding, 1998). There are numerous papers that investigate palaeoclimatic periodicities recorded in this loess-paleosol deposit, and it is widely accepted that orbital cycles are preserved; at the same time, other non-orbital cycles are also reported (Lu, 1981; Kukla et al., 1990; An et al., 1990; Xu and Liu, 1994; Ding et al., 1994; Van Huissteden et al., 1997; Liu and Ding, 1998; Lu et al., 2002). Discrepancies in understanding periodicities recorded in the loess deposit persist, however, because some results claim perfect orbital frequencies, while others do not. The notable drawbacks in most of the previous investigations are: (1) use of palaeoclimatic proxy indicators which have unclear implications; (2) use of inaccurate time scales; (3) use of different mathematical tools; and (4) logical mistakes with respect to the examination of orbital cycles with an orbitally-tuned time scale.

Recently, van Huissteden et al. (1997) established an absolute chronology for the Chinese loess deposit, and the time series was analyzed by the maximum entropy

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spectrum and Thompson's multi-taper method. Their results show both orbital and non-orbital cycles in the loess record, which differs from the perfect-frequency record (Liu and Ding, 1998), but agrees with the conclusions of Lu et al. (2002). However, variations in the lower part (the low Wucheng formation) in van Huisstuden et al.'s record are different from earlier results by Kukla and An (1989) and from the recent investigation of Lu et al. (1999), suggesting an inaccuracy in the sampling. In addition, one site record should be further examined to confirm cycles recorded in the loess-paleosol record, and since traditional spectral analysis cannot describe entire frequencies in one picture, some useful information may be lost. Use of the wavelet transform and more site records, on the other hand, would help to resolve the problems (Lu et al., 2002).

In this study we extend the examination of the periodicities preserved in the Chinese loess-paleosol sequences to more than the past three million years. The grain-size index of the loess deposit, which has been regarded as a good proxy indicator of strength and frequency of the dust storms in central Asia, is employed. An absolute, not orbitally-tuned time scale is developed for the two typical loess-paleosol sequences in the Loess Plateau. Thus, two complete 3-million-year palaeoclimatic and palaeoenvironmental time series are obtained. Both the continuous wavelet transforms and the classical spectral analyses (Blackman–Tukey method) are employed to reveal the cycles in the loess-palaeosol sequence.

2. Proxy indicator of the palaeoclimatic changes and a new independent time-scale

There are many deserts and Gobi regions in central Asia and north China that produce mineral dust, which can be transported to adjacent regions and over the Pacific Ocean (Duce et al., 1980; Pye and Zhou, 1989; Rea, 1994). Under dry conditions, more mineral dust is provided via frequent major dust storms that contribute sand particles to the nearby Chinese loess deposits (Liu, 1985; Zhang et al., 1999). Therefore, the sand fraction in the loess and their underlying aeolian "Red Clay" deposits (a type of loessic sediment, Ding et al., 1998; Sun et al., 1998; Lu et al., 2001; Guo et al., 2002; Vandenberghe et al., 2004) are highly related to dry phases and associated with the major dust storms. This is because: (1) dynamic simulations and field observations have shown that sand particles are generally not transported beyond ~100 km under normal atmospheric circulation conditions except during the major dust storms (Pye, 1987; Zhang et al., 1999); (2) major dust storms occurred more frequently during the dry periods because there was less vegetation cover and stronger winds, bringing more sand particles to be deposited into the Loess Plateau (Liu, 1985; Pye and Zhou, 1989). The strengthened East Asia winter monsoon circulation is associated with cold and dry climate in the glacial period, with more frequent dust storms occurring in and around the Loess Plateau. The dry phases coincide with the frequent major dust storms and the higher loess sedimentation rates (Ding et al., 1999; Sun et al., 1999; Nugteren et al., 2004a, b). Therefore, the sand fraction, namely the particles >63 μms in the loess deposit, is a good proxy indicator of variations of the major dust storms, and this fraction is strongly related to the wet–dry climate changes in central and East Asia.

Two typical loess-paleosol-Red Clay sections of Luochuan (LC) (35°49′N and 109°30′E, with a thickness of 148 m) and Xifeng (XF) (34°45′N and 107°49′E, with a thickness of 191 m) in the central Chinese Loess Plateau have been continuously and densely sampled. Both grain-size distribution and magnetic susceptibility were measured for all 3872 samples (Fig. 1). Variations of the grain-size distribution and the magnetic susceptibility correlated well in these two sequences, which are regarded as the best two loess-paleosol sequences with complete stratigraphy and reasonable time resolution in the Chinese Loess Plateau. Thermoluminescene dating (TL), Optically stimulated luminescence dating (OSL) and palaeomagnetic reversals offer absolute age controls to these two loess-paleosol sequences, and the age frame of the two sections are well determined (Liu, 1985; Liu et al., 1988; Kukla and An, 1989; Forman, 1991; Lai, 1997).

Two steps were taken to develop an independent time scale. First, many absolute dating efforts across the Loess Plateau have demonstrated that the first loess unit (L1) and the first reddish paleosol unit (S1) in the upper part of the loess section were formed during the last glacial and interglacial periods, respectively. A detailed investigation of an absolute luminescence dating performed on the Luochuan and Xifeng sections further support this conclusion (Forman, 1991; Lai, 1997; Wang, personal communication). The uppermost part of the sections was continuously deposited during the Holocene, and the age of the top is 0 kyr before present (BP) (Liu, 1985; Kukla, 1987; An et al., 1991). The age of the bottom of the S1 paleosol was determined to be 130 kyr BP (Liu, 1985; Kukla, 1987; An et al., 1991). Palaeomagnetic investigations of these two sections provide time controls on the lower part (Liu, 1985; Liu et al., 1988; Kukla and An, 1989). The Brunhess/Matuyama (B/M) and Jaramillo/Matuyama (J/M) boundaries are located at the 8th (L8) and 13th (L13) loess unit, which are subsequently dated at 780 and 1049 kyr BP, respectively. Ages of the top and the bottom of the Olduvai subchron are 1770 and 1950 kyr BP, which can be clearly assigned to depths in the

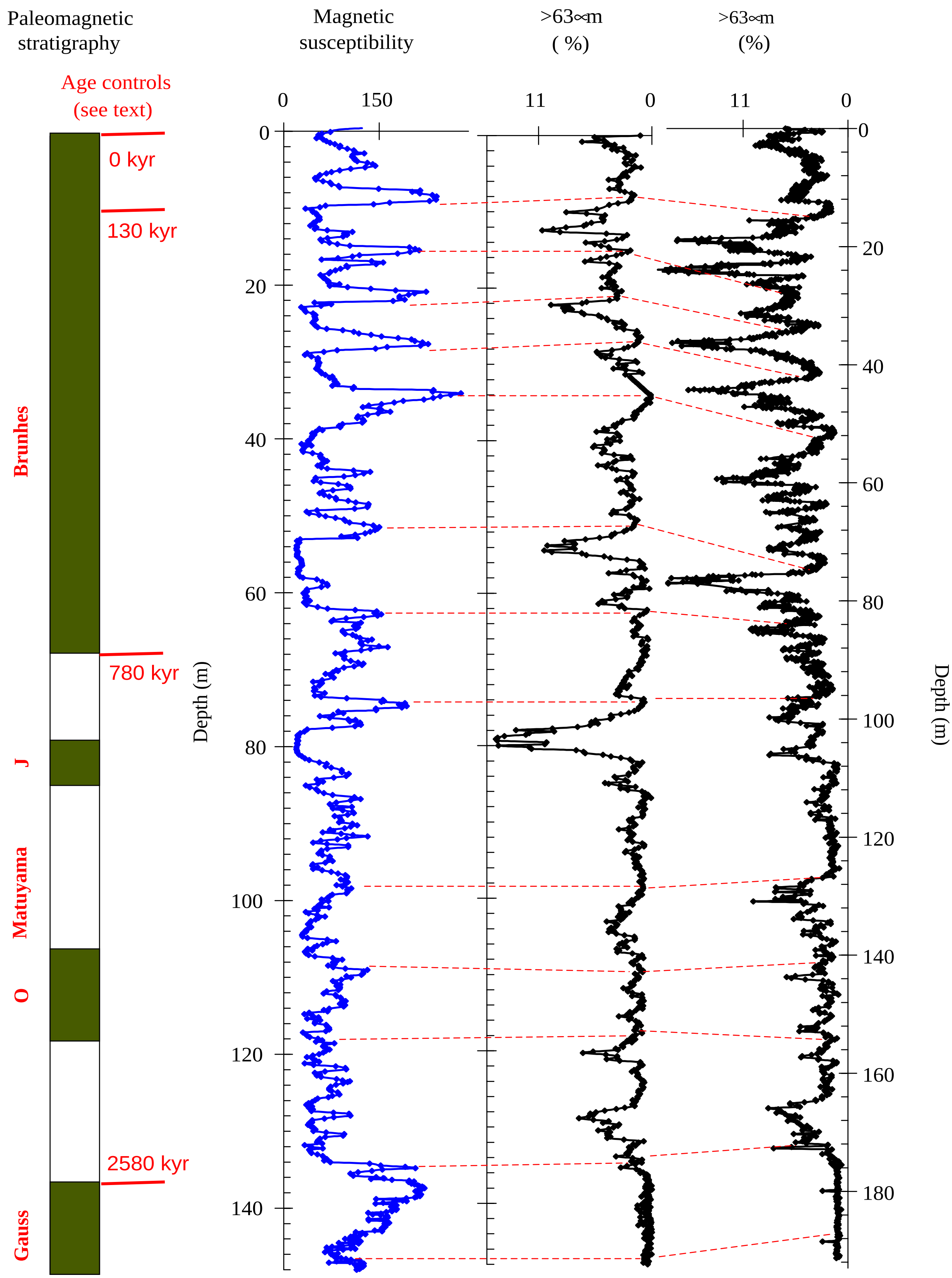

Fig. 1. Magnetic susceptibility and grain-size variations of Luochuan and Xifeng records in the central Chinese Loess Plateau. The sections are sampled at intervals of 5–20 cm, with a total of 3872 samples. Palaeomagnetic stratigraphy is from the references (Heller and Liu, 1982; Liu et al., 1988; Kukla and An, 1989). The left curve shows the magnetic susceptibility changes with depth, the middle and right curves show changes of the content of >63 μm particles with depth in the Luochuan and Xifeng records, respectively. Please note, we employ the content of >63 μm particles as a proxy indicator of major dust storm and wet–dry variations, and we employ the content of >30 μm particles as a proxy indicator of the dust sedimentation rate in the time-scale model. Please see the text for details.

magnetic susceptibility curves (refer to Fig. 1). The Matuyama/Gauess (M/G) boundary is dated at 2580 kyr BP at the bottom of the loess deposit (Kukla and An, 1989; Cande and Kent, 1995). The age beyond the M/G boundary is extrapolated by referring to the sedimentation rate of its nearest upper part.

Second, the age of each sampling level is interpolated using an age model. Because the dust sedimentation rate is proportional to the particle size in the loess deposit (An et al., 1991; Zhang et al., 1994, 1999; Porter and An, 1995; Vandenberghe et al., 1997; Nugteren et al., 2004a, b), the grain-size can be used as a proxy for the sedimentation rate for the loess-paleosol-Red Clay deposit. A positive relationship exists between the grain-size and the sedimentation rate, although the details of this quantitative relationship should be explored further. The following model (Porter and An, 1995) is used to interpolate the age of each sampling level:

$$T_m = T_1 + (T_2 - T_1)\left(\sum_{i=1}^{m} A_i^{-1} \Big/ \sum_{i=1}^{n} A_i^{-1}\right),$$

where T_1 and T_2 are the age control points, respectively (the points of age control are based on absolute luminescence dating and palaeomagnetic investigations); A_i is the accumulation rate at level i, which is assumed to be proportional to the content of the $>30\,\mu m$ particles; n is the total sampling level between T_1 and T_2; and m is the sampling level at T_1 and T_2.

One modification to the model of Porter and An (1995) is that we assume that the content of $>30\,\mu m$ particles to be proportional to the accumulation rate rather than the $>40\,\mu m$ size fraction used in their model. This is because detailed analysis of the grain-size distribution in the loess deposit at LC and XF shows that the content of $>30\,\mu m$ particle is more strongly associated with the strength of the winter monsoon (Lu et al., 1997; Lu and An, 1998) and the sedimentation rate (Lu and Sun, 2000). Using this approach, two new time series of variations of the content of the $>63\,\mu m$ particle fraction are obtained, which are regarded as good indicators of the variations of the wet–dry phase and major dust storms (Fig. 1). There are three potential sources of error in the new time scale: (1) The age

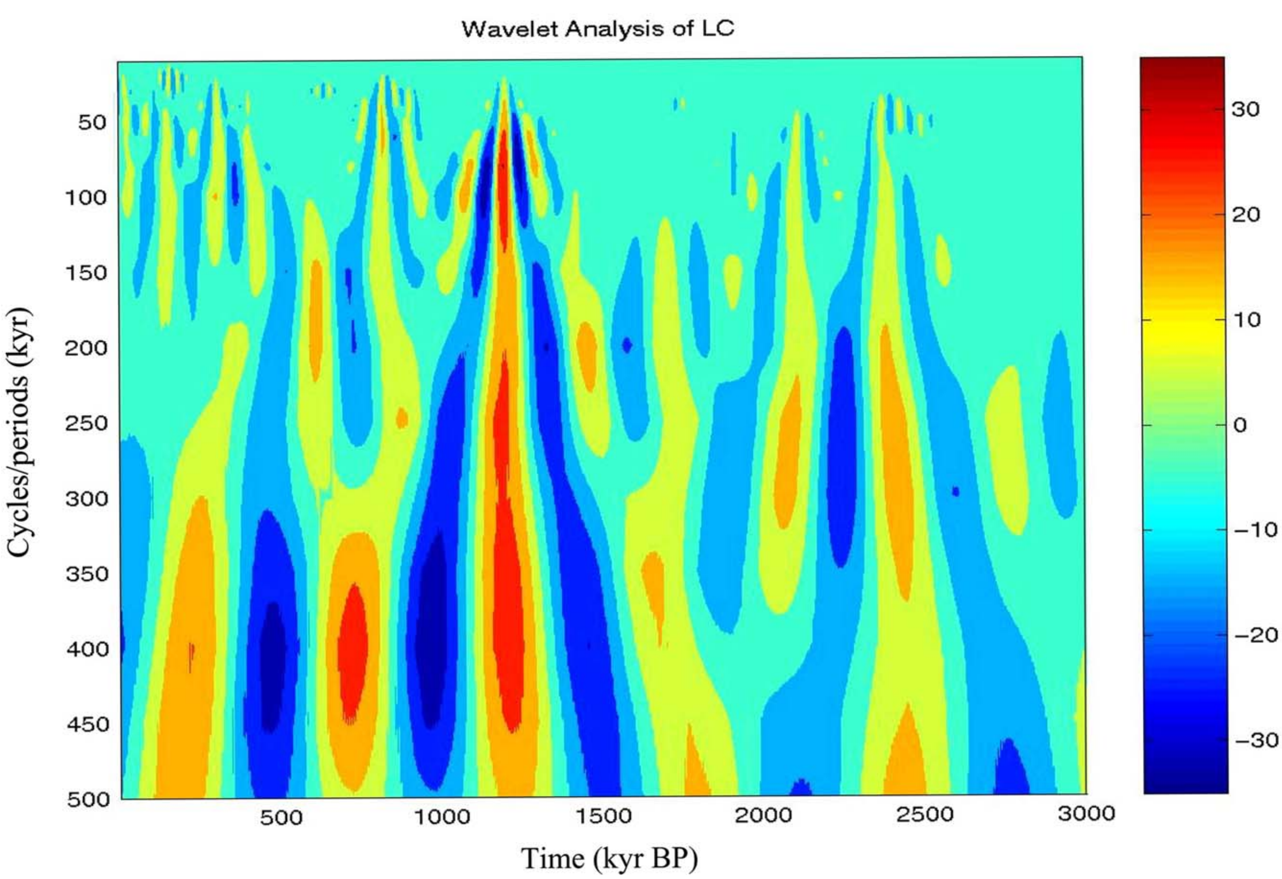

Fig. 2a. Results of the wavelet transform of the LC and XF time series. The X-axis is the time scale of the wet–dry variations (kyr) and the Y-axis corresponds to the frequencies or cycles (kyr). The blue represents the phase of the dry period with stronger and more frequent dust storms, while the red indicates the phase of weaker and less frequent dust storm events in the wet period. These figures show the frequency evolution of the palaeoclimatic changes during the past 3 million years.

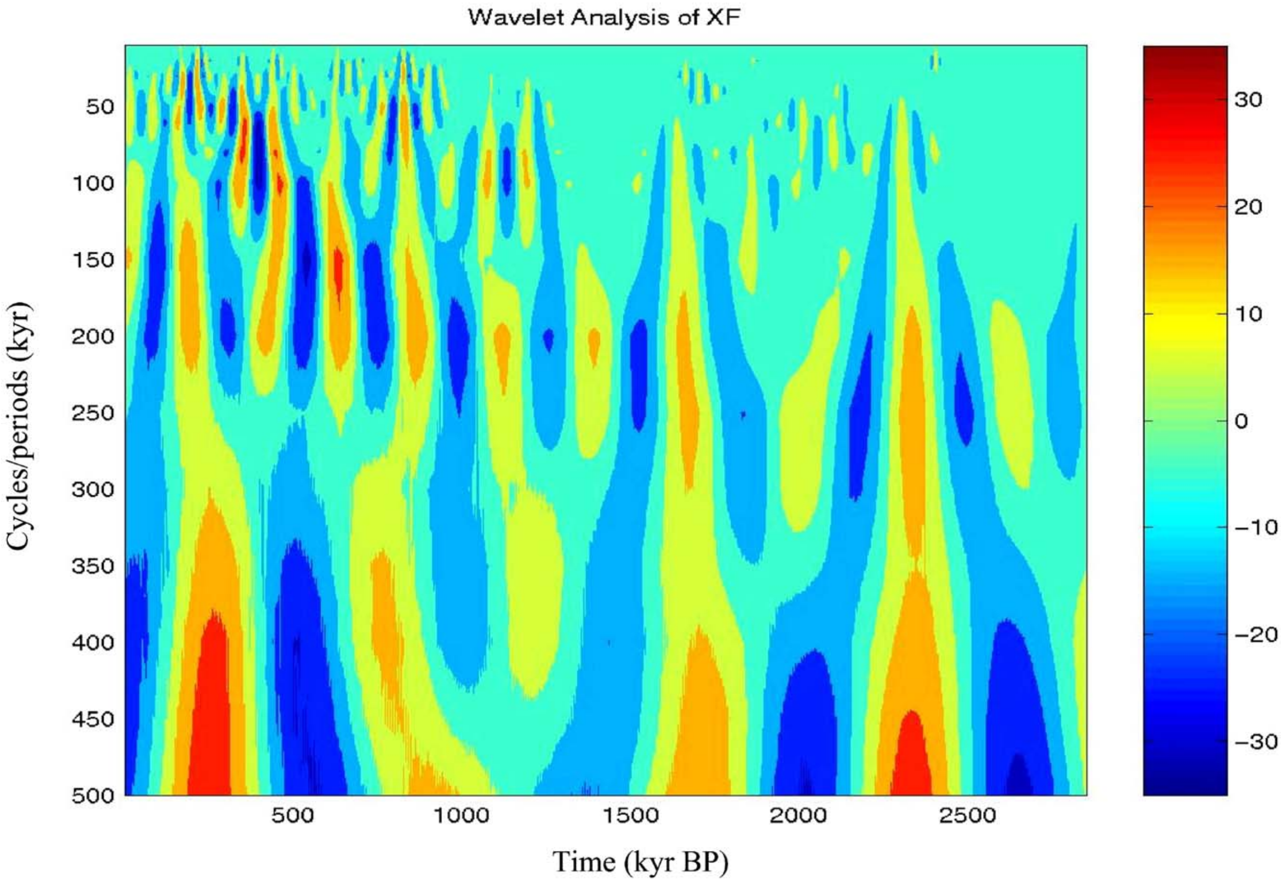

Fig. 2b.

control points assigned may cause errors of several thousand years due to a shift of different sampling levels. Nevertheless, the systematic shift error should not change cycles in the time series, and the error in time is much shorter than the periodicities discussed in this paper. (2) Deposit compaction may have an impact on the time scales. Unfortunately, there is no reliable way to exclude such influences at present time because there is several aspects control the bulk density, which is employed to estimate the compaction (e.g., Nugteren et al., 2004a). However, the compaction may have a small impaction on the palaeoclimatic of the tens of thousands-year cycles. (3) An accurate, quantitative relationship between the grain-size distribution and the sedimentation rate is not easy to obtain using the currently available data, because such a relationship changes with site and sampling amount. Therefore, a qualitative relationship between the dust sedimentation rate and the grain-size distribution is employed in this study. Despite these potential errors in the newly developed time scale, it is believed to be by far one of the best independent time scales for the Chinese loess deposit. It considers changes in the sedimentation rates, it employs absolute age controls, it uses a reasonable age model, and the input errors cannot significantly influence the tens of thousands-year cycle in the time series.

Both the wavelet transform and classical power spectral analysis are employed to examine periodicities of the palaeoclimatic variations recorded by the loess deposit. One advantage of using wavelet transform over traditional spectrum analyses is that it can provide flexible localized time-frequency (or space-wavelength) information (Weng and Lau, 1994; Zhang et al., 2001). Discrete wavelet transform and continuous wavelet transform are two fundamental kinds of wavelet analysis. Continuous wavelet analysis is more suitable for most real-valued geophysical time series (Weng and Lau, 1994). By using continuous wavelet transform, one can project the original signal to any frequency (or wavelength) domain and thereby obtain amplitude and phase in wavenumber space. The continuous wavelet transform of a square integral function F is defined as

$$W_F(a,b) = \langle F, I^*_{a,b} \rangle = a^{-1/2} \int_{-\infty}^{\infty} F(t) I^* \left(\frac{t-b}{a} \right) \mathrm{d}t,$$

where I is the base wavelet function (the asterisk denotes a complex conjugate); F is a generic function; a is the dilation parameter; and b is the translation parameter (Weng and Lau, 1994).

The Morlet function:

$$I(t) = e^{ik_I t} e^{-(|t|^2/2)}$$

is a plane wave with wavevector k_I modulated by a Gaussian envelope of unit width. This function was chosen for the current study since it is one of the mostly widely used base wavelet functions for continuous wavelet analysis [refer to Weng and Lau (1994) for more details]. The contribution from different periods/cycles as a function of time is plotted in Figs. 2a and b and will be discussed in the following sections.

At the same time, a traditional spectral analysis is applied. The classical Blackman–Tukey method (Blackman and Tukey, 1958) forms the spectral estimate by calculating the Fourier transform of the autocorrelation sequence. That is, the power spectral density is equal to the Fourier transform of the autocorrelation function (Jenkins and Watts, 1968). The Blackman–Tukey method can be implemented as follows: (1) Compute the estimated autocorrelation; (2) Multiply the estimated autocorrelation with a window; (3) Calculate the Discrete Fourier Transform of the estimated autocorrelation. The Blackman–Tukey (or windowed correlogram) method is quite efficient for estimating the continuous part of the spectrum. The method helps reduce the estimate's variance and bias and attenuates the leakage effects of the periodogram. Therefore, the method is widely used in the earth sciences. The spectral analysis with the Blackman–Tukey method is applied both to segments of the time series sliced every 500 kyr and to the entire time series (Fig. 3).

3. Palaeoclimatic periodicities in Chinese loess-paleosol sequence

An approximately 400-kyr cycle is visible in the LC record over the past three million years, and it weakly appears in the XF record (Figs. 2a, b and 3). An approximately 100-kyr cycle is apparently observed from 2600 kyr BP and becomes stronger at around 1300 kyr BP and thereafter in the LC record. In the XF record, the 100-kyr cycle is present throughout the entire time series but with very weak intensity, and it strengthens from ~ 1300-kyr BP to the present. These periodicities may be correlated with the approximately 400- and 100-kyr eccentricity cycles of the Earth's orbit, which induces solar insolation changes (Berger and Loutre, 1991). The shorter orbital cycles appear at different stages in the two time series: the 41-kyr cycle is present during the 500–1000-kyr BP, 1500–2000-kyr BP, and 2500–3000 kyr BP periods in the LC record, and in the 0–500 kyr BP and 1500–2000 kyr BP periods in the XF record. The approximately 22-kyr cycle is present during the 1500–3000-kyr BP period in the LC record and during the 2000–2500-kyr BP period in the XF record. After examining the wavelet spectrum of the LC and XF time series, the longer cycles of 400 and 100-kyr are more persistent and stronger than the shorter cycles of 41- and 22-kyr, albeit the shorter cycles should be theoretically stronger in the loess record.

The approximately 400-kyr cycle has been reported in the Chinese loess records in the previous literature but was revealed from an orbitally-tuned time series (Liu and Ding, 1998). The present investigation detects the approximately 400-kyr cycle in the Chinese loess record for the first time from an absolute, not an orbitally-tuned time series. The fact that this periodicity was missed in previous investigations may be because of the difficulty of obtaining a long, continuous and high-resolution record. The ~ 400-kyr as well as the ~ 100-kyr periodicity present in the dust time series offers new evidence that changes in the Earth's orbit induced irradiance changes that may have forced changes in the major dust storms and the wet–dry phase in central and East Asia.

There are also some other less persistent and weaker periodicities of approximately 27-, 33-, 56-, 66- and 200–300-kyr present in the LC and XF records. These do not correlate with any of the known forces at these time scales. These cycles may possibly originate from the harmonics or interactions of the orbital cycles, which is quite normal in the spectral analysis of palaeoclimatic time series (King, 1996). It is also quite possible that these cycles are caused by imperfect preservation of the loess deposit and the very low time resolution of the paleosol records. For example, the S1 paleosol occupied a time of around 60 kyr with no precession or obliquity cycle being detected. This may show that the paleosol unit has a very low time-resolution (even lower than twenty thousand years or more) ability to capture the Asian monsoon climate changes compared with other approaches, such as the well-dated stalagmite record in south China (Yuan et al., 2004).

4. Discussion: depositional process and time resolution of the loess deposit

These two loess-paleosol sections are located at the loess tableland (*Yuan*, a kind of loess landform with flat and complete stratigraphies) where their stratigraphy is nearly identical and can be correlated with other loess-paleosol sequences across the Loess Plateau, an area of hundreds of thousands of square kilometers. Thus, these two sections are among the best and most representative sections from the Chinese Loess Plateau. Perfect correlations between these two sequences (Fig. 1) and with previous results (Liu, 1985; Liu et al., 1988; Kukla and An, 1989; Lu et al., 1999) give further confidence in our sampling and measurement processes. The two typical loess-paleosol sequences are well dated by

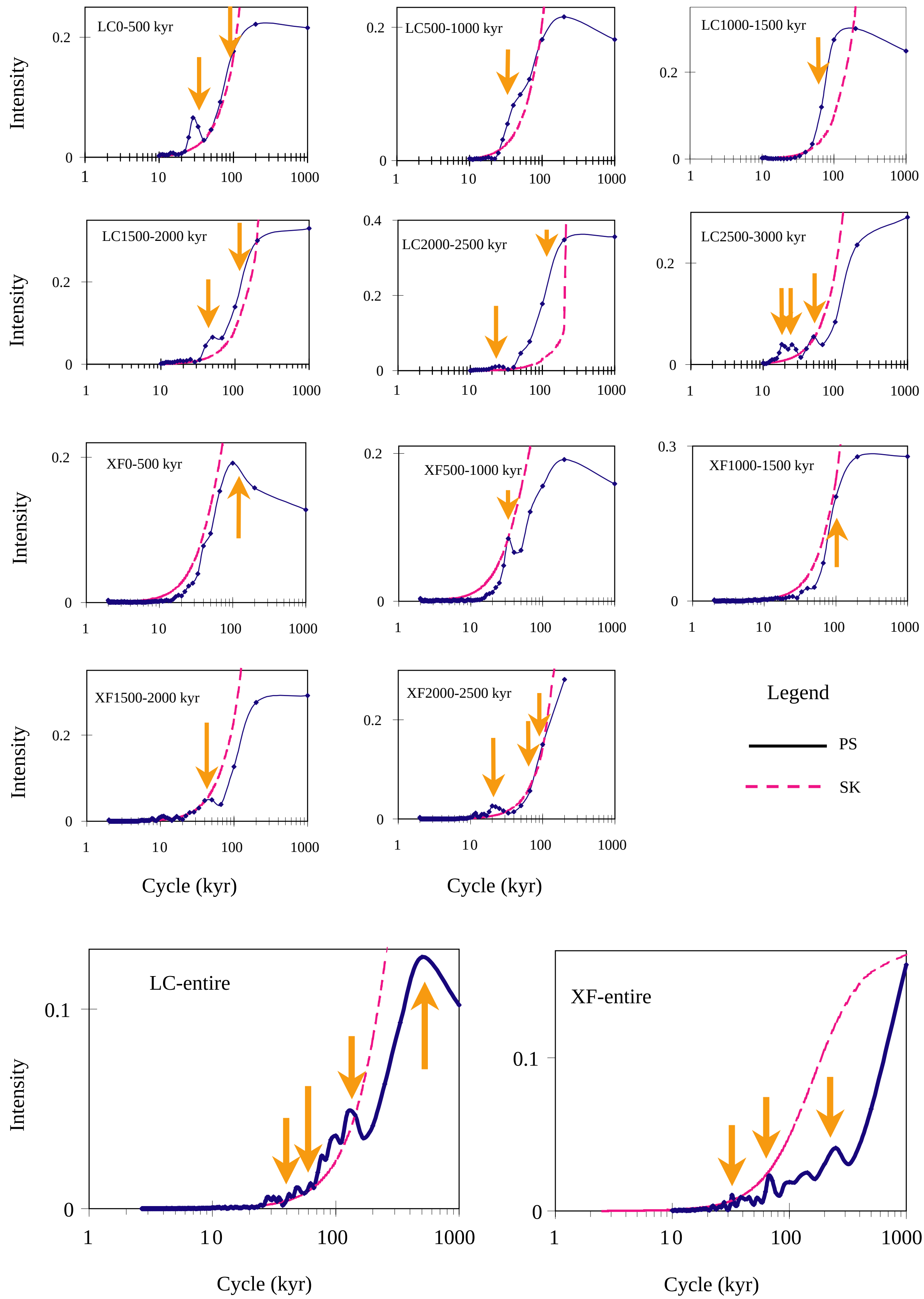

Fig. 3. Power spectrum analysis of the two time series. Spectral analysis is performed to segments of the time series sliced every 500 kyr and to the entire time series. The broken line indicates the 95% confidence level (please see the legend).

previous investigations (Heller and Liu, 1982; Liu, 1985; Liu et al., 1988; Kukla and An, 1989; Forman, 1991; Lai, 1997), further supporting that the time-scale is credible. The dust sedimentation rate model, one of the best for Chinese loess deposits so far, is used to interpolate the age of each sampling level. Since much evidence shows that the grain-size and the dust sedimentation rate are strongly and proportionally related (Porter and An 1995; Vandenberghe et al., 1997; Lu and Sun, 2000; Nugteren et al., 2004a, b), that the content of the $>30\,\mu m$ particles is employed as a good proxy indicator of the dust sedimentation rate is acceptable. Thus, a good time scale for the loess deposit is obtained on the basis of the age model. Both traditional spectral analysis and the recently developed wavelet transform have been used to examine the frequency in the time series. Therefore, the results present a complete picture of the evolution of the cycle in the Chinese loess record.

It is believed that changes in solar irradiance are the forcing function for the global glacial-interglacial changes (Imbrie et al., 1984; Berger and Loutre, 1991; Clemens and Tiedemann, 1997; Kashiwaya et al., 2001; Liu and Herbert, 2004). Linkage of the solar radiation and the wet–dry phase variations in central and East Asia may be strongly related to the glacial-interglacial alterations in the Northern Hemisphere. There are no drivers other than the solar radiation changes that are known to force the wet–dry phase and the major dust storm changes with $\sim$ 400- and 100-kyr cycles. Shifts of the cycles at $\sim$ 1800-kyr BP and at $\sim$ 1300-kyr BP are comparable with the ice volume changes in the Northern Hemisphere (Liu and Ding, 1993). We believe these phase shifts may be related to changes in ice cover, and the origin of these changes is still to be determined (Shackleton, 2000). If the variation of the solar irradiance is the fundamental driver of the wet–dry changes in central Asia, the orbital frequency should be completely preserved in the loess record. This investigation shows that only weaker cycles of obliquity and precession are preserved in the loess deposits. One tentative explanation is that the low dust deposition rate and the strong pedogenic process during the interglacial periods cause a lower time resolution, so that the shorter cycles are partially obliterated. Thus, the imperfect record of the loess time series may cause some spurious cycles.

Even though the approximately 400- and 100-kyr cycles of the solar irradiance variations are weaker than the 41- and 22-kyr cycles from theoretical calculations, the longer-time cycles are clearly preserved in the loess-paleosol record revealed by the wavelet transform analysis. One possible explanation is that the time-resolution in the paleosol unit is quite low, so that the wet–dry variations at the 41- and 22-kyr cycles are not well preserved. Since this time-resolution is quite low, previous studies that have concluded that perfect orbital cycles are recorded in the loess deposits should be carefully reexamined. We acknowledge that part of the loess deposit may have a time resolution of several thousand years, but this only holds for the high-sedimentation loess units. In other words, the loess deposits certainly record some orbital cycles but some of the cycles may be misrepresented. Our current conclusion contradicts the long-held view that Chinese loess deposits have preserved perfect orbital cycles during the past three million years. It is suggested that the dust deposition is unstable without a perfectly continuous sedimentation rate. In addition, the dust sediment is significantly modified and disturbed such that the time-resolution in part of the paleosol units is quite low.

5. Summary

Variations of the Earth orbit trajectory, which induce solar irradiation changes on the Earth, forced the climatic and the environmental changes in central and East Asia at tens to hundreds of thousands of years time scales. Only the longer cycles of approximately 400- and 100-kyr are well recorded in the Chinese loess-paleososl sequence. The theoretically stronger cycles of 41- and 22-kyr are episodically missing in the loess record because of the relatively low time-resolution of the paleosol units or the unstable depositional process of the dust. There are also cycles of 66-, 56-, 33- and 27-kyr with quite strong intensity at different stages in the loess time series. These can be explained by assuming harmonic-interaction cycles and an unstable dust deposition process.

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