

East Asian monsoon instability at the stage 5a/4 transition

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The physics involved in the abrupt climate changes of the late Quaternary have eluded paleoclimatologists for many years. More paleoclimatic records characteristic of different elements of the global climate system are needed for better understanding of the cause–feedback relationships in the system. The East Asian monsoon is an important part of the global climate system and the mechanical links between the East Asian monsoon and other climatic elements around the world may hold a key to our knowledge of abrupt climate changes in East Asia and probably over a larger part of the globe. Previous studies have detected millennial-scale winter monsoon oscillations during the last glaciation and probably also during the last interglaciation in loess sequences across China. However, less attention has been paid to the abrupt summer monsoon changes and the stage 5a/4 transition, an important period for the evolution of the East Asian monsoon when the global climate shifted towards the last glaciation. Here we report on two loess sections from eastern China which were dated using a thermoluminescence (TL) technique. The pedogenic and other sediment parameters suggest that the summer monsoon experienced a two-step abrupt retreat at the stage 5a/4 transition. The variations in the proxies for the winter monsoon are synchronized with the summer monsoon proxies during this brief interval, implying a direct and immediate link between high latitude and low latitude mechanisms. These changes may be correlated with similar climatic oscillations observed in the North Atlantic, Europe and Antarctica, raising the possibility that the forcing factors that induced these changes are global in extent.

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The past decade has witnessed considerable expansion of studies of rapid climate changes recorded in ocean sediments, ice cores and other deposits (Heinrich 1988; Broecker *et al.* 1992; Bond *et al.* 1993, 1997; Bond & Lotti 1995; Keigwin & Jones 1994; Keigwin *et al.* 1994; Porter & An 1995; Lowell *et al.* 1995; Oppo & Lehman 1995; Dansgaard *et al.* 1993; Grootes *et al.* 1993). Millennial-scale climatic oscillations have been detected in sediments not only during the last glaciation (Bond & Lotti 1995; Dansgaard *et al.* 1993) but also in the last interglaciation (Keigwin *et al.* 1994; Oppo & Lehman 1995; McManus *et al.* 1994; An & Porter 1997) as well as in the Holocene (O'Brien *et al.* 1995; Bond *et al.* 1997).

One important paleoclimatic archive, Chinese loess, has recorded the evolution of the East Asian monsoon during the late Pliocene–Pleistocene (Liu *et al.* 1985; Kukla & An 1989; Rutter *et al.* 1991; Ding *et al.* 1994). In recent years, studies of the millennial-scale climatic instability that is imprinted in the loess sections of the last glacial–interglacial cycle (Xiao *et al.* 1995; Porter & An 1995; An & Porter 1997; Guo *et al.* 1996) and other glacial periods (Ding *et al.* 1999) have been performed. It is estimated that the winter monsoon was unstable during the last glacial period (Xiao *et al.* 1995; Porter & An 1995; Liu & Ding 1998; Ren *et al.* 1996) and probably also during the last interglaciation (An & Porter 1997). For the summer monsoon, a few studies have also reported the occurrence of suborbital scale oscillations in the last glacial period (Malan loess unit

(Guo *et al.* 1996; Fang *et al.* 1999). Less attention has been paid to the transition of the last interglacial period to the last glacial period, oxygen isotope stage 5a/4, which corresponds to the S1–L1 (Malan loess) transition. As it occurs when the global climate shifted towards the last glaciation, the S1–L1 transition is important for understanding the evolution of the East Asian monsoons and the mechanical links between the East Asian monsoons and other elements of the global climate system.

Here we present data on the S1–L1 transition from two loess sections, but especially from the Zhaitang section in Beijing. Our data reveal that at the S1–L1 transition (stage 5/4), the East Asian Monsoons were characterized by a two-step abrupt change where the increased instability of the summer monsoon may be directly linked to the winter monsoon fluctuations.

Geological setting and methods

Our two sections are found within the Beijing region, an important loess-covered area outside the Loess Plateau in the eastern part of North China. These sections lie within the northern front of the present-day summer monsoon, thus the loess record in this region would have been sensitive to any abrupt changes in the summer monsoon strength in the past. The Zhaitang loess section (39°58'33"N, 115°41'7"E) (Fig. 1) is an exposure 70 km west of Beijing (An & Lu 1984).

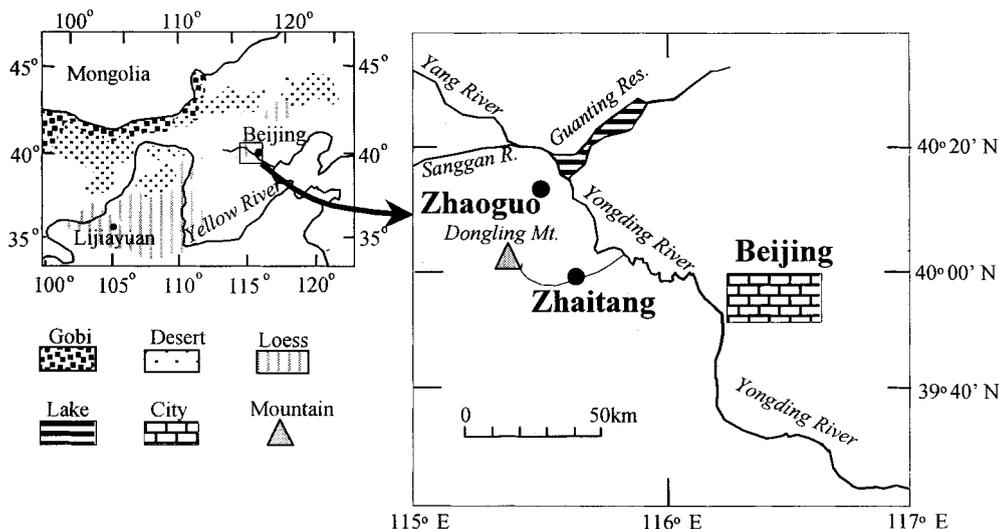


Fig. 1. Locations of the Zhaitang and Zhaoguo sections in the Beijing region and the Lijiayuan section in the northwestern part of the Loess Plateau.

Another section is located in Zhaoguo ($40^{\circ}11'56''\text{N}$, $115^{\circ}30'28''\text{E}$) (Fig. 1), a town 90 km northwest of Beijing; a 2300 m high mountain (Dongling Shan) separates the Zhaoguo section from the Zhaitang section. Nowadays, this region is dominated by monsoon circulation with annual rainfall of 450–550 mm mainly falling during the summer season. The average annual temperature is about 9–10°C with the highest temperature of 24–25°C occurring in July. Today, temperate deciduous broad-leaf forest, temperate steppe and cinnamon soil have developed, but are rarely preserved due to extensive cultivation and erosion.

The Zhaitang section was sampled at 2-cm spacing, while the Zhaoguo section was sampled at 5-cm spacing. The grain size was measured with a Sald-3001 diffraction particle analyser after the samples had been ultrasonically treated in a 20% (NaPO_3)₆ solution. Measurement of susceptibility was carried out with a Bartington MS2 susceptibility meter. CaCO_3 content was determined by analysis of the amount of CO_2 produced after sample treatment with 0.3 mol/L HCl (Yu & Wang 1988), and total organic matter content (TOC) by modified Walkley-Black method (Yu & Wang 1988).

Stratigraphy

The Zhaitang loess section is composed of two units, with a total thickness of about 13 m. The upper part is the last glacial loess (Malan Loess) while the lower part is a paleosol (S1) (Fig. 2). The stratigraphy and age estimates for this section have been studied previously (An & Lu 1984; Lu *et al.* 1987). The Zhaoguo section consists of the Malan Loess formation and the upper part of the Lishi Loess formation (from soil S1 to soil S5). We sampled S0–S1 (about 15 m) of the deposit for this study.

From the base of the Malan loess to the base of soil S1 of the Zhaitang section, there are six pedogenic beds: (1) 10.10–10.30 m (depth); 7.5YR 5/4 (Munsell color code); clay loam; weak, medium, subangular, blocky structure; few carbonate pseudomecelia; smooth, clear boundary. (2) 10.30–10.60 m; 10YR 5/3; silty; weak, medium, subangular, blocky structure; few carbonate pseudomecelia; smooth, clear boundary. (3) 10.60–10.90 m; 7.5YR 4/6; clayey; weak, medium, granular structure; abundant roots, worm pores; smooth, gradual boundary. (4) 10.90–11.10 m; 7.5YR 5/4; clayey; moderate, medium, subangular, blocky structure; common carbonate pseudomecelia; smooth, gradual boundary. (5) 11.10–11.65 m; 7.5YR 4/4; clayey; moderate, medium, granular structure; common clay skins; smooth gradual boundary. (6) 11.65–12.30 m; 7.5YR 3/4; clayey; moderate, medium, granular structure; common clay skins, common Fe–Mn films; smooth, gradual boundary.

The underlying sediment is a loess-like deposit.

A weakly developed paleosol layer is observed in depths of 10.10–10.30 m and was separated from S1 by a thin loess layer (10.3–10.6 m) (Fig. 2). This weak soil layer is also observed in the Zhaoguo section, but not as evident as in the Zhaitang section.

Thermoluminescence (TL) dating

TL dating uses the accumulated dose of ionizing radiation (unit: Gy) as a measure of the time since the sample was last exposed to daylight (Aitken 1985). This dating method has been widely used for dating loess and other eolian deposits (Wintle 1990, 1993). Previous studies have confirmed that the natural eolian transport of Chinese loess is sufficient to reset the TL clock (Lu *et al.* 1987), thus making TL dating applicable to Chinese loess. For the Zhaitang section, Lu *et al.* (1987, 1988)

Table 1. Thermoluminescence (TL) results and radioactivity data for the Zhaitang section.

Sample no.	Depth (m)	U (ppm)	Th (ppm)	K ₂ O (%)	Water content (%)	Dose rate (Gy/ka)	Plateau (°C)	ED (Gy)	a-value	Age (ka)
ZT-01	10.0	2.3	9.29	2.94	7.5	4.36	320–350	316.5 ± 4.6	0.047 ± 0.001	72.6 ± 4.7
ZT-02	10.2	1.7	11.08	2.55	8.7	4.03	360–400	305.7 ± 5.4	0.053 ± 0.003	75.8 ± 5.1
ZT-03	10.7	2.1	8.68	2.73	7.0	4.3	390–420	361 ± 2.7	0.067 ± 0.007	84 ± 5.5
ZT-04	10.8	2.2	11.47	2.35	12.4	3.84	370–390	344 ± 7.4	0.044 ± 0.001	89.6 ± 6.1

have determined the TL ages for several layers from the Malan loess to the soil S1 (Fig. 2).

In this study, we have taken four samples around the S1/L1 transition (Fig. 2) for TL dating. The sample preparation and the determination of the Paleodose were undertaken in the Xi'an Laboratory of Loess and Quaternary Geology, following the procedure of Lu *et al.* (1987, 1990). Briefly, samples were treated with H₂O₂ to remove organic material, and with HCl to remove carbonate. The 4–11 µm fraction was isolated by settling using Stoke's Law. For TL analysis, the 'Residual TL method' (Singhvi *et al.* 1982) was used. Thirty to 34 subsamples were made for each sample and the rate of TL growth was evaluated by applying additional beta (β) doses to the natural TL by a series of laboratory irradiations. All the subsamples were heated from room temperature to 500°C at a rate of 10°C/s in a pure nitrogen atmosphere. The TL intensity in the temperature range from 320°C to 420°C (the region of the paleodose plateau) is used for age assessment (Table 1). The TL signals were measured with a Daybreak TL system. The radiation dose rate was estimated by measuring the concentration of uranium (U), thorium (Th) and potassium in each sample. The U and Th concentrations were determined by neutron activation analysis, and the ⁴⁰K level was calculated from the total potassium content obtained by atomic absorption spectrometric analysis (AAS). All analysis data are summarized in Table 1.

The age of the loess at depth of 10 m is estimated as 72.6 ± 4.7 ka, and the weakly developed soil at depth 10.20 m (the middle part of the soil) is dated as 75.8 ± 5.1 ka (Table 1). Two samples at the upper part of the soil S1 are dated individually as 84 ± 5.5 (10.7 m in depth) and 89.6 ± 6.1 ka (10.8 m in depth), in good agreement with the previous estimate (Lu *et al.* 1987) in which the upper part of S1 is assigned as 84 ± 9 ka. With no apparent erosional traces, the S1 soil surface represents a transition from a wet stable climate with a relatively low aeolian flux to a cold dry period with relatively high sediment fluxes. Based on the TL ages, we can apparently place the upper boundary of the soil S1 (10.6 m) at the stage 5a/4 transition (Martinson *et al.* 1987).

Climatic proxies

The median grain size (Md) and magnetic susceptibility (MS) records of the Zhaitang and Zhouguo sections fluctuate considerably at the transition (Figs 3, 4). At the end of the last interglacial period (S1), MS decreased abruptly to a near-glacial value, while Md increased to a coarser value than in stage 5b or 5d. This was followed by an increase in MS and a synchronous decrease in Md. This brief fluctuation ceased just above 10 m (TL age 72.6 ka) in the Zhaitang section, above which the climate reached full-glacial conditions.

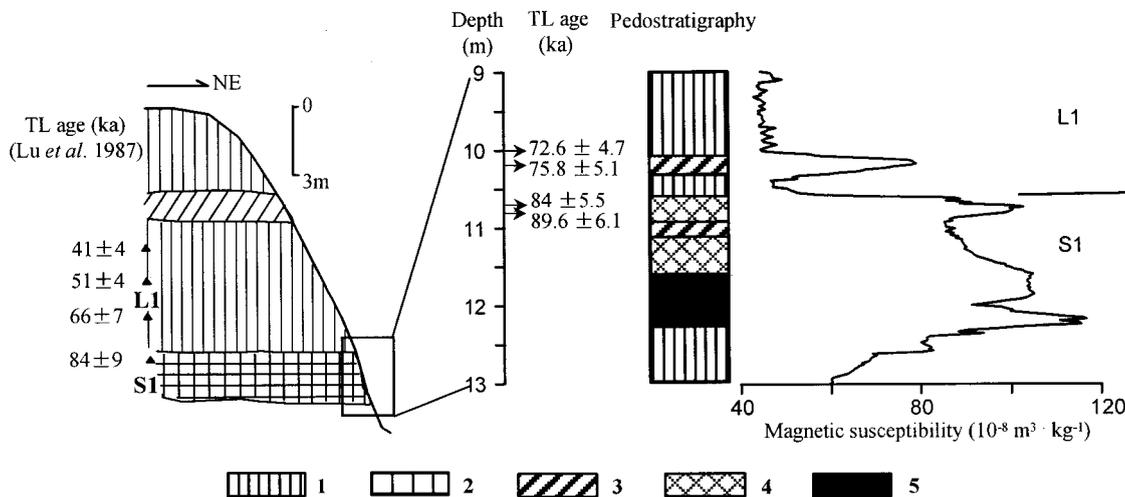


Fig. 2. Stratigraphy of the Zhaitang section and the thermoluminescence (TL) ages of the L1 (Malan Loess) -S1 transition. Also shown are TL ages of the Zhaitang section determined by Lu *et al.* (1987). Notice the thickness of the section in these two studies is different because of the excavation during the past decade (1, loess; 2, paleosol; 3, bright brown paleosol; 4, brown paleosol; 5, reddish brown paleosol).

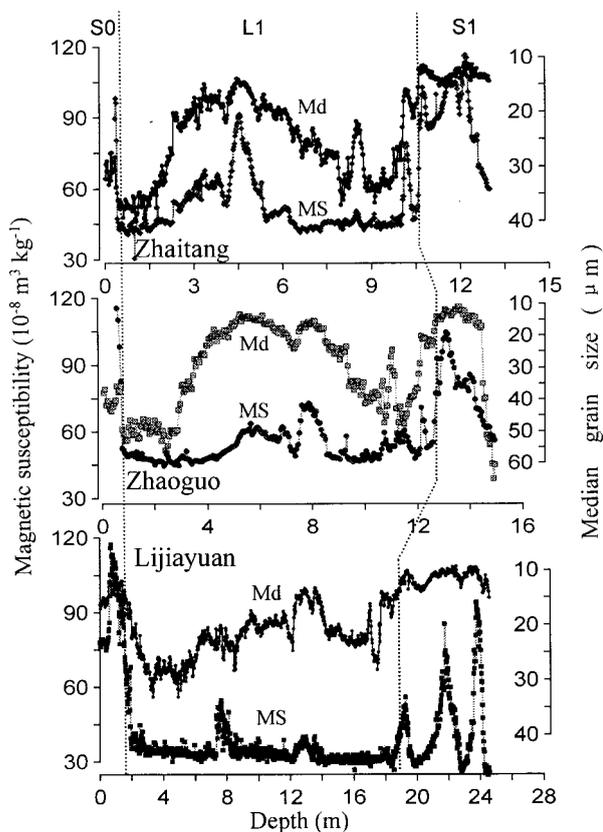


Fig. 3. Grain size and magnetic susceptibility records of the Zhaitang, Zhaoguo and Lijiayuan sections (data for the last section are from Ren *et al.* 1996) and the correlation of the abrupt climate changes at the L1/S1 transition.

The correlation of the climate changes for different sections can be made mainly based on the pedostratigraphy (Fig. 3), and it seems that the abrupt changes are revealed in a similar pattern in the Zhaitang and Zhaoguo sections. In comparison, fluctuations of Md and MS records in the Lijiayuan section (Ren *et al.* 1996) over the northwestern part of the Loess Plateau (Fig. 1) are less pronounced, with almost no imprint in the MS signal (Fig. 3). At the stage 5a/4 transition, the TOC and CaCO₃ (Fig. 4), characteristic of pedogenic processes and of leaching process (used as indicators of summer monsoon strength), also show fluctuations similar to those of the MS and Md data.

The grain size of loess is commonly regarded as a proxy of winter monsoon wind strength (Ding *et al.* 1994; Porter & An 1995; Liu & Ding 1998), and the magnetic susceptibility recorded in a loess-paleosol sequence is widely used as an approximate index of summer monsoon strength (An *et al.* 1991; Liu *et al.* 1987; Kukla *et al.* 1988). In the loess sections proximal to the desert boundaries, grain size variations may also be related to dust source changes, for example, the expansion and retreat of deserts, which in turn is influenced by winter monsoon strength. Thus the Md, MS, TOC and CaCO₃ data all indicate that the East Asian monsoon experienced a two-step abrupt change at the stage 5a/4 transition. Meanwhile, our data also show that the abrupt changes in the summer monsoon proxies (MS, TOC, CaCO₃) and in the winter monsoon proxy (Md) are synchronized.

About 2 m above the upper boundary of S1 in the Zhaitang, Zhaoguo and Lijiayuan sections, there is another fluctuation clearly shown in the Md value but not apparently expressed in the MS data (Figs 3, 4),

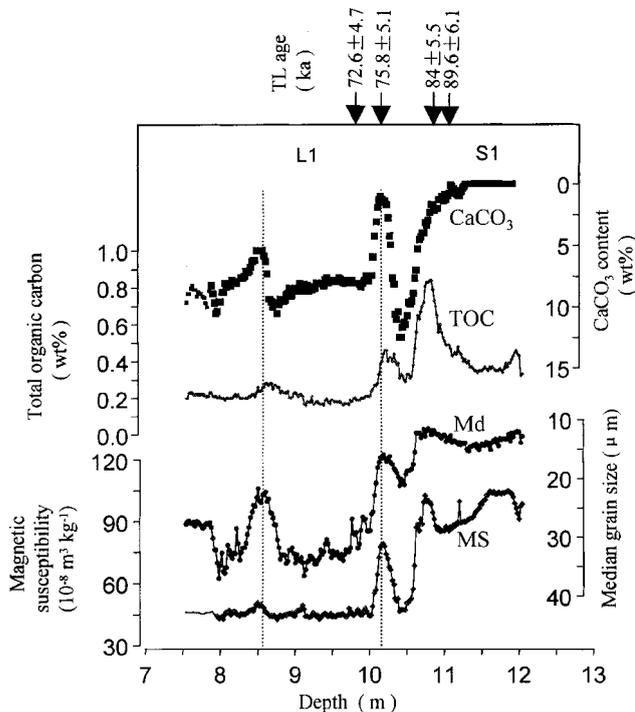


Fig. 4. Climate proxy records of the Zhaitang section at the L1/S1 transition. TL ages are also shown.

indicating a brief winter monsoon fluctuation at a time when the summer monsoon was absent from the study areas, which were then experiencing full-glacial conditions.

Discussion and conclusions

Our data reveal that East Asian monsoons experienced a two-step, abrupt change at the stage 5a/4 transition, when the global climate shifted to full-glacial conditions at the start of the last glaciation. This is clearly expressed in the grain size and MS records from the Zhaitang and Zhaoguo sections over Beijing region, but is only imprinted in the grain-size data from the Lijiayuan section over the northwestern part of the Loess Plateau. Thus, during this brief interval the summer monsoon is not strong enough to significantly influence the western part of North China. Another fluctuation observed in the Md data at about 2 m above the upper limit of the soil S1 may represent a failed reversal of the summer monsoon, but no apparent corresponding pedogenic features or MS shift have been observed. Millennial-scale climatic fluctuations have been widely recognized in Chinese loess during the last glacial period. However, possible rapid changes in climatic proxies of the loess-paleosol sequence during the last interglacial period (An & Porter 1997) are not supported by more recent work (Ding *et al.* 1999). There are also no data that show rapid summer

monsoon changes in the last interglacial period. Thus the abrupt climate changes at the stage 5/4 transition may be the first apparent suborbital scale summer monsoon (and probably also winter monsoon) fluctuation observed in the Chinese loess during the last interglacial-glacial cycle.

Based on the TL data, we have attempted to correlate the abrupt monsoon changes with the events recorded in Greenland ice and other sediments in the world during stage 5a/4 transition (Fig. 5). In view of the uncertainty in our TL age model, this correlation should be viewed as a preliminary framework. As noted in previous studies, near the stage 5a/4 transition, two maxima in $\delta^{13}\text{C}$ and wt% CaCO_3 occurred in a North Atlantic core (Keigwin *et al.* 1994; Keigwin & Jones 1994), implying that the North Atlantic circulation experienced high-frequency variability during this period. These events are also clearly documented in the GRIP core as interstadials 19 and 20 (Dansgaard *et al.* 1993) and in European pollen records from the Grande Pile peat bog (Woillard 1978; Beaulieu & Reille 1992). In the Vostok ice core in Antarctica (Petit *et al.* 1999), Sulu Sea sediment (Linsley 1996) and a pollen record in a Californian lake (Adam *et al.* 1981), similar events are also evidenced by different climatic proxies. An obvious difference between the loess and the other records at the stage 5a/4 transition is that the summer monsoon proxy has only one peak, while most of the

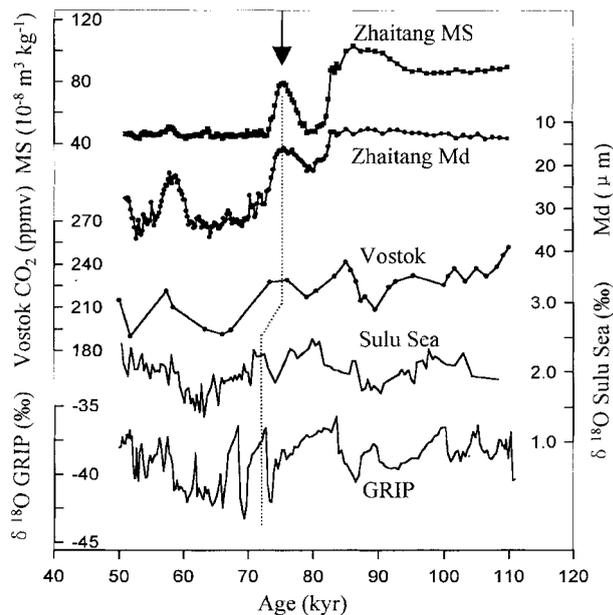


Fig. 5. Comparison of the Zhaitang climate proxy records with Vostok CO_2 data (after Petit *et al.* 1999), Sulu Sea $\delta^{18}\text{O}$ records (after Linsley 1996) and GRIP ice core $\delta^{18}\text{O}$ data (after Dansgaard *et al.* 1993) near the isotope stage 5/4 transition (arrow). The time-scale of the Zhaitang section is developed by linear interpolation based on the TL ages determined by this study and by Lu *et al.* (1987).

other records have two (Fig. 5). Recently, a detailed study of another Grande Pile peat core yielded only one Ognon interstadial (Ognon I); another event (Ognon II) probably resulted from pollen reworking (Beaulieu & Reille 1992). Thus the pattern of the fluctuations at stage 5a/4 transition is still not certain.

The mechanisms causing abrupt climatic changes in the late Quaternary are still debated. The reorganization of the North Atlantic thermohaline circulation (Broecker *et al.* 1992), ice-sheet dynamics and tropical factors have been invoked to explain the origin and rapid spread of the abrupt climatic changes. The abrupt climatic changes at the stage 5a/4 transition may serve as an important example for understanding the physics involved in the climatic instabilities of the late Quaternary. Our data suggest that rapid monsoon changes over East Asia may be related to the transitions between the interglacial and glacial regimes. We speculate that the transition may set a threshold for the monsoon instability. When conditions cross the threshold, the monsoon climate becomes unstable.

Our data also show that the two-step abrupt change in the summer monsoon and winter monsoon are synchronized at the stage 5/4 transition, implying a direct and immediate link between high latitude and low latitude mechanisms. Previous studies have noted the role of high latitude mechanisms in the Northern Hemisphere on the abrupt winter monsoon changes over East Asia (Porter & An 1995; Ding *et al.* 1999). Our data suggest that the summer monsoon also experienced abrupt fluctuations at the transition between climatic regimes, raising the possibility that low latitude mechanisms may also exert influence on rapid monsoon changes. As the summer monsoon over East Asia is an important carrier of atmospheric water vapor (Chen *et al.* 1991), abrupt changes in the summer monsoon at the stage 5/4 transition would presumably have influenced the global hydrological cycle. This raises the possibility that the abrupt summer monsoon changes at the stage 5/4 transition had a feedback to the contemporary global climate changes.

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References

- Adam, D. P., Sims, J. D. & Throckmorton, C. K. 1981: 130,000-yr continuous pollen record from Clear Lake, Lake County, California. *Geology* **9**, 373–377.
- Aitken, M. J. 1985: *Thermoluminescence Dating*. 359 pp. Academic Press, London.
- An, Z. & Lu, Y. 1984: A climatostratigraphic subdivision of late Pleistocene strata named Malan formation in north China. *Kexue Tongbao* **29**, 1239–1241.
- An, Z., Kukla, G. J., Porter, S. C. & Xiao, J. L. 1991: Magnetic

- susceptibility evidence of monsoon variation on the Loess Plateau of central China during the last 130,000 years. *Quaternary Research* **36**, 29–36.
- An, Z. & Porter, S. C. 1997: Millennial-scale climatic oscillations during the last interglaciation in central China. *Geology* **25**, 603–606.
- Beaulieu, J. L. de & Reille, M. 1992: The last climatic cycle at La Grande Pile (Vosges, France): a new pollen profile. *Quaternary Science Reviews* **11**, 431–438.
- Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J. & Bonani, G. 1993: Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature* **365**, 143–147.
- Bond, G. C. & Lotti, R. 1995: Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science* **267**, 1005–1010.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. & Bonani, G. 1997: A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**, 1257–1266.
- Broecker, W. S., Bond, G., Klas, M., Clark, E. & McManus, J. 1992: Origin of the northern Atlantic's Heinrich events. *Climate Dynamics* **6**, 265–273.
- Chen, L., Zhu, J. & Lou, H. 1991: *Monsoon Over East Asia*. 362 pp. Meteorology Press, Beijing (in Chinese).
- Dansgaard, W., Johnsen, S. J., Clausen, H. B., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjornsdottir, A. E., Jouzel, J. & Bond, G. 1993: Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* **364**, 218–220.
- Ding, Z. L., Ren, J. Z., Yang, S. L. & Liu, T. S. 1999: Climate instability during the penultimate glaciation: evidence from two high-resolution loess records, China. *Journal of Geophysical Research* **104**, 20123–20132.
- Ding, Z., Yu, Z., Rutter, N. & Liu, T. 1994: Towards an orbital time scale for Chinese loess deposits. *Quaternary Science Reviews* **13**, 39–70.
- Fang, X. M., Ono, Y., Fukusawa, H., Pan, B. T., Li, J. J., Guan, D. H., Oi, K., Tsukamoto, S., Torii, M. & Mishima, T. 1999: Asian summer monsoon instability during the past 60,000 years: magnetic susceptibility and pedogenic evidence from the western Chinese Loess Plateau. *Earth and Planetary Science Letters* **168**, 219–232.
- Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. & Jouzel, J. 1993: Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* **366**, 552–554.
- Guo, Z. T., Liu, T. S., Guiot, J., Wu, N. Q., Lu, H. Y., Han, J. M., Liu, J. Q. & Gu, Z. Y. 1996: High frequency pulses of East Asian monsoon climate in the last two glaciations: link with the North Atlantic. *Climate Dynamics* **12**, 701–709.
- Heinrich, H. 1988: Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years. *Quaternary Research* **29**, 143–152.
- Keigwin, L. D., Curry, W. B., Lehman, S. J. & Johnsen, S. 1994: The role of the deep ocean in North Atlantic climate changes between 70 and 130 kyr ago. *Nature* **371**, 323–326.
- Keigwin, L. D. & Jones, G. A. 1994: Western North Atlantic evidence for millennial-scale changes in ocean circulation and climate. *Journal of Geophysical Research* **99**, 12397–12410.
- Kukla, G. J. & An, Z. 1989: Loess stratigraphy in central China. *Palaeogeography, Palaeoclimatology, Palaeoecology* **72**, 203–225.
- Kukla, G., Heller, F., Liu, X. M., Xu, T. C., Liu, T. S. & An, Z. S. 1988: Pleistocene climates in China dated by magnetic susceptibility. *Geology* **16**, 811–814.
- Linsley, B. K. 1996: Oxygen-isotope record of sea level and climate variations in the Sulu Sea over the past 150,000 years. *Nature* **380**, 234–237.
- Liu, T. S. *et al.* 1985: *Loess and Environment*. 251 pp. China Ocean Press, Beijing.

- Liu, T. & Ding, Z. 1998: Chinese loess and the paleomonsoon. *Annual Reviews of Earth and Planetary Sciences* 26, 111–145.
- Liu, X. M., Liu, T. S., Xu, T. C., Liu, C. & Chen, M. Y. 1987: A preliminary study on magnetostratigraphy of a loess profile in Xifeng area, Gansu Province. In Liu, T. (ed.): *Aspect of Loess Research*, 164–174. China Ocean Press, Beijing.
- Lowell, T. V., Heusser, C. J., Andersen, B. G., Moreno, P. I., Hauser, A., Heusser, L. E., Schluchter, C., Marchant, D. R. & Denton, G. H. 1995: Interhemispheric correlation of late Pleistocene glacial events. *Science* 269, 1541–1549.
- Lu, Y. C., Prescott, J. R., Robertson, G. B. & Hutton, J. T. 1987: Thermoluminescence dating of the Malan Loess at Zhaitang, China. *Geology* 15, 603–605.
- Lu, Y. C., Zhang, J. Z. & Xie, J. 1988: Thermoluminescence dating of loess and paleosols from the Lantian section, Shaanxi Province, China. *Quaternary Science Reviews* 7, 245–250.
- Lu, Y. C., Zhang, J. Z. & Xie, J. 1990: Thermoluminescence dating of the fine grains of loess sections for the last about 120 ka in the Lantian County, Shaanxi Province. In Liu, T. (ed.): *Loess, Quaternary Geology and Global Change, part II*, 64–72. Science Press, Beijing (in Chinese).
- Martinson, D., Pisias, N., Hays, J. D., Moore, T. C. & Shackleton, N. J. 1987: Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000 year chronostratigraphy. *Quaternary Research* 27, 1–30.
- McManus, J. F., Bond, G. C., Broecker, W. S., Johnsen, S., Labeyrie, L. & Higgins, S. 1994: High-resolution climate records from the North Atlantic during the last interglacial. *Nature* 371, 326–329.
- O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S. & Whitlow, S. I. 1995: Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* 270, 1962–1964.
- Oppo, D. W. & Lehman, S. J. 1995: Suborbital timescale variability of North Atlantic Deep Water during the past 200,000 years. *Paleoceanography* 10, 901–910.
- Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E. & Stievenard, M. 1999: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399, 429–436.
- Porter, S. C. & An, Z. 1995: Correlation between climate events in the North Atlantic and China during the last glaciation. *Nature* 375, 305–308.
- Ren, J. Z., Ding, Z. L., Liu, T. S., Sun, J. M. & Zhou, X. Q. 1996: Climatic changes on millennial time scales – evidence from a high-resolution loess record. *Science in China (Series D)* 39, 449–459.
- Rutter, N. W., Ding, Z., Evans, M. & Liu, T. 1991: Baoji-type pedostratigraphic section, Loess Plateau, north-central China. *Quaternary Science Reviews* 10, 1–22.
- Singhvi, A. K., Sharma, Y. P. & Agrawal, D. P. 1982: Thermoluminescence dating of dune sands in Rajasthan, India. *Nature* 295, 313–315.
- Wintle, A. G. 1990: A review of current research on TL dating of loess. *Quaternary Science Reviews* 9, 385–397.
- Wintle, A. G. 1993: Luminescence dating of aeolian sands: an overview. In Pye, K. (ed.): *The Dynamics and Environmental Context of Aeolian Sedimentary Systems, Special Publication No. 72*, 49–58. Geological Society, London.
- Woillard, G. M. 1978: Grande Pile peat bog: a continuous pollen record for the last 140,000 years. *Quaternary Research* 9, 1–21.
- Xiao, J., Porter, S. C., An, Z., Kumai, H. & Yoshikawa, S. 1995: Grain size of quartz as an indicator of winter monsoon strength on the Loess Plateau of central China during the last 130,000 yr. *Quaternary Research* 43, 22–29.
- Yu, T. R. & Wang, Z. Q. 1988: *Analytical Chemistry of Soil*. 531 pp. Science Press, Beijing (in Chinese).