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Abrupt retreat of summer monsoon at the S1/L1 boundary in China

Denis-Didier Rousseau [a,b,*], George Kukla [b]

[a] *Paleoenvironnements et Palynologie, Institut des Sciences de l'Evolution (UMR CNRS 5554), Université Montpellier II-pl. E. Bataillon, case 61, 34095 Montpellier cedex 05, France*

[b] *Lamont Doherty Earth Observatory of Columbia University, Palisades, NY 10904, USA*

Abstract

At a number of localities in the Chinese Loess Plateau, the boundary between the polygenetic soil complex S1 and the overlying loess unit L1 is exceptionally sharp. Both units formed on the near-horizontal surfaces by subaerial deposition of eolian dust and are unaffected by erosion. Since the sedimentation across the boundary is essentially continuous, the feature points to a relatively rapid decline of pedogenic activity, which would otherwise mix the sediment and smooth the transition. In this respect, the boundary is not dissimilar to the “markers” in Central and Western Europe, which separate humous steppe soils of the Early Glacial interstadials from the sterile slope sediments and are interpreted as deposits of a major continental-scale dust storm. The reconstructed rate of environmental change across the boundary, whose age within the precision limits of available dating corresponds to the MIS 5/4 shift, is by an order of magnitude greater than the rate of change of orbital parameters. The deflection of atmospheric circulation in response to the build-up of continental ice sheets would also be likely to take a considerably longer time. We suggest that the most probable cause of the rapid monsoon retreat in the Loess Plateau, documented by the onset of the L1 loess deposition, is the sudden rearrangement of oceanic conveyor belt possibly triggered by the Toba volcanic explosion.

Keywords: monsoon; loess; China; global change; paleoclimate

1. Introduction

The stratigraphic framework of Chinese loess is relatively simple. Four major units, Malan, Upper Lichi, Lower Lichi, and Wucheng cover the last 2.6 million years which, in the understanding of Chinese stratigraphers, represent the Quaternary. The three youngest units dating from the last approximately 1.3 Ma describe the succession of loess layers designated by L and numbered 1 through 15 from the top down, and paleosols designated by S, and numbered downwards from 0 to 14 (Kukla and An, 1989; Liu et al., 1985). The sequence was formed by continuous deposition of eolian dust on a near horizontal platform unaffected by erosional breaks. Dust deposition appears continuous across the paleosol-loess boundaries, although it is faster during the loess formation and slower at times of the soil formation.

* Corresponding author. Tel.: +33-467-144-652; fax: +33-467-042-032.

E-mail address: denis@dstu.univ-montp2.fr (D.-D. Rousseau).

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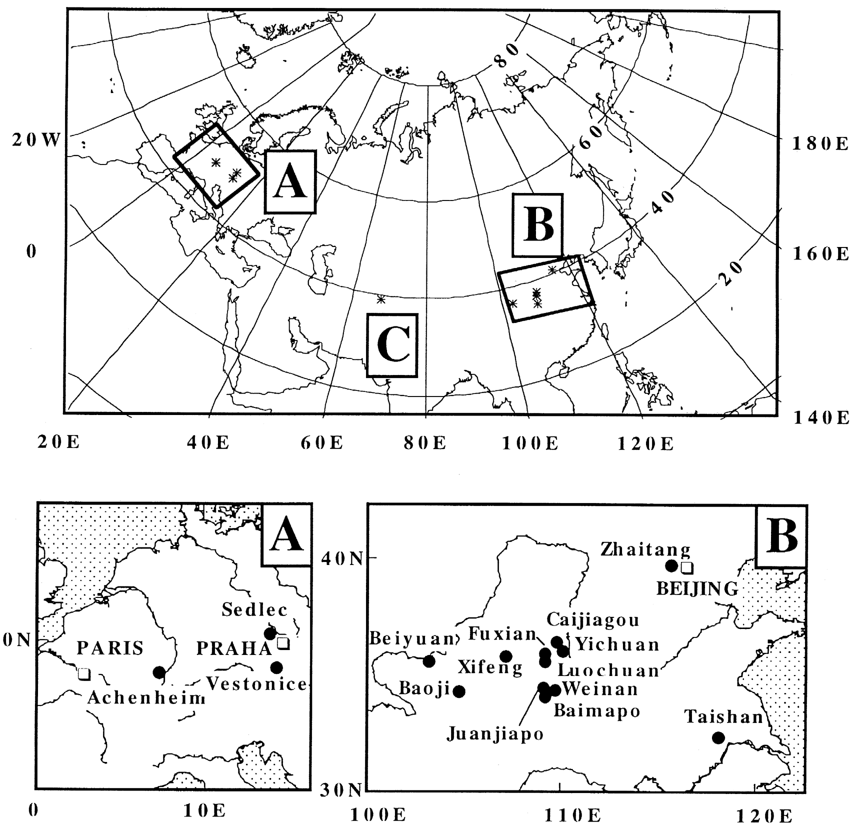

Fig. 1. Location of sites referred to in the study. (A) Localities in the Chinese Loess Plateau; (B) localities in the European loess belt. (C) Localities in Tadjekistan.

Rapid declines of pedogenic activity took place at the top of most soil complexes. Here we focus on the S1/L1 limit, which took place in the last climatic cycle, the best studied interval of the Chinese loess series. Much of the observed features occurs at older boundary horizons as well. From the numerous localities that have been studied (Liu et al., 1985, 1991), we based our discussion on a selected few location in Fig. 1.

2. Nature and climate of the S1/L1 boundary

The deposits of the last climatic cycle include a soil complex, named S1, overlain by a loess unit L1. These two units are further subdivided into several sub-units characterized by varying intensity of eolian and pedogenic activity (cf. e.g. the system proposed in Kukla and An, 1989). The S1–L1 couplet is observed all over the central Chinese Loess Plateau (Liu et al., 1985) as well as in the surrounding loess areas (Lu et al., 1987; Nie and He, 1991).

The color and the granulometric composition change abruptly at the S1/L1 boundary. The clay (> 2 μm) drops from about 50% to around 30% in Baoji (Ding et al., 1992) (Fig. 2), Luochuan and Taishan (Nie and He, 1991). Coarse silt that composes around 2% in the upper part of S1 increases to 5% at the base of L1 (Vandenberghe et al., 1997; Xiao et al., 1995). The Quartz Mean Diameter shifts more gradually (Porter and An, 1995).

The low field magnetic susceptibility, which reflects the proportion of magnetite and maghemite,

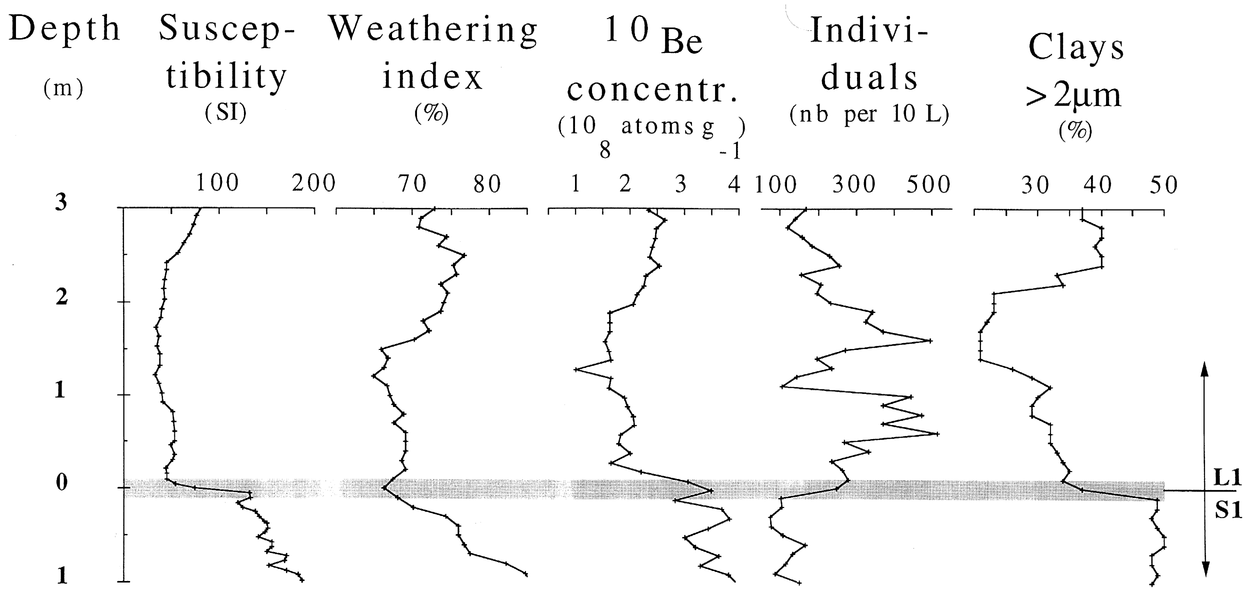

Fig. 2. Variation of selected environmental proxies in the vicinity of the S1/L1 boundary. Plotted on a relative depth scale in meters centered at the boundary. Magnetic susceptibility (Kukla and An, 1989), weathering index (Guo et al., 1996), ^{10}Be (Shen et al., 1992), number of snail individuals per unit volume (Rousseau and Wu, 1997) in Luochuan and % of clay fraction in Baoji (Ding et al., 1995).

rapidly changes from high values in S1 to low ones in the L1 (Heller et al., 1991; Kukla et al., 1990; Sun, 1995) (Fig. 2). The shift is interpreted as resulting from a major change of monsoon regime.

The weathering index calculated for the Luochuan, Weinan and Yichuan loess sections indicates a sharp drop of weathering activity at the S1/L1 boundary, reflecting a diminished rainfall (Guo et al., 1996; Liu et al., 1995) (Fig. 2).

The number of atoms per gram of ^{18}Be decreases by one half at the S1/L1 boundary in Luochuan, passing from 4×10^8 in S1 to 2×10^8 just above the limit (Beer et al., 1993; Shen et al., 1992, 1995). The variation has been linked to the rapid increase of the dust accumulation rate (Beer et al., 1993) (Fig. 2).

Gastropod communities in Luochuan show an increase of the number of individuals and of xerophilous taxa just above the boundary (Rousseau and Wu, 1997). The strong increase in the xeric individuals at the S1/L1 boundary characterized the rapid change from a relatively moist environment in the soil to a dry steppe loess. This is also reflected in the total number of individuals identified (Fig. 2).

Stable isotopes (δ^{18}O and δ^{13}C) in the carbonates of Baoji sequence (Gu et al., 1991) and isotopes in carbonate and organic matter at Juanjiapo and Luochuan also shift sharply at the S1/L1 boundary (Lin et al., 1991), indicating a rapid change from warm-wet to cold-dry environments. The same interpretation was derived from the study of plant phytoliths (Lu et al., 1991) and from pollen analyses (Sun et al., 1995b) in the Luochuan sequence.

3. Age of the S1/L1 boundary

Thermoluminescence (TL) dates were obtained at different sites in the vicinity of the boundary (Fig. 3). At the Heimugou site near Luochuan, in the center of the Loess Plateau, Forman (1991) reported two TL dates in the loess close above the boundary.

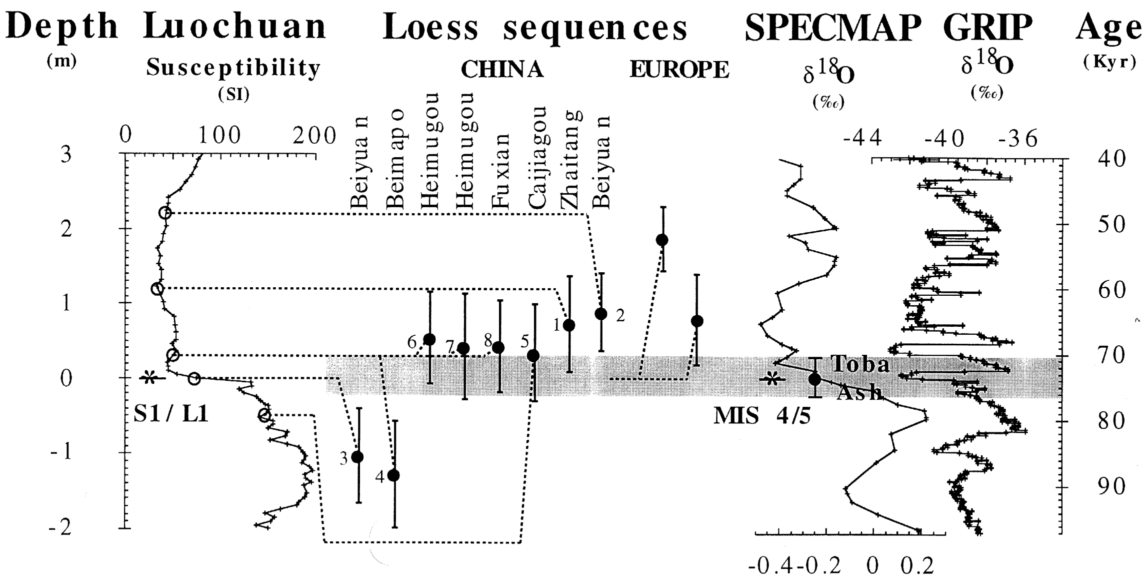

Fig. 3. Age of the S1/L1 boundary. More detail in text. Magnetic susceptibility at Luochuan on a relative depth scale centered at the S1/L1 boundary. Projected position of the TL dated samples 1 to 8 from different sites in the Chinese Loess Plateau marked on the susceptibility curve with open circles. Corresponding ages with error bars are plotted in full circles on the absolute time scale shown in the right margin. On the right, variation of δ^{18}O in benthic foraminifera from the SPECMAP stack (Martinson et al., 1987) with projected age of the Toba Ash (Rose and Chesner, 1990). Also at the right, the δ^{18}O in Greenland ice (Grip Members, 1993). The two TL dates from Europe are from Achenheim (Rousseau et al., 1998a,b).

They are 67.7 ± 7 ka (number 6 in Fig. 3) and 69.0 ± 8 ka (number 7 in Fig. 3). At Fuxian, about 30 km north of Luochuan, Sun et al. (1995b) obtained a TL date of 69.0 ± 7 ka in the loess above the boundary (number 8 in Fig. 3). Guo et al. (1996) gave a TL date of 85.7 ± 7.2 ka (number 3 in Fig. 3) in the upper part of S1 at Beiyuan near Linxia close to Lanzhou, in the western margin of the Loess Plateau. Another TL date in the same section, in the lower L1, gives 63.8 ± 5.9 ka (number 2 in Fig. 3) (An et al., 1991).

In the northern part of the Loess Plateau, in the Caijiagou section near Yulin, a TL date of 70.0 ± 7.4 ka (number 5 in Fig. 3) is reported in the upper part of S1 by Sun et al. (1995a). A TL date of 65.6 ± 7.3 ka from just above the S1/L1 boundary (number 1 in Fig. 3) comes from the Zhaitang section near Beijing (Lu et al., 1987).

All the above dates range in a relatively narrow time interval pointing to about 70–75 ka as the probable age of the boundary.

Only in Baimapo, near Lantian, in the southeastern margin of the Loess Plateau, an exceptionally high TL date of 88.5 ± 8 ka (number 4 in Fig. 3) was reported from the loess above the S1/L1 boundary (An et al., 1991).

Independent time scale is derived from the sediment thickness weighted by magnetic susceptibility (Kukla et al., 1988). In Luochuan and Xifeng, this method gives an age for the boundary of about 75 ka (Kukla et al., 1990). Also, the accretion model of Ding et al. (1995), tuned to orbital variations, gives the age of S1/L1 boundary in Baoji of about 75 ka.

In summary, the age of the S1/L1 boundary can be considered as closely corresponding and possibly coeval with the marine isotope stage (MIS) 5/4 boundary, dated at 73.9 ka by Martinson et al. (1987) and at 75 ka in the overview of Kukla and Briskin (1983).

4. Duration of the shift

In order to assess how different is the S1/L1 shift from the other boundaries of the last glacial/interglacial cycle, we have calculated the first derivative of the key climate proxies on a depth scale. We obtained the relative speed across the boundary of a shift of each proxy from two thirds of its peak interglacial value to two thirds of its full glacial level. Analyzed proxies are the grain size, the magnetic susceptibility and the number of snails preferring xerophytic habitats (Fig. 4).

It is obvious that all the parameters show, by an order of magnitude, a faster shift at the boundary

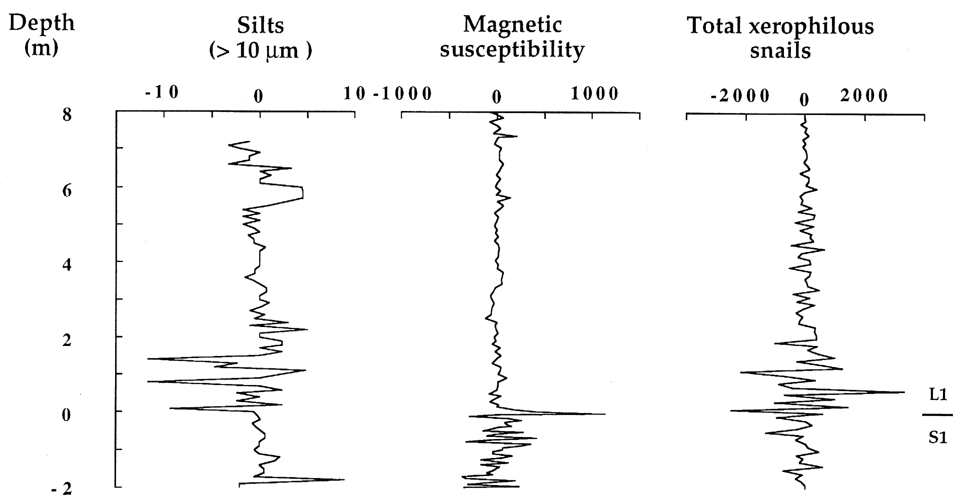

Fig. 4. Rate of change of the silt content, low field magnetic susceptibility and total number of snails per unit volume (10 l) Expressed as first derivative of measured parameters computed on the depth scale.

than in the rest of the section. The difference would be even more pronounced if the slower accretion rate of the soils had been considered. Because of the various character of the proxies, with the biological indices mostly independent of the physical ones, the variation testifies that the general environment changed substantially in an exceptionally short interval.

5. Comparison with loess outside China

Similar sharp lithologic and, presumably, also environmental change as the one observed in China have been noticed also in the loess deposits elsewhere.

In Tadjikistan (Fig. 1C), the low field magnetic susceptibility in the Karamaidan sequence shows a rapid shift at the PC1/L1 boundary interpreted as coeval with the Chinese S1/L1 limit (Forster and Heller, 1994).

In central European loess sequences (cf. location in Fig. 1B), a sharply delimited thin layer of eolian dust named "marker" separates the dark humous biogenic steppe soils, which correlate with the upper part of S1 from a biogenic slope sediments (Fig. 5). Contrary to China, the choice loess sequences studied in Europe are not in platforms, but formed on slopes. They are composed not only of paleosols and eolian loess, but include also slope sediments. They reflect climatic and environmental variations in much greater detail than platform sites.

The "markers" found numerously in these sections are light bands of silt with grain finer than that of common loess (Hradilova, 1994; Hradilova and Stastny, 1994). No significant differences from local loess were found in the petrologic composition of the

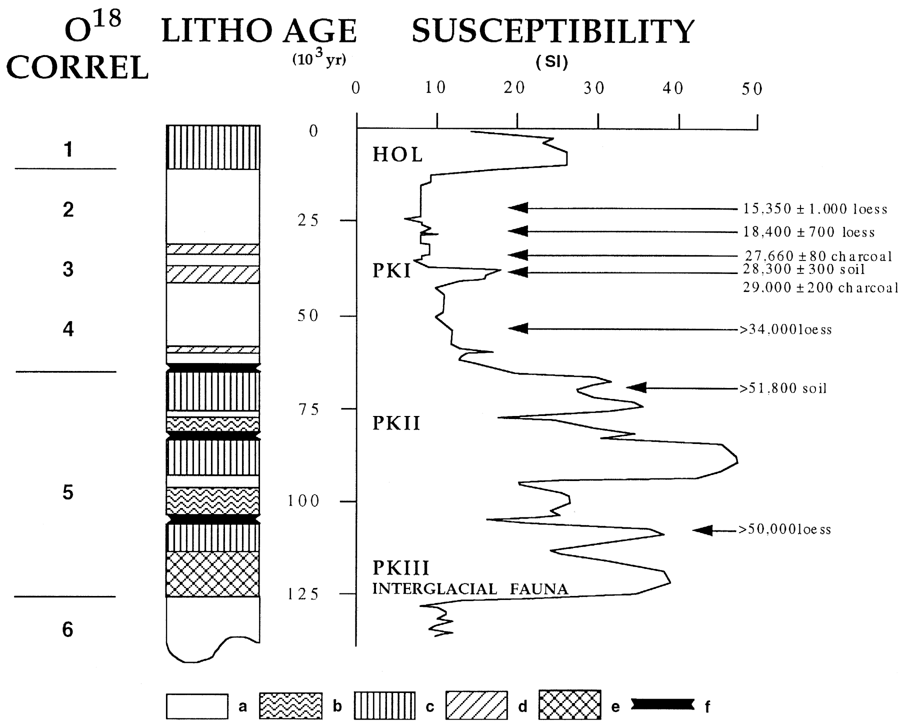

Fig. 5. Loess sequence in Vestonice (Czech Republic). Variation of magnetic susceptibility, lithology and ^{14}C dates (Klima et al., 1962) Plotted on the age scale. Lithology: (a) loess, (b) pellet sands, (c) chernosem, (d) arctic brownearth (e) B-horizon of a forest parabraunerde, (f) marker. PKI–II: numbered pedocomplexes. In the left margin correlation with marine isotope stages.

coarse fraction from local loess. The "markers" do not contain detectable volcanic shards and are believed to be deposited by continental scale dust storms, such as those that, today, sporadically affect Central China (Liu et al., 1985), France (Bücher et al., 1983; Wagenbach et al., 1996) or Eastern Europe. Their long distance eolian transport from far away source areas is indicated by the fine grain, low humus and a substantial carbonate content. At the time of marker's deposition, the topsoil in the surrounding regions was made of largely decalcified chernozems. The westernmost locality of a typical marker is Achenheim in France (Fig. 1B) (Rousseau et al., 1998a,b).

6. MIS 5/4 shift outside the loess belt

Considering the available dates of the boundary in China and of their apparent equivalent in Europe, the S1/L1 horizon and the "marker" on top of PKII may be approximately coeval with other numerous major shifts of environment believed to be coeval with the oceanic MIS 5/4 horizon. At this level, the oxygen isotope ratio of benthic foraminifera increased within several millennia to values approaching those of a fully developed glaciation. The shift was interpreted as a sign of a major growth of global ice volume on land.

In the pollen-rich lake beds, a shift from organogenic deposition toward a more detritic minerogenic sediments is registered at approximately the same time (Kukla and Briskin, 1983; Woillard and Mook, 1982).

Heusser (1989) reconstructed annual temperature and precipitation from pollen recovered in several marine cores off the Japanese Pacific coast. Both parameters dropped rapidly to very low levels at the MIS 5/4 boundary. *Sciadopitys*, a Tertiary relic taxon, which dominated the temperate coastal forests of central and southern Japan prior to 70 ka, disappeared altogether at this boundary.

The proportion of ice rafted detritus in North Atlantic sediments increased as Polar front shifted south (McManus et al., 1994) Similar change occurred in the North Pacific (Kotilainen and Shackleton, 1995). Sea surface temperature in Equatorial Atlantic remained high in summer and decreased only slightly in northern winter (McIntyre et al., 1989). As a result, the meridional temperature gradient increased substantially. Greenland ice record shows a pronounced drop of the $\delta^{18}O$ values and a high dust concentration at the 4/5 boundary (Dansgaard et al., 1993; Grip Members, 1993; Johnsen et al., 1992). The dust increase may be contemporaneous with the "marker" of central and western Europe (Rousseau et al., 1998b).

7. Discussion of possible causes

Present dust storms in Central Asia are associated with intrusions of cold air from the northwest and north (Smirnov et al., 1994). Dust storms over China show a similar pattern (Zhang et al., 1991; Wang, 1994). The origin of the Chinese loess material is seen in Takla Makan and Gobbi deserts (Liu et al., 1985). The deposition of L1 loess is likely associated with major cold air outbreaks in central and western Asia, which in turn call for semi-permanent cold air cells over this area with a negative effect on monsoon rainfall (Liang et al., 1995).

Reconstructed surface elevation of the Fennoscandian ice sheet indicates that no major ice body was in existence in MIS 5a in Asia and Europe, with the ice from the substage MIS 5b almost completely melted (Boulton and Payne, 1994). Any change of atmospheric circulation regime in response to the ice sheet build-up, which could lead to cessation of pedogenesis in the Chinese Loess Plateau, is therefore unlikely to happen suddenly. Equally improbable would be the explanation of the "markers" in Europe by such a mechanism.

Sea level during MIS 5e was already low, due to the Antarctic ice (Labeyrie et al., 1987; Shackleton, 1988). Farther lowering of an already low sea level is therefore unlikely to precipitate a rapid southern withdrawal of summer monsoon in Eastern Asia at the S1/L1 level.

Nor can such a rapid change be directly attributed to the change of orbital parameters. To be sure, the orbital setting was favoring a major cooling, obliquity was low and the insolation in boreal autumn was decreasing (Kukla et al., 1981; Kukla and Gavin, 1992). However, the orbital shifts were gradual and too slow to explain the abrupt S1/L1 boundary shift.

What then could be the probable cause? Two phenomena have a potential for influencing climate regime on a global scale suddenly. It is the overturning of ocean circulation due to the termination of thermohaline circulation, and the injection into the stratosphere of large volumes of sulfur in a major volcanic explosion.

The first process thoroughly discussed and analyzed in recent years (Bond, 1995; Bond and Lotti, 1995; Broccoli and Manabe, 1987; Broecker, 1990; Broecker et al., 1990; Keigwin and Lehman, 1994; Manabe and Stouffer, 1995) involves a sudden rearrangement of oceanic "conveyor belt", which connects the surface and deep ocean currents in a global web. The overturn is precipitated by increased freshwater influx into the Northern North Atlantic.

Negative radiative forcing of recent volcanic eruptions was well studied and blamed for substantial decrease of global mean temperatures lasting for several years (Hansen et al., 1992; Robock and Mao, 1992). The Earth's largest known eruption, of the Toba crater in Sumatra, is dated to 75 ± 2 ka. The ash was found in deep sea sediments close to the MIS 4/5 boundary in the Indian Ocean and southern Asia (Rose and Chesner, 1990). The magnitude of the eruption in terms of released sulfates was about 30 times that of the well studied recent Mt. Pinatubo event in 1991, about 10 times that of Tambora in 1815 and 60 times that of Krakatau in 1883 (McCormick et al., 1995). The impact of the Toba eruption must have been considerably stronger than any of the recent events. The location of Toba, near the equator, would have favored injection of gases and particulates into the stratosphere of both hemispheres. Its impact on the thermal and hydrologic regime at the time of favorable orbital setting might have provided a strong enough trigger for a semi-permanent reversal of oceanic circulation worldwide. Such mega-event as the Toba eruption cannot then be easily omitted from the list of potential forcings of the S1/L1 shift (Rampino and Self, 1992).

8. Conclusion

The S1/L1 boundary in China is exceptionally sharp and points to a major and abrupt change of summer monsoon regime. Within the dating accuracy of available age determinations, the boundary appears approximately coeval with the oceanic MIS 4/5 boundary. It appeared at the time of low obliquity and accelerated decrease of insolation in boreal autumn. It is similar in its character and timing with the European "markers", thin eolian deposits of continental dust storms. It is approximately dated to the time of the Toba eruption. While the time links may be purely coincidental, it is not inconceivable that a major volcanic eruption occurring at the time of favorable orbital setting triggered a rapid, irreversible shift of oceanic currents, which in turn affected the atmospheric circulation on a global scale.

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References

An, Z.S., Kukla, G., 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. Quat. Res. 36, 29–36.

Beer, J., Shen, C., Heller, F., Liu, T., Bonani, G., Dittrich, B., Suter, M., Kubik, P.W., 1993. ^{10}Be and magnetic susceptibility in Chinese loess. Geophys. Res. Lett. 20, 57–60.

Bond, G.C., 1995. Climate and the conveyor. Nature 377, 383–384.

Bond, G.C., Lotti, R., 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. Science 267, 1005–1010.

Boulton, G.S., Payne, A., 1994. Mid-latitude ice sheets through the last glacial cycle: glaciological and geological reconstructions. In: Duplessy, J.-C., Spyridakis, M.-T. (Eds.), Long-term Climatic Variations. NATO ASI Ser. Springer, Stuttgart, pp. 177–212.

Broccoli, A.J., Manabe, S., 1987. The influence of continental ice, atmospheric CO_2, and land albedo on the climate of the last glacial maximum. Clim. Dyn. 1, 87–99.

Broecker, W.S., 1990. Salinity history of the northern Atlantic during the last deglaciation. Paleoceanography 5, 459–467.

Broecker, W.S., Peng, T.H., Trumbore, S., Bonani, G., Wolfi, W., 1990. The distribution of radiocarbon in the glacial ocean. Global Biogeochem. 4, 103–117.

Bücher, A., Dubief, J., Lucas, C., 1983. Retombées estivales de poussières sahariennes sur l'Europe. Paleoceanography 24, 153–165.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahi-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjöprnsdottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-cire record. Nature 364, 218–220.

Ding, Z., Liu, T., Rutter, N.W., Yu, Z., Guo, Z., Zhu, R., 1995. Ice-volume forcing of East Asian winter monsoon variations in the past 800,000 years. Quat. Res. 44, 149–159.

Ding, Z.L., Rutter, N., Han, J.T., Liu, T.S., 1992. A coupled environmental system formed at about 2.5 Ma in East Asia. Palaeogeogr. Palaeoclim. Palaeoecol. 94, 223–242.

Forman, S.L., 1991. Late Pleistocene chronology of loess deposition near Luochan. Chin. Quat. Res. 36, 19–28.

Forster, T., Heller, F., 1994. Loess deposits from the Tajik depression (Central Asia): magnetic properties and paleoclimate. Earth Planetary Sci. Lett. 128, 501–512.

Grip Members, 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. Nature 364, 203–207.

Gu, Z., Liu, R., Liu, Y., 1991. Response of the stable isotopic composition of loess-paleosol carbonate to paleoenvironmental changes. In: T, L. (Ed.), Loess, Environment and Global Change. Science Press, Beijing, pp. 82–92.

Guo, Z., Liu, T., Guiot, J., Wu, N., Lü, H., Han, J., Liu, J., Gu, Z., 1996. High frequency pulses of East Asian monsoon climate in the last two glaciations: link with the North Atlantic. Clim. Dyn. 12, 701–709.

Hansen, J., Lacis, A., Ruedy, R., Sato, M., 1992. Potential climate impact of Mount Pinatubo eruption. Geophys. Res. Lett. 19 (2), 215–218.

Heller, F., Liu, X., Liu, T., Xu, T., 1991. Magnetic susceptibility of loess in China. Earth Planetary Sci. Lett. 103, 301–310.

Heusser, L.E., 1989. Northeast Asian climatic change over the last 140,000 years inferred from pollen in marine cores taken off the Pacific coast of Japan. In: Leinen, M., Sarnthein, M. (Eds.), Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport. Kluwer Academic Publishing, Netherlands, pp. 665–692.

Hradilova, J., 1994. New micromorphological knowledge of the last Pleistocene glacial cycle in the loess profile at Praha-Sedlec. J. Czech Geol. Soc. 39/4, 319–329.

Hradilova, J., Stastny, M., 1994. Changes in the clay fraction mineral composition in a loess profile of the last interglacial and early glacial in Praha-Sedlec. Acta Univ. Carol., Geol. 38, 229–238.

Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrump, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B., Steffensen, J.P., 1992. Irregular glacial interstadials recorded in a new Greenland ice core. Nature 359, 311–313.

Keigwin, L.D., Lehman, S.J., 1994. Deep circulation change linked to Heinrich event 1 and Younger Dryas in a middepth North Atlantic core. Paleoceanography 9 (2), 185–194.

Kotilainen, A.T., Shackleton, N.J., 1995. Rapid climate variability in the North Pacific Ocean during the past 95,000 years. Nature 377, 323–326.

Kukla, G., An, Z.S., 1989. Loess stratigraphy in central China. Palaeogeogr., Palaeoclim., Palaeoecol. 72, 203–225.

Kukla, G., An, Z.S., Melice, J.L., Gavin, J., Xiao, J.L., 1990. Magnetic susceptibility record of Chinese loess. Trans. R. Soc. Edinburgh: Earth Sci. 81, 263–288.

Kukla, G., Berger, A., Lotti, R., Brown, J., 1981. Orbital signature of interglacials. Nature 290, 295–300.

Kukla, G., Briskin, M., 1983. The age of the 4/5 isotopic stage boundary on land and in the oceans. Palaeogeogr. Palaeoclimat. Palaeoecol. 42, 35–45.

Kukla, G., Gavin, J., 1992. Insolation regime of the warm to cold transitions. In: Kukla, G.J., Went, E. (Eds.), Start of a Glacial. Series I: Global Environmental Change. Springer, Heidelberg, pp. 307–339.

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.

Labeyrie, L.D., Duplessy, J.C., Blanc, P.L., 1987. Variations in mode of formation and temperature of oceanic deep waters over the past 125,000 years. Nature 327, 477–482.

Liang, X.Z., Samel, A., Wang, W.C., 1995. Observed and GCM simulated decadal variability of rainfall in East China. Clim. Dyn. 11, 103–114.

Lin, B., Liu, R., An, Z., 1991. Preliminary research on stable isotopic composition of Chinese loess. In: Liu, T (Ed.), Loess, Environment and Global Change. Science Press, Beijing, pp. 124–131.

Loess, Environment and Global Change. In: Liu, T., Ding, Z., Guo, Z. (Eds.), The Series of the XIII INQUA Congress Science Press, Beijing, 288 pp.

Liu, T.S. et al., 1985. Loess and the Environment. China Ocean Press, Beijing, 251 pp.

Liu, T.S., Guo, Z.T., Liu, J.Q., Han, J.M., Ding, Z.L., Gu, Z.Y., Wu, N.Q., 1995. Variations of eastern Asian monsoon over the last 140,000 years. Bull. Soc. Geol. Fr. 166, 221–229.

Lu, H., Wu, N., Nie, G., Wang, Y., 1991. Phytolith in loess and its bearing on paleovegetation. The Series of the XIII InQUA Congresspp. 112–123.

Lu, Y., Prescott, J.R., Robertson, G.B., Hutton, J.T., 1987. Thermoluminescence dating of the Malan loess at Zhaitang, China. Geology 15, 603–605.

Manabe, S., Stouffer, R.J., 1995. Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. Nature 378, 165–167.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., 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. Quat. Res. 27, 1–29.

McCormick, M.P., Thomason, L.W., Trepte, C.R., 1995. Atmospheric effects of the Mt Pinatubo eruption. Nature 373, 399–404.

McIntyre, A., Ruddiman, W.F., Karlin, K., Mix, A.C., 1989. Surface water response of the Equatorial Atlantic Ocean to orbital forcing. Paleoceanography 4, 19–55.

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.

Nie, G., He, D., 1991. A new explanation regarding the provenances of materials of China's Xiashu loess. In: Liu, T. (Ed.), Loess Environmental and Global Change. Science Press, Beijing, pp. 213–227.

Porter, S., An, Z.S., 1995. Correlation between climate events in the North Atlantic and China during the last glaciation. Nature 375, 305–308.

Rampino, M.R., Self, S., 1992. Volcanic winter and accelerated glaciation following the Toba super-eruption. Nature 359, 50–52.

Robock, A., Mao, J., 1992. Winter warming from large volcanic eruptions. Geophys. Res. Lett. 19 (24), 2405–2408.

Rose, W.I., Chesner, C.A., 1990. Worldwide dispersal of ash and gases from earth's largest known eruption: Toba, Sumatra, 75 ka. Palaeogeogr., Palaeoclim., Palaeoecol. 89, 269–275.

Rousseau, D.D., Wu, N.Q., 1997a. Mollusk record of the paleomonsoon changes during the past 130,000 yrs BP in the Luochuan loess sequence (China). Geology 25, 275–278.

Rousseau, D.D., Wu, N.Q., 1997b. A new molluscan record of the monsoon variability over the past 130 000 yr in the Luochuan loess sequence, China. Geology 25, 275–278.

Rousseau, D.D., Kukla, G., Zöller, L., Hradilova, J., 1998a. Early Glacial dust storm layer at Achenheim in Alsace, France. Boreas 27, 200–207.

Rousseau, D.D., Zöller, L., Valet, J.P., 1998b. Climatic variations in the Upper Pleistocene loess sequence at Achencheim (Alsace, France). Analysis of the magnetic susceptibility and thermoluminescence chronology. Quat. Res. 49, 255–263.

Shackleton, N.J., 1988. Oxygen isotopes, ice volume, and sea level. Quat. Sci. Rev. 6, 183–190.

Shen, C.D., Beer, J., Liu, T.S., Oeschger, H., Bonani, G., Suter, M., Wölfli, W., 1992. ^{10}Be in Chinese loess. Earth Planet. Sci. Lett. 109, 169–177.

Shen, C., Yi, W., Liu, T., Beer, J., 1995. ^{10}Be chronology of loess stratigraphy. In: Wang, S. (Ed.), Scientia Geologica Sinica. Science Press, Beijing, pp. 23–30.

Smirnov, V.V., Gillette, D.A., Golitsyn, G.S., MacKinnon, D.J., 1994. The origin and evolution of dust clouds in Central Asia. Atmos. Res. 34, 169–176.

Sun, D., 1995. Preliminary study on mean annual temperature and precipitation for the last interglacial period. In: Wang, S. (Ed.), Scientia Geologica Sinica. Science Press, Beijing, pp. 153–159.

Sun, J., Ding, Z., Liu, T., 1995a. The environmental evolution of the Desert-loess transitional zone over the last glacial-interglacial cycle. In: Wang, S. (Ed.), Scientia Geologica Sinica. Science Press, Beijing, pp. 1–8.

Sun, J., Ke, M., Zhao, J., Li, B., Wei, M., 1995b. Vegetation and climate of the loess plateau in China during the Late Pleistocene. In: Wang, S. (Ed.), Scientia Geologica Sinica. Science Press, Beijing, pp. 91–103.

Vandenberghe, J., An, Z., Nugteren, G., Lu, H., Van Huissteden, K., 1997. New absolute time scale for the Quaternary climate in the Chinese loess region by grain-size analysis. Geology 25, 35–38.

Wagenbach, D., Preunkert, S., Schäfer, J., Jung, W., Tomadin, L., 1996. Northward transport of Saharan dust recorded in a deep Alpine ice core. In: Guerzoni, S., Chester, R. (Eds.), The Impact of Desert Dust Across the Mediterranean. Kluwer Academic Publishing, Dordrecht, pp. 291–300.

Wang, J.T., 1994. Modern sand storms and loess deposition in China. In: Derbyshire, E. (Ed.), Wind Blown Sediments in the Quaternary Records, London 5–8 January. p. 13.

Woillard, G., Mook, W.G., 1982. Carbon-14 dates at Grande Pile: correlation of land and sea chronologies. Science 215, 159–161.

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. Quat. Res. 43, 22–29.

Zhang, G., Wang, X., Zhang, X., 1991. The synoptic dynamic condition and the features of chemical elements of dustfall event in April 1990 in Beijing. In: Liu, T. (Ed.), Loess, Environment and Global Change. Science Press, Beijing, pp. 228–234.