Sedimentation and diagenesis of Chinese loess: Implications for the preservation of continuous, high-resolution climate records

Thomas Stevens*
Simon J. Armitage — Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, UK
Huayu Lu — Institute of Earth Environment-SKLLQG, Chinese Academy of Sciences, Xi'an 710075, China, and Department of Geography, Nanjing University, Nanjing 210093, China
David S.G. Thomas — Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, UK

ABSTRACT

Chinese loess has been extensively utilized to produce continuous and high-resolution climate records of the late Cenozoic. Such work assumes uninterrupted loess deposition and limited diagenesis. Here, closely spaced optically stimulated luminescence (OSL) dates are used to characterize the Holocene and Late Pleistocene sedimentation histories of three sites across a NW-SE transect of the Chinese Loess Plateau. The results suggest that sedimentation is episodic at subglacial-interglacial time scales, with rates rapidly varying within units and between sites. Unconformities, noneolian deposition, and mixing of sediments also appear to be common. Existing understanding of loess deposition therefore requires reexamination, while previous reconstructions of rapid climate change, not dated using absolute methods, should be regarded with caution. Loess deposits may still yield detailed climate records from specific high-sedimentation-rate strata, and evidence for rapid climate change may yet be obtainable by targeting these units through absolute dating. The rapid changes in sedimentation presented here indicate the East Asian Monsoon has the capacity to vary on millennial scales.

Keywords: Chinese loess, OSL dating, sedimentation, diagenesis, East Asian Monsoon, Quaternary.

INTRODUCTION

Sediments on the Chinese Loess Plateau (Fig. 1) are generally assumed to hold a complete and highly resolved record of late Cenozoic East Asian Monsoon change, a terrestrial equivalent of ocean sediments (Liu and Ding, 1998). Sedimentation is believed to occur almost continuously, with diagenesis having limited impact on preservation of the record. Evidence from loess of rapid climate change has been correlated to North Atlantic millennial-scale oscillations such as Heinrich Events (e.g., Porter and An, 1995), with age models supporting these reconstructions generally derived through correlation of proxies to the Martinson et al. (1987) marine $\delta^{18}O$ time scale (e.g., Hongbo et al., 1995) or from derived relationships between sedimentation rate and grain size (Vandenberghe et al., 1997; Nugteren et al., 2004). Modern patterns of loess deposition suggest that dust storms emanating northwest of the Loess Plateau (Fig. 1) are responsible for much of the current air fall (Derbyshire et al., 1998). This pattern is consistent with a winter monsoon-controlled wind as the transporting agent, although the relative contribution of different source areas complicates interpretations (Derbyshire et al., 1998).

Recently, however, Kohfeld and Harrison (2003) have highlighted discrepancies between mass accumulation rates calculated using proxy-based and absolute age models. Increasing evidence suggests that loess sedimentation may in fact be episodic, with some sections containing depositional hiatuses and disconformities caused by wind erosion (Guo and Fedoroff, 1991; Guo et al., 1996; Derbyshire et al., 1997; Singhvi et al., 2001). In addition, Lu et al. (2004) propose that some strata are affected by diagenesis so as to obscure even orbital cycle signals, while Kemp and Derbyshire (1998) indicate many paleosols are accretionary, with multiple horizons "welded" together.

In addition, a number of the assumptions and practices underpinning proxy-based age models require investigation. First, the limited number of correlation points used in many studies prohibits examination of short-term sedimentation changes (e.g., Porter and An, 1995). Second, tuning the loess record to the $\delta^{18}O$ time scale incorporates the associated ca. 5 ka error (Martinson et al., 1987). Third, studies assume a synchronicity of global ice volume and regional climate (East Asian Monsoon) change that has not been demonstrated. Fourth, despite studies suggesting that in most areas interglacial pedogenesis modifies previously deposited Late Glacial loess (e.g., Kemp and Derbyshire, 1998; Liu et al., 2004), stratigraphic or proxy "boundaries" are assumed to represent the paleosurface at times of monsoon change. Thus, in combination with the previous assumption, stratigraphic unit boundaries in loess are held to be of equivalent age to $\delta^{18}O$ (MIS) or geologic stratotype boundaries and therefore useable as known-age "tie points." If this assumption is incorrect, age models based on loess-MIS boundary correlation may also be incorrect.

Some studies use linear interpolation between "tie points" (e.g., Chen et al., 1995). Assuming that loess is primarily eolian, it should intuitively be expected that rapid changes in the northwesterly winter monsoon winds, the apparent main transporting agent for sediments that form loess (Lu and Sun, 2000), will alter the rate of loess deposition, rendering linear interpolation between widely spaced tie points untenable. A more sophisticated approach uses grain-size changes to calculate sedimentation rate variation between tie points (e.g., Porter and An, 1995) or to develop the entire age model (e.g., Nugteren et al., 2004). However, calibration of sedimentation rate to grain size is achieved by dating parts of the loess sequence through tuning to marine $\delta^{18}O$ stratigraphy.

There are therefore strong grounds for test-

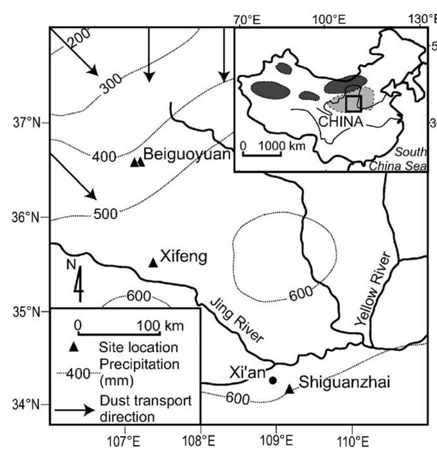

Figure 1. Map of study area including modern isohyets (mm) and potential dust transport directions with map of China (inset) showing Chinese Loess Plateau (light shading), potential source regions (dark shading), major rivers, and study area (box).

*E-mail: thomas.stevens@ouce.ox.ac.uk

ing the assumptions that loess preserves a continuous climate record and records rapid climate change. The determination of loess sedimentation rates and continuity of deposition through detailed independent age models are key steps in this process. However, many of the independent ages published to date may contain inaccuracies (Kohfeld and Harrison, 2003) and are not at the resolution required to address these issues. Despite promising earlier work (e.g., Yanchou et al., 1987), there have been few recent high-sampling-resolution luminescence studies concerned with Chinese loess (e.g., Roberts et al., 2001). This paper presents results from a high-resolution sampling (10–20 cm) and dating program focused on latest Pleistocene (upper Malan) and Holocene (Black Loam) loess/paleosols.

SETTING AND METHODS

The three sites investigated in this study, Shiguanzhi, Xifeng, and Beiguoyuan, are located on a southeast-to-northwest transect across the Chinese Loess Plateau, permitting investigation of the spatial variability of deposition associated with different environmental, sedimentary, and diagenetic contexts (Fig. 1). Differences in precipitation and distance from sediment source (Lu and Sun, 2000) cause significant facies variation in the Malan loess (L1 unit) and Black Loam (S0 unit) formations. Beiguoyuan comprises two sections located near Huanxian in Gansu Province, on the northern Loess Plateau (Fig. 1). The section with the most complete Holocene record (36°37′21.3″N, 107°17′12.2″E, 1523 masl) lies several km northwest of the main section (36°37′ 6.2″N, 107°16′57.4″E, 1545 masl) where a longer record of loess sedimentation is preserved. Sampling concentrated on the full Holocene section, entirely made up of Black Loam, and the upper 3 m of the main section that contains the Black Loam and upper Malan loess. The original section at Xifeng (Gansu Province), in the central Loess Plateau, is one of the most studied loess sections in China (e.g., Kukla et al., 1988; Maher and Thompson, 1991). A new Xifeng exposure (35°32′09.4″N, 107°43′13.5″E, 1281 masl) was sampled over the upper 4.30 m to include the entire Black Loam and upper Malan loess. At the Shiguanzhi site (34°10′22.2″N, 109°11′45.5″E, 708 masl) in Shaanxi Province, on the southeastern fringe of the plateau, the upper 1.75 m of the section was sampled to include the upper Malan loess, Black Loam paleosol, and a distinct loess layer lying above, here termed L0.

Full details of the analytical techniques used in age determination are presented in GSA Data Repository Appendix 1.[1] Coarse quartz silt (40–63 μm) was used for equivalent dose (D_e) determination using the SAR procedure (Murray and Wintle, 2000) and through construction of standard growth curves (Roberts and Duller, 2004) using a Risø TL-DA-15 TL/OSL reader (Figs. DR1 and DR2[1]). Dose rates were calculated using U, Th, and K contents measured using ICP-MS and -AES. Cosmic dose rates were calculated using present-day burial depth (Prescott and Hutton, 1994). D_e, dosimetry, and age data are presented in Table DR1[1].

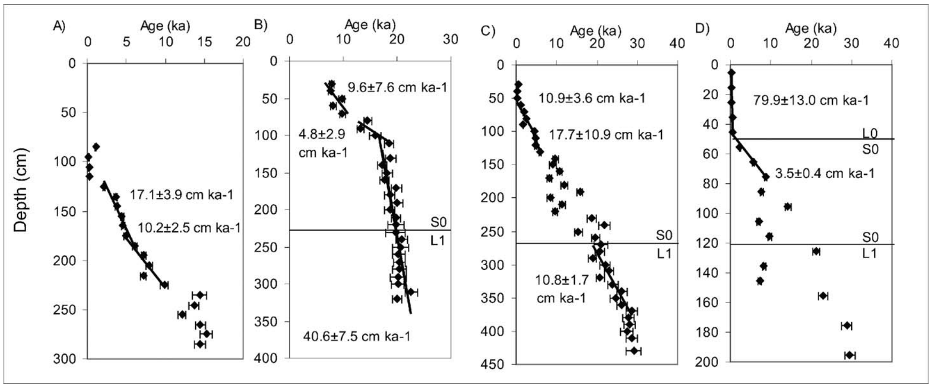

Figure 2. OSL ages and sedimentation rates (±1σ) calculated through linear regression for Beiguoyuan Holocene section (A), Beiguoyuan main section (B), Xifeng (C), and Shiguanzhi (D). Horizontal lines show stratigraphic boundaries.

RESULTS

OSL ages, stratigraphy, and sedimentation rates are presented in Figure 2 and Table DR1. The Beiguoyuan Holocene section provides a 15 ka record of deposition (Fig. 2A). The upper 80 cm of this section was not sampled because of apparent agricultural disturbance. Young age determinations for samples at 95–115 cm depths suggest that this disturbance extends to a greater depth than was apparent in the field. Below 115 cm, three distinct sedimentation rate strata can be distinguished. Relatively rapid sedimentation (17.1 ± 3.9 cm/k.y.) is observed between 2 and 5 ka, preceded by a prolonged slower phase (10.2 ± 2.5 cm/k.y.) between 5 and 10 ka. Prior to this, ages rapidly increase from 10 to 14 ka, while a cluster of ages centered on 14 ka appears to represent a phase of rapid sedimentation.

The Beiguoyuan main section provides a record of loess sedimentation from 7 to 22 ka (Fig. 2B). Despite the large errors associated with some data points, slow sedimentation is observed between 8 and 10 ka (9.6 ± 7.6 cm/k.y.), preceded by a gap in the record with potentially even slower sedimentation between 14.5 and 18.5 ka (4.8 ± 2.9 cm/k.y.). This is preceded by a phase of extremely rapid sedimentation centered on 19.6 ka (40.6 ± 7.5 cm/k.y.). The base of the S0 soil, identified visually in the field, is dated to 19 ka, indicating significant Holocene pedogenesis on Late Glacial loess. The absence of dates between 10 and 14 ka at both Beiguoyuan sections is perhaps indicative of a hiatus in sedimentation or disconformity.

The dated record of loess sedimentation at Xifeng extends from 0.3 to 29 ka and appears to show less variation than at Beiguoyuan (Fig. 2C). The Holocene record shows some variation, although changes in sedimentation rate are difficult to resolve due to large errors associated with some data points. Modern ages for the top 50 cm of this section suggest agricultural disturbance. Relatively rapid sedimentation occurs at 5 ka (17.7 ± 10.9 cm/k.y.) with reduced rates from ca. 4 ka (10.9 ± 3.6 cm/k.y.). Despite the record being characterized by broad increases in age with depth, some age inversions occur. In addition, there appears to be a break in sedimentation between 6 and 9 ka. This pattern may result from either mixing due to bioturbation or sedimentation through noneolian processes. Between 20 and 26 ka, the record appears resolvable again and shows sedimentation rates similar to the late Holocene (10.8 ± 1.7 cm/k.y.), after decreasing from very rapid sedimentation centered on 28.5 ka.

The Shiguanzhi record details loess sedimentation from 0 to 30 ka (Fig. 2D). Extremely rapid sedimentation (79.9 ± 13.0 cm/k.y.) is recorded from 0.1 to 0.6 ka, preceded by rates more than an order of magnitude slower (3.5 ± 0.4 cm/k.y.) from 0.6 to 9 ka. Dates between 85 and 145 cm show significant scatter, while from 155 to 195 cm dates show a consistent trend of increasing age with depth, indicating that they are more reliable. The

[1]GSA Data Repository item 2006183, analytical techniques and age data, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

anomalous dates from 85 to 145 cm are associated with the base of the Holocene soil and may again represent reworked sediment during pedogenesis and low sedimentation or noneolian processes. The change in sedimentation rates at 0.6 ka is coincident with the boundary between S0 and the overlying L0 unit. The past 600 yr of sedimentation at Shiguanzhi is extremely rapid and probably indicates agricultural modification of the upper soil.

LOESS SEDIMENTATION AND DIAGENESIS

While discussion of sedimentation rate changes is limited to centennial or longer timescales due to the precision of OSL dating, loess sedimentation appears to vary rapidly both within and between the studied sites. With the possible exception of the late Holocene, sedimentation rate changes are not coeval between sites and vary dramatically within all units, most obviously in S0 at the Beiguoyuan main section (Fig. 2B). Agricultural disturbance not evident from stratigraphy, broadly consistent with that observed at Duowa on the western Loess Plateau (Roberts et al., 2001) appears to be present at all three sites.

Where the Beiguoyuan main and Holocene records overlap, there is agreement in sedimentation rate, and both sections show an apparent hiatus between 10 and 14 ka. However, at the main section, sedimentation rates are low between 14 and 15 ka, whereas at the Holocene section there appears to be a rapid flux (Figs. 2A and 2B). This discrepancy implies severe lateral differences in facies preservation or emplacement either as a result of a section-specific disconformity, perhaps due to deflation or sheetwash-induced erosion during an increase in either winter or summer monsoon strength, respectively, or as a result of local sedimentation rate variation. Holocene pedogenesis on older, Late Glacial loess also appears ubiquitous. At Beiguoyuan, where the high sedimentation rate might be expected to limit pedogenesis on older loess, the S0 soil yields ages well into the Late Pleistocene. Loess dating from the beginning of the Holocene is 125 cm above the actual stratigraphic boundary at the Beiguoyuan main section. The age of the S0/L1 boundaries at Xifeng and Shiguanzhi, dated as ca. 20 ka for both sites, also indicates significant pedogenic overprinting on loess of Late Glacial age.

In parts of the Xifeng and Shiguanzhi sections, large changes and inversions in measured ages (and D_e values) are observed. The range of this variation, the fact that dates are consistent above and below these levels, and the coincidence of this variation with the base of the S0 soil suggest that this may be an effect of enhanced bioturbation and pedogenesis during the early Holocene. This is supported in that variation is most extreme at Shiguanzhi, where soil development is greatest. It is possible that sedimentation at the sites was greatly reduced for part of the early Holocene. causing Late Glacial loess to be reworked during pedogenesis. The OSL ages are therefore ''correct'' in that they date the last time the sediments were exposed due to mixing, but do not record the time elapsed since they were first emplaced. Alternatively, it is possible these sediments were deposited through low-energy alluvial, colluvial, or mass wasting processes. Detailed grain-fabric evidence is required to assess whether Chinese loess can be considered as completely eolian, as is believed by many authors (Derbyshire et al., 1998), but is beyond the scope of this paper.

IMPLICATIONS

The OSL dates show that loess deposition and diagenesis vary considerably between and within sites. As sedimentation rates and changes are not coeval across the Loess Plateau, generalizations concerning the preserved climate record cannot be made. Furthermore, the existence of section-specific sedimentation/preservation differences at Beiguoyuan highlights the importance of local conditions. The existence of within-unit variation as well as hiatuses undermines the assumption of semicontinuous sedimentation, while the low resolution of much of the record limits the potential to reconstruct rapid climate change.

It can also be noted that the geomorphic settings of the studied sites are not exceptional. Because all three sites are located in stable sedimentary basins, termed loess 'yuan,' the presence of hiatuses here suggests that they are more common in the Chinese loess record than has previously been recognized. The proximity of Beiguoyuan to the dust source regions means that at times of strong winter monsoon, when deposition at sites farther from source regions was enhanced, deflation may have predominated at Beiguoyuan, resulting in stratigraphic disconformities. Hiatuses at sites farther from source regions are more likely to have been caused by reduced sedimentation or increased sheetwash erosion in response to summer monsoon rains. The relationship of wind speed to sedimentation rate will therefore be affected by location on the Loess Plateau, with complex signatures involving rainfall, wind speed, source area, and geomorphic setting. Further sedimentological characterization may help elucidate the relative influence of these factors.

The discordance between ages of the L1/S0 and MIS 2/1 boundaries supports the contention that stratigraphic boundaries are not indicative of the true paleosurface at the onset of soil formation (e.g., Liu et al., 2004). In this study, an age offset of ~7.5 k.y. between the termination of the Pleistocene and the base of the Holocene soil is observed even closest to the dust sources at Beiguoyuan. Such an offset would propagate into age models based on stratigraphic ''tie points.''

Pedogenic and agricultural sediment mixing or deposition of loess by noneolian processes over large parts of some sections means that substantial portions of paleoclimate record will be obscured. Age models constructed using grain-size or MIS correlation techniques would not reveal such evidence and would be incorrect. At the studied sites, much of the Late Glacial record is affected, and hence a pristine record of the Late Glacial monsoon may not be preserved. Such evidence also demonstrates the danger in taking a single OSL date in isolation. At Shiguanzhi, dates 10 cm apart vary by up to 15.5 ka due to disturbance or noneolian processes (Fig. 2D).

These findings suggest that the current assumptions concerning Chinese loess sedimentation are incorrect: Loess deposition can clearly be episodic and noneolian, while the loess itself is prone to postdepositional disturbance. Consequently, contrary to the existing theoretical framework, the preserved climate record from loess cannot be considered as continuous. Furthermore, the dating and interpretation of rapid proxy change using proxy-based age models will be in substantial error. However, this does not lessen the paleoclimatic importance of Chinese loess. Since loess holds a fractured record containing periods of very rapid sedimentation, in-depth paleoclimatic information may be obtainable from these parts of the sequence using high-resolution absolute dating.

PALEOCLIMATE

The majority of the sites seem to show that sedimentation rate increases significantly during the later Holocene (from 5 to 2 ka), although the changes are only significant at the Beiguoyuan Holocene section. Assuming eolian deposition, this implies increased aridity and/or wind speed, possibly linked to increased East Asian winter monsoon activity during the later Holocene. There are further, more dramatic phases of very rapid sedimentation at Xifeng and Beiguoyuan. Although the possibility of noneolian deposition requires further investigation, the presence of these high-sedimentation-rate strata may themselves be diagnostic of rapid changes and enhancements in the winter monsoon. The pulses, centered on 28, 20, and 14 ka at the Xifeng, Beiguoyuan Holocene, and Beiguoyuan main sections respectively, are similar in age to Heinrich Events 3–1 (Bond et al., 1992), potentially indicating a connection to the North Atlantic. However, any leads and lags as well as the precise physical nature of any such link remain to be systematically investigated.

CONCLUSIONS

The belief that Chinese loess has accumulated almost uninterruptedly at a constant rate has allowed continuous, high-resolution climate records to be obtained for much of the Quaternary. However, this assumption has previously not been tested. The closely spaced OSL dates presented here indicate that the assumption of constant, uninterrupted loess deposition is too simple. Far from being a continuous process, deposition is episodic and highly variable, with contributions from noneolian processes. In addition, once emplaced, loess can be prone to mixing and erosion. Consequently, apparently continuous climate records extracted from Chinese loess, dated using stratigraphic or proxy variations, may be in substantial error. Much of the loess record may not have the resolution to provide evidence for rapid climate change, although high-sedimentation-rate strata, dated using absolute methods, may yield such information. The rapid nature of changes in sedimentation rate implies that the winter monsoon changes over millennial scales, and the timing suggests a possible link to the North Atlantic. However, while certain parts of the Chinese loess record may provide sequences of unparalleled resolution, loess does not seem to yield a continuous climate record similar to that found in ocean sediments.

ACKNOWLEDGMENTS

The authors would like to thank to Yi Shuangwen and Sun Xuefeng for help in the field, NERC for access to their ICP-MS and -AES facilities and the National Natural Sciences Foundation of China (grants 40325007 and 40121303) for fieldwork support. TS thanks Jesus College, Oxford University Centre for the Environment, and Dr. Stephen Stokes for financial support. Stephen Stokes, Richard Bailey, and other members of the Oxford Luminescence Research Group are also thanked for discussions and advice. The manuscript was also greatly improved by reviews from Ed Derbyshire and an anonymous reviewer.

REFERENCES CITED

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, I., and Ivey, S., 1992, Evidence for massive discharges of icebergs into the North Atlantic during the last glacial period: Nature, v. 360, p. 245–249, doi: 10.1038/360245a0.

Chen, F.H., Wu, R., Pompei, D., and Oldfield, F., 1995, Magnetic property and particle size variations in the late Pleistocene and Holocene parts of the Dadongling loess section near Xining, China, *in* Derbyshire, E., ed., Wind Blown Sediments in the Quaternary Record: Quaternary Proceedings, Number 4: Chichester, UK, John Wiley and Sons, p. 27–40.

Derbyshire, E., Kemp, R.A., and Meng, X., 1997, Climate change, loess and palaeosols: Proxy measures and resolution in North China: Geological Society [London] Journal, v. 154, p. 793–805.

Derbyshire, E., Meng, X., and Kemp, R.A., 1998, Provenance, transport and characteristics of modern aeolian dust in western Gansu Province, China, and interpretation of the Quaternary loess record: Journal of Arid Environments, v. 39, p. 497–516.

Guo, Z.T., and Fedoroff, N., 1991, Paleoclimatic and stratigraphic implications of the paleosol S1 in the loess sequence in China, *in* Liu, T.S., ed., Loess, environment and global change: Beijing, China, Science Press, p. 187–198.

Guo, Z.T., Fedoroff, N., and Liu, T.S., 1996, Micromorphology of the loess-paleosol sequence of the last 130 ka in China and paleoclimatic events: Science in China, v. 39, p. 468–477.

Hongbo, Z., Rolph, T., Shaw, J., and An, Z., 1995, A detailed palaeomagnetic record for the last interglacial period: Earth and Planetary Science Letters, v. 133, p. 339–351, doi: 10.1016/0012-821X(95)00089-U.

Kemp, R.A., and Derbyshire, E., 1998, The loess soils of China as records of climatic change: European Journal of Soil Science, v. 49, p. 525–539.

Kohfeld, K.E., and Harrison, S.P., 2003, Glacial-interglacial changes in dust deposition on the Chinese Loess Plateau: Quaternary Science Reviews, v. 22, p. 1859–1878, doi: 10.1016/S0277-3791(03)00166-5.

Kukla, G., Heller, F., Liu, X.M., Chun, X.T., Liu, T.S., and An, Z.S., 1988, Pleistocene climates in China dated by magnetic susceptibility: Geology, v. 16, p. 811–814, doi: 10.1130/0091-7613(1988)016<0811:PCICDB>2.3.CO;2.

Liu, Q.S., Banerjee, S.K., Jackson, M.J., Chen, F.H., Pang, Y.X., and Zhu, R.X., 2004, Determining the climatic boundary between the Chinese loess and palaeosol: Evidence from aeolian coarse-grained magnetite: Geophysical Journal International, v. 156, p. 267–274, doi: 10.1111/j.1365-246X.2003.02148.x.

Liu, T., and Ding, Z., 1998, Chinese loess and the paleomonsoon: Annual Review of Earth and Planetary Science, v. 26, p. 111–145, doi: 10.1146/annurev.earth.26.1.111.

Lu, H.Y., and Sun, D.H., 2000, Pathways of dust input to the Chinese Loess Plateau during the last glacial and interglacial periods: Catena, v. 40, p. 251–261, doi: 10.1016/S0341-8162(00)00090-4.

Lu, H.Y., Zhang, F.Q., Liu, X.D., and Duce, R., 2004, Periodicities of palaeoclimatic variations recorded by loess-paleosol sequence in China: Quaternary Science Reviews, v. 23, p. 1891–1900, doi: 10.1016/j.quascirev.2004.06.005.

Maher, B.A., and Thompson, R., 1991, Mineral magnetic record of the Chinese loess and paleosols: Geology, v. 19, p. 3–6, doi: 10.1130/0091-7613(1991)019<0003:MMROTC>2.3.CO;2.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J.L., Moore, T.C., Jr., and Shackleton, N.C., 1987, Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy: Quaternary Research, v. 27, p. 1–29, doi: 10.1016/0033-5894(87)90046-9.

Murray, A.S., and Wintle, A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose procedure: Radiation Measurements, v. 32, p. 57–73, doi: 10.1016/S1350-4487(99)00253-X.

Nugteren, G., Vandenberghe, J., van Huissteden, J.K., and An, Z., 2004, A Quaternary climate record based on grain size analysis from the Luochuan loess section on the central Loess Plateau, China: Global and Planetary Change, v. 41, p. 167–183, doi: 10.1016/j.gloplacha.2004.01.004.

Porter, S.C., and An, Z., 1995, Correlation between climate events in the North Atlantic and China during the last glaciation: Nature, v. 375, p. 305–308, doi: 10.1038/375305a0.

Prescott, J.R., and Hutton, J.T., 1994, Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long term variations: Radiation Measurements, v. 23, p. 497–500, doi: 10.1016/1350-4487(94)90086-8.

Roberts, H.M., and Duller, G.A.T., 2004, Standardised growth curves for optical dating of sediment using multiple-grain aliquots: Radiation Measurements, v. 38, p. 241–252, doi: 10.1016/j.radmeas.2003.10.001.

Roberts, H.M., Wintle, A.G., Maher, B.A., and Hu, M., 2001, Holocene sediment accumulation rates in the western Loess Plateau, China, and a 2500-year record of agricultural activity, revealed by OSL dating: The Holocene, v. 11, p. 477–483, doi: 10.1191/095968301678302913.

Singhvi, A.K., Bluszcz, A., Bateman, M.D., and Rao, M.S., 2001, Luminescence dating of loess-palaeosol sequences and coversands: Methodological aspects and palaeoclimatic interpretations: Earth-Science Reviews, v. 54, p. 193–211, doi: 10.1016/S0012-8252(01)00048-4.

Vandenberghe, J., An, Z., Nugteren, G., Lu, H., and Van Huissteden, K., 1997, New absolute time scale for the Quaternary climate in the Chinese loess region by grain-size analysis: Geology, v. 25, p. 35–38, doi: 10.1130/0091-7613(1997)025<0035:NATSFT>2.3.CO;2.

Yanchou, L., Prescott, J.R., Robertson, G.B., and Hutton, J.T., 1987, Thermoluminescence dating of Malan loess at Zhaitang, China: Geology, v. 15, p. 603–605, doi: 10.1130/0091-7613(1987)15<603:TDOTML>2.0.CO;2.

Manuscript received 28 November 2005
Revised manuscript received 10 May 2006
Manuscript accepted 18 May 2006

Printed in USA