Geology, published online on 6 December 2013 as doi:10.1130/G34857.1

Linking coarse silt production in Asian sand deserts and Quaternary accretion of the Chinese Loess Plateau

Rivka Amit[1], Yehouda Enzel[2], Amit Mushkin[1], Alan Gillespie[3], Jigjidsurengiin Batbaatar[3], Onn Crouvi[1], Jef Vandenberghe[4], and Zhisheng An[5]

[1]Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel
[2]Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem 91904, Israel
[3]Quaternary Research Center, University of Washington, Seattle, Washington 98195, USA
[4]Faculty of Earth and Life Sciences, Vrije University, De Boelelaan 1085, Amsterdam, Netherlands
[5]State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, People's Republic of China

ABSTRACT

The Chinese Loess Plateau (CLP) is a large, spatially well defined and persistent zone of loess accumulation developed near the fluctuating northwest margin of the East Asian monsoon. Many studies have analyzed its loess sediments to provide insights into paleoclimatic conditions. Although spatial and temporal variations in the grain sizes of CLP sediments are fundamental to this effort, controversy over the origin of the dominant coarse quartz silt has limited interpretations. Reexamination of the spatial pattern of grain-size distribution across the CLP and a field-scale experiment conducted in the Gobi Desert revealed a genetic association between the coarse silt fraction of the loess and primary production of coarse silt through eolian abrasion of sand in the proximal Mu-Us, Tengger, and Badain Jaran sandy deserts. Our results demonstrate the effectiveness of eolian abrasion of quartz sand in primary coarse silt production in Central Asia and identify this process as the most consistent with the well-recognized systematic northwest-southeast depositional pattern of the CLP. We suggest that only abraded coarse quartz grains transported short distances by long-term persistent eolian activity can build up thick loess sequences to form a massive and spatially well defined loess plateau. These results decouple the production and transport of coarse silt and finer silt and clay particles, which have a more distant and wider provenance, changing the constraints on previous paleoclimatic reconstructions.

INTRODUCTION

The Chinese Loess Plateau (CLP; northwest China) depositional sequence, which dates back 3 m.y., is a unique terrestrial archive (An, 2000, and references therein) for Quaternary geologists and paleoclimatologists. The search for the provenance of the CLP sediments started 2000 yr ago when Chinese scholars studied the relationship between wind-blown dust and loess (Liu, 1985). Although the subject has been the focus of numerous studies since then, the source of the CLP sediments is debated. All the large deserts of Central Asia have been considered capable of contributing silt directly by eolian redistribution and winnowing (e.g., Pye and Zhou, 1989; An et al., 1990; Ding et al., 1999; Laurent et al., 2006; Chen et al., 2007; Sun et al., 2008). Recent studies have advocated multiple silt sources from larger areas than any desert region proximal to the CLP, including large fluvial systems such as the Yellow River, to explain its composite nature and the very large volume of loess generated and transported (Maher et al., 2009; Prins et al., 2009; Stevens et al., 2010, 2013).

In spite of this implied genetic complexity, the CLP presents a systematic northwest-southeast, time-transgressive depositional spatial pattern in terms of fundamental loess properties such as median grain size, thickness, mass-accumulation rates (MAR), and magnetic susceptibility (An et al., 1990; Pye and Zhou, 1989; Porter, 2001; Xiao et al., 2002; Kohfeld and Harrison, 2003; Vandenberghe et al., 2004; Sun et al., 2004; Prins et al., 2007; Yang and Ding, 2008). Distant complex sources cannot produce such distinct patterns (Fig. 1).

Acknowledging the significance of these persistent depositional patterns and the possibility that multiple sources may be involved in supplying the wide range of silt-size material to the CLP, we parse the outstanding provenance problem into fractions of tractable size and focus on the primary constituent of the loess deposits in the CLP, i.e., the quartz-dominated coarse silt fraction. We build on first-order physical constraints previously established for limited eolian transport distance ($<10^3$ km) of coarse silt particles (Fig. DR1 in the GSA Data Repository[1]) (Tsoar and Pye, 1987), and reexamine the plausibility of proximal primary quartz-rich sources for this fraction of the CLP and their compatibility with systematic eolian depositional patterns.

[1]GSA Data Repository item 2014006, calculations of loess production through sand abrasion and figures showing data from Mongolia study site, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

APPROACH AND METHODOLOGY

The presence of coarse quartz (>16 μm) in loess-soil sequences, specifically in the northern CLP sequences (Fig. 1), has been proposed as an indicator for the proximity of the desert margin (An et al., 1990; Vandenberghe et al., 1997; Ding et al., 1999; Prins et al., 2007; Yang and Ding, 2008). However, Wang et al. (2005) argued that the low content of silt in active dunes of these proximal sandy deserts rules them out as primary sources for coarse silt in the CLP.

Studies by Crouvi et al. (2008, 2010) and Enzel et al. (2010) demonstrated a genetic relation between the coarse silt fraction of loess deposits in the low-latitude warm deserts with proximal upwind large dune fields that lack coarse silt. These studies identified the primary production of coarse silt quartz by abrasion in active sand dunes as the driving mechanism underlying the genetic association and ruled out winnowing as a major contributing process in the studied cases. Recognizing the pivotal role of eolian abrasion in our hypothesis, we carried out a natural field-scale experiment in the Gobi Desert of southwestern Mongolia designed to test whether eolian abrasion of sand is also a viable mechanism in the high-altitude cold desert environments of Central Asia. We also tested the feasibility of proximal abrading sand sources for the coarse-grained fraction of the CLP with first-order mass-balance calculations.

Field Work

The prominent Eej Hairhan Mountain granite inselberg (2250 m asl, above sea level) rises ~1050 m above the surrounding valley floor (~1200 m asl) and has a small, ~10 km^2, climbing quartz dune field on its western slopes (Fig. 2). Prominent ~50-km-long wind streaks originate from this dune field and extend eastward on top of extensive low-relief abandoned and stable alluvial surfaces. The region is characterized by extreme aridity with mean annual precipitation <50 mm/yr and 30–40 d/yr of strong northwesterly winds (>15 m/s; Dorjgotov, 2004).

Satellite images demonstrate a clear link between the dune field west of Eej Hairhan and the light toned wind streaks in its lee. To

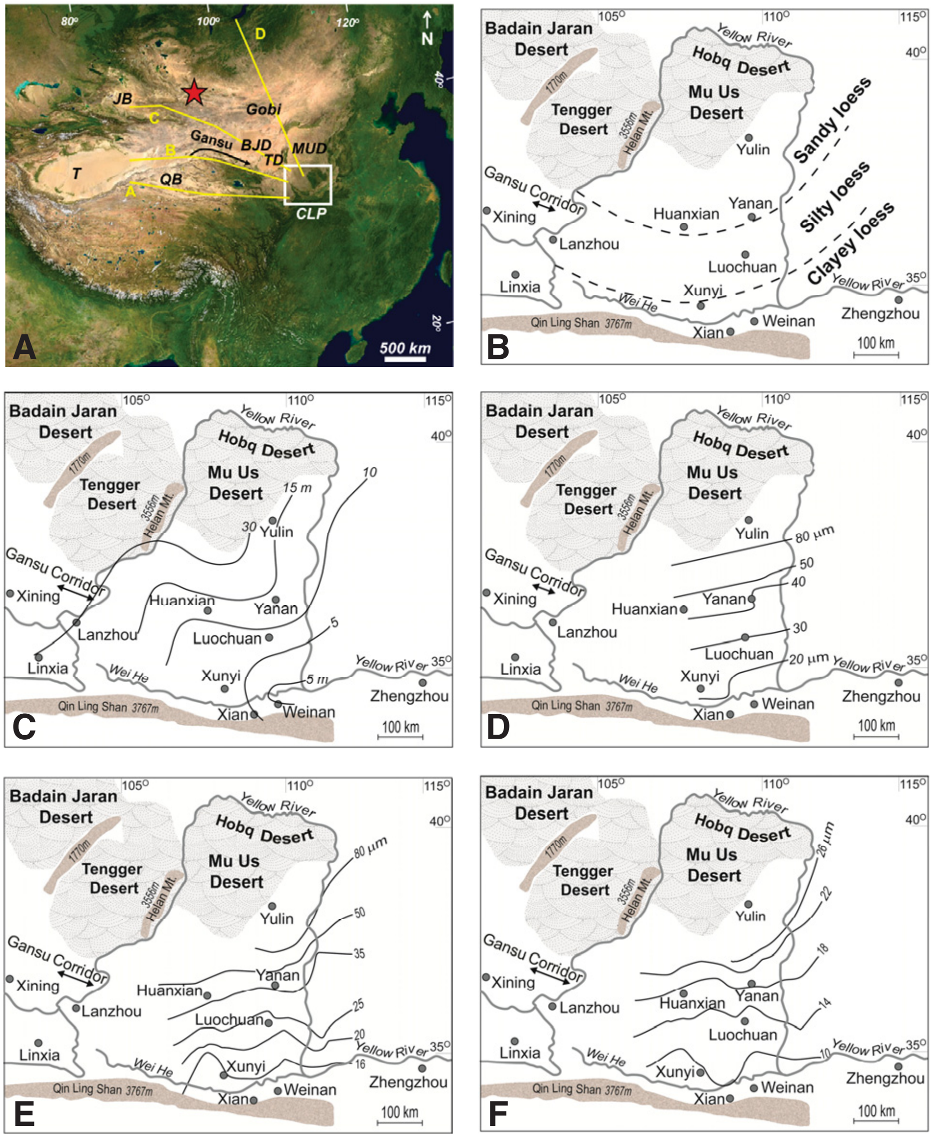

Figure 1. Spatial patterns of loess properties across Chinese Loess Plateau (CLP) indicate consistent northwest-southeast concentric decrease of loess thickness and loess grain size during glacial and interglacial times. A: Large sandy deserts of Central Asia. MUD—Mu-Us Desert; TD—Tengger Desert; BJD—Badain Jaran Desert; QB—Qaidam Basin; T—Taklimakan; JB—Junggar Basin. Red star—study area in Gobi Desert, Mongolia.Yellow lines A–D represent topographic transects from distal sandy deserts to CLP (see Fig. 3). B: Grain-size zoning across CLP (after An et al., 1990; Porter, 2001; Prins et al., 2007). C: Variation in thickness (m) of last glacial Malan loess (after Porter, 2001). D: Median diameter (μm) of grains composing surface loess sampled across plateau (after Porter et al., 2001). E: Contour map of median grain size (μm) of CLP for marine isotope stage 2 (MIS 2) (after Yang and Ding, 2008). F: Contour map of median grain size (μm) of CLP for MIS 3 (after Yang and Ding, 2008).

determine whether this genetic relation extends into geologic time scales, we also examined the particle size distribution (PSD) of quartz in the late Pleistocene calcic-gypsic and gypsic-salic Reg soils within and outside the streaks that act as effective eolian dust and sand traps (Fig. 2). We also examined quartz PSDs in the range of potentially contributing sources of eolian quartz in the study area. For this, 20 soil pits were excavated and described. Soil samples (~500 g each) were typically taken at 5–10 cm intervals down to 50–100 cm depth and PSD was determined using laser diffraction.

RESULTS

The off-streak sampling sites, which include site M3–32 on top of a small 2 km^2 basaltic bedrock outcrop where soil quartz is expected to be eolian, display a common bimodal PSD of quartz characterized by prominent fine silt (~5 μm) and medium-fine sand (~180 μm) modes (Fig. 2; Fig. DR2 in the Data Repository). Whereas long-distance eolian transport of the fine silt allows regional sources, the limited eolian transport distance of medium-fine sand requires nearby local sources. The on-streak samples consistently display a dominant ~180 μm mode and a significantly subdued ~5 μm mode, indicating on-streak enrichment in ~180 μm quartz from a nearby source (Fig. 2). The supply of eolian quartz to the wind streaks can be clearly tracked to the sand dune west of Eej Hairhan, yet this dune exhibits a much coarser unimodal PSD, with the mode at ~300 μm. The quartz PSD in all other nearby source areas rules them out as feasible contributors of 180 μm sand to the streaks, i.e., the nearby playa center deposits (unimodal, ~20 μm), playa perimeter deposits (bimodal, ~80 μm and ~6–8 μm), and alluvial fan-toe deposits (trimodal, ~90 μm, ~7 μm, and >1 μm). The rounded morphology of quartz grains in the active sand dunes (mode at 300 μm) and the sub-angular quartz sand grains (180 μm) in the wind streaks strongly support the occurrence of abrasion (Fig. DR3). Thus, eolian abrasion in the sand dune west of Eej Hairhan appears to be the mechanism most consistent with the suite of field, PSD, and scanning electron microscope observations. The Eej Hairhan experiment is not a direct analog to the CLP, because of different PSDs and transport distances. However, it demonstrates, sensu stricto, that eolian abrasion of quartz sand has been active in Central Asia.

DISCUSSION

The genetic relation between coarse silt fraction of loess deposits in the low-latitude warm deserts and in Central Asia led us to reconsider the proximal sandy deserts north and northwest of the CLP as a possible source of quartz sand grains accessible for abrasion. These sandy deserts were previously considered as potential dust sources for the CLP (Pye and Zhou, 1989; Ding et al., 1999; Kohfeld and Harrison, 2003; Laurent et al., 2006; Chen et al., 2007; Sun et al., 2008; Zhang et al., 2012). However, these studies typically regarded such sandy deserts as intermediate silt reservoirs rather than direct sources, because their PSDs (125–250 μm; Yang et al., 2012; particulate matter, PM_{10} 0.0%–0.3% and $<PM_{50}$ 0.05%–0.4%; Wang et al., 2005) were thought to be inconsistent with them being major sources for the CLP silts. A primary dynamic production of silt through eolian abrasion of quartz sand dunes under intense and persistent winds, such as identified in the deserts of Arabia and Africa (Crouvi et al., 2008, 2010) and now in Central Asia (Fig. 2), restores these sandy deserts as feasible candidates.

Invoking the primary production of silt-size material through eolian abrasion of active sand dunes highlights the potential contribution of silt from Central Asia's prominent sandy deserts, which are among the most extensive and oldest in the world. However, distal sandy deserts (>10^3 km) appear to be unlikely sources for the >16 μm coarse silt fraction of the CLP; transport distances are too great and high topographic barriers impede eolian transport of coarse silt from these sources to the CLP (Fig. 3). Thus, the

Geology, published online on 6 December 2013 as doi:10.1130/G34857.1

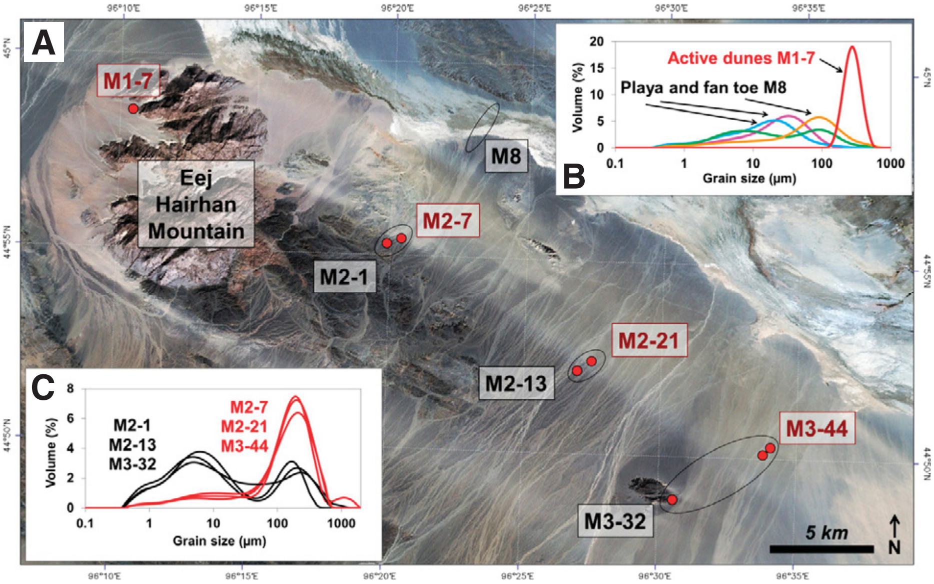

Figure 2. A: Prominent 50-km-long wind streaks originate from climbing sand dune east of granite inselberg of Eej Hairhan Mountain (2250 m above sea level) (Landsat thematic mapper true color composite). Soil sampling locations are shown (prefix M). Prominent wind direction is northwest-southeast. B, C: Grain-size distributions of surface soil samples.

association of the coarse silt quartz fraction of the CLP is more likely with proximal (<10^3 km) sandy deserts such as the Mu-Us, Tengger, and Badain Jaran.

Recognizing the significance of PSD in constraining provenance for the coarse silt fraction, we highlight the northwest-southeast spatial patterns of PSD previously mapped across the CLP and the consistent compatibility with proximal northwest sources (Fig. 1). Three CLP particle-size zones consistent with a proximal northwest source were previously mapped (Fig. 1B): sandy (~63 µm), silty (~40 µm), and clayey (<19 µm) (An et al., 1990; Vandenberghe et al., 1997; Porter, 2001). Prins et al. (2007) described the CLP as fining systematically downwind from the sandy desert margins. They also described north-south increase of the ~19 µm mode, from Huanxian to Xunyi (Prins et al., 2007, their figure 5). This is paralleled by a north-south decrease in the >63 µm fraction: the loess sequence in Yulin (northern CLP) is rich in sand and most samples 420 km to the south are devoid of this grain-size fraction (Ding et al., 1999, 2005). The south-fining trend also occurs at depth: the 50–90 µm mode at Yulin gradually changes to finer silt, 15–20 µm, at Xian (Sun et al., 2004). In contrast, the fine-silt component of the CLP (modes at 3–6 µm) shows little spatial variation (Sun et al., 2004), supporting different sources and distribution for the coarse and fine silts composing the CLP.

The systematic northwest-southeast decrease in particle size across the CLP also scales positively with the thickness and MAR (Fig. 1C) (An et al., 1990; Vandenberghe et al., 1997; Porter et al., 2001; Nugteren and Vandenberghe, 2004). This trend is paralleled by a monotonic decrease in median grain size (80 µm to 20 µm; Fig. 1D) and by the calculated MAR decrease from 100 g/cm^2/k.y. to 10 g/cm^2/k.y. (Prins et al., 2007). All are fully consistent with proximal sources to the north and northwest: the Mu-Us, Tengger, and Badain Jaran Deserts (Fig. 1A).

The northwest-southeast PSD trends have been documented for both glacial and interglacial CLP sediments (marine isotope stage, MIS 7–MIS 2), although they appear less prominent during interglacial periods (Figs. 1E and 1F) (Yang and Ding, 2008). This glacial-interglacial difference has been attributed to rigorous regional winds and much higher dust flux during glacial periods (Sarnthein, 1978; Nugteren and Vandenberghe, 2004; McGee et al., 2010). The >63 µm (sand) fraction in both interglacial paleosols and glacial loess is also greatest at the Mu-Us Desert–CLP transition (at Yulin) and dramatically decreases southward (Ding et al., 1999). In addition, under the PSD mode of the coarse silt at Yulin there is a significant amount of fine sand (Ding et al., 1999) that is uncommon in the sand field and that cannot be derived from afar. All these trends over glacial and interglacial times indicate a persistent source just to the north and northwest of the CLP.

The mass-balance calculations (for details, see Fig. DR4) indicate that even with a conservative combination of a very thin active abrading layer (~1 cm thick) over the area of the proximal sand fields, present-day wind speeds, and a very low sand abrasion efficiency (1%–5%; well within the lower limits of laboratory experiments), it is possible to accumulate the volume of coarse and fine silt stored in the CLP.

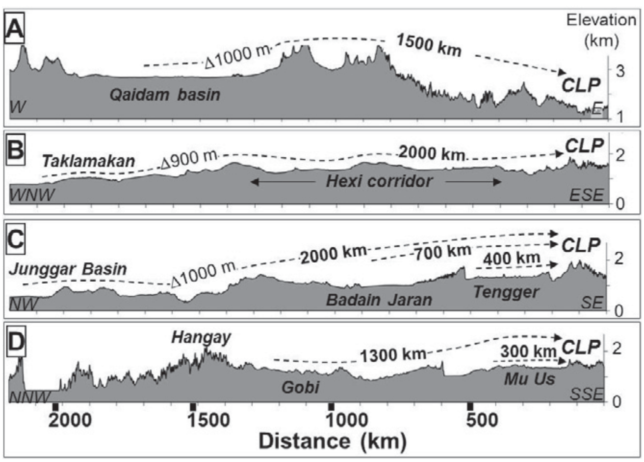

Figure 3. Topographic profiles and distances between various literature-implied sources and Chinese Loess Plateau (CLP; Δ—maximum relief between distal sandy deserts and CLP). Profile locations are in Figure 1A.

SUMMARY

We propose a genetic association between the primary production of large amounts of coarse silt through eolian abrasion of quartz sands in the proximal Mu-Us, Tengger, and Badain Jaran sandy deserts and the quartz coarse silt that is the main fraction of the CLP. This source for the coarse silt fraction of the CLP sequence is compatible with more distant sources of the CLP fine-silt material, which can be transported farther by winds of the same strength. These results decouple the production and transport of coarse silt and finer silt and clay particles, which have a more distant and wider provenance, changing the constraints on previous paleoclimatic reconstructions. In addition, this understanding leads us to advocate that paleoclimate interpretations based on the CLP sequence are strongly related to wind intensity, as previous studies emphasized (An et al., 1990, 2011; Xiao et al., 1995; Guo et al., 2002; Sun and Huang, 2006).

REFERENCES CITED

An, Z.S., 2000, The history and variability of the eastern Asian paleomonsoon climate: Quaternary Science Reviews, v. 19, p. 171–187, doi:10.1016/S0277-3791(99)00060-8.

An, Z.S., Liu, T., Lu, Y., Porter, S.C., Kukla, G., Wu, X., and Hua, Y., 1990, The long-term paleomonsoon

Geology, published online on 6 December 2013 as doi:10.1130/G34857.1

variation recorded by the loess-paleosol sequence in central China: Quaternary International, v. 7-8, p. 91–95, doi:10.1016/1040-6182(90)90042-3.

An, C.B., Zhao, J., Tao, S., Lv, Y., Dong, W., Li, H., Jin, M., and Wang, Z., 2011, Dust variation recorded by lacustrine sediments from arid Central Asia since ~15 cal ka BP and its implication for atmospheric circulation: Quaternary Research, v. 75, p. 566–573, doi:10.1016/j.yqres.2010.12.015.

Chen, J., Li, G., Yang, J., Rao, W., Lu, H., Balsam, W., Sun, Y., and Ji, J., 2007, Nd and Sr isotopic characteristics of Chinese deserts: Implications for provenances of Asian dust: Geochimica et Cosmochimica Acta, v. 71, p. 3904–3914, doi:10.1016/j.gca.2007.04.033.

Crouvi, O., Amit, R., Enzel, Y., Porat, N., and Sandler, A., 2008, Sand dunes as a major proximal dust source for late Pleistocene loess in the Negev Desert, Israel: Quaternary Research, v. 70, p. 275–282, doi:10.1016/j.yqres.2008.04.011.

Crouvi, O., Amit, R., Enzel, Y., and Gillespie, A.R., 2010, Active sand seas and the formation of desert loess: Quaternary Science Reviews, v. 29, p. 2087–2098, doi:10.1016/j.quascirev.2010.04.026.

Ding, Z., Sun, J., Rutter, N.W., Rokosh, D., and Liu, T., 1999, Changes in sand content of loess deposits along a north-south transect of the Chinese Loess Plateau and the implications for desert variations: Quaternary Research, v. 52, p. 56–62, doi:10.1006/qres.1999.2045.

Ding, Z.L., Derbyshire, E., Yang, S.L., Sun, J.M., and Liu, T.S., 2005, Stepwise expansion of desert environment across northern China in the past 3.5 Ma and implications for monsoon evolution: Earth and Planetary Science Letters, v. 237, p. 45–55, doi:10.1016/j.epsl.2005.06.036.

Dorjgotov, D., ed., 2004, Geographic atlas of Mongolia: Ulaanbaatar, Mongolia, Administration of Land Affairs, Geodesy and Cartography, 60 p.

Enzel, Y., Amit, R., Crouvi, O., and Porat, N., 2010, Abrasion-derived sediments under intensified winds at the latest Pleistocene leading edge of the advancing Sinai-Negev erg: Quaternary Research, v. 74, p. 121–131, doi:10.1016/j.yqres.2010.04.002.

Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., and Liu, T.S., 2002, Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China: Nature, v. 416, p. 159–163, doi:10.1038/416159a.

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.

Laurent, B., Marticorena, B., Bergametti, G., and Nei, F., 2006, Modeling mineral dust emissions from Chinese and Mongolian deserts: Global and Planetary Change, v. 52, p. 121–141, doi:10.1016/j.gloplacha.2006.02.012.

Liu, T.S., 1985, Loess and the environment: Beijing, China Ocean, 215 p.

Maher, B., Mutch, T.J., and Cunningham, D., 2009, Magnetic and geochemical characteristics of Gobi desert surface sediments: Implications for provenance of Chinese Loess Plateau: Geology, v. 37, p. 279–282, doi:10.1130/G25293A.1.

McGee, D., Broecker, W.C., and Winckler, G., 2010, Gustiness: The driver of glacial dustiness?: Quaternary Science Reviews, v. 29, p. 2340–2350, doi:10.1016/j.quascirev.2010.06.009.

Nugteren, G., and Vandenberghe, J., 2004, Spatial climatic variability of the Central Loess Plateau (China) as recorded by grain size for the last 250 kyr: Global and Planetary Change, v. 41, p. 185–206, doi:10.1016/j.gloplacha.2004.01.005.

Porter, S., 2001, Chinese loess record of monsoon climate during the last glacial-interglacial cycle: Earth-Science Reviews, v. 54, p. 115–128, doi:10.1016/S0012-8252(01)00043-5.

Porter, S.C., Hallet, B., Wu, X., and An, Z., 2001, Dependence of near surface magnetic susceptibility on dust accumulation rate and precipitation on the Chinese Loess Plateau: Quaternary Research, v. 55, p. 271–283, doi:10.1006/qres.2001.2224.

Prins, M.A., Vriend, M., Nugteren, G., Vandenberghe, J., Lu, H., Zheng, H., and Weltje, G.J., 2007, Late Quaternary aeolian dust input variability on the Chinese Loess Plateau inferences from unmixing of loess grain-size records: Quaternary Science Reviews, v. 26, p. 230–242, doi:10.1016/j.quascirev.2006.07.002.

Prins, M., and 10 others, 2009, Dust supply from river floodplains: The case of the lower Huang He (Yellow River) recorded in a loess-palaeosol sequence from the Mangshan Plateau: Journal of Quaternary Science, v. 24, p. 75–84, doi:10.1002/jqs.1167.

Pye, K., and Zhou, L.P., 1989, Late Pleistocene and Holocene aeolian dust deposition in north China and the northwest Pacific Ocean: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 73, p. 11–23, doi:10.1016/0031-0182(89)90041-2.

Sarnthein, M., 1978, Sand deserts during glacial maximum and climatic optimum: Nature, v. 272, p. 43–46, doi:10.1038/272043a0.

Stevens, T., Palk, C., Carter, A., Lu, H., and Clift, P.D., 2010, Assessing the provenance of loess and desert sediments in northern China using U-Pb dating and morphology of detrital zircons: Geological Society of America Bulletin, v. 122, p. 1331–1344, doi:10.1130/B30102.1.

Stevens, T., Carter, A., Watson, T.P., Vermeesch, P., Andò, S., Bird, A.F., Lu, H., Garzanti, E., Cottam, M.A., and Sevastjanova, I., 2013, Genetic linkage between the Yellow River, the Mu Us desert and the Chinese Loess Plateau: Quaternary Science Reviews, doi:10.1016/j.quascirev.2012.11.032.

Sun, D., Bloemendal, J., Rea, D.K., An, Z., Vandenberghe, J., Lu, H., Su, R., and Liu, T., 2004, Bimodal grain-size distribution of Chinese loess, and its palaeoclimatic implications: Catena, v. 55, p. 325–340, doi:10.1016/S0341-8162(03)00109-7.

Sun, J., and Huang, X., 2006, Half-precessional cycles recorded in Chinese loess: Response to low-latitude insolation forcing during the last interglaciation: Quaternary Science Reviews, v. 25, p. 1065–1072, doi:10.1016/j.quascirev.2005.08.004.

Sun, Y., Tada, R., Chen, J., Liu, Q., Toyoda, S., Tani, A., Ji, J., and Isozaki, Y., 2008, Tracing the provenance of fine-grained dust deposited on the central Chinese Loess Plateau: Geophysical Research Letters, v. 35, L01804, doi:10.1029/2007GL031672.

Tsoar, H., and Pye, K., 1987, Dust transport and the question of desert loess formation: Sedimentology, v. 34, p. 139–153, doi:10.1111/j.1365-3091.1987.tb00566.x.

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.

Vandenberghe, J., Lu, H., Sun, D., van Huissteden, K., and Konert, M., 2004, The late Miocene and Pliocene climate in East Asia as recorded by grain size and magnetic susceptibility of the Red Clay deposits (Chinese Loess Plateau): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 204, p. 239–255, doi:10.1016/S0031-0182(03)00729-6.

Wang, X., Dong, Z., Yan, P., and Hu, Z., 2005, Surface sample collection and dust source analysis in northwestern China: Catena, v. 59, p. 35–53, doi:10.1016/j.catena.2004.05.009.

Xiao, J., Porter, S.C., An, Z., Kumai, H., and 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, v. 43, p. 22–29, doi:10.1006/qres.1995.1003.

Xiao, J., Nakamura, T., Lu, H., and Zhang, G., 2002, Holocene climate changes over the desert/loess transition of north-central China: Earth and Planetary Science Letters, v. 197, p. 11–18, doi:10.1016/S0012-821X(02)00463-6.

Yang, S., and Ding, Z., 2008, Advance-retreat history of the east Asian summer monsoon rainfall belt over northern China during the last two glacial-interglacial cycles: Earth and Planetary Science Letters, v. 274, p. 499–510, doi:10.1016/j.epsl.2008.08.001.

Yang, X., Li, H., and Conacher, A., 2012, Large scale controls on the development of sand seas in northern China: Quaternary International, v. 250, p. 74–83, doi:10.1016/j.quaint.2011.03.052.

Zhang, H., Lu, H., Jiang, S.Y., Vandenberghe, J., and Wang, S., 2012, Provenance of loess deposits in the Eastern Qinling Mountains (central China) and their implications for paleoenvironment: Quaternary Science Reviews, v. 43, p. 94–102, doi:10.1016/j.quascirev.2012.04.010.

Manuscript received 19 June 2013
Revised manuscript received 10 September 2013
Manuscript accepted 10 September 2013

Printed in USA