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Spatial and glacial-interglacial variations in provenance of the Chinese Loess Plateau

Guoqiao Xiao,[1] Keqing Zong,[2] Gaojun Li,[3] Zhaochu Hu,[2] Guillaume Dupont-Nivet,[4,5,6]
Shuzhen Peng,[7] and Kexin Zhang[1]

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[1] The Chinese Loess Plateau (CLP) covers an extensive area over 440,000 km^2 and provides an unprecedented terrestrial record of Neogene climate. However, it is still unclear whether the provenance of these loess deposits is uniform or contains spatial and temporal differences. Here this is addressed by comparing detrital-zircon age spectra of typical loess and paleosol samples from three distant sites located at the western, middle, and southeastern parts of the CLP. Our results reveal that the zircon age spectra not only change between loess and paleosol layers but also vary from the western to the eastern CLP, at least during the last glacial cycle. The discrepancies of the zircon age spectra among different sites suggest that the loess provenance of CLP is heterogeneous and spatially variable, although it has been suggested that the mineralogical, elemental and isotopic compositions of loess deposits on CLP are highly homogenous spatially and in glacial-interglacial cycles. **Citation:** Xiao, G., K. Zong, G. Li, Z. Hu, G. Dupont-Nivet, S. Peng, and K. Zhang (2012), Spatial and glacial-interglacial variations in provenance of the Chinese Loess Plateau, *Geophys. Res. Lett.*, *39*, L20715, doi:10.1029/2012GL053304.

1. Introduction

[2] The Chinese Loess Plateau (CLP) contains one of the most important continental archives of Neogene climate changes [*An et al.*, 1990; *Ding et al.*, 2005; *Guo et al.*, 2002]. It covers an area over 440,000 km^2 and lies in the middle reaches of the Yellow River, bounded by the northern Tibetan Plateau to the west, the Taihang mountains to the east, the Tengger, MU Us deserts and the Yinshan mountains to the north, and the Qinling mountains to the south (Figure 1). Based on the decrease in loess thickness and grain size from the northwest to southeast, it has long been assumed that the source areas of the loess deposits on the CLP were from the arid regions upwind to the north and northwest [*Liu*, 1965, 1985]. These potential source areas include the Taklamakan, Gurbantunggut, and Kumtag deserts in western China, the Qaidam Basin on the northern Tibetan Plateau, the Badain Juran, Tengger, Ulan Buh, Hobq, and Mu Us deserts in northern China, and the Gobi (stony desert) in southern Mongolia (Figure 1).

[3] Modern climate on the CLP is controlled by the southeast-directed cold-dry winter monsoon and the northwest-directed warm-humid summer monsoon, respectively. It has been suggested that the aeolian deposits on the CLP were transported by the East Asian winter monsoon, and interbedded loess and paleosol layers reflect the changing intensities of winter and summer monsoons in response to glacial and interglacial climate changes [*An et al.*, 1990]. Deciphering the loess provenance of CLP is not only critical for understanding the atmospheric circulation patterns associated with evolution of past monsoons, but it also enables a better interpretation of the climate proxies preserved in loess [e.g., *Stevens et al.*, 2010; *Sun*, 2002]. However, there are still wide disagreements on the provenance of loess on the CLP and whether the provenance has changed significantly between glacial and interglacial periods. Some authors have suggested that the Gobi desert in southern Mongolia and the sand deserts in northern China are the dominant source areas of the loess on CLP [e.g., *Sun*, 2002; *Sun et al.*, 2008]. This view was further supported by the spatial distribution of modern dust storms [*Sun*, 2002] and the reconstruction of wind-patterns based on the contour maps of loess grain size of the last two glacial-interglacial cycles [*Yang and Ding*, 2008]. However, others have shown that the deserts in western China, especially the Taklamakan and Qaidam deserts, are very important source areas based on Sr-Nd isotopes, wind-erosion topography, and detrital zircon chronology [e.g., *Chen et al.*, 2007; *Honda et al.*, 2004; *Kapp et al.*, 2011; *Pullen et al.*, 2011]. Besides, it has recently been argued that the dominant source of Chinese loess has changed over glacial-interglacial cycles, from southern Mongolia during glacial periods, to northern China during interglacial periods [*Sun et al.*, 2008], or from the Qaidam Basin and northern Tibetan Plateau during glacial periods, to northern China and southern Mongolia during interglacial periods [*Kapp et al.*, 2011; *Pullen et al.*, 2011].

[4] Because the loess deposits across the CLP show high mineralogical, elemental, and isotopic homogeneity [*Gallet et al.*, 1996; *Jahn et al.*, 2001; *Jeong et al.*, 2011], it is appropriate to assume that the loess deposits from different parts of the CLP were derived from a common source area

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[1] State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan, China.

[2] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China.

[3] Department of Earth Sciences, Nanjing University, Nanjing, China.

[4] Geosciences Rennes UMR 6118-CRNS, Université de Rennes 1, Campus de Beaulieu, Rennes, France.

[5] Paleomagnetic Laboratory 'Fort Hoofddijk,' Department of Earth Sciences, Utrecht University, Utrecht, Netherlands.

[6] Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, Peking University, Beijing, China.

[7] Key Laboratory of Tourism and Resources Environment in Universities of Shandong, Taishan College, Tai'an, China.

Corresponding author: G. Xiao, State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan 430074, China. (xgqiaocug@gmail.com)

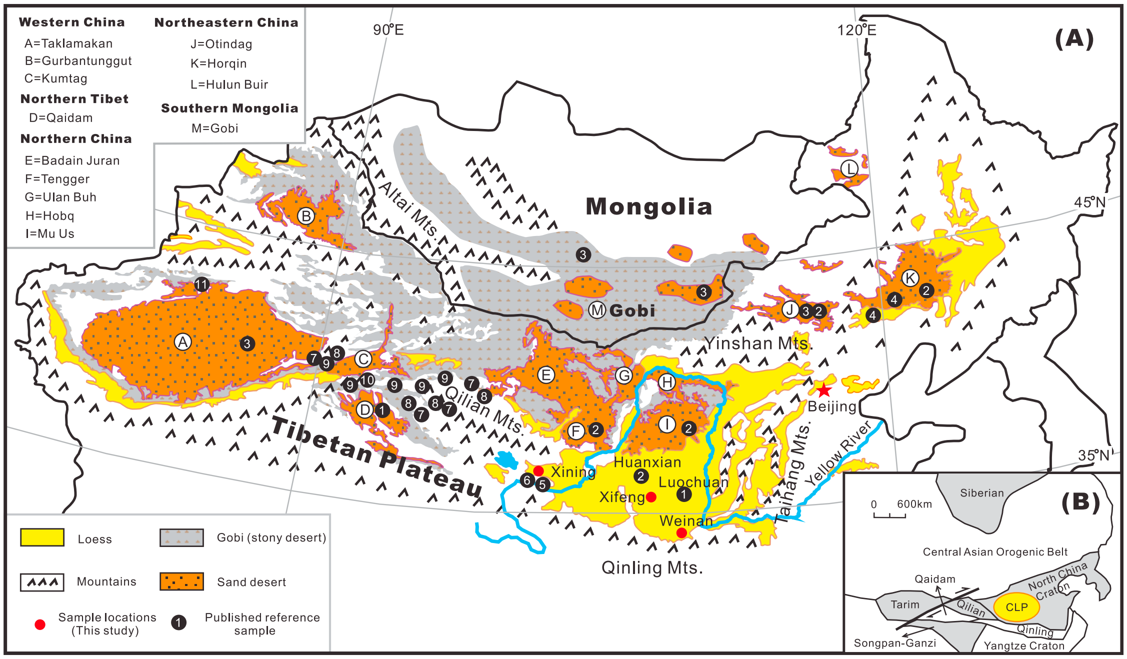

Figure 1. (a) Location of the Chinese Loess Plateau (CLP) and its potential desert source areas. The red dots denote the studied loess sections. The white numbers in black dots show the sites of published detrital zircon data cited in the text: (1) *Pullen et al.* [2011]; (2) *Stevens et al.* [2010]; (3) *Xie et al.* [2007]; (4) *Xie et al.* [2012]; (5) *Lease et al.* [2007]; (6) *Lease et al.* [2012]; (7) *Gehrels et al.* [2011]; (8) *Gehrels et al.* [2003a]; (9) *Gehrels et al.* [2003b]; (10) *Yue et al.* [2005]; and (11) *Li and Peng* [2010]. (b) Geotectonic map showing location of the CLP relative to the major continental blocks [after *Gehrels et al.*, 2011; *Xie et al.*, 2012].

[e.g., *Jahn et al.*, 2001]. However, *Maher et al.* [2009] argued that the source areas for such immense loess deposits must involve efficient formation of fine-size particles and encompass multiple sources throughout the region that are much larger than any one proximal desert. This concept is consistent with a series of comprehensive studies based on Nd-Sr isotopes, carbonate mineralogy and quartz ESR signal showing the source area of Chinese loess includes a vast arid region between Qilian and Gobi-Altay Mountains [*Li et al.*, 2007, 2011; *Sun et al.*, 2008], where high-mountain processes (including glacial grinding, cryologic breakage, tectonic stress, and fluvial comminution) have produced tremendous amounts of fine-sized particles [*Derbyshire et al.*, 1998; *Sun*, 2002] that are ultimately derived from the northern Tibetan Plateau and the Central Asian Orogenic Belt (Figure 1b) [*Chen and Li*, 2011; *Li et al.*, 2009, 2011].

[5] Obviously, to better constrain the provenance of loess on the CLP, more effective source tracing approaches are required. Recent studies have demonstrated that the single-grain zircon provenance analysis is more diagnostic than the bulk mineralogical, elemental, and even isotopic approaches in identifying the source areas of loess deposits [e.g., *Pullen et al.*, 2011; *Stevens et al.*, 2010; *Újvári et al.*, 2012; *Xie et al.*, 2012]. In this study, we determine and compare detrital-zircon age spectra of typical loess and paleosol units from western (Xining), middle (Xifeng), and southeastern (Weinan) parts of the CLP (Figure 1) that shed new light on whether the loess provenance of the ca. 1000-km-long, up to ca. 600-km-wide CLP is uniform and whether the provenance has changed significantly over glacial-interglacial cycles.

2. Materials and Methods

[6] The loess-paleosol successions at Xining (36°37′N, 101°47′E), Xifeng (35°53′N, 107°58′E), and Weinan (34°21′N, 109°31′E) have been described in detail by previous studies [*Guo et al.*, 1994; *Jahn et al.*, 2001; *Sun et al.*, 2008]. These three sites are located at western, middle, and southeastern parts of the CLP, respectively (Figure 1), and thus are ideal targets to test whether the provenance of loess deposits on CLP is uniform. Three pairs of typical loess (glacial) and paleosol (interglacial) samples of the last glacial-interglacial cycle were collected from these sites for detrital-zircon U-Pb age analysis (see the auxiliary materials for sample descriptions and analytical methods).[1] The U-Pb ages were determined using a laser-ablation inductively coupled plasma–mass spectrometer (LA-ICP-MS) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, following the analytical procedures of *Liu et al.* [2010a, 2010b]. In order to achieve a required level of statistical adequacy [*Andersen*, 2005], at least 96 individual zircon grains with suitable size (mostly between 35–60 μm) were randomly selected from each sample for measurement by a laser spot diameter of 24 μm (Figure S1 in the auxiliary material). The ages reported here

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053304.

are $^{206}Pb/^{238}U$ ages for zircons younger than 1000 Ma and $^{207}Pb/^{206}Pb$ ages for older grains. Individual zircons with <90% concordance were rejected. All analytical results are available from the auxiliary material.

3. Results

[7] Probability density plots of our six samples and two loess-layer samples published by others from Luochuan [*Pullen et al.*, 2011] and Huanxian [*Stevens et al.*, 2010] are presented in Figures 2a–2h. In the Xining site, the paleosol sample (layer S_0, Holocene) shows a dominant age population in the range of 540–360 Ma (Figure 2b), with a peak at 432 Ma, whereas the loess sample (layer L_1, last glaciation) exhibits two major age populations in the ranges of 560–380 Ma and 360–200 Ma (Figure 2a), with peaks at 422 Ma and 261 Ma, respectively. For the loess sample in Xifeng site (layer L_1, last glaciation), the most prominent age population is ranging from 520 Ma to 330 Ma (Figure 2c), with a peak at 459 Ma, whereas in the paleosol sample (layer S_1, last interglaciation) the major age population shifts to the 490–290 Ma range, with a peak at 381 Ma (Figure 2d). For the samples in Weinan, both loess (layer L_1, last glaciation) and paleosol (layer S_1, last interglaciation) samples show two major age populations in the ranges of 530–360 Ma and 350–190 Ma (Figures 2e and 2f); in addition, there are also a significant amount of younger ages (<200 Ma).

[8] Because the finer zircon grains are expected to transport longer distance and the laser spot size we used (24 μm) is larger than previous study (e.g., 14 μm [*Pullen et al.*, 2011]), our zircon age spectra may be affected by grain size induced bias. However, it is noteworthy that the age spectra of the L_1 loess layer from Luochuan [*Pullen et al.*, 2011] and Huanxian [*Stevens et al.*, 2010] also exhibit two major age populations in the 560–360 Ma and 320–230 Ma range, respectively (Figures 2g and 2h), and are similar to the loess samples from Xining and Weinan (Figures 2a and 2e), although the peaks are to some extent different.

4. Discussion

4.1. Glacial-Interglacial Provenance Variations

[9] It has been suggested that the atmospheric circulation pattern over the CLP differed significantly between glacial and interglacial periods [*An et al.*, 2012; *Kapp et al.*, 2011; *Pullen et al.*, 2011]. The mean annual position of the polar jet stream during glacial periods was probably >10° equatorward than during interglacial periods [*An et al.*, 2012; *Kapp et al.*, 2011; *Pullen et al.*, 2011]. Detailed reconstruction has demonstrated that the climate pattern over the CLP during glacial periods was characterized by a roughly W-E zonal pattern, which is significantly different from the NW-SE pattern during interglacial periods [*Hao and Guo*, 2005; *Lu and Sun*, 2000]. Therefore, it would be expected that the dust provenance on CLP would shift in association with the changes of atmospheric circulation patterns of the glacial-interglacial cycles [*Prins et al.*, 2007]. Our zircon chronological results from Xining, Xifeng, and Weinan clearly show that the zircon age spectra of the loess layers are indeed different from those of the paleosol layers (Figure 2), indicating a varying aeolian provenance on the CLP over glacial-interglacial cycles. Our results also provide empirical evidence from paleosol layers to support a recent prediction [*Pullen et al.*, 2011] that the dust provenance on CLP is different between glacial and interglacial periods that is based only on zircon ages of loess layers but not paleosols.

4.2. Spatial Differences in Chinese Loess Provenance

[10] The spatial characteristics of the detrital-zircon age spectra among different sites are more complicated than the glacial-interglacial patterns. Specifically, except for Xifeng, glacial samples show similar age populations in the 560–360 Ma and 360–200 Ma ranges, respectively, albeit the peaks are different to some extent (Figures 2a, 2c, 2e, 2g, and 2h). In contrast, paleosol samples show notable variations in the proportion of the 360–200 Ma zircon grains, increasing gradually from the western CLP to the eastern CLP, from 3.7%, 17.6%, and 23.9% for Xining, Xifeng, and Weinan, respectively (Figures 2b, 2d, and 2f). This different glacial-interglacial pattern of age spectra among Xining, Xifeng, and Weinan indicates the dust provenance on the CLP is heterogeneous and spatially variable, possibly for the following reasons. First, the sediments in the potential source areas in northern China and southern Mongolia show a predominant zircon age population in the range of 360–200 Ma (47.7%), with a relatively smaller proportion (14.1%) of zircon grains in the range of 560–360 Ma (Figure 2i) [*Stevens et al.*, 2010; *Xie et al.*, 2007, 2012]. However, the areas in the northern Tibetan Plateau and western China are predominated by the 560–360 Ma zircon grains, with a relatively limited (<20%) proportion of zircons in the range of 360–200 Ma (Figures 2j and 2k) [*Gehrels et al.*, 2003a, 2003b, 2011; *Lease et al.*, 2007, 2012; *Li and Peng*, 2010; *Pullen et al.*, 2011; *Xie et al.*, 2007; *Yue et al.*, 2005]. Hence, we argue that 1) the major age population of 560–360 Ma in all the aeolian samples is mainly derived from northern Tibetan Plateau and western China, as previous studies suggested [*Pullen et al.*, 2011; *Stevens et al.*, 2010], rather than northern China and southern Mongolia, and 2) the eastwardly increase of the 360–200 Ma proportion in the paleosol samples likely indicates that the source contribution from northern China and southern Mongolia increases eastwardly under a NW-SE climate pattern during interglacial periods [*Hao and Guo*, 2005; *Lu and Sun*, 2000]. Second, in loess samples, the relative proportions of the 560–360 Ma and 360–200 Ma zircon grains are closely similar (Figures 2a, 2c, 2e, 2g, and 2h), which cannot be simply explained by materials from the arid regions in northern China and southern Mongolia nor by the source contribution from northern Tibetan Plateau and western China, and thus suggests a mixing of sources from these regions. Third, the late Cenozoic zircon grains, although mostly with concordance <90% except one, are probably derived from the northern Tibetan Plateau, as concluded by *Pullen et al.* [2011].

[11] Additional lines of evidence support the interpretation that the dust provenance of the CLP is heterogeneous and spatially variable. First, the huge area of the CLP contains an immense volume of silts and finer-sized particles that must involve multiple sources. It has been argued that no specific desert is able to offer such vast amounts of silt materials required to form the CLP [*Maher et al.*, 2009]. Second, detailed reconstruction of wind patterns during the last glacial-interglacial cycle has demonstrated that the two most important agents for transport of dust to the CLP were northwesterly and westerly winds, but lack of northeasterly wind [*Lu and Sun*, 2000]. This wind pattern would result in the lack of

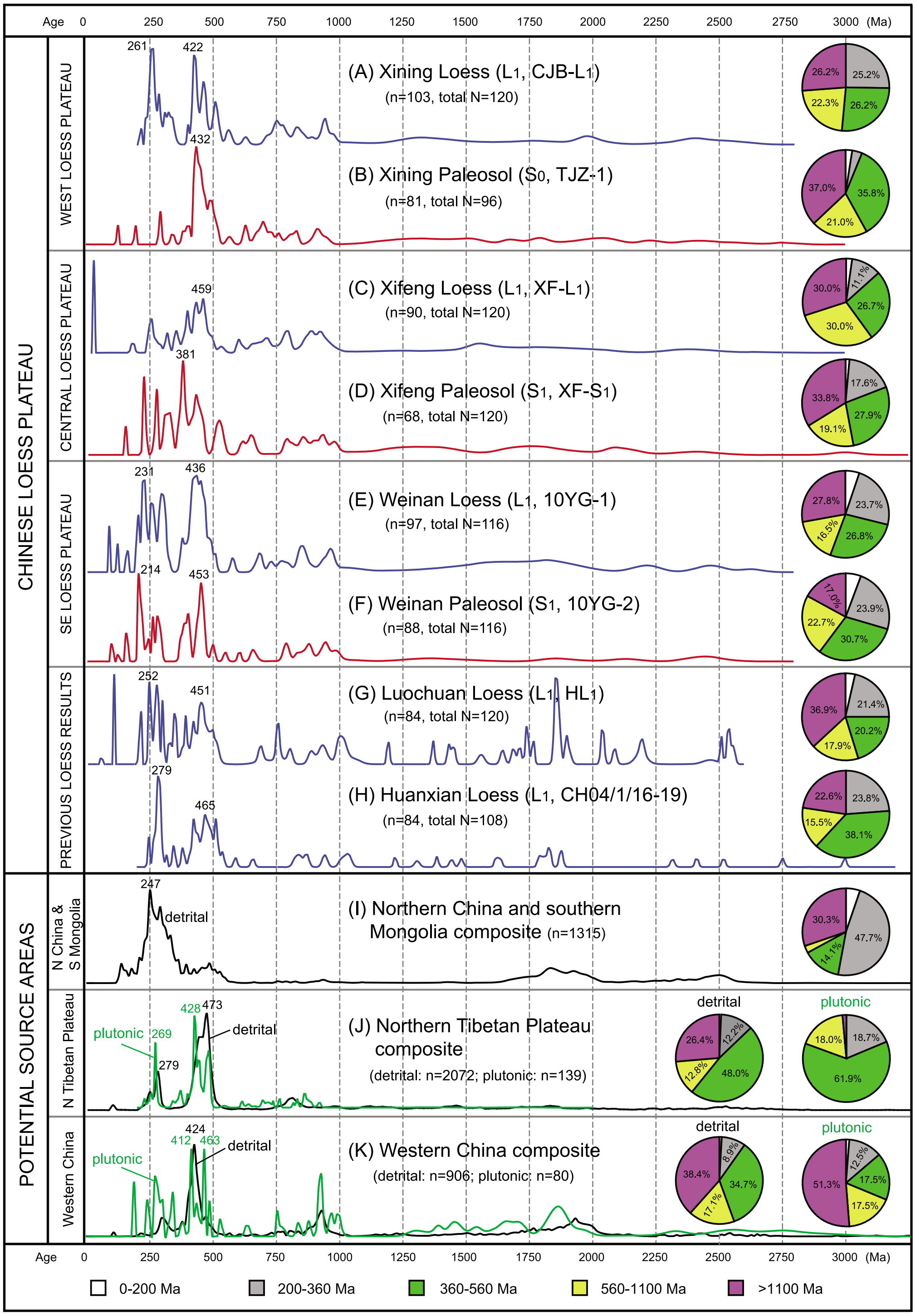

Figure 2. Probability density plots of zircon U-Pb ages from (a–h) the Chinese Loess Plateau and (i–k) its potential source areas. Figures 2a and 2b show data from Xining; Figures 2c and 2d show data from Xifeng; Figures 2e and 2f show data from Weinan; Figures 2g and 2h show data from Luochuan [*Pullen et al.*, 2011] and Huanxian [*Stevens et al.*, 2010], respectively. Figures 2i, 2j, and 2k show the compilation of published data from the potential source areas of Chinese Loess Plateau, including (Figure 2i) northern China and southern Mongolia [*Stevens et al.*, 2010; *Xie et al.*, 2007, 2012], (Figure 2j) northern Tibetan Plateau [*Gehrels et al.*, 2003a, 2003b, 2011; *Lease et al.*, 2007, 2012; *Pullen et al.*, 2011; *Yue et al.*, 2005], and (Figure 2k) western China [*Gehrels et al.*, 2003a, 2003b, 2011; *Li and Peng*, 2010; *Xie et al.*, 2007]. The pie charts show the proportions of zircon grains within different age ranges.

dust materials transported from the arid regions north of CLP, such as Mu Us desert, to the western CLP, although these northern regions are probably important sources for the eastern CLP [*Yang and Ding*, 2008].

5. Implications

[12] Previous studies have suggested that the mineralogy, Sr-Nd isotopic compositions, and elemental abundances and patterns of Chinese loess were highly homogenous in spatial and glacial-interglacial cycles [e.g., *Gallet et al.*, 1996; *Jahn et al.*, 2001; *Jeong et al.*, 2011; *Li et al.*, 2009], and the rare earth elements of Chinese loess even can be the representative of average composition of upper continental crust [*Hu and Gao*, 2008; *Jahn et al.*, 2001; *Taylor et al.*, 1983]. Many researchers are likely therefore to regard the CLP as having integrated provenance. However, our zircon age spectra from different parts of the CLP reveal that the dust provenance not only changes in glacial-interglacial cycles, but also varies from the western to the eastern CLP. This apparent contradiction may be due to (1) the single-grain provenance analysis being more diagnostic than the bulk geochemical and isotopic approaches in identifying the source of sediments with complex source areas [*Stevens et al.*, 2010; *Újvári et al.*, 2012; *Xie et al.*, 2012], such as loess deposits, and/or (2) the thorough mixing of multiple-sourced loess deposits during the transportation, deposition, and formation processes homogenizing the geochemical and isotopic signals, although the source areas are isotopically different [e.g., *Chen et al.*, 2007; *Honda et al.*, 2004].

[13] Our results show that the provenance of loess deposits on the CLP may include arid regions in western and northern China and Gobi deserts in southern Mongolia, supporting the traditional view [*Liu*, 1965, 1985], and that the glacial-interglacial changes of provenance have been strongly coupled with the changes of wind patterns. However, whether the dust materials were mainly derived from the deserts or directly transported from lacustrine and alluvial fan deposits [*Derbyshire et al.*, 1998; *Pullen et al.*, 2011; *Stevens et al.*, 2010; *Sun*, 2002] is still unsettled by this study. Wherever the source area may be, our results have provided empirical evidence to support the idea that the aeolian deposits were derived ultimately from the northern Tibetan Plateau and the Central Asian Orogenic Belt (Figure 1b) [*Chen and Li*, 2011; *Li et al.*, 2009, 2011]. However, it should be pointed out that our study does not measure the finer zircon grains, especially the size <20 μm that can be transported longer distances by wind and potentially could provide further information on dust source areas. Detailed provenance studies on deserts, lacustrine and alluvial fan deposits in western China and finer zircon grains in loess deposits are still required to further constrain the source areas of loess on the CLP.

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References

An, Z. S., T. S. Liu, Y. C. Lu, S. C. Porter, G. Kukla, X. H. Wu, and Y. M. Hua (1990), The long-term paleomonsoon variation recorded by the loess-paleosol sequence in central China, *Quat. Int.*, *7-8*, 91–95, doi:10.1016/1040-6182(90)90042-3.

An, Z., et al. (2012), Interplay between the Westerlies and Asian monsoon recorded in Lake Qinghai sediments since 32 ka, *Sci. Rep.*, *2*, 619, doi:10.1038/srep00619.

Andersen, T. (2005), Detrital zircons as tracers of sedimentary provenance: Limiting conditions from statistics and numerical simulation, *Chem. Geol.*, *216*(3-4), 249–270, doi:10.1016/j.chemgeo.2004.11.013.

Chen, J., and G. J. Li (2011), Geochemical studies on the source region of Asian dust, *Sci. China Earth Sci.*, *54*(9), 1279–1301, doi:10.1007/s11430-011-4269-z.

Chen, J., G. J. Li, J. D. Yang, W. B. Rao, H. Y. Lu, W. Balsam, Y. B. Sun, and J. F. Ji (2007), Nd and Sr isotopic characteristics of Chinese deserts: Implications for the provenances of Asian dust, *Geochim. Cosmochim. Acta*, *71*, 3904–3914, doi:10.1016/j.gca.2007.04.033.

Derbyshire, E., X. M. Meng, and R. A. Kemp (1998), Provenance, transport and characteristics of modern aeolian dust in western Gansu Province, China, and interpretation of the Quaternary loess record, *J. Arid Environ.*, *39*, 497–516, doi:10.1006/jare.1997.0369.

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

Gallet, S., B. M. Jahn, and M. Torii (1996), Geochemical characterization of the Luochuan loess-paleosol sequence, China, and paleoclimatic implications, *Chem. Geol.*, *133*, 67–88, doi:10.1016/S0009-2541(96)00070-8.

Gehrels, G. E., A. Yin, and X. F. Wang (2003a), Detrital-zircon geochronology of the northeastern Tibetan plateau, *Geol. Soc. Am. Bull.*, *115*(7), 881–896, doi:10.1130/0016-7606(2003)115<0881:DGOTNT>2.0.CO;2.

Gehrels, G. E., A. Yin, and X.-F. Wang (2003b), Magmatic history of the northeastern Tibetan Plateau, *J. Geophys. Res.*, *108*(B9), 2423, doi:10.1029/2002JB001876.

Gehrels, G., et al. (2011), Detrital zircon geochronology of pre-Tertiary strata in the Tibetan-Himalayan orogen, *Tectonics*, *30*, TC5016, doi:10.1029/2011TC002868.

Guo, Z. T., T. S. Liu, and Z. S. An (1994), Paleosols of the last 0.15 Ma in the Weinan loess section and their paleoclimatic significance [in Chinese with English abstract], *Quat. Sci.*, *14*(3), 256–269.

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

Hao, Q. Z., and Z. T. Guo (2005), Spatial variations of magnetic susceptibility of Chinese loess for the last 600 kyr: Implications for monsoon evolution, *J. Geophys. Res.*, *110*, B12101, doi:10.1029/2005JB003765.

Honda, M., S. Yabuki, and H. Shimizu (2004), Geochemical and isotopic studies of aeolian sediments in China, *Sedimentology*, *51*, 211–230, doi:10.1111/j.1365-3091.2004.00618.x.

Hu, Z., and S. Gao (2008), Upper crustal abundances of trace elements: A revision and update, *Chem. Geol.*, *253*, 205–221, doi:10.1016/j.chemgeo.2008.05.010.

Jahn, B. M., S. Gallet, and J. M. Han (2001), Geochemistry of the Xining, Xifeng and Jixian sections, Loess Plateau of China: Eolian dust provenance and paleosol evolution during the last 140 ka, *Chem. Geol.*, *178*, 71–94, doi:10.1016/S0009-2541(00)00430-7.

Jeong, G. Y., S. Hillier, and R. A. Kemp (2011), Changes in mineralogy of loess–paleosol sections across the Chinese Loess Plateau, *Quat. Res.*, *75*(1), 245–255, doi:10.1016/j.yqres.2010.09.001.

Kapp, P., J. D. Pelletier, A. Rohrmann, R. Heermance, J. Russell, and L. Ding (2011), Wind erosion in the Qaidam basin, central Asia: Implications for tectonics, paleoclimate, and the source of the Loess Plateau, *GSA Today*, *21*(4), 4–10, doi:10.1130/GSATG99A.1.

Lease, R. O., D. W. Burbank, G. E. Gehrels, Z. C. Wang, and D. Y. Yuan (2007), Signatures of mountain building: Detrital zircon U/Pb ages from northeastern Tibet, *Geology*, *35*(3), 239–242, doi:10.1130/G23057A.1.

Lease, R. O., D. W. Burbank, B. Hough, Z. Wang, and D. Yuan (2012), Pulsed Miocene range growth in northeastern Tibet: Insights from Xunhua Basin magnetostratigraphy and provenance, *Geol. Soc. Am. Bull.*, *124*(5-6), 657–677, doi:10.1130/B30524.1.

Li, G., J. Chen, Y. Chen, J. Yang, J. Ji, and L. Liu (2007), Dolomite as a tracer for the source regions of Asian dust, *J. Geophys. Res.*, *112*, D17201, doi:10.1029/2007JD008676.

Li, G., J. Chen, J. Ji, J. Yang, and T. M. Conway (2009), Natural and anthropogenic sources of East Asian dust, *Geology*, *37*(8), 727–730, doi:10.1130/G30031A.1.

Li, G., T. Pettke, and J. Chen (2011), Increasing Nd isotopic ratio of Asian dust indicates progressive uplift of the north Tibetan Plateau since the middle Miocene, *Geology*, *39*(3), 199–202, doi:10.1130/G31734.1.

Li, Z., and S. Peng (2010), Detrital zircon geochronology and its provenance implications: responses to Jurassic through Neogene basin-range interactions along northern margin of the Tarim Basin, Northwest China, *Basin Res.*, *22*(1), 126–138, doi:10.1111/j.1365-2117.2009.00440.x.

Liu, T. S. (1965), *The Loess Deposits in China*, 244 pp., Science Press, Beijing.

Liu, T. S. (1985), *Loess and the Environment*, 251 pp., China Ocean Press, Beijing.

Liu, Y., S. Gao, Z. Hu, C. Gao, K. Zong, and D. Wang (2010a), Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen: U-Pb dating, Hf isotopes and trace elements in zircons from mantle xenoliths, *J. Petrol.*, *51*(1-2), 537–571, doi:10.1093/petrology/egp082.

Liu, Y. S., Z. C. Hu, K. Q. Zong, C. G. Gao, S. Gao, J. Xu, and H. H. Chen (2010b), Reappraisement and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS, *Chin. Sci. Bull.*, *55*, 1535–1546, doi:10.1007/s11434-010-3052-4.

Lu, H. Y., and D. H. Sun (2000), Pathways of dust input to the Chinese Loess Plateau during the last glacial and interglacial periods, *Catena*, *40*(3), 251–261, doi:10.1016/S0341-8162(00)00090-4.

Maher, B. A., T. J. Mutch, and D. Cunningham (2009), Magnetic and geochemical characteristics of Gobi Desert surface sediments: Implications for provenance of the Chinese Loess Plateau, *Geology*, *37*(3), 279–282, doi:10.1130/G25293A.1.

Prins, M. A., M. Vriend, G. Nugteren, J. Vandenberghe, H. Lu, H. Zheng, and G. Jan Weltje (2007), Late Quaternary aeolian dust input variability on the Chinese Loess Plateau: inferences from unmixing of loess grain-size records, *Quat. Sci. Rev.*, *26*(1-2), 230–242, doi:10.1016/j.quascirev.2006.07.002.

Pullen, A., P. Kapp, A. T. McCallister, H. Chang, G. E. Gehrels, C. N. Garzione, R. V. Heermance, and L. Ding (2011), Qaidam Basin and northern Tibetan Plateau as dust sources for the Chinese Loess Plateau and paleoclimatic implications, *Geology*, *39*(11), 1031–1034, doi:10.1130/G32296.1.

Stevens, T., C. Palk, A. Carter, H. Lu, and P. D. Clift (2010), Assessing the provenance of loess and desert sediments in northern China using U-Pb dating and morphology of detrital zircons, *Geol. Soc. Am. Bull.*, *122*(7-8), 1331–1344, doi:10.1130/B30102.1.

Sun, J. M. (2002), Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau, *Earth Planet. Sci. Lett.*, *203*(3-4), 845–859, doi:10.1016/S0012-821X(02)00921-4.

Sun, Y. B., R. Tada, J. Chen, Q. S. Liu, S. Toyoda, A. Tani, J. F. Ji, and Y. Isozaki (2008), Tracing the provenance of fine-grained dust deposited on the central Chinese Loess Plateau, *Geophys. Res. Lett.*, *35*, L01804, doi:10.1029/2007GL031672.

Taylor, S. R., S. M. McLennan, and M. T. McCulloch (1983), Geochemistry of loess, continental crustal composition and crustal model ages, *Geochim. Cosmochim. Acta*, *47*(11), 1897–1905, doi:10.1016/0016-7037(83)90206-5.

Újvári, G., A. Varga, F. C. Ramos, J. Kovács, T. Németh, and T. Stevens (2012), Evaluating the use of clay mineralogy, Sr–Nd isotopes and zircon U–Pb ages in tracking dust provenance: An example from loess of the Carpathian Basin, *Chem. Geol.*, *304-305*, 83–96, doi:10.1016/j.chemgeo.2012.02.007.

Xie, J., F. Y. Wu, and Z. L. Ding (2007), Detrital zircon composition of U-Pb ages and Hf isotope of the Hunshandake sandy land and implications for its provenance [in Chinese with English Abstract], *Acta Petrol. Sin.*, *23*(2), 523–528.

Xie, J., S. Yang, and Z. Ding (2012), Methods and application of using detrital zircons to trace the provenance of loess, *Sci. China Earth Sci.*, *55*(1), 1–10, doi:10.1007/s11430-11012-14428-x.

Yang, S., and Z. Ding (2008), Advance–retreat history of the East-Asian summer monsoon rainfall belt over northern China during the last two glacial–interglacial cycles, *Earth Planet. Sci. Lett.*, *274*(3-4), 499–510, doi:10.1016/j.epsl.2008.08.001.

Yue, Y., S. A. Graham, B. D. Ritts, and J. L. Wooden (2005), Detrital zircon provenance evidence for large-scale extrusion along the Altyn Tagh fault, *Tectonophysics*, *406*(3-4), 165–178, doi:10.1016/j.tecto.2005.05.023.