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Detrital zircon evidence for the ternary sources of the Chinese Loess Plateau

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ABSTRACT

The provenance of Chinese loess is fundamental for understanding its origin, transportation and climatic significance. In this paper, eight samples were collected for detrital zircon age analysis, five from different deserts, and three from the Jingbian Section in the northern Chinese Loess Plateau, covering an age range of 2.6–0.03 Ma. The new results, integrated with knowledge of relevant topography and wind patterns, demonstrate that the age spectra of the detrital zircons in the loess are different from those of the sands from the Tarim, Junggar and Qaidam basins, implying that these basins were not the sources of the silts of the Loess Plateau. Further analysis suggests that the three sources for the loess are: (1) clastic materials eroded from the mountains of the Central Asian Orogenic Belt (especially the Gobi Altai and Hangay), (2) clastic loess-sized materials generated by erosion of the Qilian Mountains in the NE Tibetan Plateau, and (3) minor clastic debris derived from the mountains of the North China Craton. Thus, silts of the Loess Plateau have a complex origin, although inland basins, long believed to be important sources, have only a minor role at most.

1. Introduction

The Chinese Loess Plateau is characterized by the most widespread, continuous and thickest loess in the world. It has been well studied especially since the pioneering loess investigations led by the late Professor Liu Tungsheng in the 1960s. His early achievements were mainly embodied in three loess books (Liu, 1964, 1965, 1966), together with the highly cited book published later (Liu, 1985). These publications have been the most valuable literature of loess research in China.

On the Loess Plateau, the thickest loess can be up to 300 m, and contains tens of loess-paleosol cycles, which can be well correlated with the fluctuations of marine oxygen isotopes that resulted from glacial-interglacial cycles during the Quaternary (Heller and Liu, 1982, 1984; Liu, 1985; Kukla, 1987; An et al., 1991; Ding et al., 1994, 1998, 2000, 2001, 2002; Guo et al., 1996; Sun and Huang, 2006). However, although the provenance of Chinese loess is essential for understanding its transportation pathways and climatic significance, the source of this sediment is still controversial. A pioneering study, based mainly on spatial-scale particle size variations, shows a zonal distribution from northwest to southeast across the Loess Plateau, suggesting that the loess was derived from upwind northwestern *gobi* (gravel desert), and sandy desert regions (Liu, 1966).

Subsequently, Sr, Nd, and Pb isotopes in the sediments of Chinese deserts and loess were used to study the provenance of aeolian deposits on the Loess Plateau (Liu et al., 1994; Sun, 2002a, 2005; Rao et al., 2006; Chen et al., 2007; Sun and Zhu, 2010). However, results from these studies are not in complete agreement with one another. Liu et al. (1994) argued that the loess on the Loess Plateau was sourced from the Tarim Basin, and certainly not from the Junggar Basin. By analyzing isotopic, chemical and mineralogical characteristics of the < 20 µm fraction of loess together with modern meteorological data, Sun (2002a) concluded that the loess in the Loess Plateau was mainly derived from the *gobi* and deserts in southern Mongolia and the adjoining arid regions in China, but not from three arid basins (Tarim, Junggar, and Qaidam) in northwestern China. Rao et al. (2006) suggested that the Tarim Basin, the deserts in central and western Inner Mongolia and the Tibetan Plateau are the main sources of the Chinese Loess Plateau using statistical analysis of a Nd isotopic dataset from northern China. Chen et al. (2007) proposed that the main source regions of the Loess Plateau were the Badain Jaran, Tengger, and Qaidam Deserts in northern China, whereas the Taklimakan Desert in the Tarim Basin was not the provenance of the Loess Plateau sediments. The most recent study, utilizing heavy-mineral, bulk-petrography analyses, and detrital-zircon U–Pb geochronology, rules out any direct eolian sediment

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transport from the Tarim Basin to the Chinese Loess Plateau (Rittner et al., 2016).

In recent years, the new technique of determining the U-Pb ages of detrital zircons has been applied to the loess and deserts of China (Xie et al., 2007, 2012; Stevens et al., 2010; Xiao et al., 2012; Che and Li, 2013; Nie et al., 2015; Licht et al., 2016). However, most of these studies have focused on direct comparisons of the age spectra between the loess and their potential deserts, and this has given rise to many controversial ideas about the provenance of the loess of the Loess Plateau. These different views about the potential sources can be summarized as follows: the Qilian Mountains (Stevens et al., 2010), a heterogeneous and spatially variable provenance (Xiao et al., 2012), the northern Tibetan Plateau and Gobi Altay Mountains (Che and Li, 2013), Yellow River sediments (Nie et al., 2015), and Yellow River sediments combined with older loess deposits (Licht et al., 2016).

The use of U-Pb dating to track the source regions of dust and loess deposits is complex, particularly because similar age peaks are commonly found in the age probability distributions of sediments in different regions, even if they are not in the dust pathways. To understand the provenance of aeolian deposits, the interpretations cannot use only U-Pb ages, but must be integrated with the knowledge of geomorphology and the dust pathways from the source regions to the Loess Plateau.

In this paper, we present new U-Pb ages of detrital zircons from potential desert sources and loess samples of different ages in the northern Loess Plateau, combined with geomorphological considerations and modern dust storm information. We will extend our discussion on the provenance of Chinese loess and consider its relationship with the large tectonic domains in northern China.

2. Geological setting, materials and methods

In China, the total area covered by loess is about 440,000 km^2 (Liu, 1985). The most continuous and thickest loess is in central North China where it forms the Chinese Loess Plateau (Fig. 1). To its north and northwest, *gobi* and sandy deserts are widespread in the arid and semiarid regions. In addition to the Loess Plateau, loess is also sparsely distributed in the peripheral regions of the three northwestern inland basins (Tarim, Junggar and Qaidam, Fig. 1).

In this paper, eight samples were collected for detrital zircon age analysis. Of these, five sand samples were taken from the Taklimakan desert in the Tarim Basin, the Gurbantünggüt Desert in the Junggar Basin, the Qaidam Basin, the Ulan Buh Desert, and the Mu Us Desert (Fig. 1). In addition to these sand samples, three loess samples (L1, L15, and L33) were taken from the Jingbian Section in the northern Loess Plateau (Fig. 1). The Jingbian Section contains 33 loess-paleosol cycles ("L" represents glacial loess, and "S" represents interglacial paleosol following Liu (1985)), which are underlain by aeolian Red Clay of Tertiary age (Fig. 2). The Quaternary loess-soil couplets and the Red Clay are 252 m and 30 m thick, respectively. Previous magnetostratigraphic study yielded a basal age of 2.6 Ma for the Quaternary loess-paleosol sequence and an age range of 3.5–2.6 Ma for the Red Clay (Ding et al., 1999). Another magnetic polarity study showed that the Brunhes-Matuyama (B/M) magnetic reversal boundary at 0.78 Ma, and the Jaramillo normal subchron of 1.05–0.99 Ma are found in the middle to lower parts of the loess-paleosol sequence (Guo et al., 2002, Fig. 2). Based on these paleomagnetic polarity studies, the high-resolution climatic records of this section have been correlated with the marine oxygen isotope record, yielding a detailed time-scale for each loess and paleosol (Ding et al., 2005). Our loess samples at Jingbian were collected from the middle parts of L1, L15, and the base of L33. Using the time-scale established by Ding et al. (2005), the ages of the three loess samples are estimated to be 0.03 Ma, 1.2 Ma, and 2.6 Ma, respectively.

Bulk samples used for detrital zircon separation were firstly passed through a jaw crusher followed by a disc mill with a sieved rock fraction of 60–250 μm, then followed by standard separation using heavy liquids and a magnetic separator as the methods described by Gehrels et al. (2006).

The separated zircon grains used for U-Pb dating were mounted on adhesive tape, and enclosed in epoxy resin to make zircon mounts. The zircon grains in the mounts were polished to about half their thickness, and photographed in reflected and transmitted light before being analyzed using the laser ablation ICP-MS method.

A VG PQ Excell ICP-MS equipped with a New Wave Research UV213

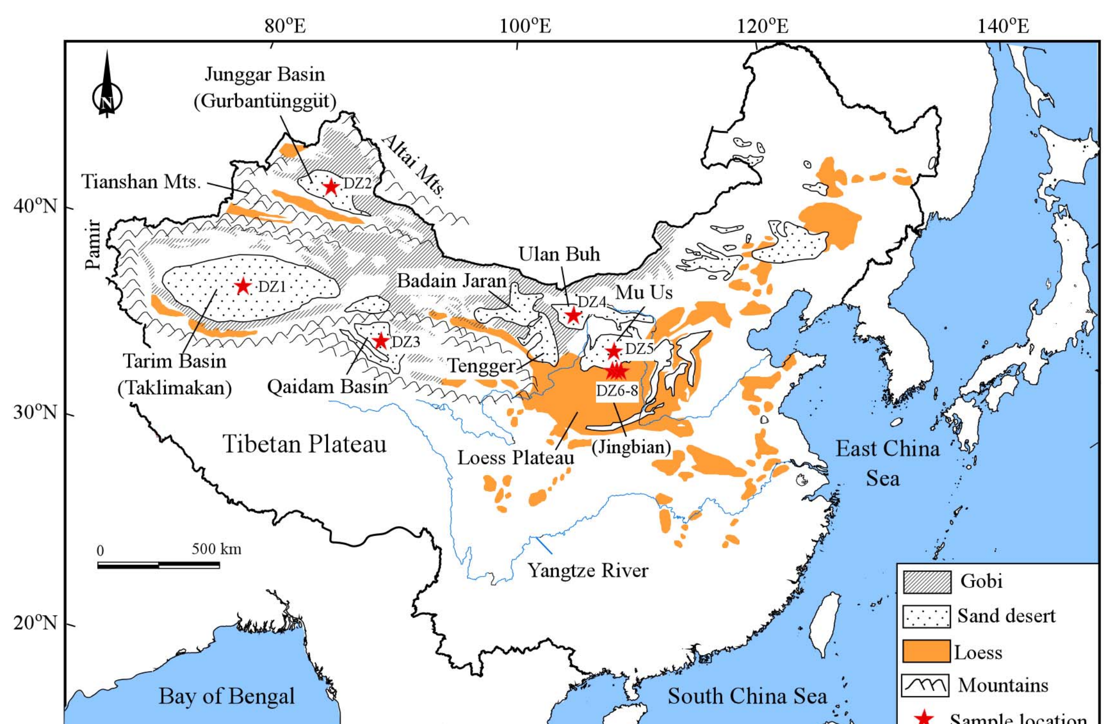

Fig. 1. Map showing the mountains, *gobi*, sand desert and loess distributions, and the locations of samples taken for U-Pb age analysis of detrital zircons.

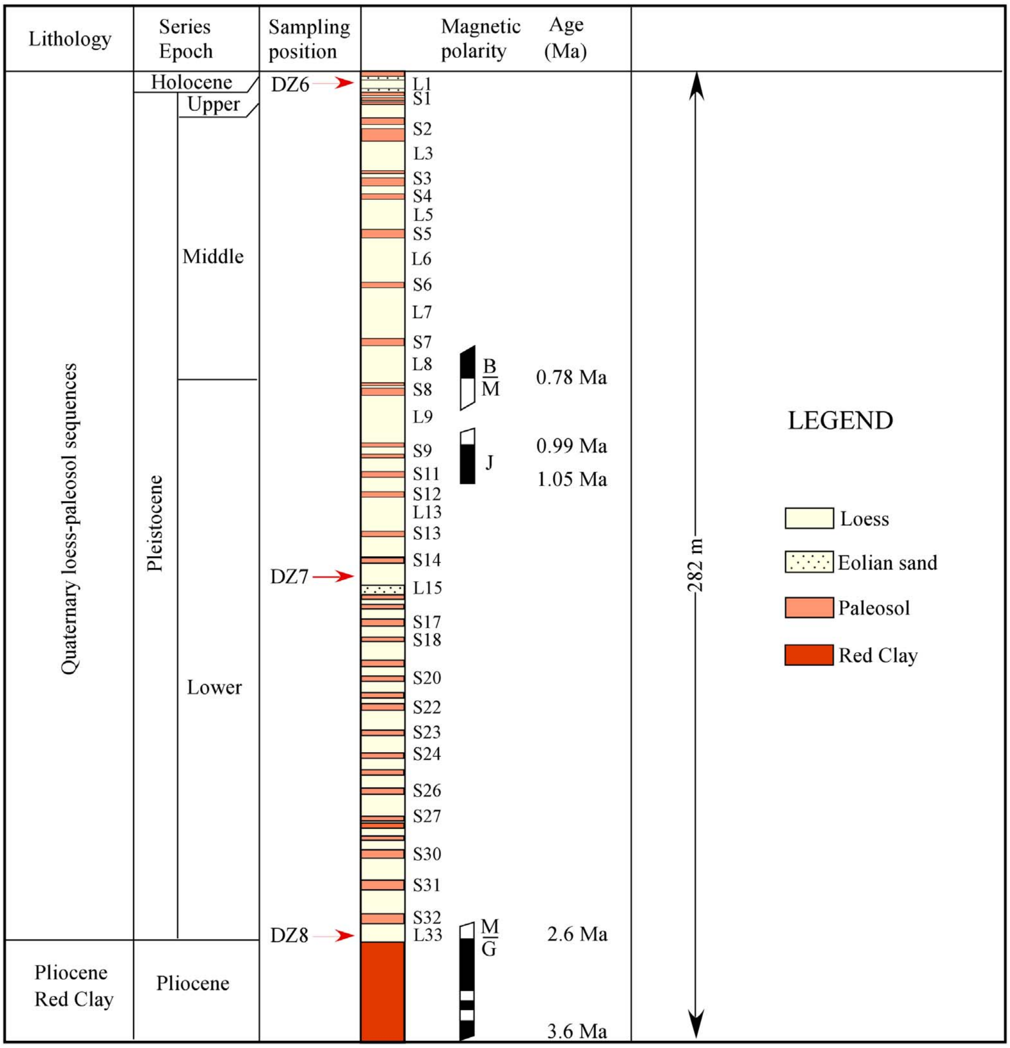

Fig. 2. Stratigraphic division of the Jingbian section, which is located in the northern Loess Plateau. The red arrows indicate the positions of the three loess samples. "L" represents glacial loess, and "S" represents interglacial paleosol. The paleomagnetic polarity of the Pliocene Red Clay is after Ding et al. (1999), whereas the Brunhes-Matuyama (B/M) magnetic reversal and the Jaramillo (J) normal subchron are after Guo et al. (2002).

laser ablation system was used for the zircon U-Pb analyses at the Department of Earth Sciences, the University of Hong Kong. The ICP-MS has a quadrupole mass analyzer, which is able to scan the mass spectrum from 3 to 250 very quickly. In this study, masses 202, 204, 206, 207, 232 and 238 were detected. In most cases, mass 204 is lower than the detection limit, and so the common lead correction was not conducted. ^{235}U was not collected due to its very low abundance. The ratio of $^{207}Pb/^{235}U$ is deduced from the product of the $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}U$ ratios multiplied by 137.88. The laser system delivers a beam of 213 nm UV light from a frequency-quintupled Nd:YAG laser machine. Most analysis spot sizes are 40 μm and at a 10 Hz repetition rate. Typical ablation time was 40 s, resulting in pits 30–40 μm depth. The instrument settings and detailed analytical procedures are described by Xia et al. (2004). In order to reduce elemental fractionation, helium carrier gas was used to transport the ablated sample materials from the laser-ablation cell *via* a mixing chamber to the ICP-MS torch after mixing with argon gas. Data were calculated using GLITTER 4.4 (GEMOC, Macquarie University, Sydney, Australia) and corrected for both instrumental mass bias and isotopic fractionation against the international zircon standard 91500.

Zircon U–Pb ages were calculated using the U decay constants of $^{238}U = 1.55125 \times 10–10\ year^{-1}$, $^{235}U = 9.8454 \times 10–10\ year^{-1}$ and Isoplot 3 software (Ludwig, 2003). Individual analyses are presented with 2σ errors and in concordia diagrams, and uncertainties in age results are quoted at the 95% level (2σ). In this study, $^{207}Pb/^{206}Pb$ ages were used to construct an age histogram for zircons older than 1000 Ma, but $^{206}Pb/^{238}U$ ages were used for zircons younger than 1000 Ma (Pell et al., 1997). As each detrital zircon grain may be derived from a different source rock, more than 70 grains were analyzed for each sample for an acceptable statistical sample size.

3. Results

The results from eight individual detrital zircon samples were plotted on concordia diagrams (Fig. 3) and age-probability plots (Fig. 4). The age distributions display the following characteristics.

First, for all samples, the most prominent age peak has an age range of 500–250 Ma (Fig. 4). Detailed analysis of the detrital zircons of 1000–0 Ma shows, however, that the peak of 500–250 Ma can be subdivided into two peaks of 360–250 Ma and 500–420 Ma (Fig. 5). Moreover, the peak of 500–420 Ma in the desert samples from the three inland basins of Tarim, Junggar, and Qaidam is more prominent than that of the other samples.

Second, compared with the samples from the Ulan Buh and Mu Us Deserts and the loess samples from the Jingbian Section, the samples from the three inland basins have relatively low contents of zircons that are older than 1800 Ma of early Proterozoic to Archean age and more zircons that are younger than 200 Ma (Fig. 4).

Third, the sample from the Gurbantünggüt Desert of the Junggar Basin is different from all the other samples because of the lack of zircons older than 1500 Ma (Fig. 4).

Finally, the zircon age distributions in the three loess samples from

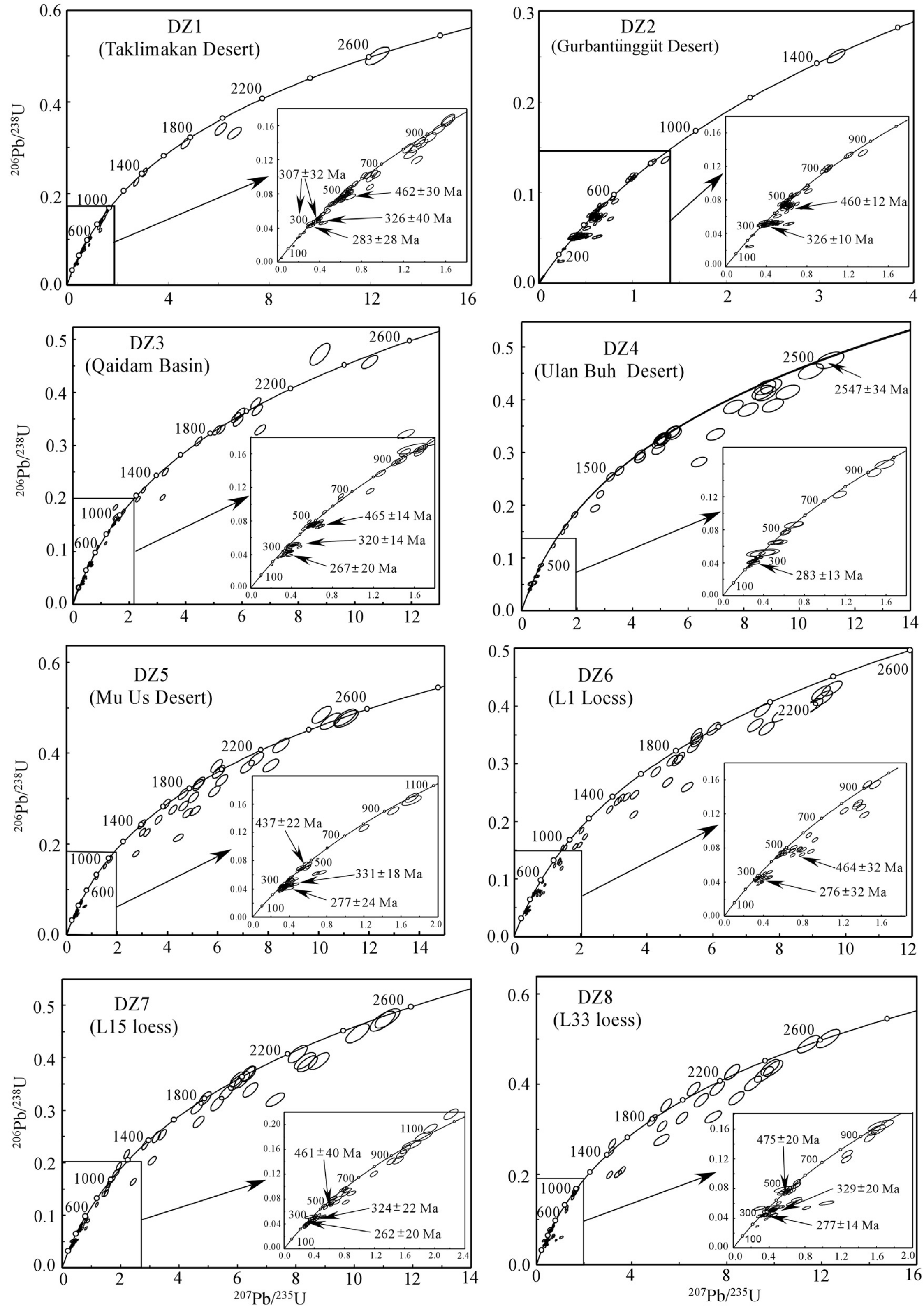

Fig. 3. Concordia plots of $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ and corresponding ages for samples collected from the deserts and loess in this study.

the Jingbian Section are very similar (Figs. 4 and 5), suggesting that, although they have widely separated ages of 0.03 Ma, 1.2 Ma, and 2.6 Ma, zircons on the Chinese Loess Plateau have had a similar provenance through the Quaternary.

4. Discussion

4.1. Provenance of loess on the Loess Plateau

As aeolian deposits, loess-sized materials are usually transported for long distances, well mixed, and commonly contain a wide range of

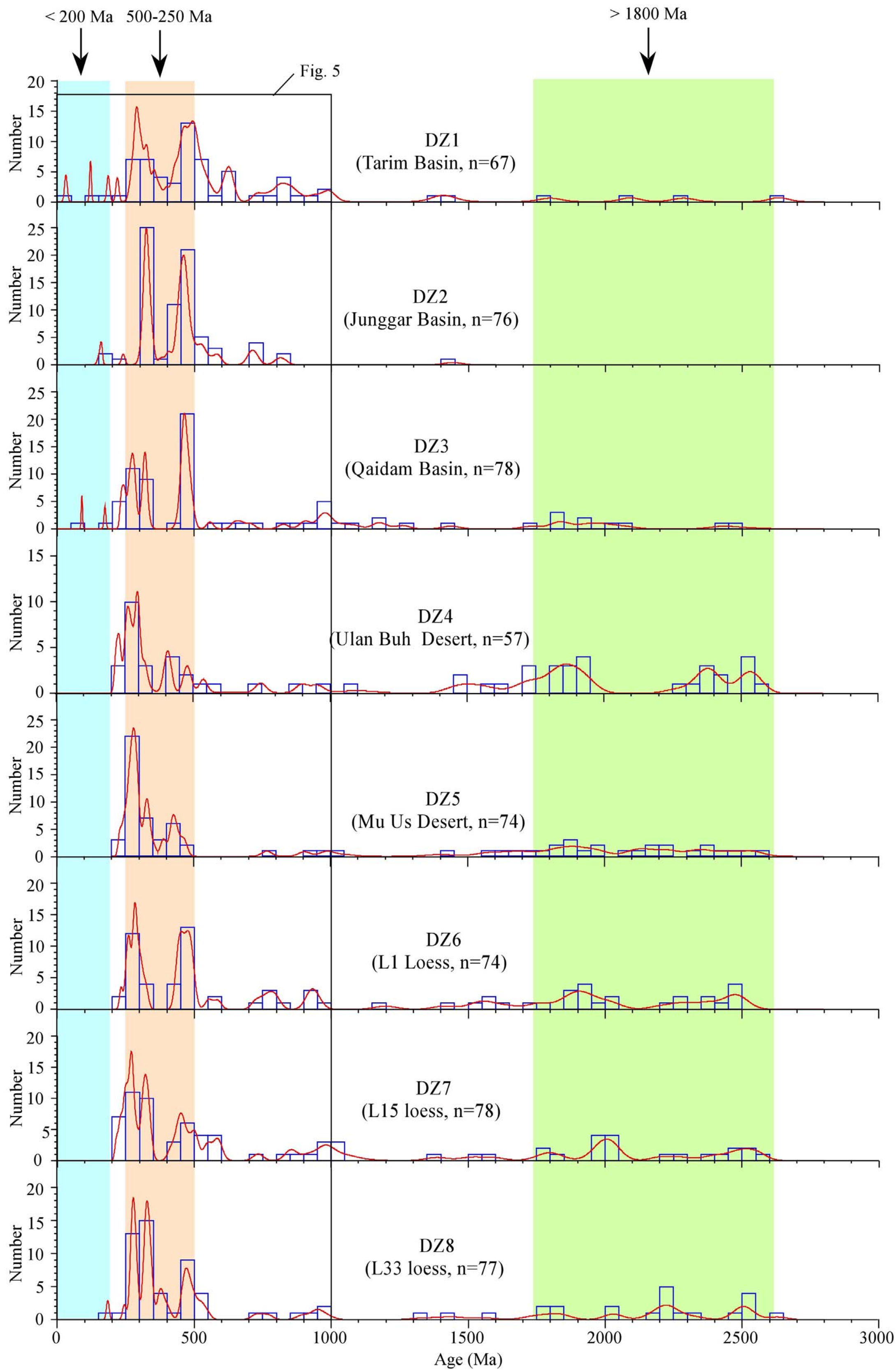

Fig. 4. Relative probability (curves in red) of detrital zircons in the desert and loess samples, showing data from 3500 to 0 Ma. For ages < 1000 Ma, the $^{206}Pb/^{238}U$ age is used, whereas the $^{207}Pb/^{206}Pb$ age is used for zircon > 1000 Ma. Note that all the samples are dominated by 500–250 Ma zircons, but the samples from the three inland basins (Tarim, Junggar, and Qaidam) have relatively low contents of zircons older than 1800 Ma.

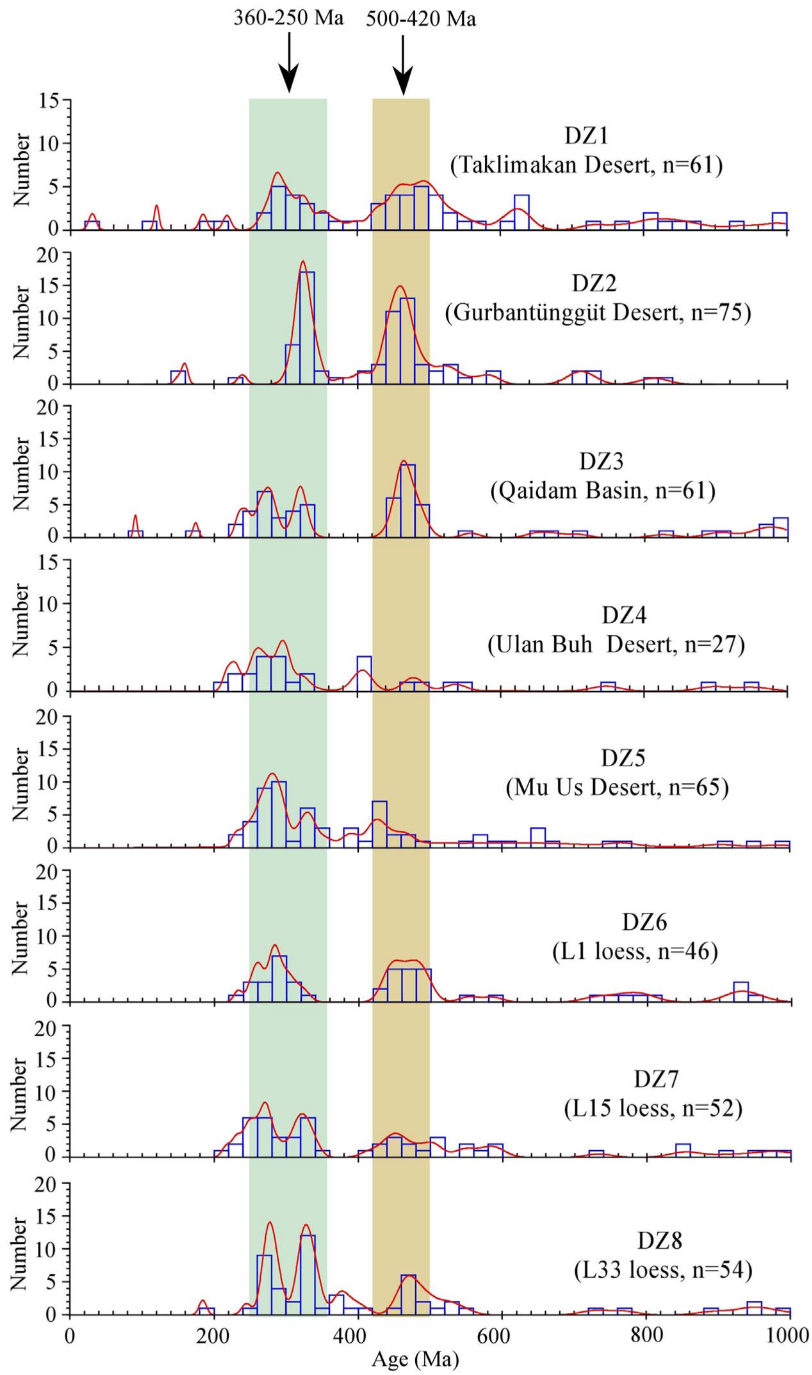

Fig. 5. Probability density plots (in red) of U-Pb zircon ages in our samples, showing ages from 1000 to 0 Ma. Note that the sand samples from the three inland basins have relatively more prominent age peaks at 500–420 Ma.

minerals. That is why the chemical compositions of loess can be used, to some extent, as the average value of the upper crust, as suggested by Taylor et al. (1983). But due to the specific properties of air-borne dust, the provenance of loess cannot be established by using the Sr, Nd isotopic ratios or U-Pb ages of detrital zircons only; geomorphology and dust pathways must also be considered.

In this paper, our new U-Pb ages of detrital zircons show that the age distributions of the three loess samples are similar to those of the desert samples taken from the Ulan Buh and Mu Us deserts belonging to the northern *gobi* and deserts adjacent to the Loess Plateau, but they are different from the desert samples from the three northwestern inland basins. These basins (Tarim, Junggar, Qaidam) are characterized by fewer zircons older than 1800 Ma (Fig. 4) and by their relatively higher contents of 500–420 Ma zircons (Fig. 5). Our new U-Pb ages suggests that these three inland basins are not the major sources of the Loess Plateau.

Such a conclusion based on U-Pb ages of zircons is supported by near-surface wind patterns, indicated by the movement directions of sand dunes (Zhu et al., 1980, Fig. 6a), and by the uppermost distribution limits of loess in the downwind mountains in the three inland basins (Fig. 6b–e).

In the Junggar Basin, the prevailing near-surface wind is northwesterly (Fig. 6a), and dust entrained from this basin is transported by northwesterly winds downwind to the Tianshan Mountains. Due to the blockage by these high mountains, dust derived from the Junggar Basin has accumulated in the northern piedmont of the Tianshan Mountains, forming a series of elongated loess ridges whose long axes are parallel to the prevailing winds (Fig. 6b). Field investigations indicate the upper limit of the loess cover in the piedmont of the Tianshan Mountains is at ~2400 m above sea level (asl), which is much lower than the average

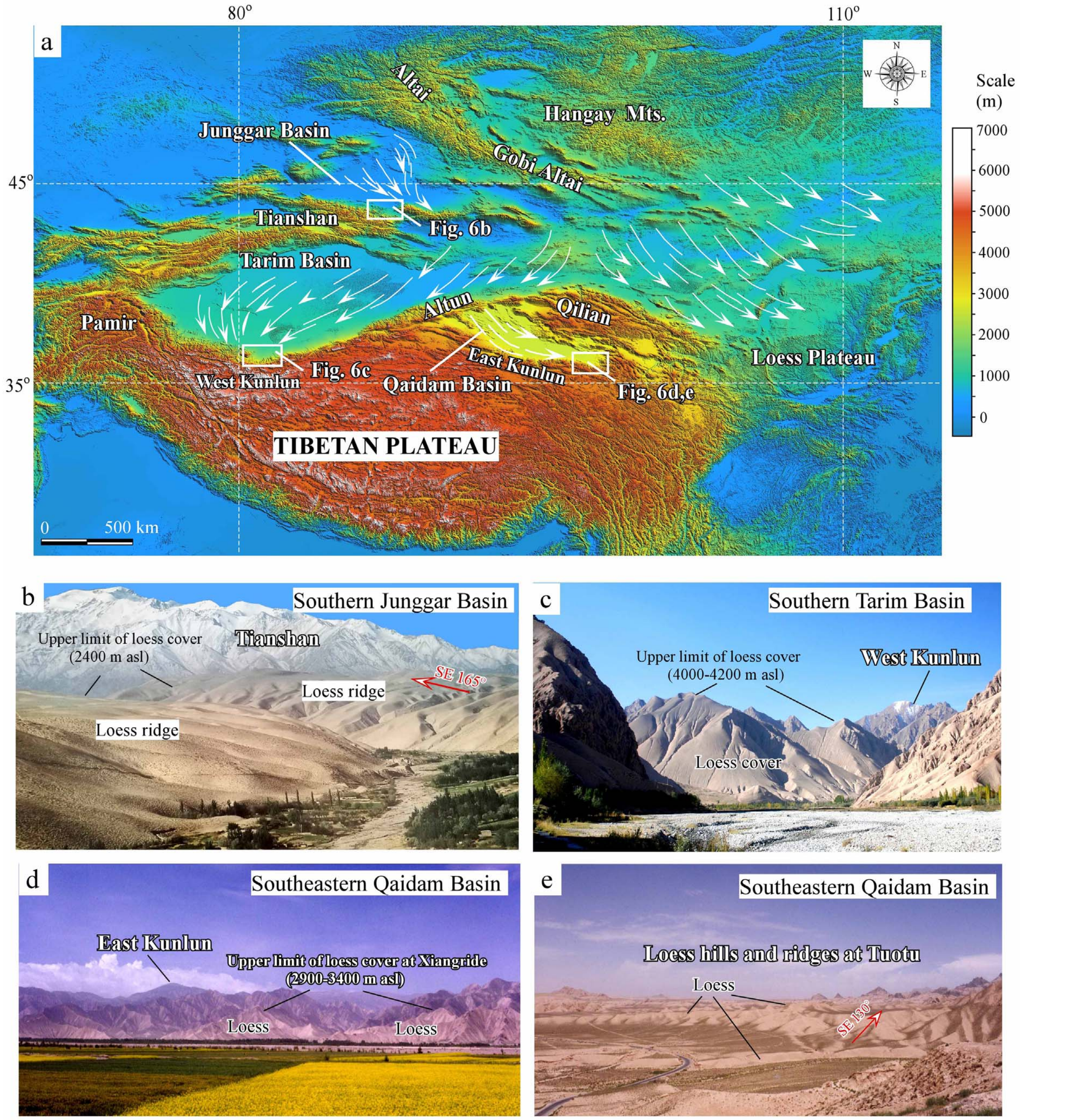

Fig. 6. (a) Map showing the near-surface wind directions (arrow) based on sand dune orientations in the deserts. Noting the prevailing winds in the three basins of Junggar, Tarim, and Qaidam are all blocked by the downwind high mountains. (b) Upper limits of loess on the windward slopes of the North Tian Shan, which are much lower than the mountain peaks, indicating dust entrained from the Junggar Basin is blocked by the Tian Shan. Upper limits of loess cover on the West Kunlun (c) and East Kunlun (d), which are both lower than the height of these mountains, implying that dust transported by near-surface winds was not able to move out of the Tarim and Qaidam basins, respectively. Field investigations indicate that dust entrained from the Qaidam Basin mainly accumulated in the southeastern part of the basin, forming a widespread loess cover, hills and ridges (e).

elevation of 4000 m asl of the Tianshan Mountains (Fig. 6b). Therefore, the dust entrained from the Junggar Basin is deposited on the northern flanks of the Tianshan Mountains and does not reach the Loess Plateau. This is mirrored by the distinct U-Pb age distributions of detrital zircons from the Junggar Basin compared to samples from the Loess Plateau (Fig. 4). These results are in agreement with the geochemical evidence of Liu et al. (1994).

In the Tarim Basin the prevailing wind is northeasterly in the central and eastern parts of the basin, and only in the west does the wind move to northwesterly due to the blockage of the Pamir salient (Fig. 6a). In most cases, the dust entrained by the above prevailing winds is transported to the northern flanks of the West Kunlun Mountains where it accumulates as loess (Sun, 2002b). The upper elevation limit of the loess cover is about 4000–4200 m asl (Zhang et al., 1994), which is lower than the average elevation of more than 5500 m asl in the West Kunlun Mountains (Fig. 6c). Given this topographic setting, dust entrained in the Tarim Basin is blocked by the West Kunlun Mountains and cannot move out of the basin. Thus, the Tarim Basin cannot be the source of silts in the Loess Plateau either. Rarely, dust in the Tarim Basin can be entrained to more than 6000 m asl by extremely strong convection. During conditions such as this, the dust is transported by a upper-level westerly jet for more than 5000 km. It is not deposited in the Loess Plateau, but instead it ultimately accumulates in the remote Pacific Ocean (Sun, 2002a). A case study of a dust storm event on May

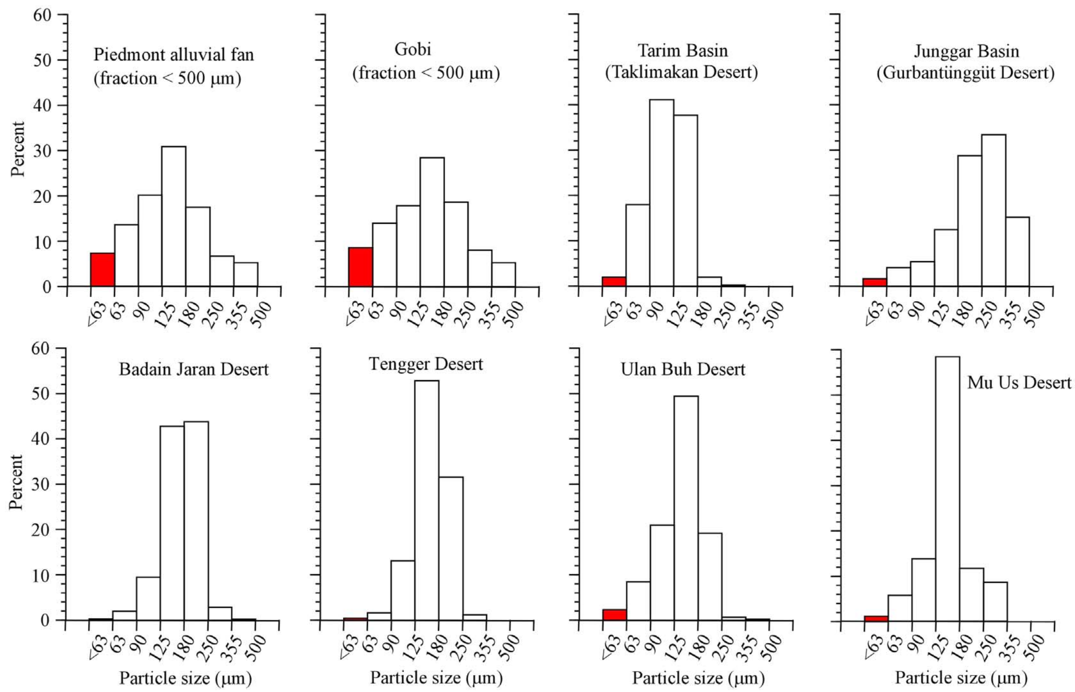

Fig. 7. Particle-size distributions in the alluvial fan, *gobi* and sand deserts. Note the lower contents of the silt and clay fraction (< 63 μm, in red) in the sand desert samples. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

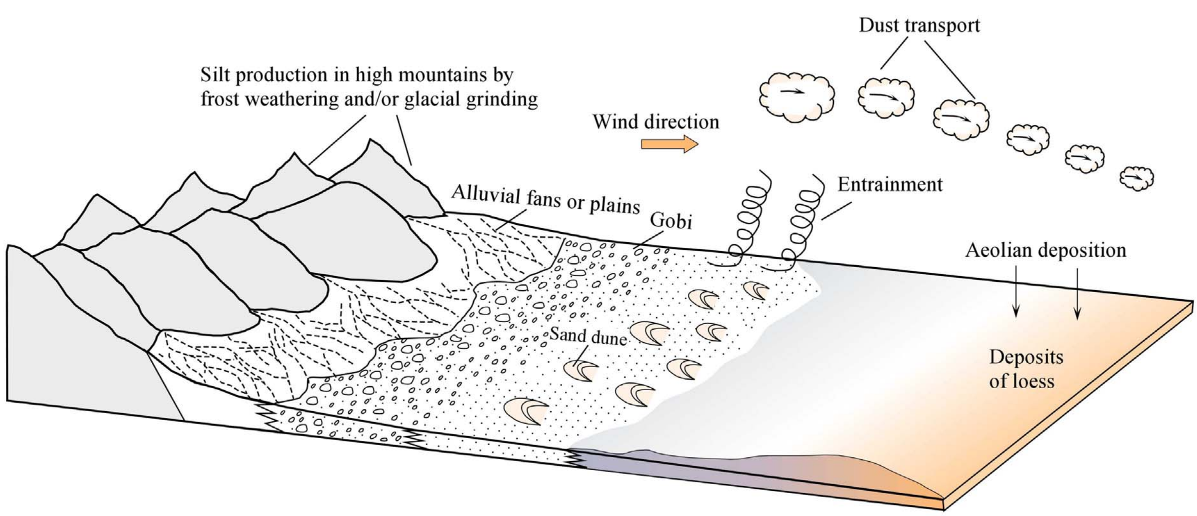

Fig. 8. A conceptual model shows the processes associated with loess deposition, including the loess-size material production in high mountains by frost weathering and glacial grinding, the outwash of alluvial fans and plains by streams, and the wind-sorting processes that lead to the zonal distributions of the *gobi*, desert, and loess. Note that the mountain processes have played a fundamental role in the production of loess-size materials.

18–19, 1986, in the Tarim Basin, demonstrates that the dust entrained to more than 6000 m asl was transported by a westerly jet to the Pacific (Li, 1989). During this dust-storm event, the ground-based meteorological stations in northern China did not detect any dust fall on the Loess Plateau (Sun et al., 2001). Deep-sea sediment records show that dust from Asia has accumulated in the Pacific over much of the Quaternary (Hovan et al., 1989).

The Qaidam Basin, where the prevailing wind is northwesterly (Fig. 6a) is an intermontane basin bounded by the Altun Mountains to the north, the Qilian Mountains to the northeast, and the East Kunlun Mountains to the southeast (Fig. 6a). As a closed topographic depression, dust entrained from the Qaidam Basin is not easily moved out of the area, but accumulates mainly in the piedmont areas to the southeast along the flanks of the East Kunlun Mountains. The upper limit of loess on the windward slopes of the East Kunlun Mountains is 2900–3400 m asl (Liu, 1965), which is lower than the average elevation of more than 4500 m asl of the East Kunlun Mountains (Fig. 6d). Dust from this basin accumulates mainly on the piedmonts downwind, forming widespread loess hills and ridges at Xiangride and Tuotu in the southeastern Qaidam Basin (Fig. 6e). Due to blockage by the high mountains, dust from the Qaidam Basin is unable to reach the Loess Plateau.

It is worthwhile stressing that large fields of wind-eroded landforms of parallel ridges and troughs (called *yardangs* by local people) of subaerially exposed lacustrine sediments in the interior of the northwestern Qaidam Basin indicate severe wind erosion and dust production during the Quaternary (Zhu et al., 1980; Bowler et al., 1987; Kapp et al., 2011). However, we do not totally agree with the view of Kapp et al. (2011) that wind erosion and dust production in the Qaidam Basin are the major source of dust for the Loess Plateau. We present three lines of evidence that argue against this view. First, the total area of the

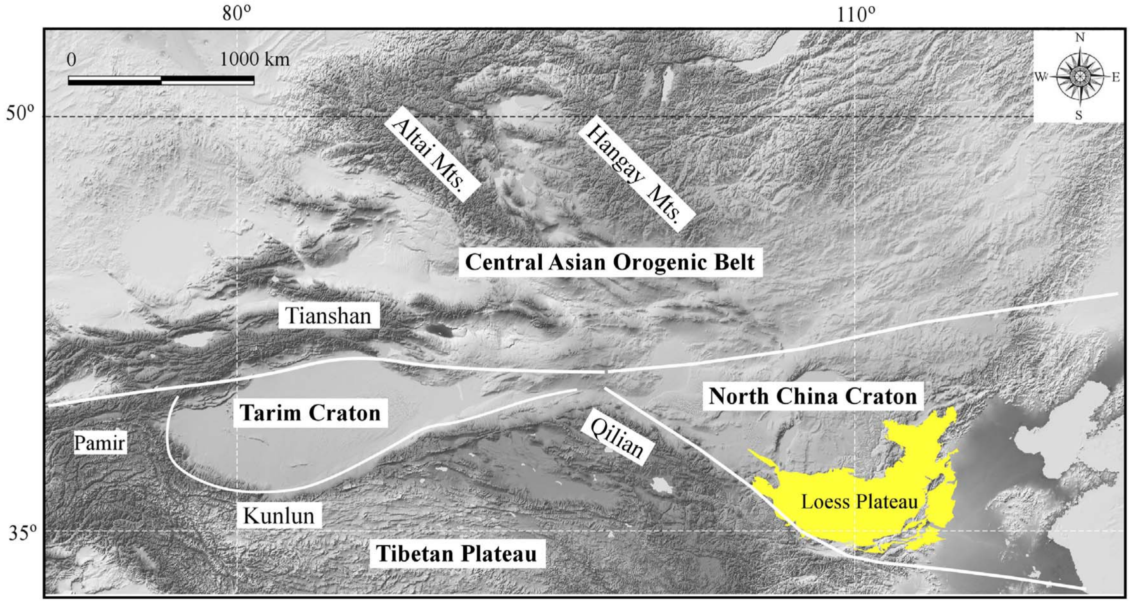

Fig. 9. The major geotectonic units in northern China, including the Central Asia Orogenic Belt (Tian Shan, Altai, and Hangay mountains), the Tarim and North China Cratons, and the northern Tibetan Plateau. The Loess Plateau is just within the North China Craton.

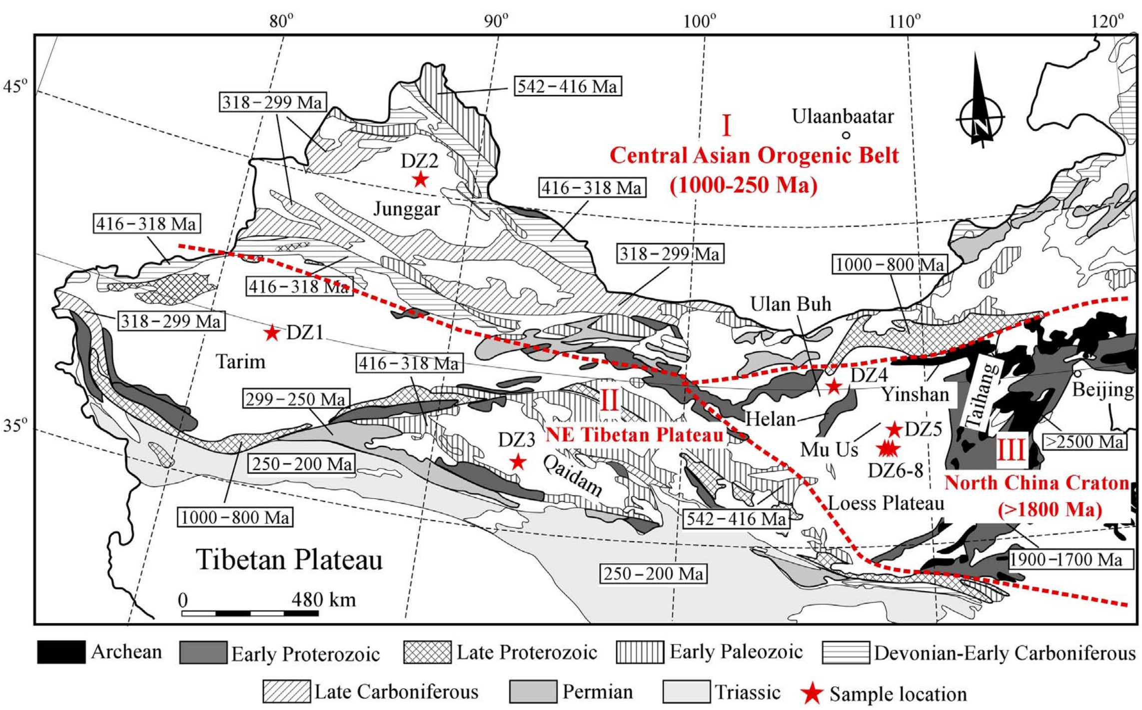

Fig. 10. Map showing the ages of geological units in the Central Asian Orogenic Belt (I), the Northeastern Tibetan Plateau (II), and the North China Craton (III). Note that the Palaeoproterozoic and Archean blocks of older than 1800 Ma occur mainly in the North China Craton.

yardang landforms of China is only about 20,000 km^2 (Guo et al., 2012); this includes the *yardangs* both in the Qaidam Basin and in Xinjiang. Even if we consider the total area of *yardangs* in all of China, it is less than 5% of the total area of 440,000 km^2 of the Loess Plateau. Thus, from volumetric considerations along, aeolian erosion of lacustrine sediments only cannot be the primary source of dust in the Loess Plateau. Second loess on the Loess Plateau can be up to 300 m thick, this requires a huge dust source. Third, one cannot consider only the dust production by wind erosion, because the geomorphological features along the dust pathway must also be taken into account. Even if there is considerable dust production in the interior of the northwestern Qaidam Basin, transport of much of it will be blocked by the high mountains downwind, and thus it will accumulate on the windward slopes of the southeastern Qaidam Basin. We conclude, therefore, that the contribution of dust from the Qaidam Basin to the Loess Plateau can only be minor.

4.2. Potential effect of mountain processes on loess-sized material production

The existence of appropriate source materials is fundamental for the formation of loess in downwind regions. To date, many different hypotheses have been proposed about the loess-sized material production, including glacial grinding (Smalley, 1966), frost weathering (Zeuner,

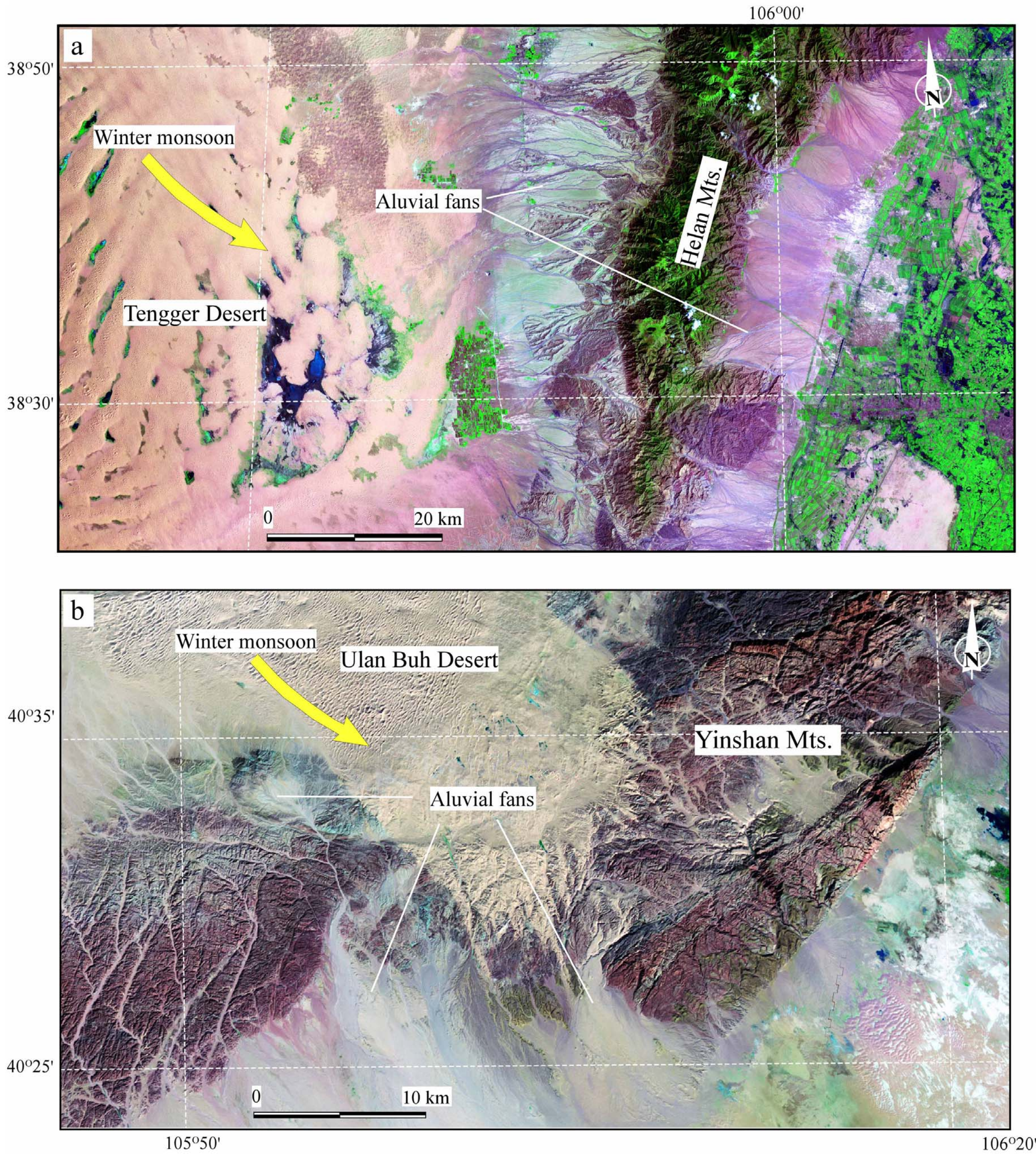

Fig. 11. The clastic debris produced by mountain processes in (a) the Helan and (b) the Yinshan mountains of the North China Craton are outwashed to the piedmonts forming overlapping alluvial fans, which provide limited source materials for both the adjacent deserts and the downwind Loess Plateau. The yellow arrow marks the prevailing northwesterly winter monsoon in the dust storm seasons in North China. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1950), salt weathering (Goudie et al., 1979; Pye and Sperling, 1983), aeolian abrasion (Whalley et al., 1982), and fluvial comminution/aeolian abrasion (Wright 2001a, 2001b). The traditional view of "desert" loess in China was first proposed by Obruchev (1911). However, Smalley and Vita-Finzi (1968) suggested that there are no specific desert processes which could produce the vast amounts of silt required to form large loess deposits. Derbyshire et al. (1998) suggested that the alluvial fans along the Qilian Mountains could be important sources of loess in the western Loess Plateau. Sun (2002a) argued that although the *gobi* and sand deserts in southern Mongolia and the adjoining regions of China can be regarded as the main source regions of the Loess Plateau, these *gobi* and sand deserts, serve as dust- and silt-holding areas rather than as dominant silt producers.

In this study, in order to better determine the mechanism for the loess-sized material production, we analyze the particle distributions of both sand dune samples taken from six Chinese deserts (Taklimakan Desert, Gurbantünggüt Desert, Badain Jaran Desert, Tengger Desert, and the Mu Us Desert, see locations in Fig. 1) and two samples from the piedmont alluvial fans and the nearby *gobi* in the northern Qilian Mountains

Pye (1987) suggested that only particles of < 63 μm can be transported by wind in suspension, whereas sand- or gravel-size particles can only be transported by saltation or by creep. Our particle size analyses indicate that the contents of silt and clay contents (< 63 μm) in the alluvial fan and the *gobi* samples are 7.2% and 8.5%, respectively. The silt and clay contents of the dune sand samples are even lower, generally less than 2% (Fig. 7). It is worth noting that the silt and clay contents in the samples from the Tengger and Badain Jaran deserts are

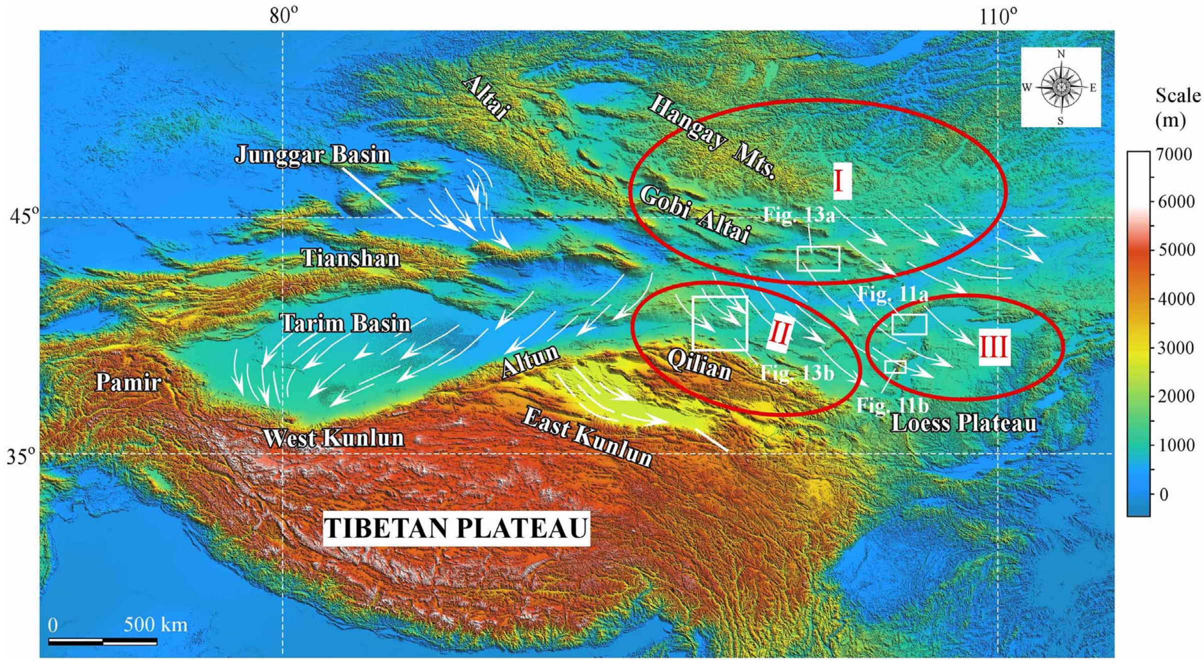

Fig. 12. Map showing the ternary provenances of loess for the Loess Plateau, including (I) the alluvial fans in the Central Asia Orogenic Belt, (II) the alluvial fans in the north Qilian Mountains in the northeastern Tibetan Plateau, and (III) a minor source from the North China Craton. Arrows indicate the near-surface prevailing winds in winter and spring.

only 0.3% and 0.17%, respectively (Fig. 7). Therefore, quantities of silt and clay in sand desert samples are minor in comparison to those of the alluvial fan and *gobi* samples.

A basic geographic feature of China is that *gobi*, sandy desert, and loess regions are distributed principally along the flanks of mountain ranges (Fig. 1), implying a close link between mountain processes and loess-size material production. This link can be illustrated with our conceptual model (Fig. 8). The production of loess-sized materials in high mountains can be associated largely with the mountain processes of glacial grinding and frost weathering, followed by fluvial transport of clastic materials to the piedmont areas, forming large-scale, alluvial fans or plains, and wind sorting on the alluvial materials resulting in the facies changes of *gobi*, sandy desert (aeolian sand), and loess. In this context, mountain processes have played a dominant role in the loess-size material production in China. There is abundant evidence of glacier advances in China's and Mongolia's mountains in the Quaternary (Zhou et al., 2004; Yi et al., 2006; Blomdin et al., 2016).

4.3. Three potential sources of loess in the Loess Plateau

The close link between mountain processes and the loess-sized material production leads naturally to a discussion of the main geotectonic domains in China and their contributions to the provenance of loess on the Loess Plateau. In northern China and neighboring Mongolia, the main geotectonic units include the Central Asian Orogenic Belt, the Tarim and North China Cratons, and the northern Tibetan Plateau (Fig. 9). It is interesting that the Loess Plateau is located just in the North China Craton.

The Central Asian Orogenic Belt is the largest Phanerozoic accretionary orogenic belt in the world, extending from the Ural Mountains to the Pacific Ocean and from Siberia to Tibet (Sengör et al., 1993; Windley et al., 2007; Sun et al., 2008; Xiao et al., 2009). It consists of a series of mountain ranges, including the Tianshan, Altai, Hangay, and other more eastern mountains (Fig. 9). Rocks in the Central Asian Orogenic Belt have an age range of 1000–250 Ma (Windley et al., 2007; Xiao et al., 2015). In contrast, the North China Craton has a history from 3800 to 1800 Ma (Zhao et al., 2001; Zhai and Santosh, 2011), and includes several micro-blocks, which finally amalgamated to form a craton at around 1800 Ma (Kusky et al., 2016).

In order to discuss the provenance of loess on the Loess Plateau, we summarize the ages of the geological units in the Central Asian Orogenic Belt (I), the Northeastern Tibetan Plateau (II) and the North China Craton (III) (Fig. 10). Together with the U-Pb ages of the detrital zircons and prevailing wind patterns, we can then discuss the provenances of the desert and loess samples.

The Junggar Basin is surrounded by mountains belonging to the Central Asian Orogenic Belt (Fig. 10). The dominant Paleozoic age of rocks in these mountains (542–251 Ma) can account for the prominent age peak of 500–250 Ma in the sand samples from the Junggar Basin. Additionally, because the ages of rocks in the Central Asian Orogenic Belt are 1000–250 Ma, the ages of zircons, except for one grain of 1400 Ma, are all younger than 1000 Ma. Sands in the Tarim and Qaidam basins are also derived mainly from Paleozoic rocks, where tectonic units older than 1800 Ma are very limited (Fig. 10), and these can account for the age peaks of 500–250 Ma, and the few zircons older than 1800 Ma (Fig. 4).

In contrast to the sand from the three inland basins, the Ulan Buh and Mu Us deserts and the Loess Plateau are all located within the North China Craton (Fig. 10). In this region, there are extensive areas of rocks older than 1800 Ma or even > 2500 Ma that exposed in the Taihang, Helan, and Yinshan Mountains (Fig. 10). Alluvial fans of the Yinshan and Helan Mountains (see location in Fig. 10) provide materials for the nearby deserts (Fig. 11). This can account for the great number of zircons older than 1800 Ma in the samples from the Ulan Buh and Mu Us deserts. Additionally, these alluvial fans are upwind of the Loess Plateau, where the older zircons can be transported by northwesterly winds of the winter monsoon to the Loess Plateau. In this context, loess on the Loess Plateau has an additional provenance of materials derived from the mountains of the North China Craton, as indicated by the high number of zircons older than 1800 Ma in the loess samples at Jingbian.

Based on the detrital zircon ages and the prevailing wind patterns, the aeolian deposits on the Loess Plateau has three sources (Fig. 12), the most important source is the Central Asia Orogenic Belt where the extensive alluvial fans of the Gobi Altai (Fig. 13a) and the Hangay mountains supply large volumes of loess-sized materials that are

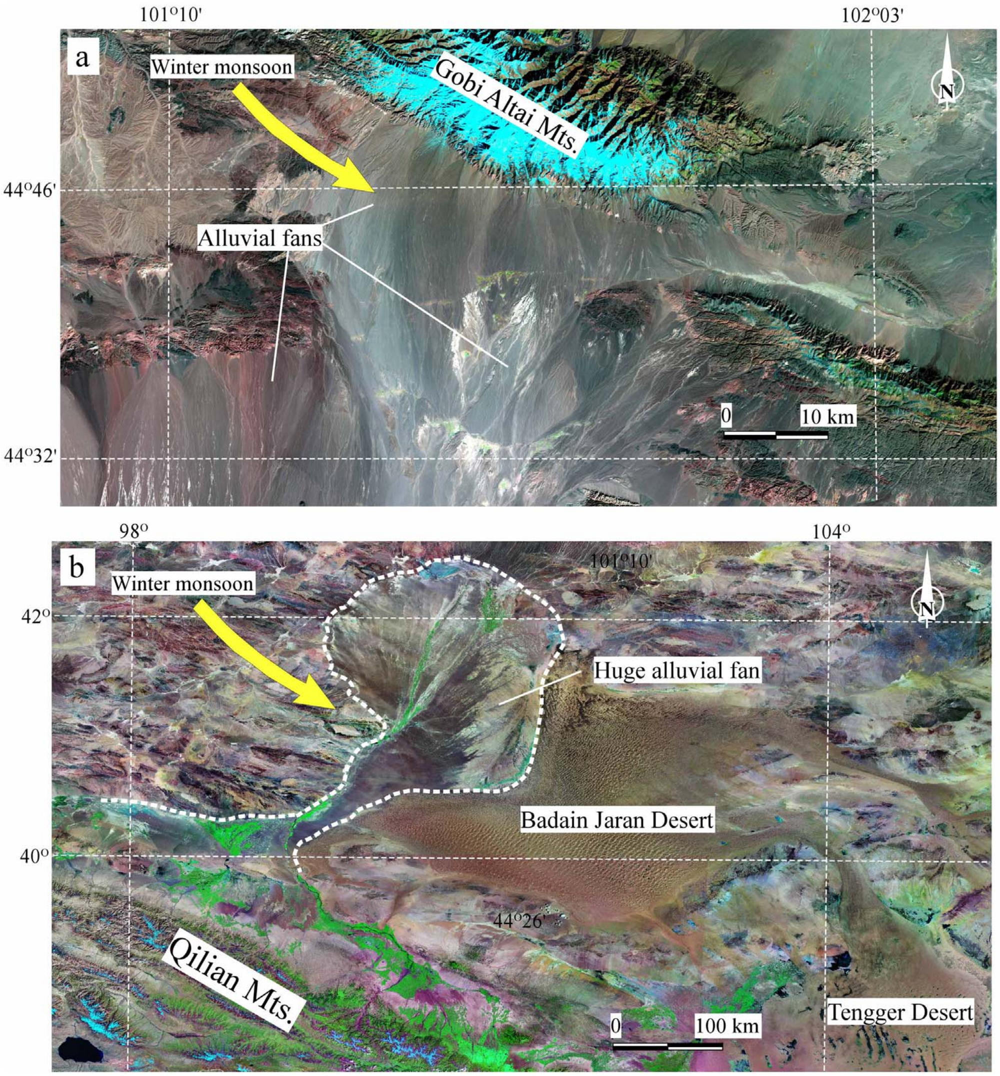

Fig. 13. Maps showing the chains of alluvial fans in the Gobi Altai in the Central Asia Orogenic Belt (a), and the huge alluvial fan (indicated by a dashed line) in the Qilian Mountains (b). These alluvial fans provide huge volumes of materials for the adjacent deserts and loess on the Loess Plateau. The yellow arrow indicates the prevailing northwesterly winter monsoon in the dust storm seasons in North China. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

transported to the Loess Plateau by the northwesterly wind monsoon. This is indicated by the dominant age range of 500–250 Ma of the detrital zircons in the loess and by the dominant Paleozoic age of the Central Asia Orogenic Belt.

The second source is associated with the mountain processes of the Qilian Mountains in the northeastern margin of the Tibetan Plateau (Fig. 12). Glacial grinding and frost weathering of the Qilian Mountains lead to the production of huge volumes of clastic materials, which are ultimately transported to the northern and northeastern piedmont areas of the Qilian Mountains, where they form several large alluvial fans (Fig. 13b). The largest of these fans may be as much as 350 km long and 150 km wide (Fig. 13b). They are also in the dust pathway and are also an important provenance especially for the loess on the western Loess Plateau.

The third loess source is perhaps less important and is associated with the mountain processes in the North China Craton (Fig. 12). Alluvial fans of the Helan, Yinshan, and Taihang mountains provide loess-sized materials for the Loess Plateau. This interpretation is supported by the relatively high content of zircons older than 1800 Ma in the loess at Jingbian.

5. Conclusions

Based on detrital zircon age analysis of samples from different deserts and loess site in the northern Loess Plateau, integrated with known topographic features and wind patterns, we draw the following conclusions:

(1) The age spectra of detrital zircons in the loess samples in the northern Loess Plateau are different from those of the sand samples from three inland basins (Tarim, Junggar and Qaidam) in northwestern China, but they are similar to the sand samples from the northern deserts (such as the Ulan Buh and Mu Us deserts) adjacent to the Loess Plateau, which implies a sedimentological weak link between the Loess Plateau and the three largest inland basins.
(2) The age spectra of the detrital zircons of different-aged loess samples show a similar pattern, suggesting that the provenance did not change significantly from the beginning of the Quaternary to the last glacial period.
(3) There are three potential sources for the loess on the Loess Plateau. The first is the deflation and transportation of clastic materials derived from the Central Asian Orogenic Belt (especially the Gobi Altai and Hangay mountains) upwind directions of the Loess Plateau. The second source is the loess-sized materials generated by mountain processes of the Qilian Mountains in the northeastern margin of the Tibetan Plateau. The third minor source is clastic debris derived from the neighboring mountains of the North China Craton (3800–1800 Ma). Thus, the sources of aeolian silts for the Loess Plateau are complex, the long-held belief that inland desert basins in northwestern China are the sources of loess is not

supported by isotopic and geomorphologic data.

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