# Geochemical characterization of major elements in desert sediments and implications for the Chinese loess source

Wancang ZHAO, Lianwen LIU, Jun CHEN and Junfeng JI

Citation: SCIENCE CHINA Earth Sciences; doi: 10.1007/s11430-018-9354-y
View online: http://engine.scichina.com/doi/10.1007/s11430-018-9354-y
Published by the Science China Press

SCIENCE CHINA
Earth Sciences

•RESEARCH PAPER•

https://doi.org/10.1007/s11430-018-9354-y

# Geochemical characterization of major elements in desert sediments and implications for the Chinese loess source

Wancang ZHAO[1,2], Lianwen LIU[2], Jun CHEN[2] & Junfeng JI[2*]

[1] *Chongqing Key Laboratory of Karst Environment, School of Geographical Sciences, Southwest University, Chongqing 400715, China;*
[2] *Ministry of Education Key Laboratory of Surficial Geochemistry, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China*

Received September 21, 2018; revised February 18, 2019; accepted April 3, 2019; published online May 29, 2019

**Abstract** Mineral dust released from the desert is one of the important components of atmospheric aerosols. Arid and semi-arid deserts, sandy lands in northern China and their adjacent Gobi Desert lands in northern China and neighboring Mongolia (hereinafter referred to as Gobi) are potential sources of mineral dust in Asia. However, there is currently a lack of systematic studies on the characteristics of major elements in the potential mineral dust source area. This study investigates the major elements of 310 surficial sand samples in the stabilized and semi-stabilized dune fields from 12 deserts/sandy land and Gobi in northern China and southern Mongolian Gobi and compiles published data. We identify four regions with distinct geochemical characteristics: (1) Taklimakan, Kumtag and Qaidam deserts in western China; (2) Badain Jaran, Tengger, Hobq, and Mu Us deserts in the central and western regions of northern China; (3) Hulun Buir, Onqin Daga and Horqin sandy lands in northeast China; and (4) Gobi and Gurbantunggut deserts. The spatial distributions of the $SiO_2$ and CaO contents in Chinese deserts are highly variable. The average content of $SiO_2$ generally reflects an increasing trend from west to east, while the average content of CaO shows a decreasing trend from west to east. We demonstrate that the spatial variation of major elements is likely controlled by two key scenarios: the composition of source rocks and the mineral maturity caused by the supply of fresh materials. The $SiO_2/(Al_2O_3+K_2O+Na_2O)$ ratio of desert sediments is relatively lower in western China and may be caused by high ferric-magnesia and high carbonate minerals; this ratio is relatively higher in the northeast sandy lands and may be linked to a lack of fresh material supply and the presence of high K-feldspar minerals in source rocks. The deserts can be further distinguished by ternary diagrams with $SiO_2/10$-CaO-$Al_2O_3$, $(K_2O+Na_2O)$-CaO-$Fe_2O_3$ and CaO-$Na_2O$-$K_2O$. The comparison of major elements between desert sediments and loess suggests that the western and/or central deserts in China may be the potential provenances of loess on the Loess Plateau.

**Keywords** Desert, Loess, Major elements, Eolian, Dust, Carbonate

**Citation:** Zhao W, Liu L, Chen J, Ji J. 2019. Geochemical characterization of major elements in desert sediments and implications for the Chinese loess source. Science China Earth Sciences, 62, https://doi.org/10.1007/s11430-018-9354-y

## 1. Introduction

Since the uplift of the Tibetan Plateau in the late Cenozoic accompanied by the Paratethys Sea retreat and global cooling, the atmospheric circulation in China has switched from a planetary wind system to a monsoon system. The moisture transport from the ocean to the interior basin has been hindered, and along with a foehn effect and topographical enclosure, the interior of Asia has become drier. Large amounts of sand sediments in the front mountain basin are continuously produced through surface processes such as wind erosion and river transportation. The weathering/denudation materials on the high mountains provide a potential sand source to vast deserts and/or the Gobi Desert (Lu and Guo,

* Corresponding author (email: Jijunfeng@nju.edu.cn)

2014; Zheng, 2016; Guo, 2017). With surface winds, coarser grains of sand in arid and semi-arid desert/sandy lands undergo physical collision and produce large quantities of fine particles. These fine minerals are subsequently released and transported in downwind directions, thereby accumulating in relatively flat/highlands and/or basins. The history of building the environmental coexistence of the Chinese Loess Plateau and deserts can be dated to 22–25 Ma (Guo et al., 2002; Qiang et al., 2011; Zheng et al., 2015). With geomorphic conditions and the local climate system, a large amount of silt material is provided in the inland areas of northern China and neighboring Mongolia (Smalley, 1995; Zheng, 2016). From the geological perspective, the production, emission, transportation and deposition of Asian dust are closely associated with regional tectonic-geomorphic-climatic configurations. Desert/Gobi areas in China and neighboring Mongolia have become one of the major dust provenances in the world (Engelbrecht and Derbyshire, 2010), which not only affects the chemical composition of the atmosphere and human health but also plays an important role in the biogeochemical cycle of climate change. The geochemical characteristics of elements, minerals and isotopes in northern China and the neighboring Mongolia Gobi Desert have provided valuable information for deciphering the regional tectonic and climatic history and for identifying the transport pathways of eolian dust and the control mechanism of mineral dust emissions.

In recent decades, numerous studies have focused on major and trace elements, isotopes and mineralogy in sediments from deserts and Gobi in China. In the early 1990s, the Taklimakan Desert was widely considered to be an important provenance of the Chinese Loess Plateau based on evidence from elemental ratios and Sr-Nd isotopic composition (Liu et al., 1993, 1994). By comparing the illite types and its crystallinity, Ji et al. (1999) concluded that illite in loess from the Chinese Loess Plateau is derived from pre-existing sediments and very low- to low-grade metamorphic rocks. Sun (2002) used the ratio of elements, Sr-Nd isotopes and mineralogical characteristics to demonstrate that the Gobi Desert between China and Mongolia and the southern parts of the Badain Jaran Desert, Tengger Desert, Ulan Buh Desert and Mu Us Desert are the main source areas of the Loess Plateau. However, some Sr-Nd isotopic tracer studies suggested that dust released from the Taklimakan Desert and the west-central Inner Mongolia and/or northeast Tibetan Plateau desert may be the source areas of the Chinese Loess Plateau (Rao et al., 2006; Yang et al., 2007). Recent field studies combined with remote sensing observations have shown two major Asian dust source areas, with one in the Taklimakan Desert and the other in the vast arid area between the Qilian Mountains, Altay Mountains and Mongolian Gobi (Shao and Dong, 2006; Chen et al., 2017). In addition, studies using source tracers with U-Pb ages for zircon, spin signals and $\delta^{18}O$ of quartz have suggested that the provenance of the Taklimakan Desert, Gurbantunggut Desert, Badain Jaran Desert, Tengger Desert and Mongolian Gobi is related to the nearby tectonic uplift (Sun et al., 2007, 2013). Pullen et al. (2011) compared the U-Pb ages of zircon crystals between Loess Plateau strata and potential source areas, and they suggested that the loess was largely derived from the Qaidam Basin and the northern Tibetan Plateau. The C-O isotopes in detrital dolomite suggest that the Badain Jaran Desert and Hexi Corridor contribute more eolian material to the Loess Plateau than to the eastern Tibetan Plateau (Chen and Li, 2011). The $^{234}U/^{238}U$ is a new source tracer in recent studies, and the loess in the Chinese Loess Plateau can be best explained by the mixing of three end-member dust sources on the northwestern transportation trajectory, namely, (1) the Gobi Desert, (2) the Ordos Desert, and (3) the Qilian Mountains (Li et al., 2018). Collectively, these studies show that Chinese loess was ultimately derived from the materials eroded from two tectonic settings: The northern Tibetan Plateau and the Central Asian Orogenic Belt (Chen et al., 2007; Chen and Li, 2011; Zhao et al., 2014).

Previous studies on major element geochemistry in Chinese deserts and the Gobi mostly only focused on a single desert, such as the Taklimakan Desert or Badain Jaran Desert (Yang et al., 2007; Hu and Yang, 2016). A systematic comparison among all deserts is still needed. Before releasing to the atmosphere, fine sand particles, as potential mineral dust, can be affected by the source rock signature, the tectonic memory of the sediments in certain situations, and subsequent physical and chemical weathering processes; these processes include sedimentary recycling, weathering, mineral fractionation, hydraulic sorting, and diagenetic processes (Bauluz et al., 2000). Therefore, systematically comparing the major element geochemistry in desert sediments may help identify the origins of desert dust. This study reports the major element geochemistry in sediments from 12 deserts and compiles published major element data. We investigate the geochemical characteristics of major elements in northern China and the adjacent Gobi in northern China and neighboring Mongolia (hereinafter referred to as Gobi) as potential Asian dust source areas.

## 2. Geologic settings and samples

Deserts (including semi-arid sandy land) in North China and adjacent Mongolia located in the Asian inland are characterized by an extremely dry climate due to the blocking of water vapor by the surrounding plateau and mountains that are distributed in the arid and semi-arid temperate regions. They also showed an arc zone distribution (35°N–50°N, 75°E–125°E). Since the Cenozoic uplift of the Tibet Plateau, a basin-mountain geomorphology pattern has existed in the northern Tibetan Plateau (NTP) (Zhu et al., 1980; Fang et al., 2001; Liu and Qin, 2005; Wang et al., 2011). As a joint result of the topography of the plateau and atmospheric circulation, the drought gradually increases from east to west. Active and stabilized dunes coexist in the Taklimakan Desert, while fixed and semi-fixed sand dunes are generally found in the Badain Jaran and Tengger Deserts, and particularly in the northern areas of the Tengger Desert. Fixed and semi-fixed dunes are also dominant in the Taklimakan Desert due to the block effect of the Tianshan Mountains, which intercept part of the moisture from Siberia. In contrast, sandy lands (including Horqin, Hulun Buir and Onqin Daga sandy lands) in northeast China are semi-arid and consist of various mosaics of wetlands, agricultural areas, and stabilized and/or semi-stabilized and/or active eolian sands. In short, desert areas in western China are primarily located in endorheic basins surrounded by high mountains, while the sandy lands in northeast China are located in semi-closed sedimentary basins bordered by flat steppe terrain and mountainous landscapes. From a tectonic perspective, deserts in North China are strongly related to the tectonic zone and the mountain ranges resulting from continental cracking and collisional orogeny (Xin et al., 2006). The Taklimakan and Kumtag deserts in western China are located on the Tarim Block; meanwhile, the Qaidam Desert in the Qaidam Block may be related to the Yangtze Paleocontinent, which was separated from the Tarim Block due to the formation of the proto-Tethys Ocean. The Badain Jaran and Tengger deserts are located in the Alashan Block; the Hobq and Mu Us Deserts are located in the Ordos Craton. The Helan Mountains are sandwiched by continental margin basins, thus separating the Tengger Desert from both the Hobq and Mu Us Deserts on the Ordos Craton. The Gurbantunggut Desert, Hunlun Buir sandy land, Onqin Daga sandy land, Horqin sandy land and Gobi are located in or near the Central Asian Orogenic Belt (Tianshan Mts.–Daxinganling Mts). The plate collision has helped form a unique basin-mountain framework under the compression-strike-slip structure (Tapponnier and Molnar, 1976).

Samples of surface sand (within the upper 30 cm) were collected from the 12 major Chinese deserts and sandy lands as potential sources for eolian dust. Samples in the Mongolian Gobi Desert were taken systematically from dried riverbeds or hydrocephalus depressions within Gobi/sandy deserts by scratching off 1–2 cm of thick clay mud crust (Sun et al., 2013) (Figure 1). The oxides of the major elements of sample powders (<200 mesh in an agate mill) were determined using a Thermo Scientific ARL 9900 X-ray fluorescence spectrometer (XRF). Prior to the XRF analysis, powdered samples were heated to 110°C for 6 h, followed by heating in a muffle furnace at a temperature of 815°C for 2 h to determine LOI (loss on ignition). A flat glass disk was prepared from the melt. Sample powders were melted in a furnace at more than 1000°C after mixing with lithium borate or a lithium metaborate flux in proper proportions. The disk was then analyzed by XRF for the oxides of major elements, including $SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$, MgO, CaO, MnO, $Na_2O$, $K_2O$, and $P_2O_5$. According to the measured values of standards (GSR-1 and GSR-3), the relative standard deviation is approximately ±1% for elements with concentrations >1.0 wt% and approximately ±10% for the elements with concentrations <1.0 wt%. The reproducibility of the measurements is less than 2% for Si, Ti, Al, Fe, Mg, K, Na and Ca, and less than 5% for Mn and P.

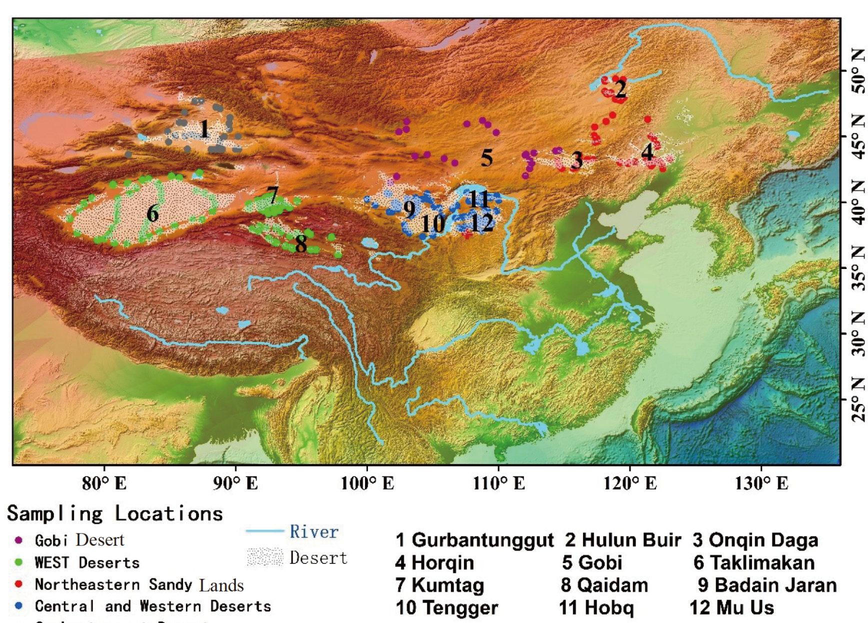


**Figure 1** Map of the sampling locations.

## 3. Results

### 3.1 Major elemental characteristics from sediments in Chinese deserts and the Gobi Desert

Table 1 reports the weight percentages of major elements of the bulk samples in Chinese deserts, which are consistent with previous studies (Table 2) (Hu and Yang, 2016; Liu et al., 1993; Liu B et al., 2016; Maher et al., 2009; Wang et al., 2012; Yang et al., 2007; Ren et al., 2014). We summarize the space distribution characteristics of the major-elemental content within bulk sand samples: (1) $SiO_2$ is the most abundant major element in all deserts and is highly variable within one desert. $SiO_2$ is generally lower in the West and higher in the East. Comparatively, the average $SiO_2$ levels in the Taklimakan, Qaidam and Gurbantunggut deserts in the West are lowest among all deserts (<70%), close to that of the upper crust (UCC) (Figure 2). In contrast, the $SiO_2$ content is relatively higher in Hulun Buir, Onqin Daga and Horqin sandy lands in Northeast China, with an average $SiO_2$ of 85%. (2) The CaO also greatly varies spatially and is generally higher in the West and lower in the East. The average CaO in the Taklimakan and Qaidam Deserts is more than 8%, while the average CaO in the Hulun Buir and Onqin Daga sand samples is less than 1%. (3) The $SiO_2$ in bulk sand samples is significantly higher than UCC, while other elements, including $Al_2O_3$, $TiO_2$, $Fe_2O_3$, $Na_2O$, MgO, $P_2O_5$ and MnO are mostly depleted relative to UCC. (4) The Taklimakkan, Qaidam and Kumtag deserts are enriched in CaO, while the Gobi Desert is enriched in MnO, MgO, CaO, $K_2O$ and $P_2O_5$. In contrast, $P_2O_5$ is more enriched in the Tengger and Gobi Deserts (Figure 2). (5) We also observe grain size effects in major elements (<28 μm, 28–75 μm, >75 μm). In coarse grain sizes, $SiO_2$ increases, while $Al_2O_3$, $Fe_2O_3$, MgO, CaO, $TiO_2$ and LOI decrease (Appendix Figure S1, http://earth.scichina.com).

### 3.2 The major elemental characteristics of regional geochemistry in Chinese deserts

Based on the geographical distribution and major elemental geochemical signatures for bulk samples, we identify four regions in Chinese deserts (Figures 2–4):

(1) WEST Deserts, including the Taklimakan, Kumtag (Xu et al., 2011) and Qaidam Deserts. They are located in the Tarim Block and the Qaidam Block in the NTP and are characterized by low $SiO_2$ (55–81.3%), high CaO (1.5–27.6%), and high $Al_2O_3$, $Fe_2O_3$, MnO, MgO and $Na_2O$ (Tables 1 and 2).

(2) Central and Western Deserts, including the Badain Jaran and Tengger Deserts. They are located to the east of the Mu Us and Hobq Deserts on the west side of the Helan Mountain. They are mainly characterized by moderate contents of both $SiO_2$ (56.4–82.8%) and CaO (0.6–3.3%).

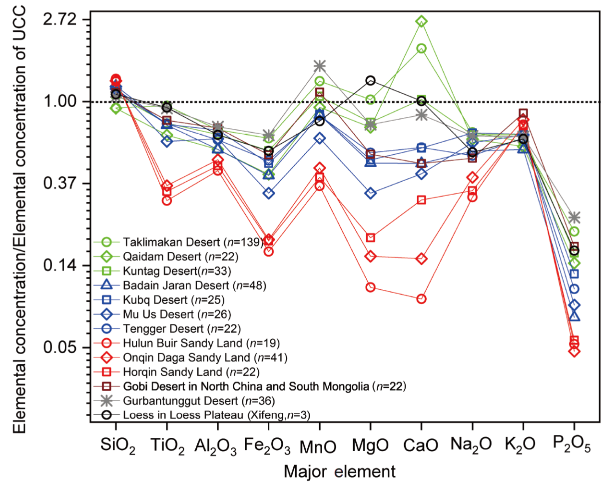


**Figure 2** Elemental ratios of desert sediments in China and Mongolia.

Comparatively, $Al_2O_3$, $Fe_2O_3$, MgO, MnO, $TiO_2$, $Na_2O$, $P_2O_5$ and other oxide contents in Central and Western Deserts fall within the range between the WEST Deserts and Chinese Northeastern Sandy Lands (Table 1; Figure 3).

(3) Northeastern Sandy Land, including Hulun Buir, Horqin and Onqin Daga sandy lands in northeast China (Liu and Yang, 2013). They are characterized by high $SiO_2$ and low CaO, while the average $Al_2O_3$, $Fe_2O_3$, MgO, MnO, $TiO_2$, $Na_2O$ and $P_2O_5$ are lower than those in the WEST Deserts and the Central and Western Deserts, except for the relatively higher content of $K_2O$ (2.17–3.49%) (Table 1; Figure 3).

(4) Gobi and Gurbantunggut Deserts, including the Gobi Desert in north China and the south of Mongolia. They show similar major element geochemistry with the Central and Western Deserts, with moderate average $SiO_2$ and high average $P_2O_5$ and $K_2O$ (Table 1; Figure 3). The Gurbantunggut Desert is surrounded by mountains such as Tianshan and Altai and is located in the Junggar Basin. However, structurally, it belongs to the Central Asian Orogeny Belt, and their contents of major elements are close to those in the Gobi.

## 4. Discussion

### 4.1 Distribution pattern of the major elements in Chinese desert

The results displayed in Table 1 clearly demonstrate that the major elements in desert sediments show a wide spatial variation. The enrichment of one element is often accompanied by the relative depletion of other elements. Therefore, analyzing the correlation among different elements is necessary, considering that the major elements are controlled by the dominant minerals in the desert (He T, MLA analysis results, unpublished data).

**Table 1** Major element contents of deserts

| Desert | | $n$ | | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEST Desert | | | Max | 72.5 | 0.98 | 14.2 | 5.27 | 0.111 | 2.98 | 17.27 | 3.54 | 2.82 | 0.151 |
| | Taklimakan | 37 | Avg | 64.9 | 0.52 | 10.6 | 2.96 | 0.067 | 2.04 | 7.69 | 2.38 | 2.09 | 0.103 |
| | | | Min | 50.2 | 0.14 | 7.2 | 2.01 | 0.039 | 1.46 | 2.70 | 1.40 | 1.67 | 0.058 |
| | | | Max | 78.0 | 0.71 | 11.3 | 3.78 | 0.070 | 3.06 | 29.20 | 5.68 | 2.88 | 0.140 |
| | Qaidam | 22 | Avg | 60.7 | 0.33 | 8.5 | 2.06 | 0.047 | 1.60 | 11.18 | 2.46 | 1.96 | 0.070 |
| | | | Min | 30.4 | 0.14 | 5.4 | 1.17 | 0.030 | 0.52 | 3.54 | 1.50 | 1.06 | 0.035 |
| Central and Western Desert | | | Max | 87.0 | 0.49 | 10.6 | 3.46 | 0.070 | 1.92 | 3.98 | 2.93 | 2.29 | 0.080 |
| | Badain Jaran | 23 | Avg | 79.9 | 0.30 | 8.5 | 2.10 | 0.039 | 1.04 | 1.83 | 2.08 | 1.89 | 0.047 |
| | | | Min | 72.7 | 0.10 | 5.8 | 0.94 | 0.020 | 0.40 | 0.90 | 1.40 | 1.37 | 0.020 |
| | | | Max | 83.6 | 0.57 | 13.3 | 4.53 | 0.077 | 2.82 | 7.96 | 3.53 | 3.02 | 0.147 |
| | Hobq | 26 | Avg | 77.9 | 0.30 | 10.2 | 1.86 | 0.034 | 0.73 | 1.95 | 2.47 | 2.32 | 0.048 |
| | | | Min | 56.4 | 0.14 | 7.3 | 1.01 | 0.020 | 0.35 | 0.88 | 1.58 | 1.77 | 0.024 |
| | | | Max | 84.7 | 0.67 | 13.0 | 2.42 | 0.070 | 1.24 | 5.40 | 3.56 | 3.07 | 0.082 |
| | Mu Us | 30 | Avg | 77.8 | 0.30 | 10.4 | 1.64 | 0.033 | 0.65 | 1.88 | 2.68 | 2.41 | 0.044 |
| | | | Min | 69.6 | 0.13 | 6.2 | 0.90 | 0.019 | 0.32 | 0.60 | 1.38 | 1.68 | 0.018 |
| | | | Max | 81.6 | 0.49 | 12.1 | 3.21 | 0.065 | 1.69 | 4.56 | 3.54 | 3.14 | 0.060 |
| | Tengger | 23 | Avg | 77.3 | 0.35 | 9.5 | 2.31 | 0.041 | 1.11 | 2.15 | 2.11 | 2.38 | 0.044 |
| | | | Min | 71.0 | 0.26 | 8.1 | 1.78 | 0.027 | 0.70 | 0.73 | 1.39 | 1.86 | 0.030 |
| Northeastern Sandy Lands | | | Max | 91.8 | 0.34 | 9.3 | 1.77 | 0.038 | 0.45 | 1.79 | 1.91 | 3.46 | 0.061 |
| | Hulun Buir | 23 | Avg | 87.9 | 0.13 | 6.0 | 0.64 | 0.015 | 0.18 | 0.41 | 1.17 | 2.46 | 0.021 |
| | | | Min | 79.9 | 0.04 | 3.9 | 0.30 | 0.007 | 0.07 | 0.17 | 0.75 | 1.84 | 0.000 |
| | | | Max | 90.9 | 0.30 | 9.3 | 1.97 | 0.040 | 1.02 | 2.58 | 2.04 | 3.49 | 0.047 |
| | Onqin Dga | 26 | Avg | 85.4 | 0.16 | 7.3 | 0.82 | 0.020 | 0.27 | 0.53 | 1.50 | 2.76 | 0.021 |
| | | | Min | 79.9 | 0.06 | 4.6 | 0.35 | 0.010 | 0.06 | 0.16 | 0.81 | 1.92 | –0.004 |
| | | | Max | 94.3 | 0.51 | 11.6 | 2.37 | 0.051 | 1.72 | 7.99 | 2.58 | 3.25 | 0.072 |
| | Horqin | 21 | Avg | 84.8 | 0.16 | 6.9 | 0.89 | 0.019 | 0.40 | 1.22 | 1.30 | 2.53 | 0.026 |
| | | | Min | 66.2 | 0.04 | 2.6 | 0.34 | 0.003 | 0.12 | 0.06 | 0.47 | 1.21 | –0.005 |
| Gobi and Gurbantunggut Desert | | | Max | 83.5 | 0.71 | 16.5 | 6.29 | 0.115 | 3.17 | 5.98 | 3.23 | 5.06 | 0.203 |
| | Gobi in North China and Mongolia | 19 | Avg | 71.7 | 0.42 | 11.6 | 2.89 | 0.062 | 1.27 | 2.15 | 2.00 | 3.08 | 0.095 |
| | | | Min | 52.8 | 0.18 | 7.9 | 0.95 | 0.020 | 0.22 | 0.35 | 1.09 | 2.36 | 0.020 |
| | | | Max | 94.3 | 0.79 | 16.5 | 8.54 | 0.180 | 3.97 | 11.35 | 5.63 | 3.36 | 0.300 |
| | Gurbantunggut | 36 | Avg | 69.7 | 0.46 | 11.2 | 3.31 | 0.077 | 1.66 | 3.57 | 2.56 | 2.22 | 0.122 |
| | | | Min | 47.7 | 0.04 | 2.4 | 0.38 | 0.023 | 0.17 | 0.22 | 0.24 | 0.89 | 0.010 |

(1) Si and Al are the two most important elements with the highest content. We find a significant negative correlation between $SiO_2$ and $Al_2O_3$ ($R^2$=0.63, $n$=420), with the highest correlation in Northeastern Sandy Lands (up to 0.90, $n$=44), followed by Gobi, Taklimakan, Kumtag and Qaidam deserts in the WEST Deserts. High concentrations of $SiO_2$ in desert samples imply that quartz and feldspar are the most abundant minerals. The high $Al_2O_3$ mainly comes from aluminosilicate minerals, such as feldspar, mica and clay minerals. The significant negative correlation between $SiO_2$ and $Al_2O_3$ reflects that the quartz dilution can strongly affect the chemical compositions of the desert sediments (Figure 3a). The WEST Deserts contain high contents of carbonate minerals (Li et al., 2007), resulting in the weaker correlation coefficient between $SiO_2$ and $Al_2O_3$.

(2) $K_2O$ is significantly positively correlated to $Al_2O_3$. The Northeastern Sandy Lands and part of the Gobi Desert show a correlation coefficient of 0.68 ($n$=44), while the WEST Deserts and Central and Western Deserts show a correlation coefficient of 0.66 ($n$=376). These deserts show similar correlations; however, $K_2O$ in the Northeastern Sandy Lands and part of the Gobi Desert samples is significantly higher than in other deserts, thereby indicating more K-bearing silicate minerals and K-metasomatism in their silicate minerals. $Na_2O$ is also significantly correlated to $Al_2O_3$ (Figure 3b); however, they are not as easily distinguished as $K_2O$ and

**Table 2** Statistical table of the major element contents of deserts in the literature[a)]

| Desert | | | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEST Desert | Taklimakan | Max | 74.3 | 1.05 | 15.7 | 7.21 | 0.126 | 4.05 | 12.10 | 3.60 | 3.26 | 0.180 |
| | | Avg | 64.2 | 0.45 | 10.8 | 3.08 | 0.061 | 2.15 | 7.15 | 2.56 | 2.15 | 0.100 |
| | | Min | 51.7 | 0.22 | 9.6 | 1.69 | 0.029 | 1.07 | 2.30 | 2.17 | 1.56 | 0.052 |
| | Kumtag | Max | 81.3 | 0.66 | 14.0 | 5.63 | 0.084 | 3.63 | 9.39 | 3.09 | 3.43 | 0.151 |
| | | Avg | 71.7 | 0.38 | 10.2 | 2.75 | 0.053 | 1.71 | 4.31 | 2.59 | 2.27 | 0.079 |
| | | Min | 55.3 | 0.20 | 8.1 | 1.52 | 0.031 | 0.55 | 1.45 | 1.36 | 1.66 | 0.051 |
| Central and Western Desert | Badaim Jaran | Max | 85.2 | 1.00 | 14.0 | 6.10 | 0.085 | 4.10 | 7.39 | 3.65 | 2.68 | 0.057 |
| | | Avg | 74.1 | 0.46 | 9.8 | 2.77 | 0.046 | 1.42 | 2.59 | 2.39 | 2.09 | 0.023 |
| | | Min | 54.4 | 0.22 | 6.2 | 0.97 | 0.031 | 0.41 | 1.02 | 1.58 | 1.64 | 0.007 |
| | Mu Us | Max | 82.8 | 0.39 | 12.4 | 2.19 | 0.041 | 1.12 | 3.24 | 3.44 | 2.69 | 0.082 |
| | | Avg | 79.1 | 0.31 | 9.7 | 1.64 | 0.032 | 0.72 | 1.74 | 2.36 | 2.26 | 0.042 |
| | | Min | 75.3 | 0.18 | 7.6 | 0.90 | 0.019 | 0.41 | 0.60 | 1.54 | 1.68 | 0.018 |
| Northeastern Sandy Lands | Onqin Daga | Max | 90.7 | 1.38 | 10.6 | 3.42 | 0.100 | 0.56 | 1.49 | 2.69 | 3.64 | 0.050 |
| | | Avg | 85.2 | 0.35 | 7.7 | 1.20 | 0.029 | 0.31 | 0.64 | 1.81 | 2.73 | 0.027 |
| | | Min | 77.8 | 0.08 | 4.9 | 0.45 | 0.010 | 0.17 | 0.24 | 1.18 | 1.86 | 0.020 |
| Gobi and Gurbantunggut Deserts | Mongolian Gobi | Max | 61.2 | 1.20 | 16.3 | 8.50 | 0.180 | 16.48 | 18.67 | 1.82 | 3.48 | 0.420 |
| | | Avg | 56.2 | 0.92 | 14.5 | 6.80 | 0.132 | 4.57 | 5.66 | 1.37 | 2.79 | 0.253 |
| | | Min | 47.1 | 0.56 | 9.4 | 3.61 | 0.050 | 3.20 | 1.95 | 0.88 | 1.77 | 0.050 |

a) Taklimakan: Honda and Shimizu (1998), Yang et al. (2007), Zhu and Yang (2009); Kumtag: Xu et al. (2011); Badaim Jaran: Hu and Yang (2016); Mu Us: Liu B et al. (2016); Onqin Daga: Liu and Yang (2013); Mongolian Gobi: Maher et al. (2009).

$Al_2O_3$ (Figure 3b). This is probably because Na mainly exists in Na-plagioclases and K is mostly found in K-feldspar, muscovite and illite (Jeong et al., 2008), and these minerals often co-existed in the desert sediments. Therefore, the significant correlation between Na, K and Al most likely reflects that the change in minerals is synchronous. The $Fe_2O_3$ and $Al_2O_3$ contents also showed a significant positive correlation, indicating that iron in iron oxides, Fe-bearing silicates (Lu et al., 2017), mafic/ultramafic detritus and Fe in ferromagnesia silicate minerals may change synchronously during desert sedimentary evolution. The $Fe_2O_3$ content is relatively higher in the WEST Deserts but lower in the Northeastern Sandy Lands (Figure 3g).

(3) CaO and MgO are dominant in silicate and carbonate minerals. Ca mainly exists in plagioclase and apatite, while Mg mainly exists in chlorite and shows lower contents in silicate minerals such as amphibole, pyroxene and biotite. Both Ca and Mg are generally found in carbonate minerals such as dolomite and calcite. CaO is positively correlated with MgO in the WEST Deserts and the Central and Western Deserts. The correlation between CaO and $Al_2O_3$ is weak, and the CaO content in some samples is as high as 15%, which is consistent with higher dolomite and/or calcite concentrations in the WEST deserts. The CaO and MgO contents in the Northeastern Sandy Lands are lower than those in the Central and Western Deserts. The positive relationships between CaO and $Al_2O_3$ further indicate that Ca in the Northeastern Sandy Lands is mainly controlled by silicate minerals (Figure 3f).

(4) The $Fe_2O_3$ content of all samples shows a significant positive correlation with MnO and $TiO_2$ (Figure 3h and 3i) ($R^2$=0.91 for MnO; $R^2$=0.93 for $TiO_2$). The results indicate that Fe, Mn and Ti in the desert sediments do not produce an obvious decoupling in the subsequent geological process, which is probably because Mn and Ti can substitute Fe in minerals related to isomorphism.

(5) A significant positive correlation is observed between the MgO and $Fe_2O_3$ contents (Figure 3d), particularly in the Northeastern Sandy Lands and the Central and Western Deserts, thereby indicating that Fe and Mg mainly exist in ferromagnesite silicates and cannot be easily decoupled in the geological processes (Liu et al., 2001). The MgO is high in the WEST Deserts and deviates significantly from the correlation line of MgO and $Fe_2O_3$, thus indicating that the high Mg content is more likely to be derived from carbonate minerals, especially Mg-rich dolomite (Li et al., 2007). The positive correlation between MgO and CaO in the WEST Deserts also reflects that the high content of carbonate minerals is the main source of MgO and CaO in these deserts (Figure 3f) (Li et al., 2007).

### 4.2 Major elemental provenance in Chinese and Gobi deserts

We identify four main categories of major elements with significant mineral differences, namely, $SiO_2$ related to the

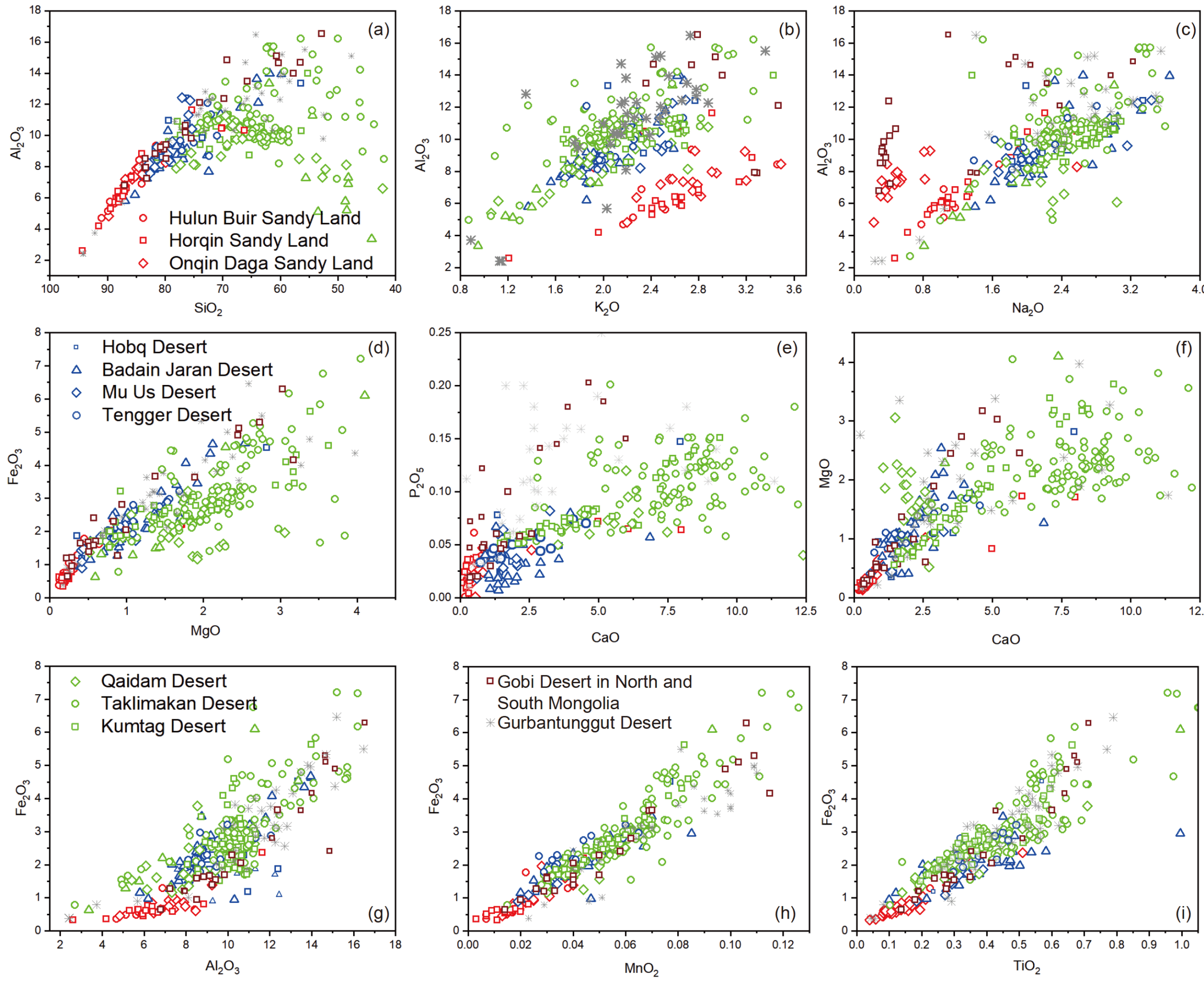


**Figure 3** Cross-plots of the major elements of desert sediments in China and Mongolia.

change in quartz; CaO change reflecting the carbonate minerals; Fe, Ti and Mn controlled by ferromagnesite silicates and heavy minerals; $K_2O$ and $Na_2O$ indicating the change in the main K-bearing minerals (K-feldspar, muscovite and illite) and Na-plagioclases. In addition, changes in MgO are related to the carbonates and ferro-magnesium silicates. To eliminate the effect of carbonate dilution, a proxy is required to indicate the changes in elements in silicates.

The $SiO_2/Al_2O_3$ ratio may indicate the relative change in quartz/silicates. Its average value is 8.31 in all samples ($n$=420). The ratio ranking from lowest to highest is WEST Deserts with an average value of 6.43 ($n$=194), the Gobi Desert (7.40, $n$=37), the Central and Western Deserts (8.33, $n$=124), Gurbantunggut Desert (8.38, $N$=36) and the Northeastern Sandy Lands (13.52, $n$=44). The quartz contents in the WEST Deserts are lower than those in the eastern deserts.

The content of carbonates/silicates can be reflected by the $CaO/Al_2O_3$ ratio, with an average value of 0.41 in all samples ($n$=420). The sequence of the $CaO/Al_2O_3$ ratio from lowest to highest is the Northeastern Sandy Lands (0.11, $n$=44), Gobi (0.16, $n$=37), the Central and the Western Deserts (0.22, $n$=124), the Gurbantunggut Desert (0.31, $n$=36) and the WEST Deserts (0.76, $n$=194). In short, the ferromagnesite silicates and carbonate minerals in the western deserts show higher contents than those in the eastern sandy lands.

$Na_2O/Al_2O_3$ and $K_2O/Al_2O_3$ may reflect the relative contents of plagioclase and K-bearing minerals (K-feldspar, muscovite and clay minerals) in silicate minerals, respectively. The average values of $K_2O/Al_2O_3$ and $Na_2O/Al_2O_3$ in Chinese desert are 0.25 ($n$=420) and 0.23 ($n$=420), respectively. For each desert, the $Na_2O/Al_2O_3$ in the Gobi is 0.14 ($n$=37), the Northeastern Sandy Lands is 0.20 ($n$=44), the Gurbantunggut Desert is 0.23 ($n$=36), the Central and the Western Deserts is 0.23 ($n$=124), and the WEST Deserts is 0.21 ($n$=194). The average $K_2O/Al_2O_3$ value in the Northeastern Sandy Lands is 0.39 ($n$=44), the Gobi is 0.23 ($n$=37), the Central and Western Deserts is 0.23 ($n$=124), and the WEST Deserts is 0.21 ($n$=194). The K-feldspar content in the

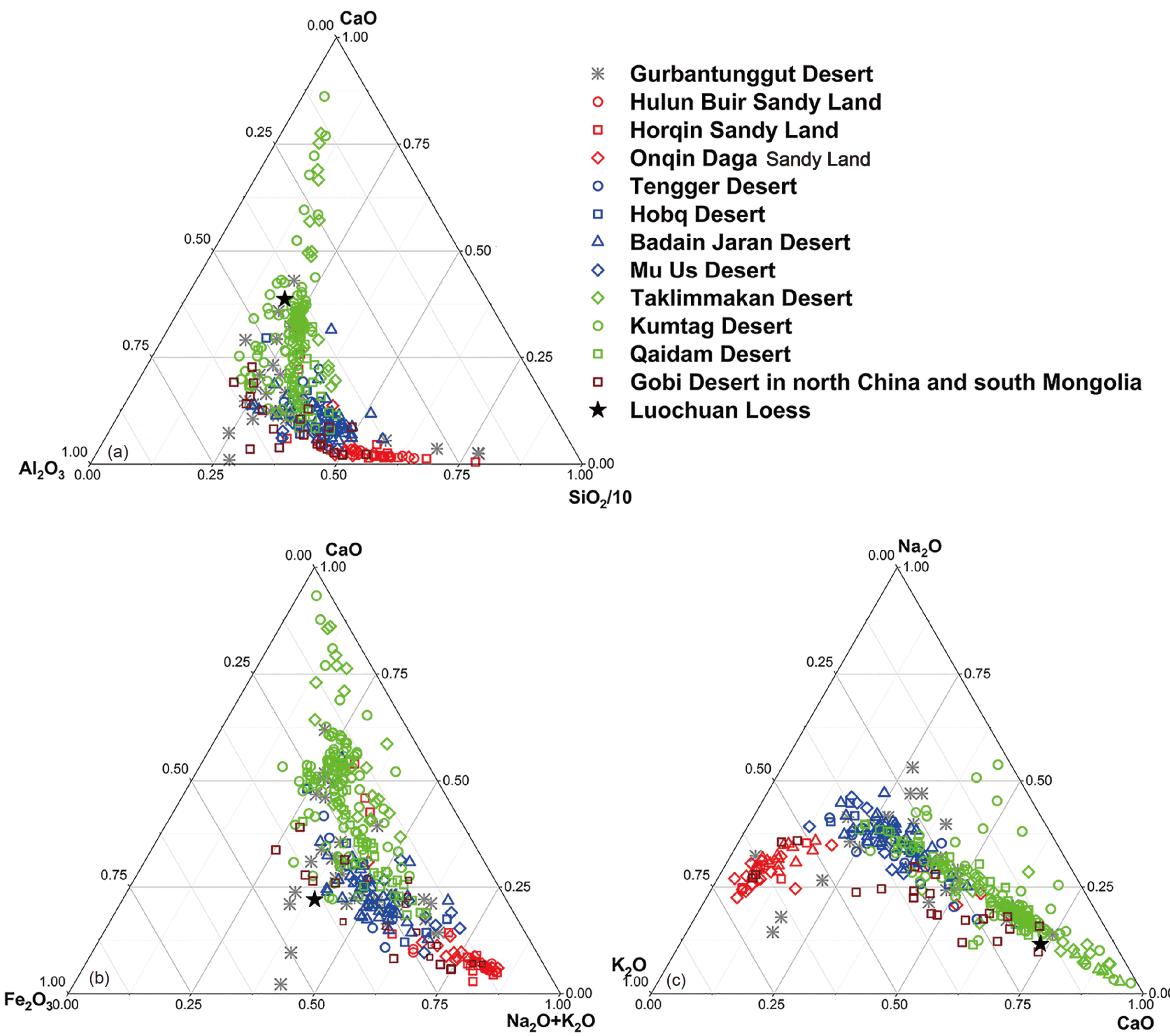


**Figure 4** Ternary diagram of the major elements in China and Mongolia. (a) $SiO_2$/10-CaO-$Al_2O_3$; (b) ($Na_2O$+$K_2O$)-CaO-$Fe_2O_3$; (c) CaO-$Na_2O$-$K_2O$.

eastern sandy lands is higher than that in the western deserts, and the albite and/or Na-plagioclases in the western deserts is higher than the eastern sandy lands (He et al., 2016).

We use the ternary diagrams ($SiO_2$/10-CaO-$Al_2O_3$, ($K_2O$+$Na_2O$)-CaO-$Fe_2O_3$ and CaO-$Na_2O$-$K_2O$) to distinguish the origins of desert sediments (Figure 4c). $SiO_2$/10-CaO-$Al_2O_3$ is used to indicate the relative content of quartz-carbonate-silicate minerals; ($K_2O$+$Na_2O$)-CaO-$Fe_2O_3$ is indicative of the relative content of feldspar-carbonate-ferromagnesian silicates; and CaO-$K_2O$-$Na_2O$ reflects the relative change of (carbonate+plagioclase)-K-bearing feldspar-albite/Na-plagioclases. In Figure 4a, the WEST Desert is characterized by significantly higher carbonate minerals, and lower quartz and silicate minerals; while the Northeastern Sandy Lands show significantly higher quartz minerals. In Figure 4b, the WEST Desert is characterized by higher carbonate minerals, lower quartz and moderate amounts of silicate minerals; while the Northeastern Sandy Lands are characterized by higher quartz minerals. Moreover, higher content of K-feldspar and/or muscovite are found in Gobi Desert sediments and part of the Northeastern Sandy Lands (Figure 4c).

### 4.3 Controlling factors on major elemental contents in Chinese deserts

The major elements in Chinese desert sediments are controlled by multiple factors, such as surface morphology, source rocks, and clastic mineral composition, which are ultimately controlled by the geologic tectonic setting. Deserts with similar tectonic settings and regional geological backgrounds may have indistinguishable source rocks and therefore indistinguishable major element geochemistry.

The primary factor for the variability of major elements is the composition of parent rocks in the source area. The CaO and $K_2O$ contents may reflect the differences in mineral sources (Figures 2 and 3). Higher CaO in the WEST Deserts, especially in the Qaidam and Taklimakan deserts, is linked to their carbonate-rich minerals (Li et al., 2007). It is possible that physical weathering produces finer carbonate mineral particles, which are then preferably transported downwind, resulting in increased carbonate minerals in the central deserts. However, the weak correlation between Ca and Al may reject this hypothesis (Figure 3e). Chemical weathering may result in the leaching of carbonate minerals; however, the extremely low rainfall in deserts indicates that dissolved Ca ions would not be removed without the outflow river in WEST Deserts. Therefore, the dissolution and re-precipitation of carbonates are unlikely to have a major effect on the CaO content. The Chinese Loess Plateau has a higher average annual precipitation than WEST Deserts and contains large amounts of carbonate minerals (Meng et al., 2015). Substantial findings have suggested the proximity of most desert sources in China (Zhu et al., 1980; Chen and Li, 2011; Fu and Wang, 2015; Hu and Yang, 2016), that is, the desert sediments likely originated from surrounding mountains. The regional geochemical map (Xie, 2012) has shown that the marine sedimentary carbonate rocks are widely distributed in the Kunlun Mountains and have provided substantial carbonate minerals to the Taklimakan and Qaidam deserts through river transportation, thereby leading to higher CaO in these two deserts. Carbonate rocks are also found in the northern part of the Kumtag Desert, the Tianshan and Altai Mountains around the Gurbantunggut Desert (Xie, 2012), the northern margin of the Qilian Mountains, the Alashan Mountains and the southern part of the Helan Mountains around the Badain Jaran Desert, Tengger Desert, Hubq Desert and Mu Us Desert. However, with a much smaller total scale than the Kunlun Mountains, particularly in the Ordos region (Li et al., 2007; Chen and Li, 2011; Xie, 2012), the average CaO is lower in these deserts. A lack of carbonate strata around the Hulun Buir, Horqin and Onqin Dag sandy lands explains their low CaO content. Two distant regions related to the source of K can be identified in Figure 2b. The $K_2O$ in the Northeastern Sandy Lands is relatively high, which may be related to the presence of K-rich granite (Liu J Q et al., 2016), K-rich basalt and monzonitic granite in the northeastern region. A portion of samples on the continuous vast Gobi Desert in China and Mongolia also show higher $K_2O$, probably due to their close proximity to the Northeastern Sandy Lands.

These distinct spatial characteristics of the major elements, and specifically the CaO, are consistent with those of the calcite/quartz and dolomite/quartz (Li et al., 2007). Our major elements data indicate that carbonate minerals in desert sediments are closely controlled by the geological background and the distribution of carbonate strata in the denudation area. This finding is further supported by the $\delta^{18}O_{quartz}$ of desert sediments, which depends on the bedrock type of the mountains around deserts (Fu et al., 2004, 2015). In view of the tectonic setting, the regional distribution characteristics of the major element geochemistry are consistent with the Sr-Nd and Nd-Hf isotopic studies (Chen et al., 2007; Zhao et al., 2014); these all suggest that differences in major elemental geochemistry from west to east are caused entirely by the heterogeneity of materials at their source.

The second controlling factor of major elements is the mineral maturity resulting from the supply of fresh materials. We first discuss the weathering processes, including denudation, weathering, transportation and deposition. In the chemical weathering processes, carbonate minerals are dissolved and re-precipitated under certain conditions; feldspar and ferriomagnesia silicate minerals gradually transform into secondary clay minerals. These weathering products are then transported in the forms of suspended particles and secondary minerals. The silicate minerals (e.g., quartz and feldspar) are more resistant to chemical weathering, thereby becoming relatively enriched in coarse-fractions. In the physical weathering processes, minerals including carbonate, ferromagnesia silicate and plagioclase are less resistant to physical weathering; therefore, they experience fragmentation and become enriched in suspension materials. The transportation process further moves the solution and/or suspension to a remote area, such as the ocean, while coarser sand material is deposited in the sedimentary basin; however, some studies suggested that the quartz/feldspar ratio does not vary with their transported distance (Nesbitt and Young, 1996; Potter et al., 2001).

These findings combined with the chemical and physical weathering processes may help explain the spatial differences in the major element geochemistry in Chinese deserts. First, the Chinese deserts are supplied with different weathering products and undergo distinct degrees of chemical and physical weathering processes. The chemical weathering is relatively weaker in arid and semiarid regions in the WEST Deserts, such as the Taklimakan Desert. These deserts are surrounded by the Tianshan, Pamir, Kunlun and Altun Mountains with large river drops, little vegetation, and a large ice and snow cover on the mountain top (due to more developed glaciers during the Quaternary glacial period). Furthermore, the physical weathering is relatively stronger in these areas, which facilitated the accumulation of more than 500 meters of sediments in the Tarim Basin since the Quaternary. Today, the Tarim River and other rivers continue to provide much material to the desert. On the other hand, in the Northeastern Sandy Lands, the source areas (such as the Daxing'an Mountains and the Xiliao River) have larger vegetation coverage. The relatively weaker physical weathering and stronger chemical weathering, as well as grassland degradation, result in a smaller material supply to the sandy lands. The degree of physical and chemical weathering is moderate in the Central and Western Deserts, receiving huge alluvial and lacustrine sediments originated from the Qilian Mountains. Second, the transportation processes may also help explain the major element differences. The transportation in the WEST Desert is dominated by the interior rivers, which contain suspended and dissolved materials and enter the desert interior region, leaving poorly sorted materials. The transportation in the Eastern Sandy Land is dominated by interior and exterior rivers, which ultimately enter the ocean, leaving better-sorted sand particles. Last, in view of the weathering mode after the formation of the deserts, the WEST Deserts are dominated by mobile dunes with stronger physical erosion and weaker chemical weathering, while the eastern deserts are dominated by stabilized sand dunes with weaker physical and stronger chemical weathering.

Mineral maturity is defined as a compositional state of a clastic sedimentary body, wherein a dominance of quartz and an absence or a minority of less-resistant particles such as feldspars, detrital carbonates or lithic fragments (Ruxton, 1968; Blatt et al., 1972; Pettijohn et al., 1972) indicates a lower mineral maturity. The maturity can be represented by $SiO_2$-($Al_2O_3$+$K_2O$+$Na_2O$) (Muhs, 2004) (Figure 5a) or $SiO_2$-($Al_2O_3$+$K_2O$+$Na_2O$+CaO+MgO) (Figure 5b). The western Taklimakan, Qaidam and Kumtag Deserts show a lower mineral maturity with a lower $SiO_2$/($Al_2O_3$+$K_2O$+$Na_2O$) ratio (4.21, $n$=194) (Figure 4c). This is probably related to the enhanced erosion/weathering in these areas due to the uplift of the Tibetan Plateau and local climate change. The sufficient mineral supply contains lower $SiO_2$ and higher Fe, Mg, and P. The $SiO_2$/($Al_2O_3$+$K_2O$+$Na_2O$) in the Gurbantunggut Desert is 4.17, which is close to those in the WEST Deserts and is probably related to the fresh materials from the Tianshan and Altay Mountains.

The $SiO_2$/($Al_2O_3$+$K_2O$+$Na_2O$) is as high as 8.26 in the Hulun Buir, Horqin and Onqin Daga sandy lands, which may be associated with the flat terrain and a lack of fresh weathering materials. The Badain Jaran Desert, the Tengger Desert, the Kubq and the Mu Us Desert are located on the east and west sides of Helan Mountain. The weathering materials from the surrounding Qilian Mountain and Helan Mountain are limited and cannot be adequately supplied to these deserts, resulting in a moderate ratio of $SiO_2$/($Al_2O_3$+$K_2O$+$Na_2O$ (5.89). In general, the $SiO_2$/($Al_2O_3$+$K_2O$+$Na_2O$) in Chinese deserts has shown an increasing trend from west to east (Figure 5c). The degree of mineral maturity is ultimately controlled by the level of inheritance from the source bedrock from surrounding terrain through weathering processes, even though the chemical weathering process is weak. To summarize, the spatial differences in the major elemental geochemistry in Chinese deserts are controlled interactively by the uplift of the plateau, Asian inland aridification and Asian monsoon climate, which shows a comprehensive reflection of the long-term denudation and weathering of its source rocks.

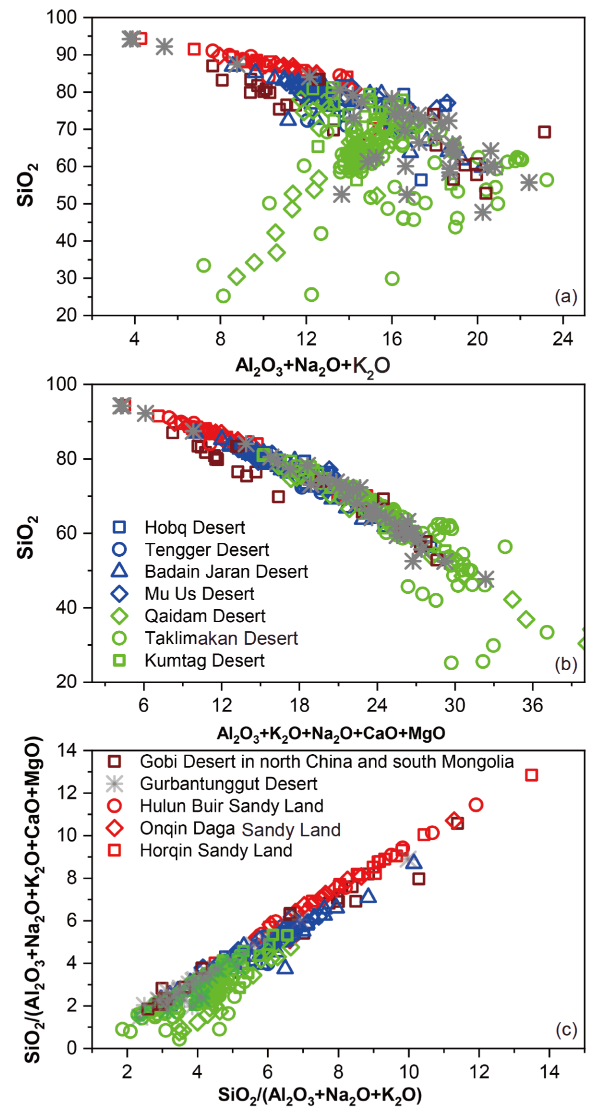


**Figure 5** Chematic diagram of quartz relative to carbonate, feldspar and detritus represented by the major elements of desert sediments.

## 4.4 Implications for the Chinese loess source

The silt fraction is deflated and emitted by atmospheric circulation from deserts and/or sandy lands in the interior of Asia, and the vast continuous Gobi in China and Mongolia, to the east or southeast China and even remote oceans. The silt material accumulates in the downwind direction, forming extensive and thick loess deposits on the Loess Plateau, which is one of the world's largest loess deposits. Surface materials, transported from northwestern deserts to the Loess Plateau, are mixed by fluvial processes, wind erosion and other mechanical handling into different size fractions. The major elemental composition in loess can therefore represent the average composition of materials in a large area. For example, heavy minerals, such as quartz and feldspar, are more resistant to mechanical crushing and chemical weathering, making their movement by wind transportation difficult. Meanwhile, the lighter silty material is preferentially transported and deposited downwind. Although loess inherits the composition characteristics of desert sediments, it nonetheless differs from the desert compositions. For example, the $SiO_2/(Al_2O_3+K_2O+Na_2O)$ ratio of loess ranges from 2.10 to 4.06 (Chen et al., 2001; Xiong et al., 2010), which is lower than those of the Taklimakan Desert. This suggests that mineral sorting during the transportation may leave quartz and other heavier minerals in the desert, which is consistent with higher magnetic susceptibility in the desert than in the loess (Maher et al., 2009). The wind strength and the distance from the source area (Liu, 1985; Peng and Guo, 2001) may also affect the loess deposits. The particle sizes in loess vary temporally and spatially. A strengthened winter wind and a location closer to the source area can lead to a larger size in the dust particles. Some studies have suggested that the chemical compositions in loess can be affected by the particle sizes (Liu, 1985). That is, higher Si and Na elements are often found in coarser grains, while high Fe, Al, K and Mg are often associated with the loess with smaller particle sizes. The chemical weathering after deposition further changes the major element geochemistry in loess. A strengthened East Asian summer monsoon brings abundant rainfall at the southeast region in the Chinese Loess Plateau and introduces strong pedogenesis and eluviation. As a result, Ca, Na, Mg and other elements become depleted due to the leaching processes (Chen et al., 2001). These factors interact with each other, making it difficult to trace loess sources with major element geochemistry. However, the potential relationship between deserts and loess may still be found from the distribution characteristics of Ca-rich carbonates and Al-, K- and Fe-rich silicate minerals.

Carbonate minerals are enriched in the loess from the Chinese Loess Plateau (Liu, 1985) with a distinct spatial and temporal variation (Meng et al., 2015). They are more easily dissolved and re-precipitated compared to silicates. Comparing the carbonates in loess and desert sediments may provide information on identifying the source areas of loess (Li et al., 2007; Wang et al., 2005). The carbonate content in Caoxian loess is relatively low at 15%, which cannot be explained by pedogenesis after deposition (Meng et al., 2015). Caoxian is located in the west of the Loess Plateau where the role of soil weathering is weak (Meng et al., 2015). We may infer that these carbonate minerals may originate from the upwind deserts, i.e., the Badain Jaran Desert, the Tengger Desert, the Kubq and Mu Us Desert. The average $CaO/Al_2O_3$ in loess is 0.86, which is significantly higher than the averages in the Badain Jaran Desert, Tengger Desert, Kubq and Mu Us Desert (0.24). This large difference is unlikely to be explained by the difference in silicate minerals and carbonates when transporting and depositing from deserts to the Loess Plateau. The average $CaO/Al_2O_3$ in loess in northeast China (0.17) (Xie and Chi, 2016) is higher than that in the Northeastern Sandy Lands (0.11). The enrichment factor of carbonate minerals is smaller than 2 from source to sink in northeast China. Therefore, only the carbonate minerals from the Taklimakan, Kumtag and Qaidam Deserts (an average $CaO/Al_2O_3$ of 0.76) mixing into loess of the Loess Plateau may explain the higher carbonate minerals in the loess. This is consistent with previous studies using $\delta^{18}O$ in quartz or Sr-Nd isotopes to suggest that the WEST desert and the Central and Western Deserts are potential sources of loess in the Chinese Loess Plateau (Zhang and Fu, 2016; Li et al., 2018; Rao et al., 2006; Pullen et al., 2011; Chen and Li, 2011; Chen et al., 2007).

The composition of silicate minerals can also help identify the potential source areas of loess. The changes in K, Al and Fe in the desert samples are highly coupled in the same desert region (Figure 2), which could be inherited by the loess. $Fe_2O_3/Al_2O_3$ and $K_2O/Al_2O_3$ may reflect the changes in ferromagnesite and K-feldspar relative to mica, respectively. The ferromagnesite and K-feldspar are less affected by wind sorting, making them one of the source tracers for loess. The average $Fe_2O_3/Al_2O_3$ ratio in the 45–75 μm fraction in the Xifeng loess is 0.27 (Liu, 2002), and the average ratio of $Fe_2O_3/Al_2O_3$ in the 20–63 μm fraction in the Baishui loess and red clay is 0.29 and 0.31, respectively (Xiong et al., 2010). $Fe_2O_3/Al_2O_3$ in the coarse loess falls into the range between the WEST Deserts and the Central and Western Deserts. The average $K_2O/Al_2O_3$ in the 45–75 μm fraction of the Xifeng loess is 0.21 (Liu, 2002), and the 20–63 μm fraction for Baishui loess and red clay is 0.20 (Xiong et al., 2010). Both the $K_2O/Al_2O_3$ ratios in the Central and Western Deserts (0.21) and in the WEST Deserts (0.23) are different from the $K_2O/Al_2O_3$ in the Northeastern Sandy Lands (0.44). These comparisons suggest that both silicate fractions emitted from the Central and Western Deserts and/or the WEST Deserts are potential sources of loess materials in the Loess Plateau. This is further supported by Luochuan loess falling far away from the Northeastern Sandy Lands. The spatial heterogeneity of major elemental compositions in Gobi and Mongolia makes it difficult to clarify its relationship with loess in the Chinese Loess Plateau (Sun, 2002; Chen et al., 2007; Maher et al., 2009; Sun et al., 2013).

## 5. Conclusions

(1) We identify four regions in Chinese deserts based on major element geochemistry. The $SiO_2$ and CaO contents are highly variable within one desert. Generally, $SiO_2$ increases from west to east, while CaO decreases from west to east. The $K_2O$ is higher in the Hulun Buir, Onqin Daga and Horqin

sandy lands than in other deserts.

(2) Depletions of $Al_2O_3$, $TiO_2$, $Fe_2O_3$, $Na_2O$, MgO, $P_2O_5$ and MnO relative to UCC are found in Chinese desert sediments, due to the silicate dilution effect. The major elements in Chinese deserts are mainly controlled by two factors: Fresh material supplies and the parent rock in source areas, which ultimately reflect the regional tectonic characteristics. The WEST Desert and the Central and Western Deserts are characterized by low mineral maturity, which may be related to the tectonic uplift and a sufficient supply of fresh materials. The Northeastern Sandy Lands are characterized by a high mineral maturity, which may be associated with a relatively stable tectonic structure and a lack of fresh materials. High CaO in the western deserts may be linked to carbonate-rich minerals from source areas, while the high $K_2O$ in the east sand lands is related to abundant K-feldspar and K-bearing silicate minerals in the granites. The deserts can be distinguished by ternary diagrams with $SiO_2$/10-CaO-$Al_2O_3$, ($K_2O$+$Na_2O$)-CaO-$Fe_2O_3$ and CaO-$Na_2O$-$K_2O$ (Figure 4) and with $SiO_2$/$Al_2O_3$-($K_2O$+$Na_2O$)-(CaO+MgO), $SiO_2$/$Al_2O_3$-$K_2O$-$Na_2O$ (Appendix Figure S2, http://earth.scichina.com).

(3) The major element geochemistry in this study suggests that the WEST desert and the Central and Western Deserts are potential sources of loess in the Chinese Loess Plateau. Carbonates in the loess are most likely to have inherited carbonate-rich minerals from upwind in the WEST Deserts.

**Acknowledgements** *We acknowledge senior researcher Youbin Sun at the Institute of Earth Environment (IEE), the Chinese Academy of Sciences (CAS), for Mongolian Gobi samples; associate Prof. Xiaoyong Wang at the School of Geographic and Oceanographic Sciences, Nanjing University, and Prof. Wenbo Rao at the School of Earth Sciences and Engineering, Hohai University, for providing samples. We also thank Dr. Xianqiang Meng, Tong He, Jiawei Da, Shilei Li and others for their help with this work. We thank Wanyi Lu for improving the language of the manuscript and two reviewers for helpful comments. This work was supported by the National Natural Science Foundation of China (Grant Nos. 41673095, 41230526, 41690111 & 41877369) and the Fundamental Research Funds for the Central Universities (Grant No. Swu118203).*

## References

Bauluz B, Mayayo M J, Fernandez-Nieto C, Gonzalez Lopez J M. 2000. Geochemistry of Precambrian and Paleozoic siliciclastic rocks from the Iberian Range (NE Spain): Implications for source-area weathering, sorting, provenance, and tectonic setting.. Chem Geol, 168: 135–150

Badarch G, Dickson Cunningham W, Windley B F. 2002. A new terrane subdivision for Mongolia: Implications for the Phanerozoic crustal growth of Central Asia. J Asian Earth Sci, 21: 87–110

Blatt H, Middleton G, Murray R. 1972. Origin of Sedimentary Rocks. Englewood Cliffs: Prentice-Hall

Chen J, An Z S, Liu L W, Ji J F, Yang J D, Chen Y. 2001. Variations in chemical compositions of the eolian dust in Chinese Loess Plateau over the past 2.5 Ma and chemical weathering in the Asian inland. Sci China Ser D-Earth Sci, 44: 403–413

Chen J, Li G J. 2011. Geochemical studies on the source region of Asian dust. Sci China Earth Sci, 54: 1279–1301

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

Chen S Y, Huang J P, Li J X, Jia R, Jiang N X, Kang L T, Ma X J, Xie T T. 2017. Comparison of dust emissions, transport, and deposition between the Taklimakan Desert and Gobi Desert from 2007 to 2011. Sci China Earth Sci, 60: 1338–1355

Engelbrecht J P, Derbyshire E. 2010. Airborne mineral dust. Elements, 6: 241–246

Fang X M, Lv Q L, Yang S L. 2001. Kunlun loess and plateau uplift in relation to inland aridification and desertification processes in China (in Chinese). Sci China Ser D-Earth Sci, 45: 289–299

Fu X D, Wang Y S. 2015. Provenance studies of Chinese deserts: Review and outlook. Acta Sedimental Sin, 33: 1063–1073

Fu X D, Yang X P. 2004. Primar determination and analysis of the $^{18}O$ values of quarze in northern Chinese deserts. Quat Sci, 24: 243

Guo Z T. 2017. Loess Plateau attests to the onsets of monsoon and deserts (in Chinese). Sci Sin Terrae, 47: 421–437

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, Liu T S. 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature, 416: 159–163

He T, Liu L, Chen Y, Sheng X, Ji J. 2016. Plagioclase sub-species in Chinese loess deposits: Implications for dust source migration and past climate change. Quat Res, 85: 17–24

Honda M, Shimizu H. 1998. Geochemical, mineralogical and sedimentological studies on the Taklimakan Desert sands. Sedimentology, 45: 1125–1143

Hu F G, Yang X P. 2016. Geochemical and geomorphological evidence for the provenance of Aeolian deposits in the Badain Jaran Desert, northwestern China. Quat Sci Rev, 131: 179–192

Jeong G Y, Hillier S, Kemp R A. 2008. Quantitative bulk and single-particle mineralogy of a thick Chinese loess-paleosol section: Implications for loess provenance and weathering. Quat Sci Rev, 27: 1271–1287

Ji J, Chen J, Lu H. 1999. Origin of illite in the loess from the Luochuan area, Loess Plateau, Central China. Clay Miner, 34: 525–532

Li L, Chen J, Chen Y, Hedding D W, Li T, Li L, Liu X, Zeng F, Wu W, Zhao L, Li G. 2018. Uranium isotopic constraints on the provenance of dust on the Chinese Loess Plateau. Geology, 46: 747–750

Li G J, Chen J, Chen Y, Yang J D, Ji J F, Liu L W. 2007. Dolomite as a tracer for the source regions of Asian dust. J Geophys Res, 112: D17201

Liu B, Jin H, Sun Z, Zhao S. 2016. Geochemical weathering of Aeolian sand and its palaeoclimatic implications in the Mu Us Desert, northern China, since the Late Holocene. J Arid Land, 8: 647–659

Liu J Q, Chen L H, Zeng G, Wang X J, Zhong Y, Yu X. 2016. Lithospheric thickness controlled compositional variations in potassic basalts of Northeast China by melt-rock interactions. Geophys Res Lett, 43: 2582–2589

Liu J, Qin X. 2005. Evolution of the environmental fram ework and oas is in the Tarim Basin (in Chinese). Quat Sci, 25: 533–539

Liu C Q, Masuda A, Okada A, Yabuki S, Zhang J, Fan Z L. 1993. A geochemical study of loess and desert sand in northern China: Implications for continental crust weathering and composition. Chem Geol, 106: 359–374

Liu C Q, Masuda A, Okada A, Yabuki S, Fan Z L. 1994. Isotope geochemistry of Quaternary deposits from the arid lands in Northern China. Earth Planet Sci Lett, 127: 25–38

Liu L W. 2002. The evolution history of East Asian monsoon on the Loess Plateau during the last 3.6 Ma based on mineralogical and elemental geochemistry studies. Dissertation for Doctoral Degree. Nanjing: Nanjing University

Liu T. 1985. Loess and Environment. Beijing: Science Press

Liu L W, Chen J, Wang H T, Chen Y. 2001. A chemical index of weathering without effect of wind sorting: Fe/Mg ratios in the acid-insoluble phases of loess deposits. Chin Sci Bull, 46: 1384–1387

Liu Z T, Yang X P. 2013. Geochemical-geomorphological evidence for the

provenance of Aeolian sands and sedimentary environments in the Hunshandake Sandy Land, Eastern Inner Mongolia, China. Acta Geol Sin-Engl Ed, 87: 871–884
Meng X Q, Liu L W, Balsam W, Li S L, He T, Chen J, Ji J F. 2015. Dolomite abundance in Chinese loess deposits: A new proxy of monsoon precipitation intensity. Geophys Res Lett, 42: 10391–10398
Lu H Y, Guo Z T. 2014. Evolution of the monsoon and dry climate in East Asia during late Cenozoic: A review. Sci China Earth Sci, 57: 70–79
Lu W Y, Zhao W C B, WLu H Y, Liu P, Lu Z L, Ji J F. 2017. Iron mineralogy and speciation in clay-sized fractions of Chinese desert sediments. J Geophys Res-Atmos, 122: 13458–13471
Maher B A, Mutch T J, Cunningham D. 2009. Magnetic and geochemical characteristics of Gobi Desert surface sediments: Implications for provenance of the Chinese Loess Plateau. Geology, 37: 279–282
Muhs D R. 2004. Mineralogical maturity in dunefields of North America, Africa and Australia. Geomorphology, 59: 247–269
Nesbitt H, Young G. 1996. Petrogenesis of sediments in the absence of chemical weathering: Effects of abrasion and sorting on bulk composition and mineralogy. Sedimentology, 43: 341–358
Pettijohn F J, Potter P E, Siever R. 1972. Sand and Sandstone. New York: Springer-Verlag
Peng S, Guo Z. 2001. Geochemical indicator of original eolian grain size and implications on winter monsoon evolution. Sci China Ser-D Earth Sci, 44(Suppl): 261–266
Potter P E, Huh Y, Edmond J M. 2001. Deep-freeze petrology of Lena River sand, Siberia. Geology, 29: 999
Pullen A, Kapp P, McCallister A T, Chang H, Gehrels G E, Garzione C N, Heermance R V, Ding L. 2011. Qaidam Basin and northern Tibetan Plateau as dust sources for the Chinese Loess Plateau and paleoclimatic implications. Geology, 39: 1031–1034
Qiang X, An Z, Song Y, Chang H, Sun Y, Liu W, Ao H, Dong J, Fu C, Wu F, Lu F, Cai Y, Zhou W, Cao J, Xu X, Ai L. 2011. New eolian red clay sequence on the western Chinese Loess Plateau linked to onset of Asian desertification about 25 Ma ago. Sci China Earth Sci, 54: 136–144
Ren X Z, Yang X P, Wang Z T, Zhu B Q Z D G, Rioual P. 2014. Geochemical evidence of the sources of Aeolian sands and their transport pathways in the Minqin Oasis, northwestern China. Quat Int, 334-335: 165–178
Rao W, Yang J, Chen J, Li G. 2006. Sr-Nd isotope geochemistry of eolian dust of the arid-semiarid areas in China: Implications for loess provenance and monsoon evolution. Chin Sci Bull, 51: 1401–1412
Ruxton B P. 1968. Measures of the degree of chemical weathering of rocks. J Geol, 76: 518–527
Shao Y, Dong C H. 2006. A review on East Asian dust storm climate, modelling and monitoring. Glob Planet Change, 52: 1–22
Smalley I. 1995. Making the material: The formation of silt sized primary mineral particles for loess deposits. Quat Sci Rev, 14: 645–651
Sun J. 2002. Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. Earth Planet Sci Lett, 203: 845–859
Sun Y, Chen H, Tada R, Weiss D, Lin M, Toyoda S, Yan Y, Isozaki Y. 2013. ESR signal intensity and crystallinity of quartz from Gobi and sandy deserts in East Asia and implication for tracing Asian dust provenance. Geochem Geophys Geosyst, 14: 2615–2627
Sun Y, Tada R, Chen J, Chen H, Toyoda S, Tani A, Isozaki Y, Nagashima K, Hasegawa H, Ji J. 2007. Distinguishing the sources of Asian dust based on electron spin resonance signal intensity and crystallinity of quartz. Atmos Environ, 41: 8537–8548
Tapponnier P, Molnar P. 1976. Slip-line field theory and large-scale continental tectonics. Nature, 264: 319–324
Wang G C, Cao K, Zhang K X, Wang A, Liu C, Meng Y N, Xu Y D. 2011. Spatio-temporal framework of tectonic uplift stages of the Tibetan Plateau in Cenozoic. Sci China Earth Sci, 54: 29–44
Wang X, Xia D, Zhang C, Lang L, Hua T, Zhao S. 2012. Geochemical and magnetic characteristics of fine-grained surface sediments in potential dust source areas: Implications for tracing the provenance of Aeolian deposits and associated palaeoclimatic change in East Asia. Palaeogeogr Palaeoclimatol Palaeoecol, 323-325: 123–132
Wang Y Q, Zhang X Y, Arimoto R, Cao J J, Shen Z X. 2005. Characteristics of carbonate content and carbon and oxygen isotopic composition of northern China soil and dust aerosol and its application to tracing dust sources. Atmos Environ, 39: 2631–2642
Xie X J. 2012. Geochemical Atlas of China. Beijing: Geology Press
Xie Y, Chi Y. 2016. Geochemical investigation of dry- and wet-deposited dust during the same dust-storm event in Harbin, China: Constraint on provenance and implications for formation of Aeolian loess. J Asian Earth Sci, 120: 43–61
Xin H T, Wang H C, Zhou S J. 2006. Geological events and tectonic evolution of north margin of the Qaidam Basin. Geol Survey Res, 29: 311–320
Xiong S, Ding Z, Zhu Y, Zhou R, Lu H. 2010. A ~6 Ma chemical weathering history, the grain size dependence of chemical weathering intensity, and its implications for provenance change of the Chinese loess-red clay deposit. Quat Sci Rev, 29: 1911–1922
Xu Z, Lu H, Zhao C, Wang X, Su Z, Wang Z, Liu H, Wang L, Lu Q. 2011. Composition, origin and weathering process of surface sediment in Kumtagh Desert, Northwest China. J Geogr Sci, 21: 1062–1076
Yang X, Zhu B, White P D. 2007. Provenance of Aeolian sediment in the Taklamakan Desert of western China, inferred from REE and major-elemental data. Quat Int, 175: 71–85
Zhang F, Fu X. 2016. Relationships between oxygen isotope compositions of quartz and grain size from dune sands and fluvial-lacustrine sediments in the Taklimakan Desert. Geol Rev, 62: 73–82
Zhao W, Sun Y, Balsam W, Lu H, Liu L, Chen J, Ji J. 2014. Hf-Nd isotopic variability in mineral dust from Chinese and Mongolian deserts: Implications for sources and dispersal. Sci Rep, 4: 5837
Zheng H. 2016. Asia dust production ramped up since latest Oligocene driven by Tibetan Plateau uplift. Natl Sci Rev, 3: 271–274
Zheng H, Wei X, Tada R, Clift P D, Wang B, Jourdan F, Wang P, He M. 2015. Late Oligocene-early Miocene birth of the Taklimakan Desert. Proc Natl Acad Sci USA, 112: 7662–7667
Zhu B, Yang X. 2009. Chemical weathering of detrital sediments in the Taklamakan Desert, Northwestern China. Geogr Res, 47: 57–70
Zhu Z D, Wu Z, Liu S, Di X M. 1980. Introduction to Chinese Desert (revised). Beijing: Science Press

(Responsible editor: Haibin WU)