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Grain-size study of aeolian sediments found east of Kumtagh Desert

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ABSTRACT

A grain-size study was conducted on the surface sediments found east of Kumtagh Desert and its connected geomorphic units, such as the wadi, wetland, oasis, and alluvial fan. The frequency, cumulative curves, and scatter diagrams of four grain-size parameters, namely, the mean grain size, sorting, skewness, and kurtosis, were plotted to study the grain-size characteristics of each sediment. Multiple discriminant analyses were applied to distinguish the deposition environments. Results indicated large diversities in the sediments from different environments. The aeolian sediments from the sandy desert and the gobi land show uniform characteristics or homogeneous changes. The sand resources from the eastern part of the desert can be considered as the alluvial deposits from the southern Altyn Tagh Mountain carried by several erosion gullies. Meanwhile, the western Mingsha Megadune inherited sediments from the nearby Danghe River. The discriminant functions proposed by Sahu can distinguish the deposition process. However, these functions lose their accuracy when applied to heavily eroded aeolian and gobi sediments.

1. Introduction

The grain-size study is a basic and popular method used to determine the sedimentary environment, the dynamics, deposition mechanism, and the development of the aeolian landforms, as well as the transportation and sorting of aeolian particles (Sahu, 1964; Visher, 1969; Barnorff-Nielsen and Christiansen, 1988; Wang et al., 2003; Farrell et al., 2012; Guan et al., 2013). Over the past century, numerous measurement methods and analysis models were developed for grain-size research (Bagnold, 1937; Konert and Vandenberghe, 1997; Flemming, 2007; Vandenberghe, 2013). The grain-size study of a certain aeolian unit, usually found in the desert or loess land, has been carried out worldwide from a single dune level to a sand sea level (Wang et al., 2003).

The Kumtagh Desert, located in the northwest inland of China, is unique because of its feather-like dunes (Dong et al., 2008; Wang et al., 2009). This desert contains most of the aeolian landform types, including deposition units, such as flat sand surfaces, bush dunes, barchan dunes, grid dunes, linear dunes, star dunes, and their compositions, as well as erosion units, such as yardang, flat gobi, and gravel piles (Dong et al., 2011a). The abundance of landform units makes Kumtagh Desert an ideal place to study arid land geomorphology, and to evaluate arid environments, climate change, and the environmental response of the Qinghai–Tibetan Plateau's uplift. However, the Kumtagh Desert remains the least explored desert in China because of its harsh environment (Dong et al., 2008). Only after the first scientific investigation in 2004 (E et al., 2006) did researchers have the opportunity to collect samples and study the mineralogical, geochemical, and grain-size characteristics of desert sands and their potential sources (Wei et al., 2007; He et al., 2009; Xu et al., 2011). Despite the insufficient research history and quantity, previous research mainly focused on sand sediments within the desert, while the surrounding source areas were generally overlooked. The study of sediments beyond the desert border is necessary because the conditions of source areas serve a key function in the understanding of the formation, development, and migration of the desert.

In this study, the grain-size analysis of surface aeolian sediments was conducted on the eastern part of Kumtagh Desert and its connected geomorphic units, such as wadi, wetland, oasis, and alluvial fan. This study aims to investigate the variations of surface sediments from different landforms, as well as to evaluate their sources, migration, and circulation in a typical arid region.

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2. Material and methods

2.1. Study area

Kumtagh Desert covers an area of 2.28×10^4 km^2 and is located east of the Tarim Basin, northwest of the Lop Nur Depression, and at the north edge of the Qinghai–Tibetan Plateau. The prevailing wind direction is northeast, followed by northwest. The eastern part of the desert touches the Xihu (which is translated as "lake at the west") Wetland National Nature Reserve, which protects the Dunhuang Oasis, wherein the world-renowned Mogao Grottos and Crescent Spring are located. The Xihu Reserve is a natural desert wetland, but over the past 60 years, it has been eroded by climate change and wind-blown sand problem from 2500 km^2 to 980 km^2.

The southern arm of the Kumtagh Desert extents eastward, covering a low branch of the Altyn Tagh Mountain found at the north edge of the Qinghai–Tibetan Plateau. This mountain branch, also known as the southeast edge of the Kumtagh Desert, is cut by several seasonal streams (i.e., erosion gullies) originating from the alluvial fan of the Altyn Tagh Mountain and vanishing toward the Xihu Wetland. Barchan chains can be found over this mountain branch. Different underlying sediments can be observed, indicating that the sand materials are from outside sources. Further east, Danghe River, which is the water source of Dunhuang Oasis, separates the Kumtagh Desert region from another sand dune area, i.e., the Mingsha Megadune, the material sources of which have yet to be confirmed (Fig. 1).

2.2. Samples and analytical methods

Twenty-two sediment samples weighing 500 g each were collected from the six types of landform surfaces: A1 to A2 are points from the alluvial fan north of the Altyn Tagh Mountain, whereas A3 and A4 are the original surface sediments in the south and middle part of the mountain branch. G1 to G5 are gobi points from north of the desert to west of the Dunhuang Oasis. K1 to K5 are sandy samples from the flat dunes at the eastern edge of the Kumtagh Desert. In particular, K3 to K5 were obtained from the north, middle, and south of the Altyn Tagh Mountain branch. Sediment M was located in the flat sand on the western edge of the Mingsha Megadune. R1 was located in the upstream watershed of the Danghe River, while R2 was from the downstream flood zone of the Danghe River to the west of Sediment M. R3 was located in the wadi surface periphery of the Xihu Wetland. Finally, V1 to V4 were vegetated points from shrubland in the yardang (V1), Xihu Wetland (V2), north of the Dunhuang Oasis (V3), and east of the Dunhuang Oasis (V4) (Fig. 1).

Grain-size distribution data were determined to be between 0.02 and 2000 μm by using a Malvern Mastersizer laser grain-size analyzer, which resulted in a better than 1% accuracy and better than 1% variation in terms of reproducibility. Values were converted to the Φ (phi) unit. Before each measurement, chemical pretreatment following the procedure by Konert and Vandenberghe (1997) was performed to isolate the discrete particles and provide evenly dispersed suspension particles. Grain-size parameters were calculated based on the Folk and Ward method (Folk and Ward, 1957). The discrimination functions from Sahu (1964) were used to distinguish the sedimentary environments of these aeolian particles.

3. Results and discussions

3.1. Grain-size distribution

The classification of the different grain sizes intuitively expresses the fraction of each grain-size group. The frequency and cumulative plots of the grain-size distribution provide useful information on particle components and their sedimentary conditions. The three main sediment transport patterns, namely, suspension, saltation, and surface creep, can be observed from the curves (Visher, 1969).

The grain-size distributions of the sediments from the six environments are shown in Table 1, and their frequency and cumulative curves, based on the logarithmic particle size method proposed by Udden (1914) and Wentworth (1922), are given in Fig. 2. The previous grain-size parameters of the sand from the Eastern Kumtagh Desert (EK) (He et al., 2009) and the crescent dunes in the Taklimakan Desert (CT) (Wang et al., 2003) were compared with the results.

The grain-size distributions clearly differed among different environments. The alluvial sediments from the Altyn Tagh Mountain (A1 and A2) showed no dominant size group and similar

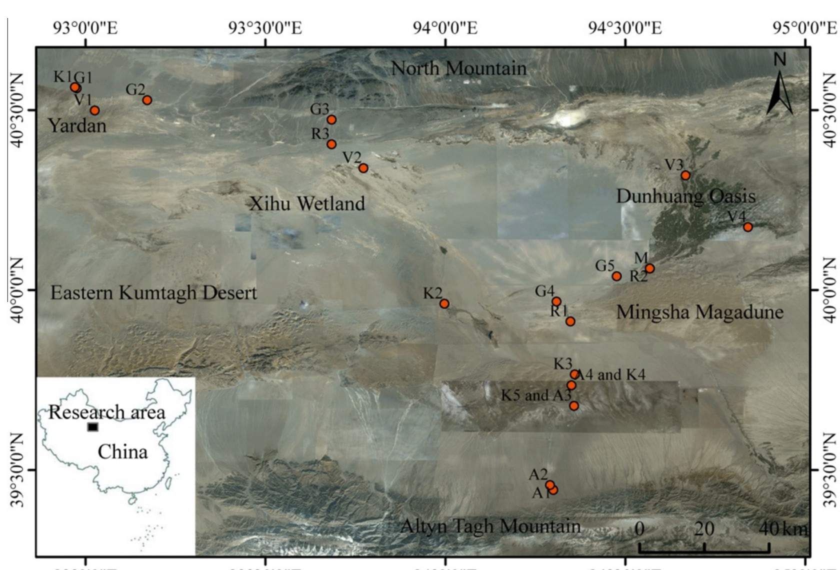

Fig. 1. Sampling sites of the study. Image data taken from Google Earth.

Table 1
Grain size composition of the different sediments.

Sample %	Clay <5 μm	Silt 5–50 μm	Very fine sand 50–100 μm	Fine sand 100–250 μm	Medium sand 250–500 μm	Coarse sand 500–1000 μm	Very coarse sand 1000–2000 μm
A1	5.44	16.12	19.23	20.86	19.42	17.45	1.49
A2	8.78	27.49	25.23	21.91	9.68	6.76	0.13
A3	3.18	8.35	22.77	51.51	14.04	0.15	0
A4	13.65	67.64	14.78	3.93	0		
G1	3.14	5.99	23.02	54.84	11.24	1.29	0.48
G2	4.05	8.60	17.23	49.28	17.60	3.02	0.22
G3	3.96	10.36	15.64	41.81	21.94	6.29	0.00
G4	4.05	7.82	19.68	41.71	17.19	8.42	1.14
G5	6.34	10.73	11.53	37.20	25.98	8.22	0
K1		0	0.40	36.40	47.59	15.60	0
K2	1.27	2.85	11.21	67.38	17.06	0.23	0
K3	0	0.05	20.33	69.24	10.35	0.03	
K4	0	0.04	27.91	71.05	1.00	0	
K5	0	0.07	31.64	68.05	0.24	0	
M	0	2.73	1.91	36.94	50.86	7.57	0
R1	2.39	7.93	26.96	48.50	11.28	2.68	0.26
R2	1.63	5.05	12.33	56.16	23.46	1.37	0
R3	1.19	3.58	4.76	40.67	35.64	13.67	0.49
V1	0	0.03	5.73	33.87	35.04	22.94	2.39
V2	9.35	31.59	29.60	20.32	5.93	3.21	0
V3	6.62	26.45	21.96	31.57	12.83	0.56	0
V4	2.59	6.59	15.47	46.84	23.38	5.13	0
EK[a]	0	0.12	22.21	59.86	17.78	0.02	0
CT[b]		0	23.18	75.97	0.85	0	

[a] Data from east of the Kumtagh Desert from He et al. (2009).
[b] Data from the crescent dunes in the Taklimakan Desert from Wang et al. (2003).

bimodal profiles, indicating different sedimentary components (Fig. 2a). A2 contained less coarse particles than A1, which indicates a reduction in current energy along the way out of the mountain area. The cumulative curve of A1 transformed into a linear shape because of the similar contents of the different size groups. The original surface sediments of A3 showed a smooth, unimodal shape frequency curve with over 50% fine sand and an S-shape cumulative curve. A4 showed a flat-headed frequency curve with about 67% silt content. A3 had fluvial current characteristics, with a crest size of approximately 150 μm and a small creep population. A4 was composed of loess soil, with similar contents reported to be some Chinese loess (Ye et al., 1998).

For the gobi sediments found northeast of the Kumtagh Desert (G1) to the west of the Dunhuang Oasis (G5), unimodal frequency curves with increasing crest grain–size values and S-shaped cumulative curves with decreasing gradients were observed (Fig. 2b). From G1 to G5, the crest particle sizes changed from 140 μm to 220 μm. These observations indicate the strengthening of wind-sand activity from the west to the east over this gobi area, as aeolian particles reach a balance with local wind power during the sorting, transporting, and deposition processes. This characteristic is also in accordance with the observations of Taklimakan Desert (Chen, 1993).

The K1 to K5 sediments from the Eastern Kumtagh Desert showed the same frequency curve shapes along with increasing grain sizes. Their cumulative curves shared the same gradient, which was steeper than those G series despite the grain-size locations of the truncation points on the profiles (Fig. 2c). This observation indicates good sorting powered by similar wind energy. The content of coarse sand decreased from K1 to K5, indicating a finer-grained trend from north to south of the aeolian materials east of the desert. Another indication is that this finer grained trend is affected by the northern winds. From K1 to K5, the peak grain size values of the frequency curves are reduced from 320 μm to 130 μm. The sands were coarser than the fine sand from CT. The sand dunes north of the desert and near the location of K1, which are close to the typical yardang aeolian landform, suffered from serious wind erosion. Thus, the surface sand from this area was clearly coarser than that from any other place. The average content of K2 to K5 at each grain-size group agreed well with that of EK, and had a correlation of 0.99.

Sediment M at the west edge of the Mingsha Megedune found east of the Danghe River flood zone, showed similar grain-size characteristics as K1, and nearly 60% was composed of medium to coarse sand. However, a small hump exists at the finer side of the maximum value on the frequency curve (Fig. 2d), indicating that the existence of a mixture of silt.

The R1 to R3 samples had a broad size range, varying from clay to very coarse sand. They shared curves similar to those in A3, indicating water-related environments (Fig. 2e). From upstream (R1) and downstream (R2) of the Danghe River to the lower reach of the wadi (R3), the grain size became coarse because of the removal of the fine materials powered by flood water.

Samples from the vegetated areas also had broad size ranges. V1 had more coarse creep material because of the strong wind erosion northeast of the Kumtagh Desert. Both V2 and V3 were from well-protected bushlands and comprised over 30% of clay and silt. The grain-size characteristics of V4 exhibit significant similarity with those of the R-series sediments, indicating a fluvial character during the deposition process (Fig. 2f).

3.2. Grain-size parameters

A scatter plot of the four statistical grain-size parameters in the Φ measurement unit, namely, mean grain size (Mz), standard deviation or sorting (σ), skewness (SK_1), and kurtosis (K_G), can be used to reflect the differences in the sedimentary characteristics, as well as to distinguish the depositional environments. Significant differences were found in the parameters of the aeolian particles from different environments in this region (Fig. 3).

The parameter values from the eastern border of the Kumtagh Desert are close to the EK that was reported by He et al. (2009), but are coarser and less sorted than the CT in the Taklimakan Desert (Wang et al., 2003). The desert sands were generally finer and

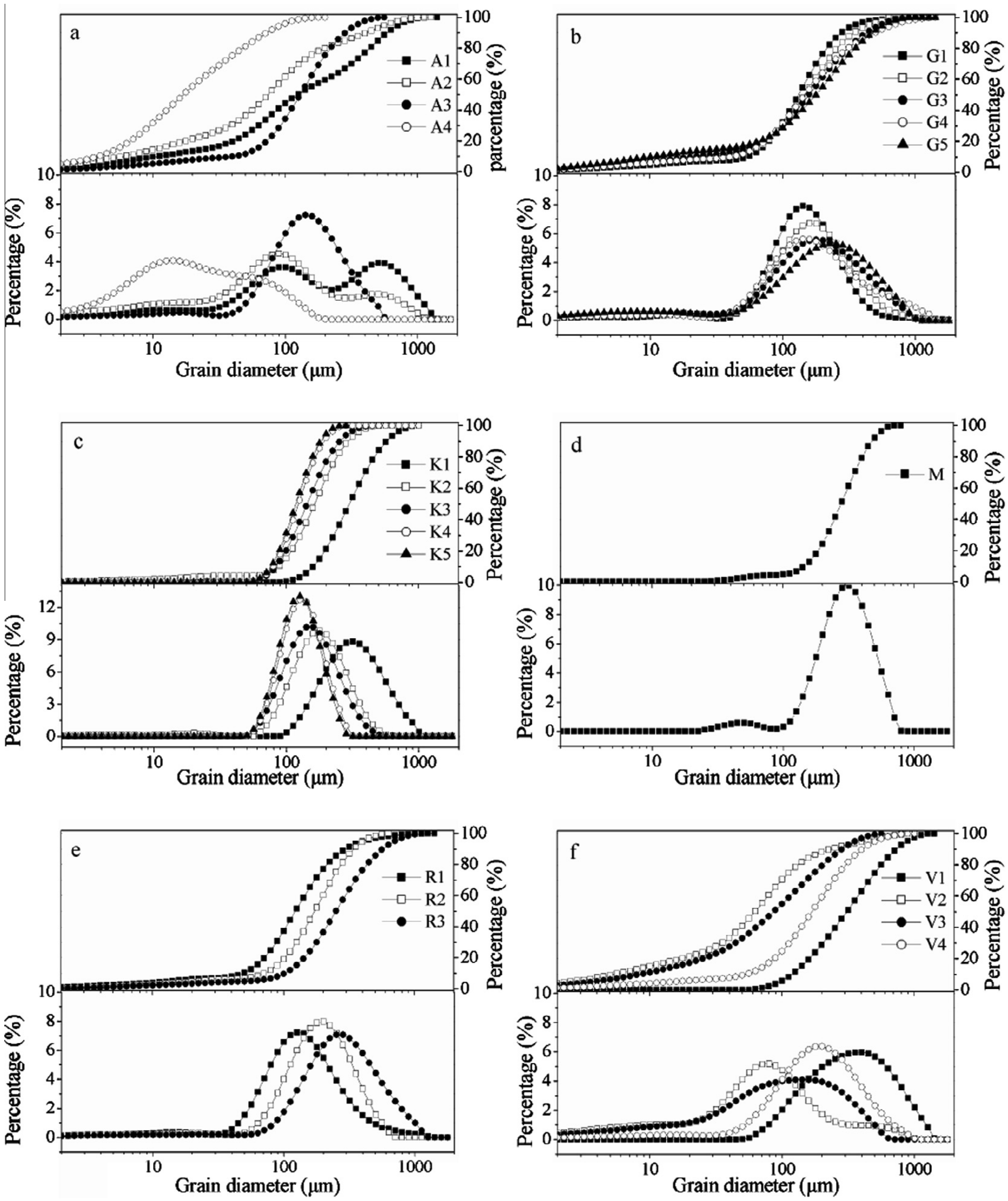

Fig. 2. Cumulative probability and frequency curves of different sediment types.

better sorted, with a near-symmetrical skewness and a more moderate kurtosis than other sediments. The aeolian sediments from the downwind areas tended to be finer and better sorted. For example, the mean size of the desert sands (K1 to K5) decreased from 1.57 Φ to 2.91 Φ, and the sorting decreased linearly from 0.71 to 0.49. The relation of the sorting and the mean grain size of the desert samples is

$$\sigma_K = 0.99 - 0.16Mz, \; R^2 = 0.56.$$

For the gobi samples, the relation is

$$\sigma_G = 8.58 - 2.67Mz, \; R^2 = 0.91.$$

where σ_K and σ_G are the fitted sorting values for the K and G samples, respectively.

The SK_1 and K_G values for the K samples were stable and close to each other, indicating a balanced status of aeolian sediments with wind energy. This finding proves that the sand covering the Altyn Tagh Mountain branch has the same transportation/deposition dynamics as the north desert sands. For the G samples, the SK_1 shows an inverse relation with the mean grain size, and K_G has a positive relation. However, for the samples from other environments, no clear variation trend was observed. Therefore, the scatter plots of the grain-size parameters can be used to distinguish aeolian sediments from others.

3.3. Discrimination of deposition environments

The deposition environments of the sediments can be determined by using the statistical method based on grain-size parameters. Linear discrimination using grain-size parameters is an effective way to distinguish aeolian sediments. The discriminant functions proposed by Sahu (1964) were applied by He et al.

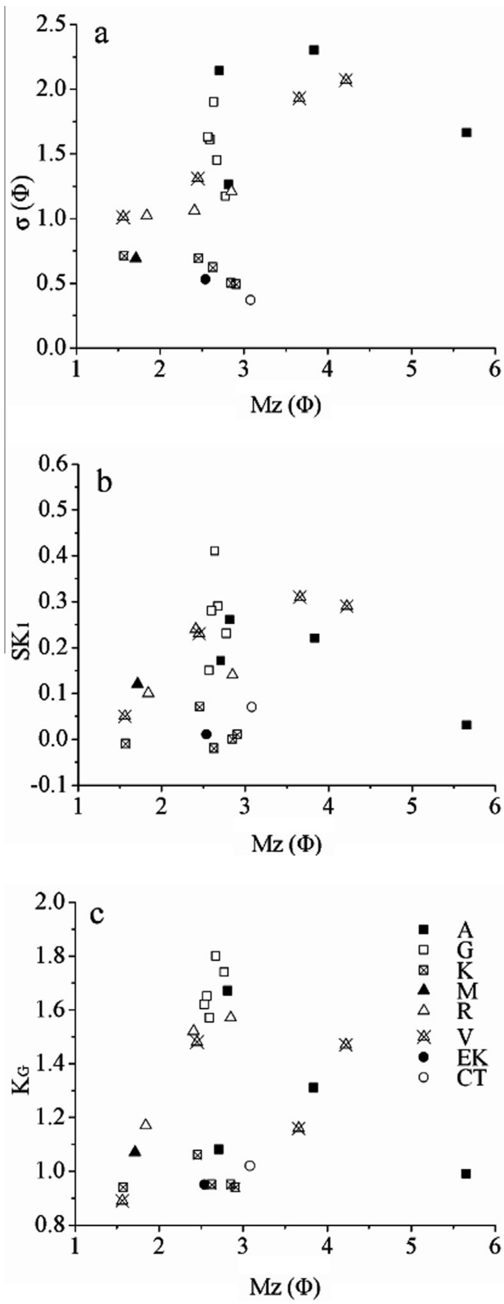

Fig. 3. Grain–size parameters of the different sediments. EK and CT: same as in Table 1.

(2009) and Dong et al. (2011b) to the sand samples taken from the Kumtagh Desert. The four functions used are as follows:

1. $Y1 = -3.5688Mz + 3.7016\sigma^2 - 2.0766SK_1 + 3.1135K_G$
   Y1 less than −2.7411 indicates aeolian deposition. Otherwise, proceed to Equation 2.
2. $Y2 = 15.6534Mz + 65.7091\sigma^2 + 18.1071SK_1 + 18.5043K_G$
   Y2 less than 65.3650 indicates a beach deposition. Otherwise, proceed to Equation 3.
3. $Y3 = 0.2852Mz - 8.7604\sigma^2 - 4.8932SK_1 + 0.0482K_G$
   Y3 greater than − 7.4190 indicates a shallow marine deposition. Otherwise, proceed to Equation 4.
4. $Y4 = 0.7215Mz - 0.4030\sigma^2 + 6.7322SK_1 + 5.2927K_G$
   Y4 less than 9.8433 indicates a turbidity current deposition; otherwise, it is a fluvial deposition.

The parameters given in Section 3.2 were substituted into these functions. The results present clear differences among the different sediments. A4 (loess deposition), K2 to K5, EK and CT from previous studies were determined to be aeolian sediments. A3, R1, R2, V2, and V4 were determined to be fluvial sediments. Finally, A1, A2, R3, V1, and V3 were determined to be turbidity current sediments. The turbidity current sediment is carried by the annual floods from the southern high mountains and reaches the depression areas, such as V1, north of the desert. No beach environment was indicated. These results agree with the field conditions and prove the diversity of the deposition resources and the strong regional differences in this area.

However, M and K1 were determined to be shallow marine sediments. The flat sandy land at the western toe of the Mingsha Megadune from the Danghe flood zone can be “waved” during the rainy season. Therefore, its sediments bear a shallow marine characteristic. This finding indicates that the Mingsha Megadune inherits material resources from the Danghe River, at least in the western part. The K1 sediment had similar grain parameters through the area containing K2 to K5, but its mean size was magnified by the serious wind erosion north of the gobi-desert fringe, which caused the Y1 value in the discriminant functions to be larger than the aeolian criterion.

Notably, all gobi samples were considered to be fluvial deposits. The gobi could have possibly been flooded during some storms, but wind is still the major exogenic force in the forming of the landform. The aeolian particles in the gobi area have a mean grain size similar to that of desert sands because they are protected by surface gravel. However, they have bad sorting, positive skewness, and a narrow kurtosis. This abnormal result can be explained by the absence of gobi testing samples when the functions were proposed.

3.4. Discussion on the transportation of sediments

The north desert sands, which are bounded by the north branch of the Altyn Tagh Mountain at the southeast edge of the Kumtagh Desert, clearly have a different dynamic process against the south diluvium and alluvial deposits from the Altyn Tagh Mountain. The sands covering the low mountains do not originate locally, but share homogeneity with desert sands from the north.

The large altitude difference between the south mountain and the north depression (Qu et al., 2005) causes flood deposits to be carried through the large erosion gullies to the north of the desert (e.g., from A1 to R3). The sediments can be best sorted by the strong northerly wind and deposited back to the south mountain branch (from K1 to K5). This occurrence affirms the conjecture made by Dong et al. (2011b).

The parameter analysis proves that the coarse sands at the western toe of the Mingsha Megadune are from the Danghe River. The Mingsha Megadune, which is separated by the Danghe River, Xihu Wetland, and the flat gobi, may have different sediment resources compared with the Kumtagh Desert. However, up until now, no systematic study has been carried out regarding the sediment resources at a broad scale because of the difficulty in entering these continuous great dunes.

4. Conclusions

Large diversities of sediments from different deposition environments were reported east of the Kumtagh Desert. A clearly finer-grained trend of sand was observed from the northeast to southeast part of the desert. The sand resources of the eastern desert can be the seasonal alluvial deposits from the Altyn Tagh

Mountain through several erosion gullies to the north. The western Mingsha Megadune can obtain sediments from the Danghe River.

The scatter plots of grain-size parameters can be used to distinguish the aeolian sediments from others. The discriminant functions proposed by Sahu (1964) were able to distinguish the deposition process. However, they lost their accuracy when they were applied to heavily-eroded aeolian and gobi sediments.

Analyzing the grain size of samples from the different surface sediments is an important component in understanding the deposition environments of the complex landform units in this area. This preliminary work remains limited to the sampling sites, mostly because of the difficulty to access these locations, and problem of representativeness may exist. A regular sampling grid is expected to be built in the future to conduct a more comprehensive research. More studies adopting other methods, such as lithology analysis and geological dating must also be conducted.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeolia.2014.01.001. These data include Google maps of the most important areas described in this article.

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