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The origin of bimodal grain-size distribution for aeolian deposits

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ABSTRACT

Atmospheric dust deposition is a common phenomenon in arid and semi-arid regions. Bimodal grain size distribution (BGSD) (including the fine component and coarse component) of aeolian deposits has been widely reported. But the origin of this pattern is still debated. Here, we focused on the sedimentary process of modern dust deposition, and analyzed the grain size distribution of modern dust deposition, foliar dust, and aggregation of the aeolian dust collected in Cele Oasis, southern margin of Tarim Basin. The results show that BGSD also appear in a dust deposition. The content of fine components (<20 μm size fraction) change with temporal and spatial variation. Fine component from dust storm is significant less than that from subsequent floating dust. Fine component also varies with altitude. These indicate that modern dust deposition have experienced changing aerodynamic environment and be reworked during transportation and deposition, which is likely the main cause for BGSD. The dusts from different sources once being well-mixed in airflow are hard to form multiple peaks respectively corresponding with different sources. In addition, the dust deposition would appear BGSD whether aggregation or not. Modern dust deposition is the continuation of ancient dust deposition. They both may have the same cause of formation. Therefore, the origin of BGSD should provide a theoretical thinking for reconstructing the palaeo-environmental changes with the indicator of grain size.

1. Introduction

Loess and other aeolian deposits often present bimodal grain size distribution (BGSD) with a coarse (the modal size is of >20 μm) and a fine component (the modal size is of <20 μm). Many researchers regarded that the coarse component (>20 μm) can only be transported through surface wind by saltation and/or short-range suspension (Tsoar and Pye, 1987; Pye, 1987, 1995), and that the fine component (<20 μm) can be widely dispersed and long-range transported (Windom, 1975; Glaccum and Prospero, 1980; Tsoar and Pye, 1987; Pye, 1987, 1995). Generally, different peaks of grain size distribution were suggested to delegate different sedimentary process (Middleton, 1976; Ashley, 1978; Bagnold and Barndorff-Nielsen, 1980). So, it has been regarded that two sub-components of the aeolian deposits were from different sources (Pye and Zhou, 1989; Sun et al., 2004, 2008b; Muhs and Benedict, 2006; Vandenberghe et al., 2006; Lim and Matsumoto, 2006).

Granularity is an excellent proxy for reconstructing paleo-environment changes. The motion feature of detrital particles in the airflow has been described since 1930s (Bagnold, 1941; Gillette et al., 1974; Tsoar and Pye, 1987; Pye, 1995). Based on the motion laws of aeolian dust, some researchers have long noted that there existed certain relationship between granularity and East Asia winter monsoon. So, many researchers have tried to trace the material sources of the loess on Chinese Loess Plateau (CLP) since 1960s (Liu, 1965; Liu, 1966). And later, based the granularity analysis of high resolution loess profiles, some researchers regarded the granularity has completely and systematically recorded the evolutionary of the East Asia winter monsoon since 2.6 million (Ding et al., 1994), which made it as one of three best archives of paleo-environmental changes (the other two are ice core and deep-sea sediment core).

In Northern China, two types of atmospheric circulations influence the regional climate during dust storm seasons, i.e., the East-Asia winter monsoon prevailing at low altitude and the westerlies prevailing at high altitude (Chen, 1991; Qiao and Zhang, 1994). Sun et al. (2002) and Sun et al. (2004) presented bimodal grain size distribution (BGSD) (with a coarse modal size of

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20–40 μm and a fine modal size of 2–8 μm) of loess on Chinese Loess Plateau (CLP) by mathematical fitting. They argued that the coarse component was transported by low-altitude East-Asia winter monsoon, and the fine component was transported by high-altitude westerlies (Sun et al., 2004). Similar results have also been found in Cheju Island (Korea) and Central Asian loess (Lim and Matsumoto, 2006; Vandenberghe et al., 2006). So, the fine component was used as an intensity indicator of the westerly circulation (Sun, 2004; Lim and Matsumoto, 2006). However, some other researchers suggested that most of the dusts (including both the coarse and fine components) on CLP were from the proximal sources, which were transported by the low-altitude East Asia winter monsoon (Sun et al., 2001; Sun, 2002; Prins et al., 2007). This denied the viewpoint that fine component of the loess on CLP was from a significantly different source.

To the sources of the loess on CLP, Sun et al. (2001) and Sun (2002) found that the loess was mainly from the Gobi deserts of southern Mongolia and northern China (including the Badain Jaran Desert, Tengger Desert, Ulan Buh Desert, Hobq Desert and Mu Us Desert), which were transported by the low level atmosphere circulation (Prins et al., 2007). Moreover, Sun et al. (2008a) inferred that fine quartz particles (<16 μm) on CLP were also from the Gobi deserts of southern Mongolia and northern China based on the analysis of crystallinity index of fine-grained (<16 μm) quartz and electron spin resonance signal intensity. Shi and Liu (2011) further concluded that more than 90% of fine particles of modern aeolian deposits on CLP came from the southern Mongolia and northern China being transported via the low-level atmosphere, whereas the dust from Taklimakan Desert were mainly transported further to the pacific via the upper-level westerlies.

In addition, the phenomena of aggregation and/or fine particles adhering to larger ones in modern dust have often been found under the scanning electron microscope (SEM) (Pye, 1987, 1995; Falkovich et al., 2001; Derbyshire et al., 1998). So, Pye (1987) and Qiang et al. (2010) argued that the fine particles of aeolian deposits could be caused by aggregation and/or fine particles adhering to larger ones, and dispersed when measurement was taken. Moreover, the post-depositional pedogenesis could also make the coarse particles smaller which increases the content of fine silt (Dixon et al., 1984; Sun et al., 2000). All of these also undermine the multi-sources origin of the aeolian deposits with BGSD or even the validity of the fine particle components as an intensity indicator of westerlies.

From the aforementioned debate, some problems could be raised: How does the fine component (<20 μm) of BGSD in aeolian deposits produce? Whether or not the two sub-peak components delegate different sources? Or can the fine sub-peak component be as an intensity indicator of the high-level westerly circulation? At present, the sedimentary process (including the origin of BGSD) of the aeolian deposits has not been completely understood yet, and this makes us hard to exactly interpret the information from the specific size fraction of aeolian deposits in reconstructing the palaeo-environmental changes. Modern dust deposition is the continuation of dust deposition in geological history. This study aims to reveal the origin of BGSD in modern dust deposition based on the observation of their temporal and spatial variation characteristics. The origin of BGSD may provide a theoretic thinking for palaeoenvironmental changes study using the indicator of grain size.

2. Observational sites

The sampling area Cele Oasis (80°43′–80°52′E, 36°57′–37°05′N) is situated at the southern margin of Tarim Basin and at the northern foot of Kunlun Mountains. Taklimakan sandy desert and Gebi desert surround the oasis (Fig. 1). Cele Oasis covers an area of ~184 km^2, which is characterized by warm arid desert climate. The mean annual temperature is 11.9 °C with a maximum of 41.9 °C and a minimum of −23.9 °C, and the mean annual precipitation is ~35 mm with a potential evaporation of ~2600 mm (Li et al., 2009). Prevailing winds are W and WWN with 94.6% westerly threshold wind (>6 m/s) (Wan et al., 2013). The mean annual dusty days (including dust storm (the horizontal visibility being influenced by aeolian dust dropped below 1 km) and floating dust (the horizontal visibility is between 1 km and 10 km)) are of 142.4 days with mean annual dust storm of 21.2 days (Figs. 1B and 2D; Wan et al., 2009). Cele Oasis ecosystem is well developed, and an oasis-desert transition zone with 20–40% vegetation coverage surrounds northwestern edge of the oasis (Mu et al., 2013).

3. Materials and methods

3.1. Field sampling

To investigate the grain size characteristics of modern aeolian deposits, the sampling cylinders were made of polyvinyl chloride pipes. The size is 15 cm of inner diameter and 30 cm of height basing on the Chinese national standards (GB/T 15265-94) (Fig. 2A). Eight sampling cylinders were laid in Cele Oasis (Fig. 1), and numbered Q1–Q8. The sampling cylinders were all fixed at the height of ~3.5 m (Fig. 2B) so as to avoid the influence of saltation efficiently (Goossens et al., 1994). We also fixed the sampling cylinders on a sample-collecting tower respectively on the heights of 1 m, 2 m, 4 m, 6 m and 8 m at the oasis-desert transition zone (Fig. 2C), and numbered T-1 m, T-2 m, T-4 m, T-6 m and T-8 m. In addition, we laid four sampling cylinders (to gather enough aeolian dust, four samples would be mixed together) at the height of ~1.5 m on the rooftop of the laboratory building (~12 m above the ground), at Cele National Station of Observation and Research for Desert-Grassland Ecosystems. The dust deposition was collected with dry method due to the extremely low precipitation and high evaporation (Goossens and Rajot, 2008; Sow et al., 2006). To avoid the influence of dust from the surrounding tall objects, all of the sampling cylinders were laid at an open area.

In this study, we collected eight dust depositions (i.e. from Q1 to Q8) in the oasis for three periods respectively (Table 1). We also collected five dust depositions for two periods from the sample-collecting tower. In addition, we continuously collected 4 samples during a dust event on the rooftop of the laboratory building and numbered D1, D2, D3 and D4. In addition, D5 was obtained from the mixing of D1, D2, D3 and D4. For comparison, five kinds of foliar dusts on different arbors (the heights of these arbors are between 5 and 25 m) were collected at a height of 1.5–2 m in the study area on August 1, 2014 (the same time as the sixth dust event). In order to gather enough dust, we picked up 50–150 mature leaves per arbor randomly. Dust on different kinds of leaves was rinsed into the beaker with distilled water respectively, and then extracted the dust after settling ~100 h.

3.2. Sample measurement

The grain size of bulk sample was measured with a Malvern mastersizer-2000 laser grain size analyzer in the laboratory of Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Measuring range of the analyzer spans from 0.02 μm to 2000 μm with 100 size classes and the outputs were controlled <2% residual errors. The bulk samples of aeolian deposits were directly measured without any pretreatment because the samples did not experience weathering and post-depositional pedogenesis. But the sample of foliar dusts were pretreated with 20% hydrogen

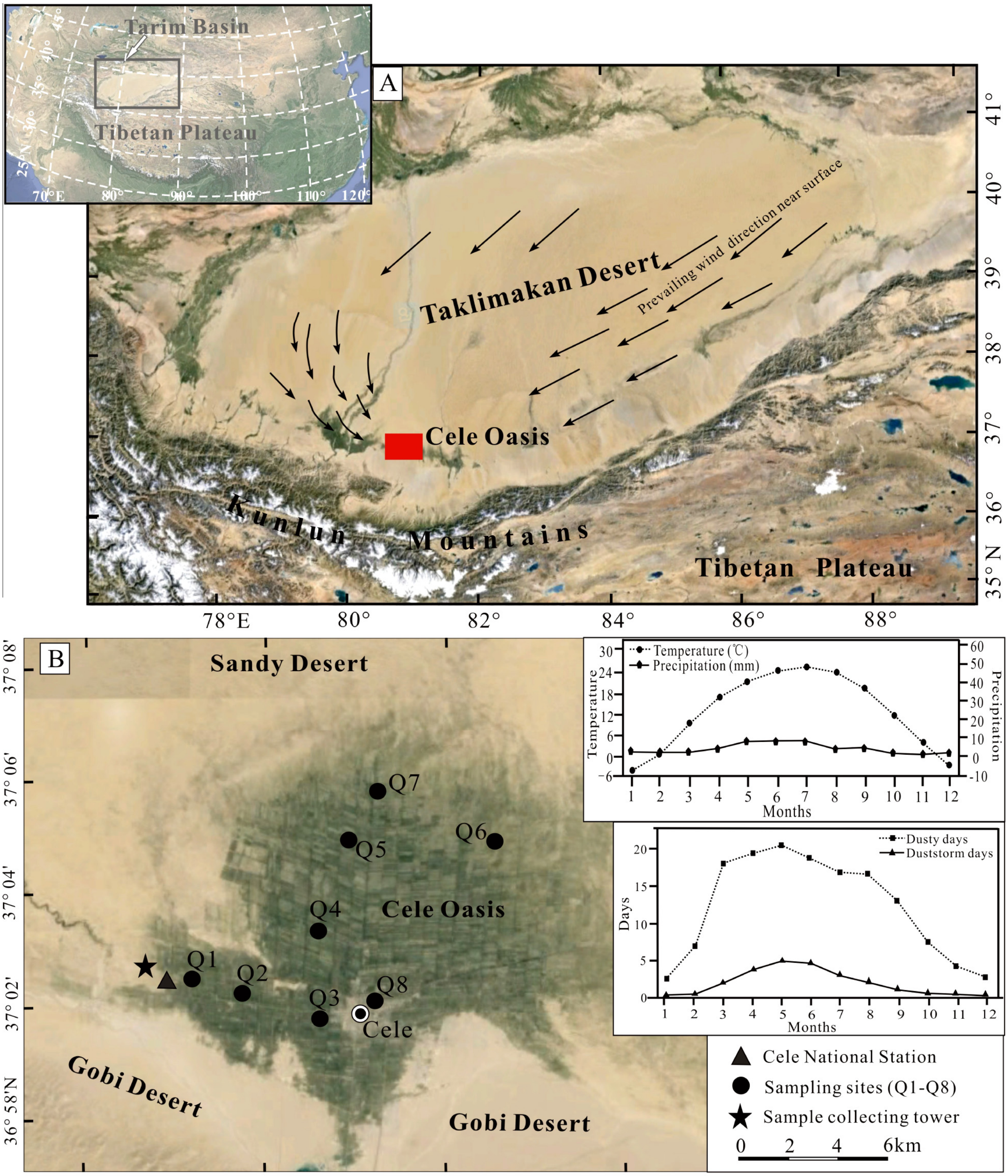

Fig. 1. Sketch map of the sampling sites and climatic characteristic (data from Wan et al., 2009 and Liu et al., 2011).

peroxide (H_2O_2) and 10% hydrochloric acid (HCl) successively to remove the organic matters and carbonates coming from the leaves. In order to fully discrete particles, the sample solution was ultrasounded for 30 s before measurement.

The micrographs of two fresh samples (without any pretreatment) were obtain under the Zeiss supra55vp scanning electron microscope (SEM) installed in Xijiang Institute of Ecology and Geography, Chinese Academy of Sciences. One of the two samples is from the dust storm (i.e. D2), and the other is from the floating dust (i.e. D4).

4. Results and discussion

4.1. BGSD of dust deposition changed with duration

Most of the three dust depositions spans from 0.4 μm to 200 μm (Fig. 3). The aeolian deposits are all BGSD with a coarse component (modal size: 70–80 μm) and a fine component (modal size: 8–15 μm) divided at the grain size of 20–30 μm. A fine tail often appears at the diameter of <2 μm. The dust deposition is

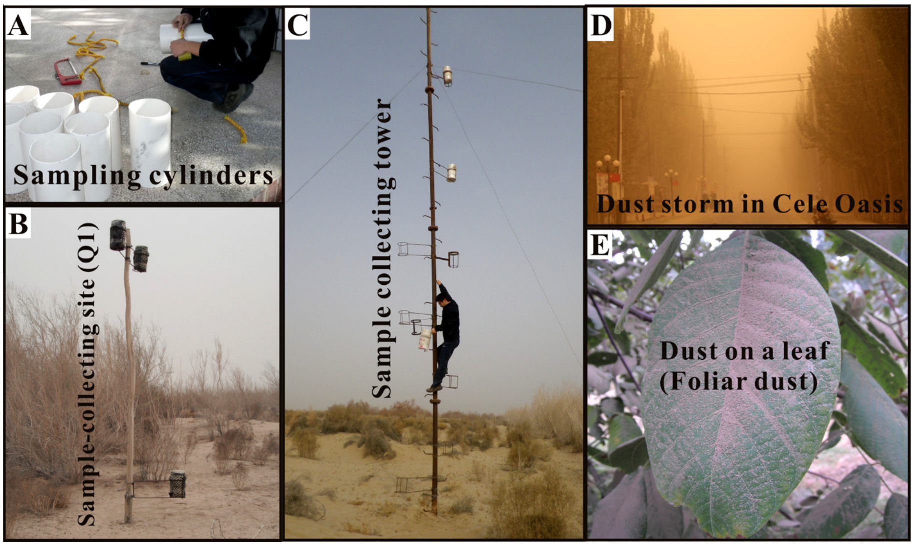

Fig. 2. The sampling devices and the aeolian dust.

Table 1
Sampling information for 6 dust events.

Dust events	Sampling sites	No. (height, m)	Time	Duration (days)	
				Dust storm	Floating dust
1	Cele Oasis	Q1–Q8 (3.5 m)	May 6–May 7 2011	~1.0	~1.0
2	Cele Oasis	Q1–Q8 (3.5)	May 8–May 13 2011	~1.5	~4.5
3	Cele Oasis	Q1–Q8 (3.5)	May 14–May 21 2011	~1.5	~6.5
4	Collecting tower	T-1 (1), T-2 (2), T-4 (4), T-6 (6), T-8 (8)	Apr. 5–May 5 2011	~30.0	
5	Collecting tower	T-1 (1), T-2 (2), T-4 (4), T-6 (6), T-8 (8)	Apr. 2–Apr. 7 2012	~1.0	~5.0
6	Rooftop of the lab building	D1 (1.5)	July 26, 12:00–27, 20:00 2014	~1.0	/
		D2 (1.5)	July 27, 20:00–28, 20:00 2014	~1.0	/
		D3 (1.5)	July 28, 20:00–29, 20:00 2014	~1.0	/
		D4 (1.5)	July 29, 20:00-Aug. 1, 20:00 2014	/	~4.0
		D5 (1.5)	July 26, 12:00-Aug. 1, 20:00 2014	~3.0	~4.0

mainly composed of fine sand and coarse silt with well sorting. Eight dust depositions all present consistent BGSD in the same period (Fig. 3). For the first dust deposition, the content of fine components (<20 μm in diameter) range from 1.7% to 3.3% with an average value of 2.3%. The second period ranges from 7.4% to 10.9% with an average content of 9.4%, whereas, the third period ranges from 10.4% to 21.1% with an average content of 15.4% (Fig. 2E). In addition, all of the three depositions have experienced dust storm and subsequently floating dust, and the duration of floating dust is: Fig. 3A (~0.5 days) < Fig. 3B (~4 days) < Fig. 3C (~6 days). Fine component (<20 μm) increases with the duration of floating dust. These indicate that BGSD can also appear in a dust deposition, and the changing aerodynamic environment can influence the BGSD characteristic.

4.2. The BGSD of dust deposition changed with height

Fig. 4A and B presents GSD of the fourth and fifth dust depositions changing with height. The fourth dust depositions all present BGSD with a fine tail (<2 μm), but vary greatly with height (Fig. 4A). Namely, the content of fine component (<20 μm in diameter) increases with height accompanying with decreasing content of coarse component. The fifth dust deposition presents similar variation characteristic of BGSD to the dust storm (Fig. 4B), i.e., the content of fine particles increases with height at the same way. These suggest that the variation heights will influence the BGSD of aeolian deposits.

4.3. The BGSD of dust deposition changes during a dust deposition

The dust depositions were collected on the rooftop of the laboratory building during the dust storm and subsequently floating dust respectively. The dust deposition during dust storm (Fig. 5: D1, D2 and D3) had few fine particles (less than 5% of <20 μm), but increased significantly during floating dust (Fig. 5, D4: more than 20% of >20 μm size faction). These show that the content of fine component changes in a dust deposition, which is influenced by the changing aerodynamic environment.

4.4. Difference of GSD between the dust deposition and foliar dust

Five kinds of foliar dust (the aeolian dust deposited on the leaves) are general unimodal GSD with a fine tail (<2 μm), and the modal sizes change with each other (Fig. 6). They are significantly different from dust deposition in the sampling cylinder, which are all BGSD (Figs. 3–6). These may be caused by the mechanical sorting of various plants leaves when the dust deposited on them. These indicate that the leaves can influence the GSD of dust depositing on the leaves.

4.5. The surface features of the dust deposition

Fig. 7 presents the surface features of the fresh dust deposition under the scanning electron microscope (SEM). These SEMs show that most of the particles are of being highly dispersed state,

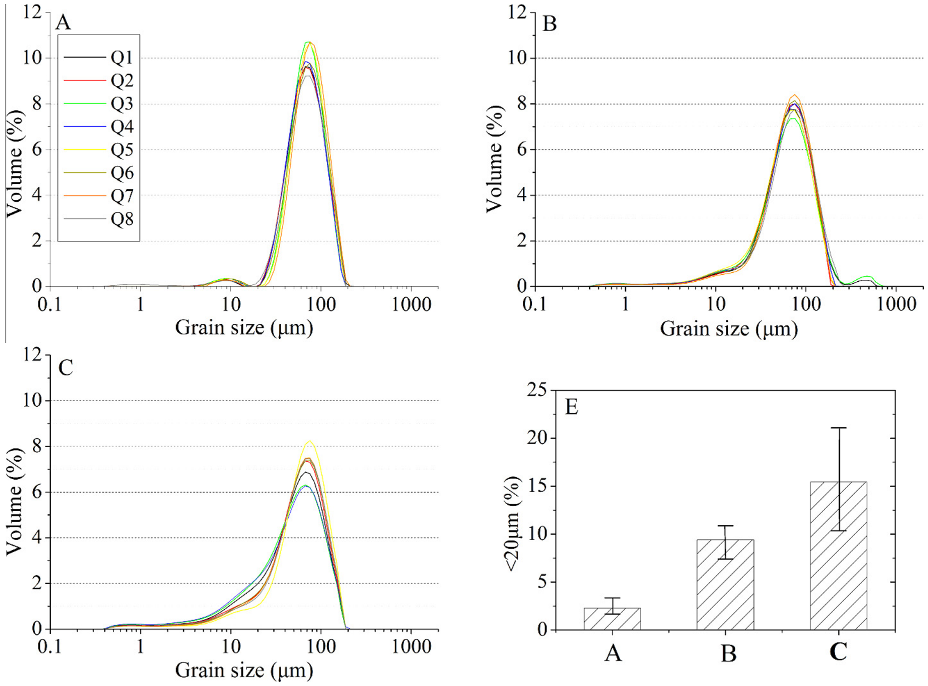

Fig. 3. BGSD of dust deposition in different periods. (A) Dust event happened from May 6 to May 7, 2011; (B) from May 8 to May 13, 2011; (C) from May 14 to May 21, 2011; (E) the percent content of <20 μm size fraction. Vertical bars in Fig. 3E present the ranges of data (Max. and Min.).

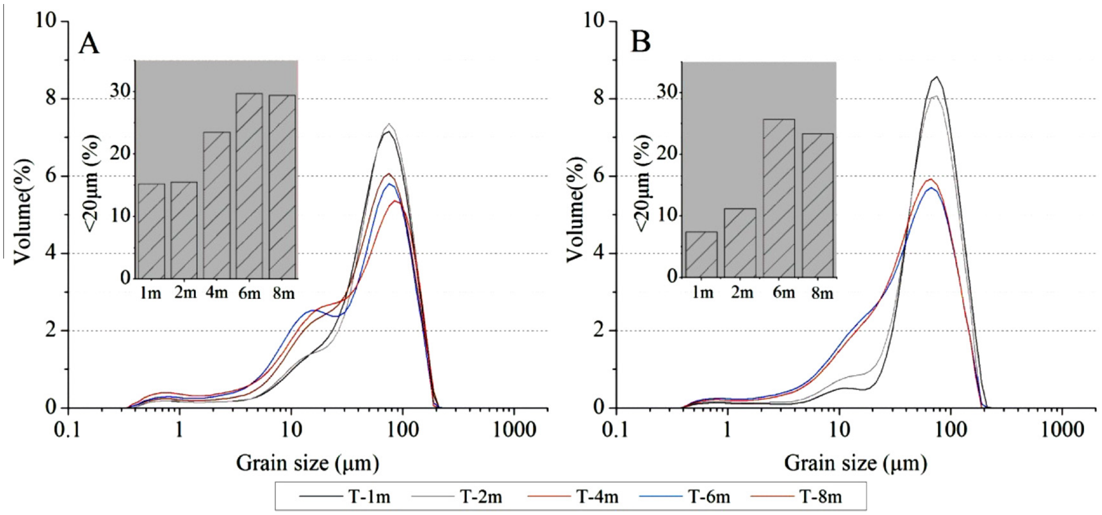

Fig. 4. Variation characteristics of BGSD with height. (A) Dust event happened from April 2 to April 7, 2012; (B) dust event happened from April 5 to May 5, 2011.

except that some particles smaller than 2 μm adhered to the larger particles (Fig. 7A2 and 7B2). The content of fine component is little in dust storm (D2), but increases apparently in subsequently floating dust (D4). These suggest that the appearance of fine component in dust deposition is not caused by aggregation and/or fine particles adhering to the coarse particles.

4.6. The origin of BGSD for modern aeolian deposits

It is a common phenomenon that aeolian deposits in Cele Oasis present BGSD with a coarse component (modal size: 70–80 μm) and a fine component (modal size: 8–15 μm), which are divided at the grain size of 20–30 μm. Based on the analysis of temporal and spatial characteristics of GSD, the results show the formation of BGSD. Firstly, the BGSD of eight dust depositions (Q1–Q8) in different sampling sites are very consistent in the same period, which various size fractions have an equal proportion (Fig. 3). Temporally, the content of fine component deposited in different periods changes obviously (Fig. 3E). The content of fine component is little in the dust storm, but gradually increases with the duration of floating dusty days (Fig. 3E; Table 1). These indicate that the content of fine component has changed between dust storm weather and the subsequent floating dust weather. Field observation in Cele Oasis showed that the wind velocity was obvious high during the dust storm, but dropped significantly and stopped finally during the subsequent floating dust weather. The changing aerodynamic environment during dust deposition should be the main cause for BGSD.

Secondly, this viewpoint is supported by the dust deposition collected during July 26, 12:00–August 1, 20:00 2014 (Fig. 5).

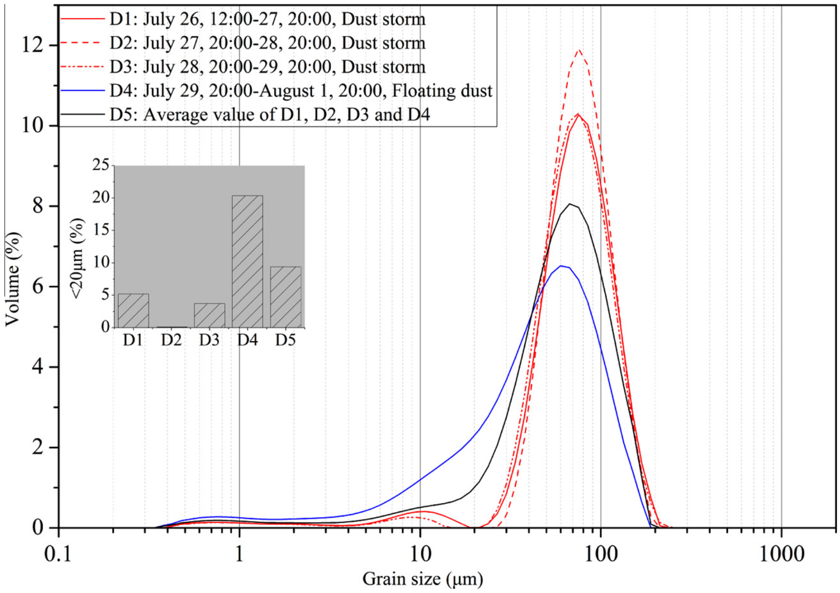

Fig. 5. The GSD characteristics of dust deposition during a dusty weather.

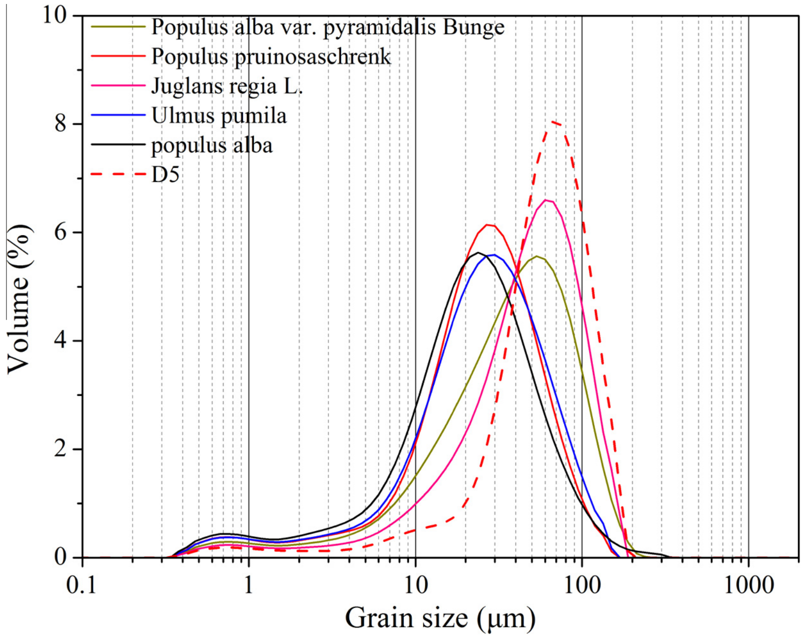

Fig. 6. Comparison of GSD patterns between the foliar dust and dust deposition.

The content of fine component was little in the dust storm, but significantly increased during the subsequently floating dusty weather (Figs. 5 and 7).

Moreover, the dust depositions collected from the sample-collecting tower show that fine components gradually increase with height not only in the dust storm (Fig. 4A) but also in the long period accumulation during April 5–April 5, 2011 (Fig. 4B). These indicate that the changing height can also influence the BGSD of aeolian deposits.

In a word, the BGSD of modern aeolian deposits, observed in Cele Oasis, reveals that coarse particles (>20 μm) in most of dust deposition accompany with some fine particles, and the content of fine component changes with temporal and spatial variation. The dust has been sorted by airflow during transportation and deposition. All of these indicate that the appearance of fine particles is probably caused by the changing aerodynamic environment, which is the main origin of BGSD.

Generally, fine detrital particles (<20 μm) have a U_f/u_* ratio of being less than 0.1 under typical wind storm conditions (U_f represents the settling velocity of the detrital particle, and u_* is the drag velocity of the wind current), they can be widely dispersed and long-range transported by the upper-level airflow (Gillette, 1977; Tsoar and Pye, 1987). So Sun et al. (2004) and Lim and Matsumoto (2006) regarded that the coarse component and fine component of aeolian deposits in different peaks were from different sources. Namely, the coarse component was short-range transported by the low-level atmosphere circulation, whereas, the fine component was long-range transported by the upper-level westerlies and then deposited far from the sources.

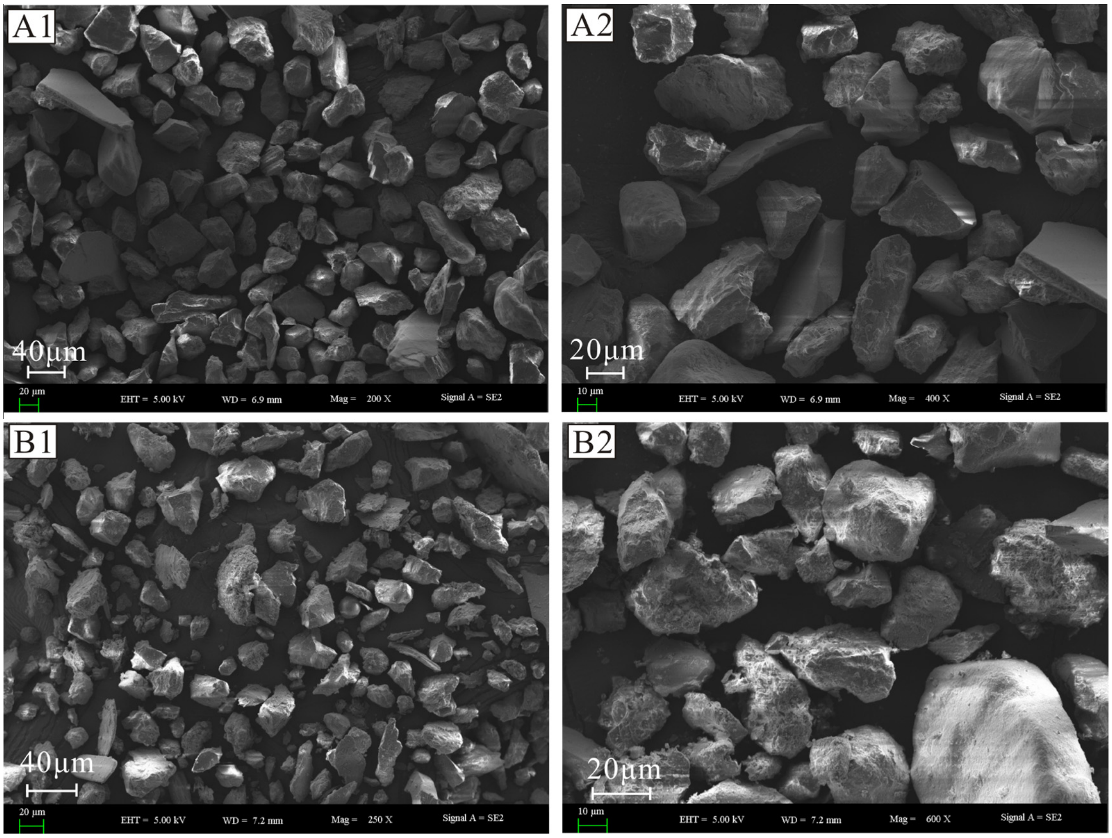

Fig. 7. Scanning electron micrographs of fresh dust deposition in Cele Oasis (A1 and A2: particles in dust storm (i.e., D2); B1 and B2: particles in floating dust after the dust storm (i.e., D4)).

However, particles <20 μm can also settle down during floating dust weather when the wind velocity decreases and even stops. Modern dust deposition observed in Cele Oasis showed that BGSD can appear in a dust deposition (Fig. 3). The GSD of aeolian deposits changes temporally from dust storm weather to the subsequent floating dust weather (Fig. 5). It indicates both of the coarse component and fine component did not come from different sources. In addition, the fine component would hardly take up such large proportion (up to 21%; Fig. 3) in a short period if it was the atmospheric "background dust". Furthermore, the floating dust presenting unimodal GSD also undermines the viewpoint that dust mixing the different material sources would present multimodality. Conversely, even if they indeed come from different sources, the dust components should be well-mixed in airflow during transportation and deposition under the influence of aerodynamic environment. They are hard finally to form multiple peaks respectively corresponding with different sources. Therefore, we consider that the different sources are not the main origin of BGSD.

Aggregation appears in soil during pedogenic processes, which make the fine particles increase when measures grain size in a highly dispersed state (Sun et al., 2000). Aggregation was also reported in modern aeolian dust (Pye, 1987; Derbyshire et al., 1998; Falkovich et al., 2001; Qiang et al., 2010). Pye (1987) and Qiang et al. (2010) regarded that aggregation and/or adhesion in aeolian dust was the main origin of fine component of BGSD pattern. However, the following phenomena observed in Cele Oasis undermine this viewpoint. Firstly, the micrographs of fresh samples under SEM show little aggregation, or adhering of fine particles to the coarse particles (Fig. 5: D4; Fig. 7). Secondly, if aggregation is the main origin of BGSD, fine particle component should have co-varied with the coarse particles component, which would have made the BGSD characteristics of different periodical aeolian deposits similar to each other. However, the aeolian deposits collected in different periods show apparently different content of fine particles (<20 μm size fraction; Fig. 3). Even the content of fine particles varies obviously from dust storm to subsequent dusty weather (Fig. 5). Thirdly, the GSD of aeolian deposits during the same dust storm should be consistent with height because of aggregation. However, the content of fine particles in Cele's aeolian deposits changes with height (Fig. 4). Finally, five kinds of foliar dust all presented unimodal size distribution pattern which were completely different from the aeolian deposits. These may be caused by the mechanical sorting of various plants leaves when the aeolian dust deposited on them. Therefore, aggregation is likely not the main origin of BGSD.

In addition, Sun et al. (2000) regarded that the post-depositional pedogenesis could increase the content of fine particles. However, the quartz particles separated from the loess, which are more weathering resistance and more reflecting the grain size characteristics of aeolian deposits, also present BGSD (Xiao et al., 1995; Sun et al., 2000; Feng et al., 2014). So, post-depositional pedogenesis of the aeolian deposits may be not the main origin of the fine particles. Further, the particles caused by post-depositional pedogenesis are generally smaller than 2 μm (Bronger and Heinkele, 1990; Sun, 2006), which are not the main component of the sub-peak. Moreover, the dust deposition in Cele Oasis, which have not experienced any post-depositional pedogenesis, also presented BGSD. So the post-depositional pedogenesis is probably not the main origin of BGSD.

The aforementioned analyses indicate that the detrital particles once being entrained into the air would be reworked during transportation and deposition. BGSD of modern aeolian deposits are likely caused by the changing aerodynamic environment. Whereas, other causes such as aggregation, post-depositional pedogenesis

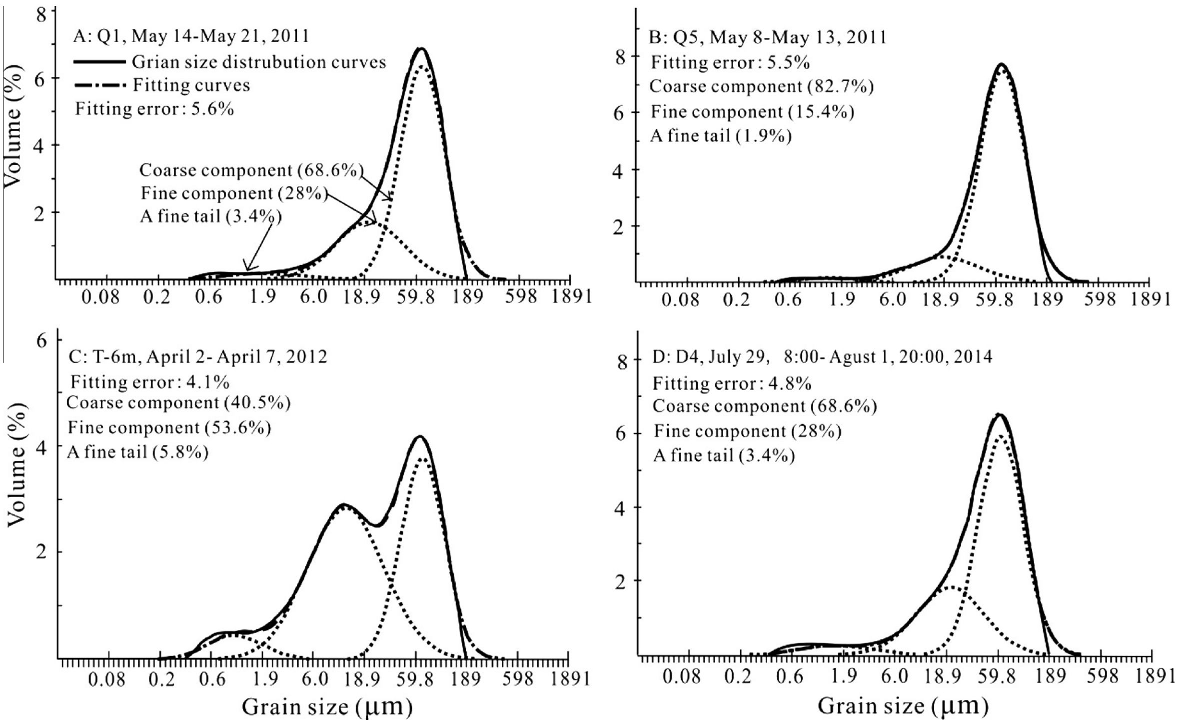

Fig. 8. Mathematical portioning of the coarse and fine grain size component of aeolian deposits at Cele Oasis.

and/or being from different sources are not the main origins, which may also intensify this phenomenon if they exit.

4.7. The insights from the origin of modern aeolian deposits

The origin of Chinese loess deposits have been discussed for many years (Liu et al., 1993, 1994; Sun, 2002; Honda et al., 2004; Chen et al., 2007; Guan et al., 2008). Most researchers supported that the coarse component of loess on Chinese Loess Plateau was low-level transported which can delegate the intensity of dust storm and be as an intensity indicator of East Asia winter monsoon. But to fine component, many researchers have different viewpoints, such as being from a different provenance (Windom, 1975; Glaccum and Prospero, 1980; Tsoar and Pye, 1987; Pye, 1987, 1995), aggregation and/or adhering of fine particles to larger ones in the modern aeolian dust (Pye, 1987, 1995; Falkovich et al., 2001; Derbyshire et al., 1998), or the post-depositional pedogenesis (Dixon et al., 1984; Sun et al., 2000). It is likely that all of these phenomena do exist during dust deposition on Chinese Loess Plateau. However, what important now is which factors are too important to be ignored.

Based on the analysis of the GSD of modern dust deposition at Cele Oasis, the results show that BGSD also appears in various modern dust depositions, which cannot be from a different source. Even, two sub-peaks of the BGSD are accurately fitted (Fig. 8) based on the mathematical fitting method mentioned by Qin et al. (2005). And the content of fine peak component can be more than 50% (Fig. 3C), which cannot be ignored. Therefore, we regarded the dust would be resorted once they were entrained into the air, and transportation and deposition at certain aerodynamic environment. Whether the BGSD appears or not should not be influenced by the sources, aggregation and/or adhering to larger particles and post-depositional pedogenesis. In addition, it has been found that the loess around the Tibet Plateau whose material were from the proximal sources can also present BGSD, which the transporting dynamic were the katabatic wind, the glacial wind and/or the local mountain-valley wind (Zhang et al., 2014; Pan et al., 2014; Feng et al., 2014; Lin and Feng, 2015). Therefore, it cannot be compelling that the unmixing sub-peaks of the dust deposition delegate different sources, and even that the fine component can be as an intensity indicator of the high-level westerlies.

5. Conclusions

Modern dust deposition in Cele Oasis provides an excellent media to understand the origin of BGSD of aeolian deposits. Based on the analysis of BGSD of Cele's dust deposition, we found that BGSD also appears in a dust deposition. The content of fine components (<20 μm) change with temporal and spatial variation. The fine component from dust storm is significant less than the one from subsequent floating dust in a dust deposition. Fine component also changes with altitude. These indicate modern dust deposition with BGSD has experienced changing aerodynamic environment, and been reworked during transportation and deposition, which is likely the main cause for BGSD. The particles from different sources once being well-mixed in airflow are hard to form multiple peaks corresponding with different sources. In addition, aeolian deposits would appear BGSD whether aggregation or not. Consequently, aeolian deposits with BGSD cannot be simply regarded as multi-sources origin, or even that fine component in the loess is an intensity indicator of the westerlies.

Modern dust deposition is the continuation of dust deposition in geological history. BGSD not only appear in modern dust deposition but also in ancient aeolian deposits. They both probably have the same origin. Therefore, the origin of BGSD of aeolian deposits in this study may provide a theoretic thinking for reconstructing the paleo-environmental changes with the indicator of grain size.

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