Two Alternating Processes of Particle Size Distribution of Barchan Dunes at the Edge of the Oasis in Hexi Corridor, Gansu

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Abstract Barchan dunes are a common type of dune. There are a lot of barchan dunes at accumulated sand-belts of the oasis edge of Hexi desert area of Gansu. What is characteristic of the particle size of barchan dunes? How is this particle size characteristic formed? Characteristics of particle size were analyzed in this paper by comprehensive investigation and sampling in Hexi Corridor desert area, and repeated sampling and determination in Minqin desert area. The results showed that: ① The particle size of 0.25–0.05 mm and particle size of 0.5–0.25 mm were the main ingredients at the surface 0–5 cm depth of barchan dunes and barchan dune chains in desert area in Hexi Corridor of Gansu. Sand in Gulang desert area was relatively finer and the particle size was quite different from that of Jinchang, Linze, Jinta and Minqin desert area; ② The particle size was changed from coarse to fine from the bottom to the top of the dunes in the main wind direction (NW) process. i.e. there was the most silt at the top of the dunes, followed by the middle of the leeward slope. The bottom of the windward slope had the most coarse sand, followed by the middle of the windward slope. The barchan dunes were changed from coarse to fine, then from fine to coarse from the bottom to the top of the dunes in the reverse wind direction (SE) process, i.e. there was the most silt in the middle of the windward slope, followed by the top of sand dunes. The bottom of the windward slope had the most coarse sand, followed by the middle of the windward slope. The standard deviation and coefficient of variation of sand dune particle size in the main wind direction process was larger, and the standard deviation and coefficient of variation of sand dune particle size in the reverse wind direction process was smaller; ③ The two processes of the main wind direction (NW) and the reverse wind direction (SE) led to alternating changes in particle size in various parts of the dunes. Two different conclusions on particle size distribution of barchan dunes in windward slope were due to the observation season differences.

Keywords Barchan dune, Particle size, Wind speed, Hexi desert area of Gansu
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Barchan dunes are a major type of dune that is generally distributed on the relatively open flat gravel or sticky beach land at the downwind edge of the desert. The special morphological characteristics of barchan dunes originate from their special environment, and different sand dune forms in turn form different sand dune flow fields[1].

The sedimentary structure of the dunes contains climate environment information of the dune development process. The particle size distribution of the dune surface contains a large amount of environmental information and flow field information[2-3]. Therefore, there are many research reports on dune particle size at home and abroad, such as the research on particle size of barchan dunes[4-5], pyramid dunes[6-7], lateral dunes[8], lattice dunes[9], coastal dunes[10], etc. There is also the research on the effects of artificial measures on sand dune size[11-12], but the conclusions are not completely consistent.

The research on particle size of barchan dunes mainly focused on two aspects: particle size distribution and sedimentary structure. In terms of particle size distribution, there were two generally opposite conclusions. One research concluded that from the bottom of the windward slope to the top of the dune, there was a general trend becoming fine, while the top of the dunes became coarser. The other research conclusion was that the particle size of barchan dunes from the bottom of the slope to the top of the dunes tended to be coarser. The particle size of the leeward slope was finer than that of the windward slope. The degree of sorting was best in the dune ridge, and gradually became poorer to two slopes[4, 15-17]. The US geoscientist Folk et al.[18] pointed out that this difference was caused by the particle size composition of sand source sediments. Yang Yanyan[2] believed that the distribution of surface particle size of sand dunes was affected by both sand sources and dynamic processes, mainly depending on which factor had a greater impact.

The sedimentary structure of the dune characterizes the formation process of sand dunes and the formation environment of sand dunes. By anatomizing the sedimentary structure of the sand dunes, we can study the accumulation law of particle size during the formation of sand dunes. However, on the one hand, barchan dunes are mostly mobile dunes, and the sand is loose, and the excavation profile is difficult. On the other hand, due to the repeated accumulation of sand flow, the sedimentary structure of barchan dunes is very complicated, and the results of the study on the sedimentary structures of barchan dunes parallel and perpendicular to the prevailing wind direction in New Mexico are not ideal[19]. Ortiz et al.[20] used GPR to study the internal structure of coastal barchan dunes in the Ebro Delta of Spain, and pointed out that there were many overlapping units inside the dunes. The slope angle of the sand dunes on the windward slope can reflect the strong degree of sandstorm activity. The greater the inclination angle of the bedding is, the stronger the sandstorm activity is. Li Zhizhong's early research[21] showed that the degree of seasonal and longer-period wind direction changes, sand dune size and shape changes also affected sedimentary structural features.In summary, although there are many reports on the particle size of sand dunes, they are basically related to the size

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distribution of sand dunes, and their conclusions are not consistent, especially lack of particle size formation process of different environments and sand dunes. So what is characteristic of the particle size of barchan dunes in the desert area of Hexi Corridor in Gansu? How is this particle size characteristic formed? This article made a preliminary analysis about it.

1 Research area and observation research methods

1.1 Research area

Hexi area of Gansu that refers to the five cities of Wuwei, Jinchang, Zhangye, Jiuquan and Jiayuguan in the west of the Yellow River. The geographical position is between 92°45'E–104°15'E and 36°35'N–42°45'N. The south side of the area is Qilian Mountains, and the east, north and west sides are surrounded by Tengger Desert, the Badain Jaran Desert and the Kumtag Desert. There are desert and sporadic sandy land of 7.54 × 10^2 km^2. There are a large number of tall barchan dunes and barchan dune chains at the edge of the oasis (Fig. 1).

1.2 Observation research methods

Based on a comprehensive survey of barchan dunes and barchan dune chains on the edge of the Hexi Oasis in Gansu, ① Determination of dune height, width and slope: measure dune height (highest point) and leeward with Leica D5 laser range finder. The distance and height difference between the highest point of the dune and the sand ridge line were determined by this method.The dune width was measured on Google Earth. ② Sand sample collection: 12 sand sample sampling positions were uniformly determined on the sand dunes, and the sampling depth was 0–5 cm, and sand samples were taken at each sampling point of 25 observation dunes and dune chains (Fig.2). The main wind direction (NW) particle size sampling date was April 2015, and the reverse wind direction (SE) particle size sampling time was September 2015. The reverse wind direction was only sampled on the Minqin crescent sand dunes (Fig.2). In this paper, the length of the dune chord was the distance between the ends of the two wings of the sand.

1.3 Data analysis

The particle size data of the sampling area of all the sample areas were compared in the sand dunes of different campus areas. The particle size analysis of the two wind direction processes only used the particle size data of Minqin sample area. Particle size analyzer adopted MASTERSIZER-2000. Particle size classification: coarse sand (0.5–2.0 mm), medium sand (0.25–0.5 mm), fine sand (0.05–0.25 mm), silt (0.005–0.05 mm) and sticky sand (<0.005 mm). The correlation coefficient was used to express the relationship between particle size and wind speed. The variance analysis method was used to test the significance of the difference between the samples and the correlation significance between the indicators. All data analysis was done with SPSS 13.0.

2 Result and analysis

2.1 Particle size differences in different sample areas

Barchan dunes in Hexi area of Gansu were mainly distributed on the upwind edge of Minqin Oasis on the western margin of Tengger Desert and the upwind edge of the Jinchang oasis and the windward edge of the Jinta oasis on the western edge of the Badain Jaran Desert (Fig.1). The average height of barchan dunes was 8.92 m and the highest was 11.58 m (Minqin). The average width is 111.79 m and the widest is 147.6 m (Minqin). The average chord length (the distance between the horns) was 185.58 m and the widest was 264.5 m (Jinta). The average slope of the leeward slope is 31.78°, and the steepest was 32.9° (Minqin). The average trend was N49.44°W, and the west-north of the Jintasha area at the western end of the corridor is larger (N63°W). The average height of barchan dune chain was 9.81 m and the highest was 17.84 m (Jinta). The average width is 79.19 m, and the widest is 163.3 m (Jinchang). The average chord length was 129.39 m, and the widest was 306.8 m (Jinta). The average slope of leeward slope was 30.43°, and the steepest was 32.6° (Minqin). The average trend was N50.18° W.

There were no barchan dunes in Gulangsha District and Linzesha District. In order to compare the particle size differences of sand dunes in different areas of Hexi Corridor desert area, we also obtained particle size samples at the same time (late April, 2015) in Gulangsha and Linzesha desert area. The statistical results

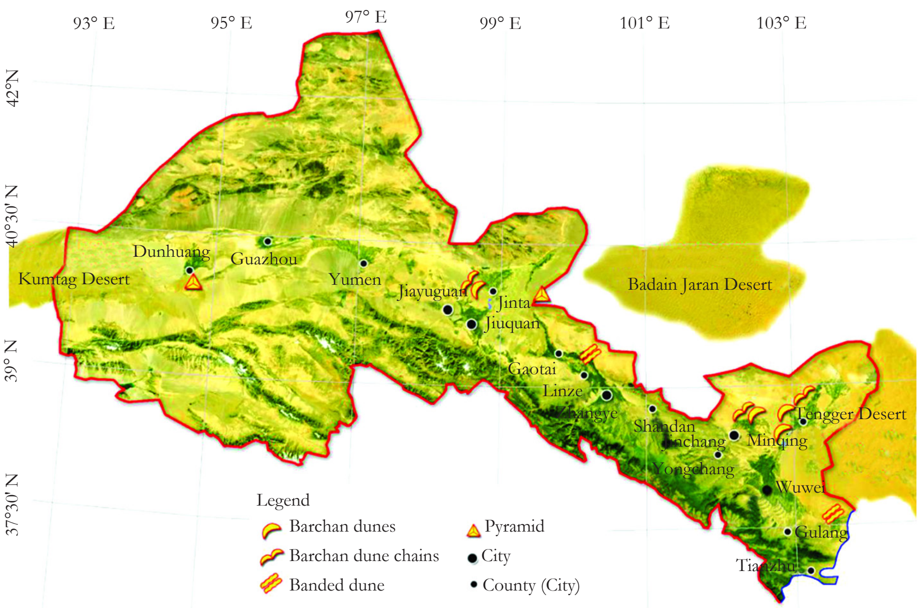

Fig.1 Distribution area of barchan dune and barchan dune chains in Hexi desert area of Gansu

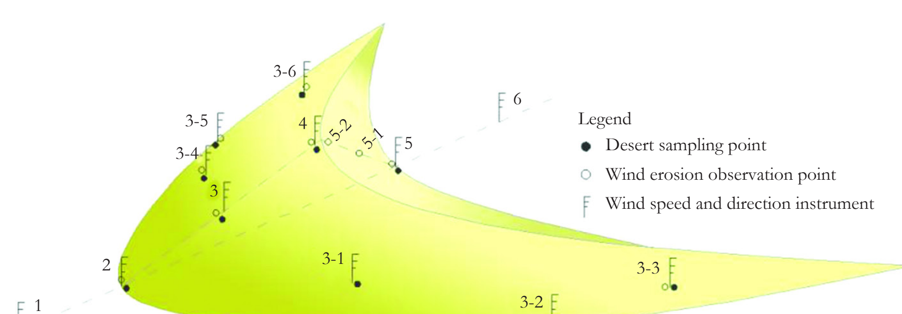

Fig.2 Schematic diagram of observation sample points of barchan dunes

showed that the sand particles of the above three types of sand dunes were dominated by fine sand and medium sand. The average fine sand in the wind-slope slopes of the sand dunes accounted for 56.1%, and the medium sand accounted for 36.4%. The average fine sand in each area of the sand dunes accounted for 56.6% and medium sand accounted for 38.8%. The fine sand on the windward slope of the Gulang desert area at the eastern end of the corridor was the most, followed by Minqin desert area,then followed by the Jintasha area, Linzesha area and Jinchangsha area. In the middle section of the corridor, the medium sand on the windward slope of the sand dunes in the Linzesha area were the most, and gradually decrease from east to west.The medium sand on the windward slope of the Gulang desert area was the least. There was about 10% coarse sand on the windward slope of the sand dunes in Minqin, Jinchang and Jintasha areas, and about 5% coarse sand on the windward slope of the sand dunes in Linzesha area, while there was no coarse sand on the windward slope of the sand dunes in Gulangsha area. Except for the small amount of silt in the sand dunes on the sand dunes in Linze, Jinchang and Minqinsha areas, there were no silt on the windward slope of the sand dunes in Gulang and Jintasha areas and the sand dunes in all the sample areas (Fig.3).

Table 1 Morphological characteristics of barchan dune and barchan dune chains in Hexi desert area of Gansu

Dune type	Sample area	Dune number	Particle size characteristic				
			height//m	leeward//°	width//m	Chord length//m	Trend
Barchan dunes	Minqin	1	9.75	32.60	123.6	206.5	N48° W
		2	11.16	32.20	143.9	243.6	N48° W
		3	9.32	32.40	122.2	179.6	N48° W
		4	7.92	32.90	67.80	103.6	N45° W
		5	7.55	31.50	87.60	174.5	N46° W
		6	11.58	31.60	147.60	143.9	N46° W
		7	8.61	30.10	123.30	93.8	N46° W
		8	8.42	31.70	115.20	260.2	N55° W
	Jinta	9	6.01	31.05	74.90	264.5	N63° W
Barchan dune chains	Minqin	10	3.76	32.60	27.00	92.2	N46° W
		11	7.05	32.60	42.30	56.5	N46° W
		12	4.36	29.60	10.80	76.0	N46° W
		13	6.76	31.80	28.20	58.4	N45° W
		14	10.08	31.50	17.40	35.4	N45° W
		15	12.16	33.10	110.90	223.3	N50° W
	Jinchang	16	7.74	28.10	163.30	155.9	N43° W
		17	10.97	31.20	133.60	139.9	N56° W
		18	7.85	25.10	89.90	156.7	N49° W
	Jinta	19	17.84	28.00	129.40	122.2	N63° W
		20	19.29	31.10	118.30	306.8	N63° W

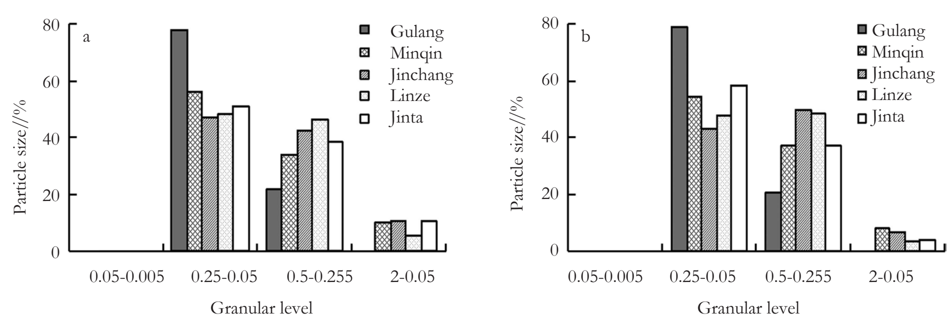

Fig.3 Particle size distribution in sand aera, *a* in windward slope, *b* in leeward slope

2.2 Particle size distribution of dunes in two wind direction processes in Minqin sand area

2.2.1 Dune particle size after the main wind direction process The main wind direction in Minqin desert area was NW. Spring was the season of heavy wind and sandstorm from March to May every year. It was the most in April, followed by March and May.The seasonality of the wind direction distribution was very strong, that is, the NW, NNW and WNW winds were mostly in the spring, and the SE, ESE and SSE winds appear in summer from June to August. In spring of 2000–2014, the average NW, NNW and WNW winds of ⩾ 5 m/s occurred 64.0 times, of which NW, NNW and WNW winds of ⩾ 10 m/s were 6.4 times, while in summer, SE, ESE and SSE winds of ⩾ 5 m/s occurred 5.3 times, of which SE, ESE and SSE winds of ⩾ 10 m/s were 2.1 times (Fig.4).

The results of particle size analysis in late April of 2015 (after NW strong wind) showed that there was very little silt content of 0.005–0.05 mm on Barchan dunes in Minqin desert area, and it was mainly distributed at the top of the dune and the middle of the leeward slope (Fig.5a). The fine sand content of 0.05–0.25 mm was more. From the bottom of the windward sand dune to the top of the dune to the upper part

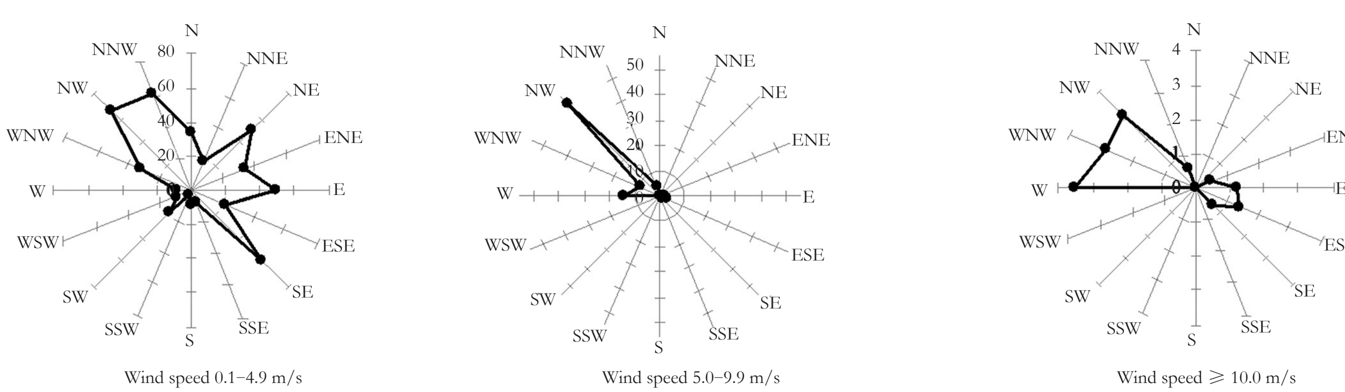

Fig.4 Distribution of wind speed and wind direction in Minqin desert area from 2000 to 2014

of the leeward slope, there was an increasing trend. To the bottom of the leeward slope, there was an decreasing trend (Fig.5b).There was an increasing trend from the dunes to the bottom of the windward slope and the bottom of the leeward slope (Fig.5c). The coarse sand content of 0.5–2.0 mm was less. It was mainly distributed in the bottom and middle of the windward slope. From the bottom of the windward slope to the top of the sand dune to the middle of the leeward slope, the trend was decreasing, and to the bottom of the leeward slope the trend was increasing again (Fig.5d).

Here were the particle size distribution characteristics of the two wings of the windward slope: The silt content of 0.005–0.05 mm was also little, and there was a decreasing trend from the middle of the windward slope to the two wings (Fig.5e). The fine sand content of 0.5–0.25 mm was the most, and the distribution was relatively uniform (Fig.5f). The medium sand content of 0.25–0.5 mm was more, and there was also a decreasing trend from the middle of the windward slope to the two wings (Fig.5g). The coarse sand content of 0.5–2.0 mm was less, and there was an increasing trend from the middle of the windward slope to the two wings (Fig.5h).

2.2.2 Dune particle size after the reverse wind direction process. The wind direction on October 24 was SE, and the wind speed at the top of No.2 dune (No.4) reached 7.23 m/s, and the daily average wind speed was 3.17 m/s.

The sampling results on October 26 showed that silt of 0.005–0.05 mm was mainly concentrated in the middle, top and leeward slopes of the sand dunes, and the content was also very small, less than 0.4% (Fig.6a). The fine sand content of 0.05–0.25 mm was significantly increased and tended to be uniform (Fig.6b). The position with the least coarse sand content of 0.5–2.0 mm was at the top of the dunes and the upper part of the leeward slope, and the overall content had a decreasing trend (Fig.6d).

2.3 Dune particle size differences between the two processes

The comparison between the particle size distribution characteristics of the main wind direction of each of the three sand dunes (Fig.5) and the reverse wind direction process (Fig.6): The average particle size of the silt (0.005–0.05 mm) was smaller than the average particle size of the anti-wind process, and the average standard deviation and average coefficient of variation of the particle size were larger than the standard deviation and average coefficient of variation of the average particle size of the anti-wind process. The average particle size of the fine sand (0.05–0.25 mm) was smaller than the average particle size of the reverse wind direction process, and the average standard deviation and the average coefficient of variation are larger than the average standard deviation and the average coefficient of variation of the same-level particle size in the reverse wind direction process. The average particle size, average standard deviation and average coefficient of variation of medium sand (0.25–0.5 mm) were larger than the average particle size of the same grade, average standard deviation and average coefficient of variation in

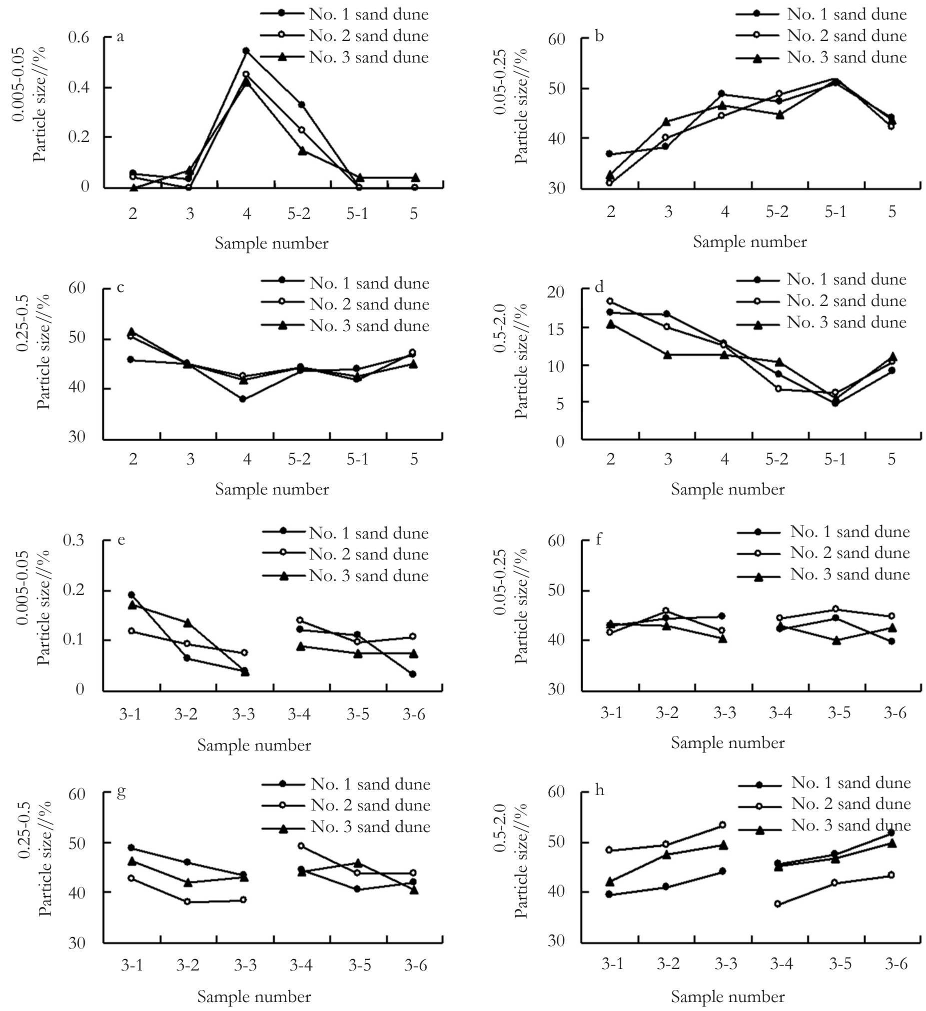

Fig.5 Particle size distribution under main wind direction

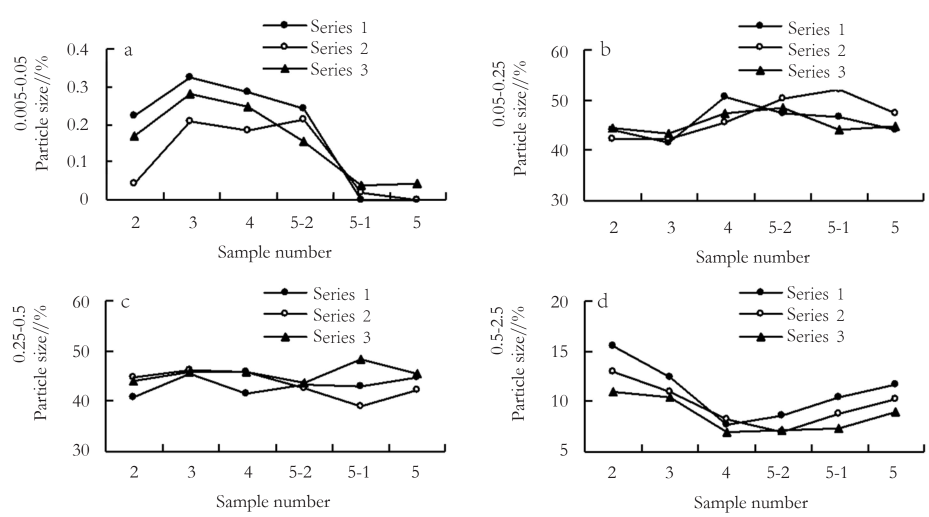

Fig.6 Particle size distribution under reverse wind direction

Table 2 Sand dune particle size difference comparison of the two processes

Particle size mm	Dune number	Main wind direction process			Anti-wind direction process		
		Average %	Standard deviation %	Coefficient of variation	Average %	Standard deviation %	Coefficient of variation
0.005–0.05	1	0.98	0.21	1.27	1.07	0.13	0.73
	2	0.74	0.17	1.40	0.66	0.09	0.83
	3	0.74	0.14	1.18	0.93	0.09	0.59
	Average	0.82	0.17	1.28	0.89	0.10	0.72
0.05–0.25	1	273.57	6.39	0.14	274.16	2.92	0.06
	2	262.18	6.99	0.16	280.12	3.70	0.08
	3	270.17	6.25	0.14	272.80	1.84	0.04
	Average	268.64	6.54	0.15	275.69	2.82	0.06
0.25–0.5	1	265.89	2.91	0.07	259.50	1.68	0.04
	2	271.95	2.95	0.07	261.20	2.54	0.06
	3	272.40	3.14	0.07	273.30	1.56	0.03
	Average	270.08	3.00	0.07	264.67	1.93	0.04
0.5–2.0	1	59.96	5.05	0.51	66.40	2.52	0.23
	2	65.15	4.43	0.41	58.30	1.95	0.20
	3	56.82	3.45	0.36	52.00	1.62	0.19
	Average	60.64	4.31	0.43	58.90	2.03	0.21

the reverse wind direction process. The average particle size, average standard deviation and average coefficient of variation of coarse sand (0.5–2.0 mm) were aslo larger than the average particle size of the same grade direction, average standard deviation and average coefficient of variation in the reverse wind direction process. (Table 2)

It can be seen that the standard deviation and coefficient of variation of the dune particle size in the main wind direction process were also larger, and the standard deviation and coefficient of variation of the dune particle size in the reverse wind direction process are also smaller.

3 Discussion

(1) It can be seen from Fig.3 and Fig.4 that there are many fine sands in Gulang sand area, and there are fewer medium sand and no coarse sand, and the particle size distribution is significantly different from that in Jinchang, Linze, Jinta and Minqin sand areas(Fig.5). The main reason is that the gale in the Gulang sand area is relatively small. The windy day with an average of $\geqslant$ 8 and above for many years is 4.5 d·a-1, while the upwind direction of Wuwei is 9.7 d·a^{-1}, Minqin 25.1 d·a^{-1}, and Hexi Corridor averaged 18.4 d·a^{-1}. The sample of Gulang sand area is located on the southern edge of Tengger Desert. The reason for the lack of strong wind is that the sample is close to the piedmont area.

(2) As previously known, one study suggested that the sand particles became from coarse to fine from the bottom of the windward slope of the dunes to top. The other study suggested that the sand particles changed from fine to coarse from the bottom of the windward slope of the dunes to top[13-14]. The reason for these two different outcomes may be related to the observation season.In the main wind direction (NW) process ,the change was from coarse to fine from the bottom of the windward slope of the dunes to top. In the reverse wind direction (SE) process, the change was from coarse to fine and then was from fine to coarse from the bottom of the windward slope of the dunes to top. That is to say, the wind blew the fine sand in the leeward slope in the opposite direction, and then rose after crossing the sand ridge line (Fig.7). The larger the wind speed, the farther the fine sand flew and accumulated in the upper part of the windward slope. For this reason, there are many different overlapping units and inclined bedding in the sedimentary structure of the dunes[20].

(3) In some areas, such as the northern sand margin of Linzesha area (the southwestern edge of the Badain Jaran Desert), the leeward slope is relatively flat (28.2–31.5°) due to the large SE winds in summer and autumn. When the NW winds occur in spring, the wind and sand flow rises along the windward slope. When crossing the sand ridge line, the relatively coarse sand particles fall down by gravity. Only the fine sand continues to move forward, and the coarser the sand, the earlier it lands.The coarser sand that landed at the top of the leeward slope naturally slipped, thus forming a falling sand slope.The falling sand slope of barchan dune and the barchan dune chain in Minqin sand area is a straight line, while in the banded sand raft in Linzesha area, due to the gentle leeward slope, an obvious slip line was formed on the upper part of the leeward slope (Fig.8).

(4) The coarse sand particle size of the windward and leeward slopes of barchan dune chain was less then that of barchan dune. It may be due to the wide wings of the crescent-shaped dunes and the strong sorting effect. And the barchan dune chain could only be open at both ends, and the sand dunes in the middle of the chain do not have open areas on both sides. The airflow consumes energy as it

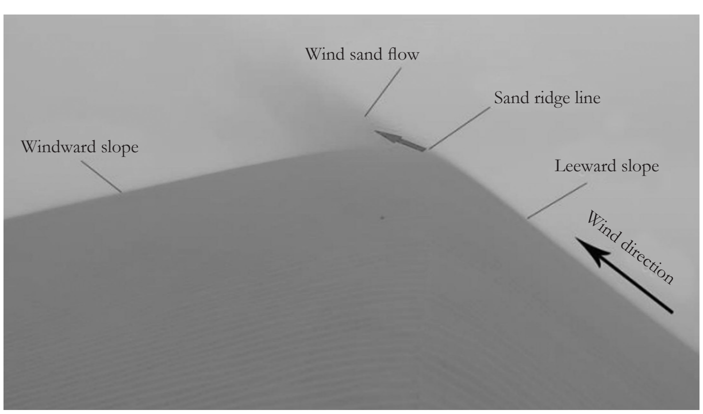

Fig.7 Flying situation after sand flow across the desert ridge line from the leeward slope

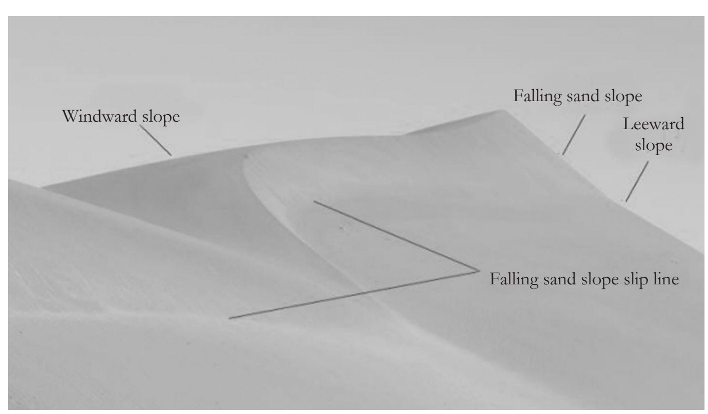

Fig.8 Situation of quicksand slipped on the upper part of leeward slope

rose along the slope of the dunes[1], therefore, the wind selection effect was smaller than the independent barchan dunes.

(5) The existing research[2] stated that there were two cases of separation and coincidence between the highest point of the barchan dune and the sand-ridge line, and pointed that it was caused by the change of wind direction. In fact, this conclusion was not accurate, and it was because of the aforementioned strong wind in the opposite direction to the main wind direction. For example, the No.4 barchan dune of this article, after the NW strong wind in spring, its sand ridge line coincides with the highest point, while after several SE winds in summer, its sand ridge line is separated from the highest point. The reason is that the SE wind blows the sands from the leeward slope and it accumulates behind the sand ridge line and forms the highest point of the sand dune (Fig.7).

(6) Both environmental and dynamic factors led to the formation of particle size characteristics of barchan dunes. Environmental factors include the status of sand sources, as well as their own morphological characteristics, such as high and low forms, whether in the form of a chain, etc. Dynamic factor was mainly wind speed.The environmental factor interacts with the dynamic factor, and its particle size was the process of repeated superposition of its environmental factors and dynamic factors. Because of this, the relative stability of the crescent was maintained.

(7) The standard deviation and coefficient of variation of dune particle size in the main wind direction were larger than those in the reverse wind direction. There are two reasons for this. First, the wind speed in the main wind direction is relatively larger, and the wind results are better. Second, the sand source in the reverse wind direction process is mainly from the fine sand and medium sand deposited by the main wind direction of the leeward slope.

4 Conclusions

The surface of barchan dunes and barchan dune chain in the Hexi area of Gansu was mainly composed of fine sand and medium sand at a depth of 0–5 cm. The sand particles in Gulang sand area were relatively fine and the particle sizes of dunes in Jinchang, Linze, Jinta and Minqin dunes were quite different.

In the main wind direction (NW) process, the change was from coarse to fine from the bottom of the windward slope of the dunes to top, that is, the silt at the top of the sand dunes was the most, followed by the middle of the leeward slope. The bottom of the windward slope had the most coarse sand, followed by the middle of the windward slope. In the reverse wind direction (SE) process, the change was from coarse to fine to coarse from the bottom of the windward slope of the dunes to top, that is, the silt in the middle of the windward slope was the most, followed by the top of the dune. The bottom of the windward slope had the most coarse sand, followed by the middle of the windward slope. The standard deviation and coefficient of variation of sand dune particle size were also larger in the main wind direction process, while the standard deviation and coefficient of variation of sand dune particle size in the reverse wind direction process were smaller.

The main wind direction and the reverse wind direction process lead to the alternating change of particle size in various parts of the dunes. Due to the different observation seasons, two different conclusions about the particle size distribution of the windward slope of barchan dunes were caused.

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