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Feathered sand ridges in the Kumtagh Desert and their position in the classification system

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Feathered sand ridges in the northeastern Kumtagh Desert in China cover an area of 4016 km^2 and consist of crescent sand ridges and interridge tongue-shaped dunes. Differences in grain size, mineral composition and albedo between crescent sand ridges and tongue-shaped dunes, and between windward and leeward slopes of tongue-shaped dunes, result in their feathery appearance in aerial and satellite imagery. Measurements of the sand drift potential in the region show that the sand-moving wind for feathered sand ridges can be divided into three sectors; i.e. north-northeasterly, easterly and east-northeasterly sectors roughly corresponding to the southeast, northwest and southwest slip faces. Our findings suggests that the crescent sand ridges resulting from the connection of barchan dunes along the prevailing wind direction are longitudinal dune ridges rather than transverse ones. Tongue-shaped dunes and quasi-dune shapes have obvious distinctions and are new transverse dune types. According to McKee's dune shape classification, the feathered sand ridges are not a deformation dune type but a complex one. According to Wu's dune morphological and genetic classification, they are not dune ridges or compound dune ridges that form under the action of unidirectional winds or two winds intersecting at an acute angle, but are complex dune ridges that form under the action of three winds intersecting at an acute angle.

Kumtagh Desert, feathered sand ridge, tongue-shaped dune, morphologic characteristics, aeolian sand landform classification

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Kumtagh Desert (Figure 1) borders the Lop Nor to the northwest, the Gansu Dunhuang to the east, the Beishan in the eastern section of the Tianshan Mountains to the north, and the north piedmont of the Altyn Mountains to the south; it is located at 89°57′49″–94°54′08″E and 39°07′50″–41°00′03″N and has an area of about 23000 km^2 [1]. The main body of the desert covers the slightly sloping piedmont alluvial-diluvial plain of the Altun Mountains and lies between 835 and 2500 m altitude; the dunes of the desert are mainly barchan dunes, barchan dune chains, pyramid dunes, feathered sand ridges and compound dune ridges [2], of which feathered sand ridges are the most unique.

In the 1960s, the Kumtagh Desert was an unknown in geomorphological research on aeolian sand in China. In the early 1970s, Zhu and Wu [3] identified feathery dunes (ridges) in the northeastern desert from aerial photographs. Since the 1980s and especially since 2000, Chinese scholars including ourselves [4–16] have conducted multiple investigations and researches to the Kumtagh Desert and confirmed the presence of crescent sand ridges in the Kumtagh Desert, although some studies [11–14] have not found

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feathered sand ridges. The differing views on the existence of feathered sand ridges in the Kumtagh Desert depend on whether the "feathers" of the feather-like pattern seen in remote-sensing images are considered to be caused by a series of undulating and parallel sand balks between crescent sand ridges or by alternating bright and dark deposits without obvious height differences. In addition, researchers from other countries have reported feathery dunes in the Sahara Desert, Yemen and Sinai [17, 18], and some have even referred to forked linear dunes as feathery dunes and categorized them as a deformation dune type [19]. Therefore, it is necessary to determine whether feathered sand ridges exist in the Kumtagh Desert and to intensively study the morphological and classification characteristics of dunes.

Since 2004, we have continuously investigated feathered sand ridges in the Kumtagh Desert [5, 8–10]. In recent years, through interpretation of the region's feathered sand ridges from aerial and satellite photographs and ground investigations (including spectral determinations, observations of the near-surface wind regime and test trench observations of crescent sand ridges) and grain size and mineral analyses, we confirmed the presence of feathered sand ridges.

1 Morphological characteristics of feathered sand ridges in the Kumtagh Desert

Feathered sand ridges in the Kumtagh Desert mainly exist in the region of 91°24′48″–92°48′32″E and 40°01′12″–40°27′48″N and at 850–1050 m altitude. The region borders the Aqik fault valley and Yardan National Geological Park to the north and northeast, respectively, and transforms to flat sand land and an aeolian sand multiple-landform (e.g. barchan dune chains, longitudinal dune ridges and mega-dunes) region to the southeast and southwest respectively; the region covers 4016 km^2, accounting for 17.5% of the desert's total area (Figure 1). As viewed from aerial and satellite photographs (Figure 2), the northeast-southwest-oriented bright dune ridges look like pteryla (also referred to as stems [20, 21]), while the alternating bright and dark undulating sand bodies between crescent sand ridges look like feathers (also referred to as pinnules [20, 21]). Therefore, in terms of the nomenclature of the dune's quasi-shape and the relation between dune's quasi-shape and wind dynamic, it is appropriate to refer to them as feathered sand ridges.

Feathered sand ridges in the Kumtagh Desert consist of crescent sand ridges and interridge tongue-shaped dunes. Crescent sand ridges resembling pteryla result from the connection of a series of barchan dunes along the prevailing wind direction; tongue-shaped dunes resemble feathers on both sides of the pteryla and are perpendicular to the prevailing wind direction.

1.1 Crescent sand ridges

Aerial and satellite photographs and a ground investigation have shown that there are at least 54 obvious crescent sand ridges in the region of feathered sand ridges in the Kumtagh Desert, and almost all have bends or branches to different degrees. On the northwest side of a crescent sand ridge, there are many zigzagging convex sand bodies (Figure 2). The statistical results for 35 selected dune ridges (Figure 3) show that the crescent sand ridges have a northeast (43°–58°)-southwest (223°–238°) orientation, ridge length

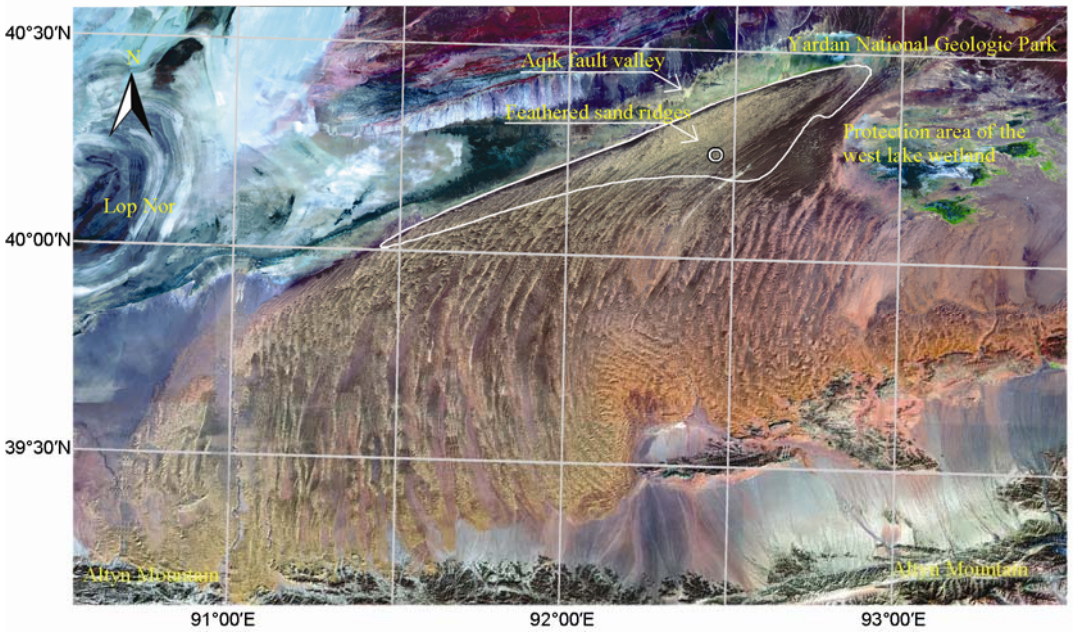

Figure 1 TM image of Kumtagh Desert and distribution of the feathered sand ridges. ◎ Represents the location of automatic meteorological station.

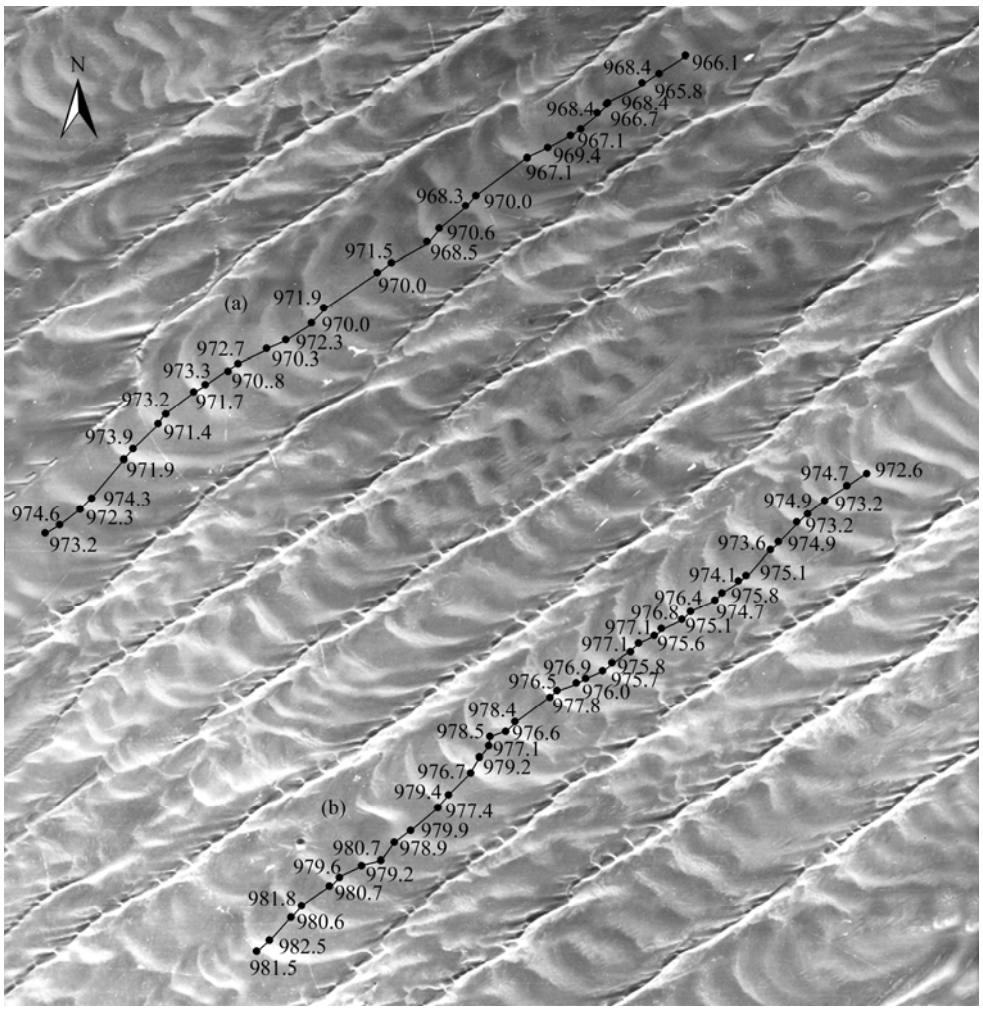

Figure 2 Aerial photograph of feathered sand ridges (cited from ref. [10]). (a) and (b) represent the measuring line of longitudinal section of tongue-shaped dune, center point: 40°14'22.33"N, 92°25'12.67"E, photographed time: October 1972.

of 4–22 km (9–18 km for 72% of ridges), ridge width[1)] of 27–140 m (30–90 m for 74% of ridges), ridge height[2)] of 3–19 m (10–16 m for 81% of ridges), and spacing between vertical axes of adjacent crescent sand ridges of 87–1265 m (100–500 m for 73% of ridges). According to the low-altitude powered paragliding and ground surface observations, the bright dune ridges seen in aerial and satellite photographs are actually grayish yellow in color, the zigzagging convex sand body on the northwest side of a dune ridge is actually the northwest horn of a barchan dune, while the southeast horn is connected to another downwind barchan dune (Figure 4), suggesting that the crescent sand ridge is composed of a series of barchan dunes. According to the measurement results for several representative barchan dunes obtained using RT2000 theodolite, the longitudinal axial line of such a dune and the longitudinal axial line of the crescent sand ridge form an included angle of about 9° (Figure 5). The two wings of the dunes are asymmetrical; generally, the northwest wing is long and the southeast wing short. The spacing between the two wings is 30–66 m (average 51 m) and the included angle is 44°–120° (average 80°). The waist section of the dune is also asymmetrical; the southeast side (mean slope of 24.8°) is slightly steeper than the northwest side (mean slope of 23.3°). The maximum slope on the windward side of the dune is 18°, with 70% of the windward slope being gentler than 15°, and the minimum slope on the leeward side of the dune is 31.5°. The length of the dune's windward slope is about 3–5 times the length of the leeward slope (Table 1). The southwest slip face of the crescent sand ridge is clear in terms of the geomorphic shape (Figure 5), and the northwest slip face can be seen from the profile of the test trench (Figures 5 and 6). Figure 6 shows that (1) platy cross lamina (dip angle of 6°–15°) have a structure with reverse grain order, with the

1) Ridge width refers to the horizontal distance between two horns of barchan dunes forming the dune ridges.
2) Ridge height refers to the relative height of the barchan dune top.

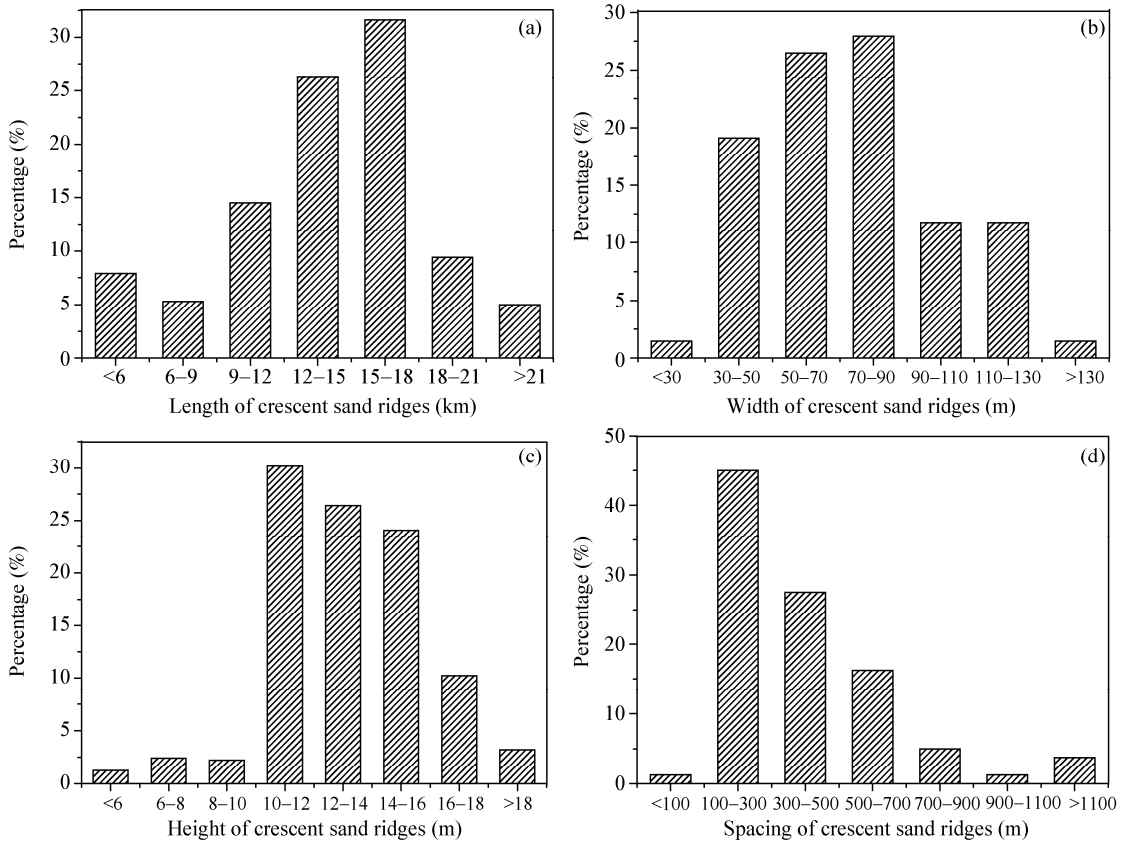

Figure 3 Statistical diagram of feathered sand ridges parameter measurement.

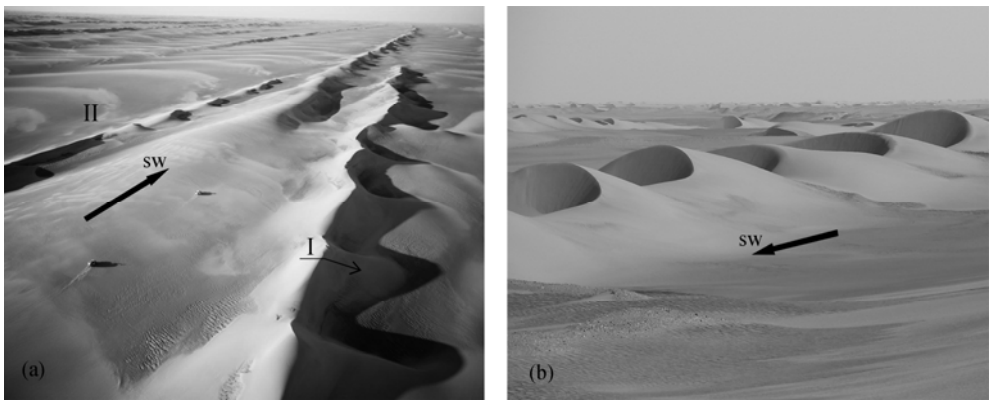

Figure 4 Low altitude and ground surface photograph of feathered sand ridges. (a) Low altitude photograph of feathered sand ridges, cited from ref. [10]; I, northwest horn of barchan dune left by dune ridge, II, tongue-shaped dune; location: 40°12′40.62″N, 92°06′25.98″E, photographed height 150 m, photographed time: October 2006. (b) Ground surface photograph of feathered sand ridge shows the southeast horn of barchan dune and downwind connection scene; location: 40°15'15.67"N, 92°19'20.92"E; photographed time: September 2005.

lamina thickness changing little, and the lamina is classified as climbing ripple lamina that form under the action of north-northeast winds and (2) low-altitude-angle (13°–27°) wedge cross-bedding comes into contact with the underlying and overlying interfaces, with lamina classified as gradual cross lamina that form in the airflow separation zone on the leeward slope under the action of easterly winds [22, 23]. These two sets of cross stratification with opposite dip directions are evidence for the alternating presence of an avalanche slope and windward slope on the northwest side of the barchan dune over time. Because the sand drift potential is the highest for the north-northeasterly wind in the region, the southeast side of the dune is steeper than the northwest side, and the leeside of the northwest slope has lamina structure, it is inferred that the dune also has alternating avalanche and windward southeast slopes.

Table 1 Morphological parameters of barchan dunes forming crescent sand ridges [20]

Location	Strike (°)	Dune spacing (m)	Dune height (m)	Leeward slope		Windward slope		Wing				Remark
				Length (m)	Slope (°)	Length (m)	Slope (°)	Spacing (m)	Included angle (°)	Length (m) E	Length (m) W	
40°10′17″N 92°20′59″E	232	101	11.0	21	31.5	101	14.0	66	108	28	52	
40°11′39″N 92°16′27″E	238	58	4.4	18	33.5	58	6.0	30	90	14	27	The dune of the same dune ridge
40°12′08″N 92°16′52″E	246	68	9.8	18	33.0	68	16.5	50	120	23	30	
40°18′46″N 92°27′50″E	240	60	3.8	7	33.0	60	10.5	56	56	42	44	
40°18′04″N 92°26′21″E	230	58	7.7	14	31.5	58	3.0	44	44	37	29	The dune of the same dune ridge
40°17′15″N 92°24′44″E	223	88	11.1	21	32.0	88	2.5	60	60	35	51	

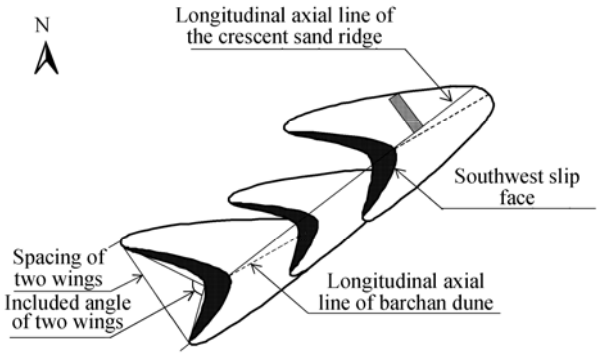

Figure 5 Schematic diagram of crescent sand ridge shape. ▦ represents the location of test trench.

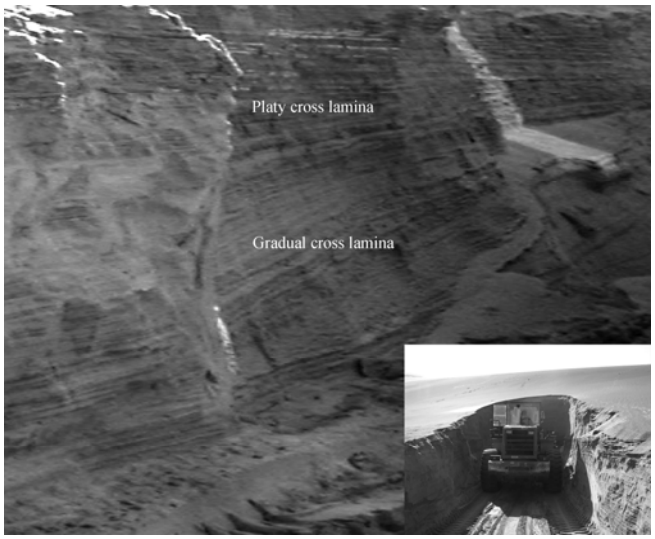

Figure 6 Sedimentary structure of northwest slope of crescent sand ridge (section strike N42°W). Insert diagram indicates the transverse test trench at the waist section of barchan dune, test trench length 25 m, width 3 m, depth at highest site 5.8 m. Location: 40°14′40.65″N, 92°31′56.00″E.

1.2 Tongue-shaped dune

Some scholars believe that the "feather" of the feather-like pattern in the Kumtagh Desert is formed by the albedo contrast of alternating bright and dark deposits between crescent sand ridges; the so-called sand balks have no obvious height difference relative to the surrounding ground surface, and it is even believed that the mineral composition of the alternating bright and dark deposits is the main cause of the feather-like pattern [11–14]. We found that the light-colored fine sand patches (2–7 cm thick, 6–11 m wide, 15–24 m spaced) covering the interridge coarse sand bed are generally 12–15 m from the crescent sand ridge and form a 60°–105° included angle with the crescent sand ridge (Figure 7). The shape, size and location of such sand patches change with wind force, and they have no obvious variation pattern and do not connect with the crescent sand ridge. Therefore, the feather-like patterns that are mutually parallel, constantly and regularly distributed, and connected with the crescent sand ridges, as shown in Figure 2, must be another stable sand body.

From the 1∶10000 longitudinal section of the tongue-shaped dune drawn using 1972 aerial photography data recorded by a digital photographic survey (JX4) (see Figures 2 and 8) and data from a ground investigation, it was found that such a sand body is a series of tongue-shaped dunes lying between crescent sand ridges. Their tongue tips protrude southwest in the direction of the prevailing northeasterly, but their two wings bend northeast in the reverse direction of the prevailing wind and connect with dune ridges; such dunes are mutually parallel and mostly do not link up and have no integrity compared with crescent sand ridges. The dune wing has a width of 140–460 m (average 261 m), gentle windward slope (2°–4°), slightly steep leeward slope (6°–8°), dune height of 1.6–4.0 m, and spacing of 70–370 m (average 170.4 m). Because of their lower height, large spacing and lack of an obvious slip face, tongue-shaped dunes are difficult to detect.

Although some scholars recognize the presence of feathered sand ridges, they believe that the "feather" of the feather-like pattern consists of dark-mineral and light-mineral micro-undulating terrain (i.e. large sand ripples) [20, 21]. According to the international classification system of

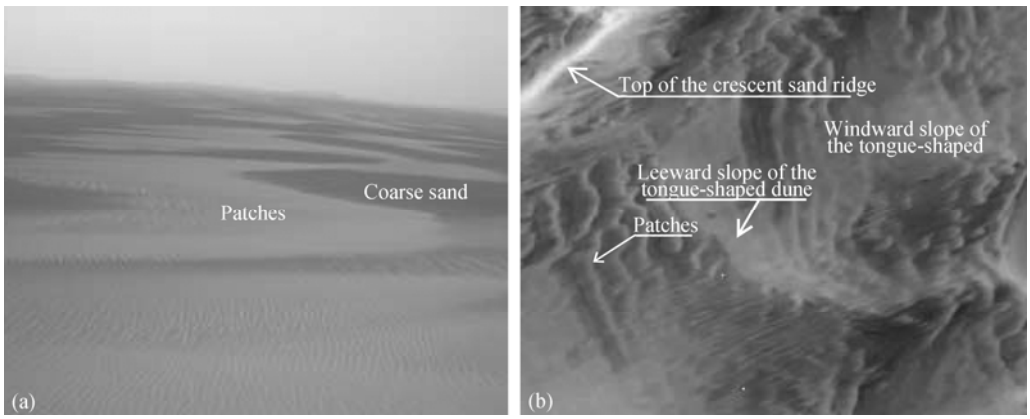

Figure 7 Surface photograph and satellite image of sand patches. (a) Surface photograph of sand patches. Location: 40°15′36.12″N, 92°31′18.50″E; photographed time: October 2006. (b) Quickbird satellite image at the same location as (a), photographed time: September 2005.

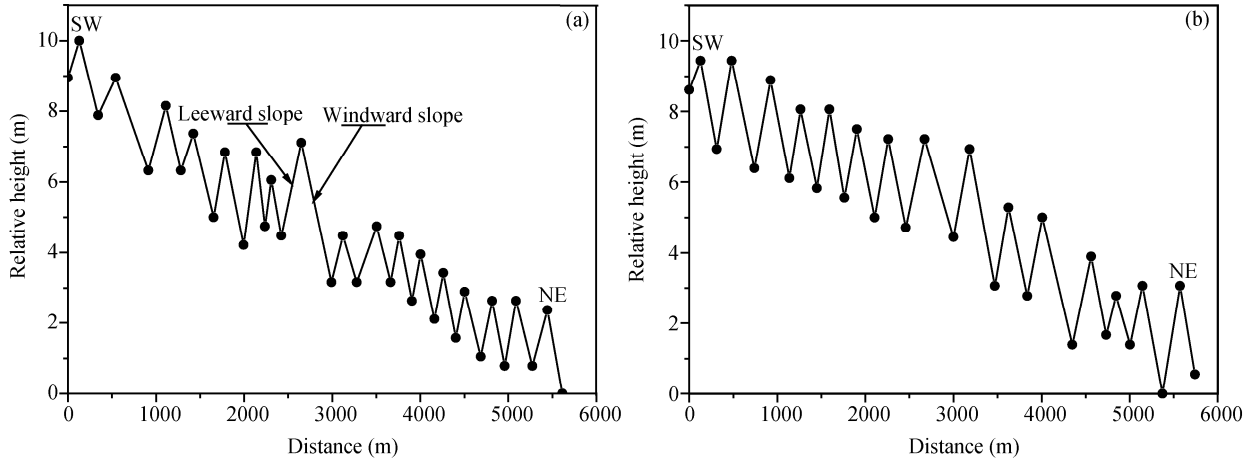

Figure 8 Height variation of longitudinal section of tongue-shaped dune.

aeolian bed morphology [24], aerodynamic sand ripples and impact sand ripples are generally 0.2–100 cm in height and 15–2000 cm in wavelength, whereas the height and wavelength of tongue-shaped dunes are far greater. Hence, the interridge wavy undulating terrain that appears feathery in the remote-sensing images are tongue-shaped dunes rather than "large sand ripples".

2 Grain size, mineral composition and albedo of feathered sand ridges

The feather-like pattern in the remote-sensing images of the Kumtagh Desert is dependent on the varying albedo. To understand the relations among grain size, mineral, albedo and terrain, we collected sand samples from different sites of feathered sand ridges for analysis and determination.

2.1 Grain size composition

Surface sand samples were collected from the northwest slope, southeast slope and ridge crest of crescent sand ridges, and the windward slope, leeward slope and dune top of tongue-shaped dunes. The sampling depth of the crescent sand ridge was 0–3 cm, while that of the tongue-shaped dune was 0–5 cm. The analysis involved first removing organic matter and carbonate from the samples and then determining the grain-size compositions using a laser grain-size analyzer (Malvern Mastersizer 2000, made in Britain). Grain-size parameters were calculated from maps drawn by Fork and Ward [25]. Because the sand materials in the region mainly consist of clastic minerals and rock debris, the basic classification of Chinese loess is used as a reference in the classification of grain size [26, 27].

Analytical results (Table 2) show that the very coarse sand-coarse sand content of the crescent sand ridge is 14.41%–40.94%, the medium sand content is 20.25%–34.21%, and the fine sand-very fine sand content is 37.97%–50.80%. The mean grain size is 0.46 mm on the northwest slope, 0.31 mm on the southeast slope and 0.30 mm on the ridge crest. The standard deviation is about 1.40 on both sides of the dune ridge and 0.95 on the ridge crest.

The very coarse sand–coarse sand content of the tongue-shaped dune is 78.53%–87.57%, the medium sand content is 6.80%, and the fine sand-very fine sand content is 4.41%–5.67%. The mean grain size is 0.83 mm on the windward slope, 0.82 mm on the dune top and 0.66 mm on the leeward slope. The standard deviation is 0.55 on the dune top, 0.54 on the windward slope and 0.53 on the leeward slope. The grain-size variations in the feathered sand ridge surface show that the tongue-shaped dune is coarser than the crescent sand ridge, the windward slope of the tongue-shaped dune is coarser than the leeward slope of the tongue-shaped dune, and the sorting of the crescent sand ridge is poor to moderate but the sorting of the tongue-shaped dune is good (according to the Fork and Ward classification standard).

2.2 Mineral composition

Surface sand samples were collected from the northwest slope, southeast slope and crest of the crescent sand ridges and from the windward slope and leeward slope of the tongue-shaped dunes to analyze the mineral composition. The sampling depth was 0–3 cm for the crescent sand ridge and 0–5 cm for the tongue-shaped dune. The measured grain size was 0.031–2 mm. The instrument used for analysis was a D8 advance diffractometer operating with Cukα radiation and having a tube voltage of 40 kV, tube electric current of 40 mA, 2θ scanning angle of 3°–45°, and step length of 0.2°.

Analytical results (Table 3) show that there are 21 heavy minerals in the sand of crescent sand ridges, of which the hornblend, allochite, opaque mineral (magnetite, hematite, and ilmenite) and actinolite contents account for 88.83% of the total heavy mineral content; the heavy mineral assembly of the aeolian sand of the crescent sand ridges is hornblend-allochite-opaque mineral-actinolite. The tongue-shaped dune sand contains 15 heavy minerals, of which opaque mineral, allochite and hornblend contents account for 91.21% of the total heavy mineral content; the heavy mineral assembly of the aeolian sand of tongue-shaped dunes is opaque mineral-allochite-hornblend. Considering the distribution of dark minerals, the tongue-shaped dune (45.66%–47.99%) has a higher concentration of dark minerals than the crescent sand ridge (21.80%–32.10%), the windward slope of the tongue-shaped dune (47.99%) has a higher concentration than the leeward slope (45.66%), and the northwest slope of the crescent sand ridge (32.10%) has a higher concentration than the crest and southeast slope (21.9% or so). It is thus seen that there is an obvious tincture contrast between the crescent sand ridge and tongue-shaped dune, windward slope and leeward slope of the tongue-shaped dune, and crest and both sides of the crescent sand ridge.

2.3 Albedo

According to the results obtained for tongue-shaped dunes using the FieldSpec Pro spectral data collector (Figure 9), the albedo of the leeward slope of the tongue-shaped dune (8.00%–25.25%, average of 20.20%) is higher than that of the windward slope (7.60%–21.20%, average of 17.10%); this is particularly obvious in the wavelength range of 600–1050 nm, with the albedo of the leeward slope being 1.2 times the albedo of the windward slope. Apparently, this is because sand grains on the windward slope are coarse and enriched in dark minerals and absorb more visible light, compared with sand grains on the leeward slope.

Because the dark mineral content and mean grain size of tongue-shaped dunes are greater than those of crescent sand ridges, we infer that the crescent sand ridge has a higher albedo than the interridge zone. According to spectral determination results, the albedo of the crescent sand ridge is twice that of the interridge zone [13], which is evidence for the bright white color of the crescent sand ridges and the leeward slopes of interridge tongue-shaped dunes, and the grayish yellow color of the interridge zone and the windward slopes of the tongue-shaped dunes in the aerial photographs (see Figure 2).

The white strips and patches on the windward slope of a tongue-shaped dune (see Figure 7(b)) are actually sand patches mainly consisting of fine sand and covering the coarse sand surface.

Feathered sand ridges not only have a unique combined

Table 2 Grain-size fractional content and Mz and σ values at different sites of feathered sand ridges [a)]

Sampling site		Percent content of grain-size fraction (grain-size unit: ϕ or mm)							Mz (ϕ)	Mz (mm)	Standard deviation (σ)
		Fine gravel	Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Coarse silt			
		4–2	2–1	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.01			
Crescent sand ridge	NW slope	0.00	18.47	22.47	20.27	28.66	9.31	0.82	1.13	0.46	1.37
	Crest	0.00	0.09	14.32	34.21	40.67	10.13	0.57	1.75	0.30	0.95
	SE slope	0.00	5.32	24.62	20.25	29.54	18.12	2.17	1.68	0.31	1.43
Tongue-shaped dune	Windward slope	0.24	31.56	56.01	7.79	3.90	0.51	0.00	0.27	0.83	0.54
	Top	0.57	28.99	57.97	6.80	3.80	1.87	0.00	0.29	0.82	0.55
	Leeward slope	0.13	10.73	67.80	15.72	5.13	0.49	0.00	0.61	0.66	0.53

a) Mean grain size (Mz)=(σ16+σ50+σ84)/3; stndard deviation (σ)=(ϕ84–ϕ16)/4+(ϕ95– ϕ5)/6.6; ϕ=–$\log_2 d$ (d is diameter, unit: mm) [28].

Table 3 Mineral constituents of feathered sand ridges (wt%)[a)]

Mineral classification	Mineral constituent	Sampling site				
		Crescent sand ridge			Tongue-shaped dune	
		NW slope	Crest	SE slope	Windward slope	Leeward slope
Dark-colored mineral	titanite	0.095	0.044	0.019	0.032	0.177
	magnetite	0.406	0.122	0.041	0.343	0.471
	haematite	0.373	0.133	0.020	0.218	0.564
	ilmenite	0.113	0.060	0.027	0.532	1.154
	taltalite	0.012	0.001	0.001	0.001	0.006
	rutile	0.005	0.002	0.000	0.003	0.007
	hornblend	3.025	0.299	0.856	0.620	0.876
	leucoxene	0.033	0.007	0.001	0.013	0.014
	allochite	0.831	0.565	0.156	0.668	1.867
	actinolite	0.936	0.131	0.022	0.000	0.000
	augite	0.007	0.001	0.000	0.000	0.000
	pyrite	0.000	0.000	△	0.000	0.000
	anatase	0.000	+	+	0.000	0.000
	zoisite	0.000	0.033	0.000	0.000	0.000
	black mica	0.000	0.000	0.000	0.001	0.008
	altered mineral	24.711	16.923	8.436	0.000	0.000
	rock debris	1.552	3.647	12.216	44.036	38.870
	carbonate	0.000	0.000	0.000	1.518	1.646
	total	32.10	21.97	21.80	47.99	45.66
Light-colored mineral	zircon	0.040	0.012	0.003	0.026	0.034
	apatite	0.064	0.002	0.003	0.006	0.004
	tremolite	0.259	0.009	0.008	0.007	0.040
	garnet	0.275	0.053	0.029	0.095	0.231
	barite	0.000	0.001	0.000	0.000	0.000
	diopside	0.001	0.000	0.000	0.000	0.000
	cyanite	0.001	0.000	0.000	0.000	0.000
	quartz	40.840	51.321	50.930	28.156	31.210
	feldspar	22.926	26.635	25.850	0.000	0.000
	potash feldspar	0.000	0.000	0.000	3.598	3.540
	anorthose	0.000	0.000	0.000	20.130	19.284
	calcite	3.497	0.000	1.383	0.000	0.000
	total	67.90	78.03	78.20	52.01	54.34

a) "+" represents 5–10 grains; "△" represents 21–50 grains.

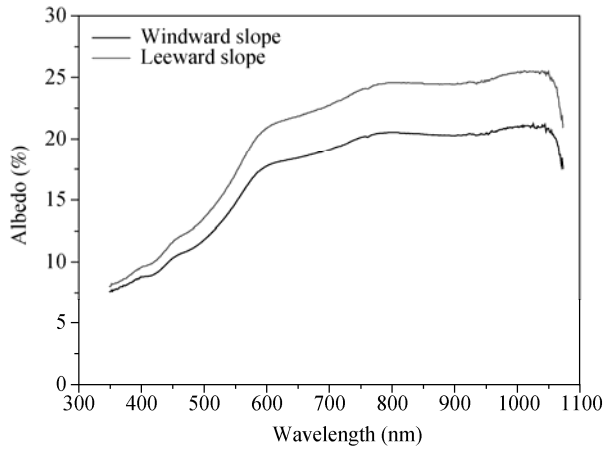

Figure 9 Light albedo at different sites of tongue-shaped dune.

shape of a crescent sand ridge and tongue-shaped dune, but also exhibit obvious differences in grain size, minerals and albedo at different sites: the crescent sand ridge has a high fine-grain content, is enriched in light-colored minerals, has high albedo and a bright white color; the interridge zone has a high coarse-grain content, is enriched in dark minerals, has low albedo, and a dark gray color; the leeward slope of a tongue-shaped dune has high fine-grain content, is enriched in light-colored minerals, has high albedo, and has bright white color; the windward slope of a tongue-shaped dune has a high coarse-grain content, is enriched in dark minerals, has low albedo, and a dark gray color. It is the difference in the albedo due to the grain size and mineral composition at different sites that results in their feathery appearance in aerial and satellite photographs.

3 Sand-moving wind regime of feathered sand ridges

Related data recorded by an automatic meteorological station (Huatron CAWS 600, standard model, location shown

in Figure 1) in the region of feathered sand ridges and the Fryberger formula [29] DP=$V^2\times(V-V_t)\times t$ (where DP is the sand drift potential, V is wind velocity, V_t is the threshold wind velocity to initiate sand movement, and t is the duration of the sand-moving wind) were used to determine (1) an annual mean sand drift potential in the region of feathered sand ridges of 422 VU, indicating a high wind energy environment; (2) annual mean directional variability index (RDP/DP) of 0.5, which is a mid-range ratio; and (3) resultant sand drift direction of 213°, forming a 10°–25° included angle with the strike of the crescent sand ridge (Figure 10). In terms of the directional variability index, the sand-moving wind regime in the region of feathered sand ridges is sharply bimodal; however, it is difficult to explain the dynamic factor by two obliquely crossing winds because crescent sand ridges in the region have three slip faces. According to 16-orientation sand drift potentials and their relations to the slip face of a dune ridge, the sand-moving wind for a feathered sand ridge can be divided into three sectors: a north-northeasterly is positively oblique to the northwest side of the dune ridge and accounts for 25.3% of the total sand drift potential; an east-northeasterly is roughly parallel to the crescent sand ridge and accounts for 12.7% of the total sand drift potential; and an easterly is positively oblique to the southeast side of the dune ridge and accounts for 21.2% of the total sand drift potential. The sand drift potential of the three wind sectors accounts for 59.2% of the total, and the sectors correspond to the three slip faces of the crescent sand ridges; i.e. the southeast, southwest and northwest slip faces. Therefore, the three wind sectors are the main dynamical conditions for the formation and development of feathered sand ridges.

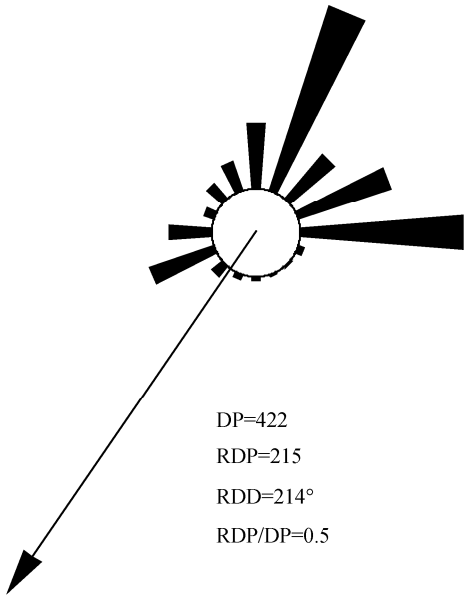

Figure 10 Mean annual sand drift potential rose of feathered sand ridges (2006–2008).

4 Morphological comparison of a feathered sand ridge and approximate dune types

The presence of quasi-circular tongue-shaped dunes between crescent sand ridges is a unique feature of feathered sand ridges (Figures 2 and 11). Although feathered sand ridges have some features that are similar to features of barchan, parabolic and reverse dunes, the direction of their horn extension, orientation of the leeward slope and formation condition are quite different. A barchan dune has two wings that spread out downwind and a convex windward slope and concave leeward slope, while a tongue-shaped dune has two wings that point upwind and a concave windward slope and convex leeward slope; a parabolic dune has horns that extend upwind and a concave windward slope and convex leeward slope, basically consistent with a tongue-shaped dune, although the shape of the former is due to the influence of vegetation, while the latter is a mobile dune owing to a lack of vegetation; a reverse dune forms under the actions of two nearly opposing winds, and thus has two leeward slopes, while a tongue-shaped dune is formed by winds with similar direction due to the interridge "funnel effect", and thus has only one leeward slope. Because of the difference between a tongue-shaped dune and the several above-mentioned dune types, and the well- developed windward slope and leeward slope, a tongue- shaped dune is significantly higher than a sand wave, sand patch and sand mound; therefore, we refer to the interridge feathery sand bodies as tongue-shaped dunes. Although the tongue-shaped dunes are horizontally arranged and exhibit a downwind strip extension, most are not interconnected; hence, the tongue-shaped dune is a new type of transverse dune rather than a longitudinal dune ridge consisting of tongue-shaped dunes.

The pteryla of a feathered sand ridge results from the linking up of barchan dunes, being referred to as crescent sand ridges by scholars of Soviet Union in the early 20th century, while in the Sahara region they are referred to as seif dunes [30]. In sand dune classification, McKee [19] referred to the bending and nearly parallel crescent sand ridges perpendicular to the prevailing wind as crescent sand ridges. In fact, these two types of crescent sand ridges are transverse dune ridges resulting from the linking up of barchan dunes perpendicular to the prevailing wind direction; apparently, such an explanation is inconsistent with the characteristics of crescent sand ridges in the Kumtagh Desert. Although the barchan dunes that form the crescent sand ridges in the Kumtagh Desert are transverse dunes, they link up along the prevailing wind direction rather than crossing the prevailing wind. For this reason, we agree to refer to the pteryla of the feathered sand ridges in the Kumtagh Desert as crescent sand ridges (or seif dunes), but they are a longitudinal dune ridges rather than transverse dune ridges.

Although the feathered sand ridges or dunes (with bases

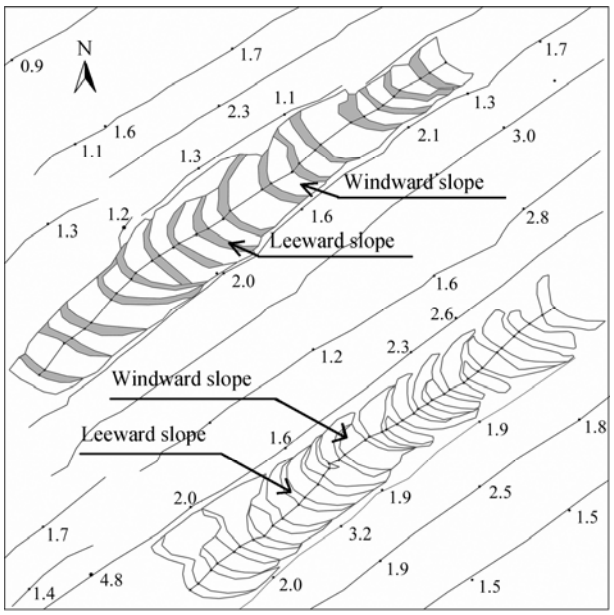

Figure 11 Plane shape of tongue-shaped dune (number in the figure indicates relative height).

on both sides connected to a series of secondary, cross or obliquely cross, and echelon-arranged dunes or other dune ridges and dune chains with star dune peaks [17, 18]) in the Sahara, Yemen and Sinai differ from the feather dune ridges (combined bodies of crescent sand ridges and interridge tongue-shaped dunes that obliquely cross crescent sand ridges) in the Kumtagh Desert, they all have a feather-like pattern. To distinguish common crescent sand ridges from other dune ridges, we agree to refer to such a special dune as a feathered sand ridge, whereas the "linear dunes with many forks at an end" mentioned by McKee [19] are not feathery dunes because they have no feather-like pattern.

5 Position of feathered sand ridges in the classification system of aeolian sand geomorphology

According to the dune shape and slip face location and number, McKee classified sand dunes as basic dunes, compound dunes, complex dunes and varieties of dunes, and feathery dunes are included in the varieties of dunes [19]. The feathered sand ridges in the Kumtagh Desert result from the linking up of longitudinal crescent sand ridges and transverse tongue-shaped dunes, and according to McKee's definition, they should be considered complex dunes. According to the morphologic/genetic classification principles, Wu suggested a three-class classification system for sand dunes in deserts of China [31]. First, sand dunes are classified into three major basic types, namely transverse dunes, longitudinal dunes and dunes that form under the action of multi-directional winds in accordance with the relationship between the dune shape and the wind regime. Second, in accordance with the stabilization degree of sand dunes, dunes are divided into two subtypes, namely bare (moving) dunes and vegetated (fixed and semifixed) dunes, and each subtype can be further explicitly divided according to dune shape. In the three-class classification system, the longitudinal dunes include crescent sand ridges that form under the action of two winds intersecting at an acute angle and dune ridges and compound dune ridges that form under the action of unidirectional winds; the feathered sand ridges are incorporated in the dune ridge and compound dune ridge types. The feathered sand ridges in the Kumtagh Desert are geomorphological shapes consisting of two dune types under the action of three winds intersecting at an acute angle. Therefore, we suggest that they belong to the first class of longitudinal dunes, second class of mobile dunes, and third class of complex dunes that form under the actions of three winds intersecting at an acute angle, and that they are juxtaposed with crescent sand ridges that form under the action of two winds intersecting at an acute angle and dune ridges or compound dune ridges that form under the action of unidirectional winds.

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