

Morphological characteristics and dynamic changes of seif dunes in the eastern margin of the Kumtagh Desert, China postprint

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Abstract

The seif dune field over the gravel desert surface in the eastern margin of the Kumtagh Desert is a valuable experimental site for the observation of dune formation and dynamics. We used high-resolution remote sensing and station observation approaches, combined with wind and grain size data, to study the characteristics of the aeolian environment and the morphologies of and dynamic changes in seif dunes. We observed the ratio of the resultant drift potential (RDP) to the drift potential (DP), which was 0.37, associated with an obtuse bimodal wind regime. The drift potentials in the west-northwest (WNW) and east-northeast (ENE) directions were dominant, and the angle between the two primary DP directions was 135.00° . The dune orientations ranged from 168.75° – 213.75° , which were parallel to the resultant drift direction (186.15°). The dune lengths ranged from 51.68 to 1932.11 m with a mean value of 344.91 m. The spacings of the dunes ranged from 32.34 to 319.77 m with a mean value of 93.39 m. The mean grain size of the sediments became finer, and the sorting became better from upwind tail to downwind tip, which indicated that the sediment of the seif dunes in the study region may be transported from northward to southward. The rate of increase in the length, the mean longitudinal migration rate of the dune tail, and the mean longitudinal extension rate of the dune tip (also called elongation rate) were 4.93, 4.63, and 9.55 m/a, respectively. The mean lateral migration vector of the seif dunes was approximately 0.11 m/a towards the west (-0.11 m/a), while the mean amplitude of lateral migration was 0.53 m/a, ignoring the direction of lateral migration. We found that the seif dune field formed first beside seasonal rivers, which can provide sediment, and then expanded downwind.

Full Text

Preamble

Morphological Characteristics and Dynamic Changes of Seif Dunes in the Eastern Margin of the Kumtagh Desert, China

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Abstract

The seif dune field over the gravel desert surface in the eastern margin of the Kumtagh Desert represents a valuable experimental site for observing dune formation and dynamics. Using high-resolution remote sensing and station observation approaches, combined with wind and grain size data, we studied the characteristics of the aeolian environment and documented the morphologies and dynamic changes of seif dunes. The ratio of resultant drift potential (RDP) to drift potential (DP) was 0.37, associated with an obtuse bimodal wind regime. Drift potentials in the west-northwest (WNW) and east-northeast (ENE) directions were dominant, with an angle of 135.00° between the two primary DP directions. Dune orientations ranged from 168.75°-213.75°, parallel to the resultant drift direction (186.15°). Dune lengths ranged from 51.68 to 1932.11 m with a mean of 344.91 m, while dune spacings ranged from 32.34 to 319.77 m with a mean of 93.39 m. Sediment mean grain size became finer and sorting improved from upwind tail to downwind tip, indicating that seif dune sediments in the study region may be transported from north to south. The rate of length increase, mean longitudinal migration rate of the dune tail, and mean longitudinal extension rate of the dune tip (elongation rate) were 4.93, 4.63, and 9.55 m/a, respectively. The mean lateral migration vector of the seif dunes was approximately 0.11 m/a toward the west (-0.11 m/a), while the mean amplitude of lateral migration was 0.53 m/a when ignoring migration direction. We found that the seif dune field initially formed beside seasonal rivers, which provide sediment, and then expanded downwind.

Keywords: seif dune; Kumtagh Desert; elongation; migration; drift potential

1. Introduction

Sand dunes are important aeolian landforms covering up to a quarter of many desert regions. Studying dune formation, development, and influencing factors is crucial for understanding geomorphological and ecological processes in desert areas and for managing natural resources (Lancaster, 1995). Linear dunes are the most widely distributed dune type, accounting for approximately 40% of the world's sand seas, and are found primarily in the Kalahari, Namib, and Simpson deserts, as well as in southern and southwestern Sahara. However, their formation and development mechanisms remain highly controversial (Fryberger, 1979; Srivastava et al., 2019). Seif dunes, which form in the absence of vegetation and align parallel to the resultant wind trend, represent one of the most important linear dune types, developing a winding shape and sharp crest that explains the term “seif” (Parteli et al., 2009; Tsoar and Parteli, 2016). Recent advances in understanding seif dune morphology, formation environment, sedimentary structure, and dynamics have been achieved through regional wind field analysis, remote sensing data, stratigraphy, and other observational methods (Bristow et al., 2000; Wang et al., 2003; Tsoar et al., 2004; Besler et al., 2013; Hu et al., 2019; Rozier et al., 2019).

Linear dunes cover 3,408 km², approximately 14% of the Kumtagh Desert in China (Dong et al., 2010). Most linear dunes in the Kumtagh Desert are raked linear dunes (also called feathery or pseudo-feathery dunes) (Dong et al., 2008; Wang et al., 2009; Dong et al., 2010; Qu et al., 2011), classified as complex linear dunes according to Lancaster (1982) and distributed mainly in the northern Kumtagh Desert (Fig. 1 [Figure 1: see original paper]). Lü et al. (2017) demonstrated that raked linear dunes arise from simultaneous growth mechanism operations.

Seif dunes occur over gravel desert surfaces (also called gobi, areas where the ground is almost entirely covered with coarse sand and gravel with sparse vegetation) in the eastern margin of the Kumtagh Desert. Their morphology differs from raked linear dunes in the northern Kumtagh Desert, with younger ages and more regular distributions, making the study region valuable for observing dune formation and dynamics. Until now, seif dunes in this region have lacked detailed investigation. We employed high-resolution remote sensing data, station observations, wind speed and direction data, and sediment grain size data to characterize the aeolian environment while documenting seif dune morphologies and dynamic changes. These results will help understand seif dune formation mechanisms and provide scientific bases for blown sand hazard control in the study region.

2.1 Study Region

The Kumtagh Desert is located at the eastern end of the Tarim Basin (39°00 - 40°47 N, 90°27 - 94°48 E) in China, covering an area of 2.28×10^4 km² (Fig. 1 [Figure 1: see original paper]). The desert developed on vast alluvial/diluvial

fans between the Altun and Beishan Mountains. Alluvial deposits and lake sediments from Lop Nur in the northwest and the Dunhuang Xihu wetland, Shule, and Danghe river beds in the east provide rich sand sources for Kumtagh Desert development (Xu et al., 2011).

The study region lies on the eastern edge of the Kumtagh Desert (Fig. 1 [Figure 1: see original paper]). The annual mean temperature is approximately 11.69°C, mean annual precipitation is about 36.19 mm, and mean annual potential evaporation is approximately 2,500 mm, indicating an extremely arid climate. The annual mean wind speed is about 3.21 m/s, with sand-driving winds concentrating in west-northwest (WNW) and east-northeast (ENE) directions. Seif dunes in the study region are distributed mainly over flat gravel desert surfaces (Figs. 2 and 3 [Figure 2: see original paper] [Figure 3: see original paper]), with *Calligonum mongolicum* sparsely distributed throughout the area.

2.2 Methods

Wind speed and direction data were obtained from automatic weather stations at the Kumtagh Desert Ecosystem Research Station (Fig. 2 [Figure 2: see original paper]), National Forestry and Grassland Administration of China (39°58'11" N, 94°01'16" E). Wind sensors were installed 10 m above ground level, with data collected at 30-minute intervals. Remote sensing images from 1965 and 2015 were acquired to monitor dune morphology and dynamic changes. The 1965 image came from an American Keyhole satellite (nominal resolution 2.7 m \times 2.7 m), while the 2015 image comprised GF-1 panchromatic band images from a Chinese high-resolution satellite (nominal resolution 2 m \times 2 m). Based on the 2015 GF-1 image, seven control points were selected to re-register the 1965 Keyhole image, achieving a total co-registration error of 1.27 m (less than 1 pixel).

Seif dunes were manually vectorized using panchromatic band images acquired in 2015 (Fig. 2 [Figure 2: see original paper]), from which dune orientation and length statistics were derived. Eleven transects roughly perpendicular to seif dune orientations were used to analyze dune spacing. In October 2016, a typical seif dune (length: 1,250 m) was selected for topographic survey using an electronic total station (PENTAX R-202N, TI Asahi Co., Ltd., Japan; accuracy: 2 mm (\pm 2 ppm)). The upwind tail, middle part, and downwind tip were measured (Fig. 4 [Figure 4: see original paper]), with encrypted measurements performed where terrain changed significantly. Six areas from upwind to downwind along the typical seif dune were selected for sediment sampling, designated as upwind tail, middle part 1, middle part 2, middle part 3, middle part 4, and downwind tip (Fig. 4 [Figure 4: see original paper]). At each sampling area, surface material (0–1 cm) was collected from the crest, windward slope, leeward slope, and dune horns, yielding 61 sediment samples. Samples were sieved at 1/3 Φ intervals, with grain diameter in millimeters transformed to phi values using Equation 1. Grain size data at each sampling area were averaged, and grain size parameters were calculated using Equations 2 and 3 from McManus

(1988).

$$\Phi = -\log_2 d,$$

(1)

where d is the grain diameter.

$$\Phi_x = \sum f m_\Phi,$$

(2)

where Φ_x is the mean grain size (Φ), f is the frequency (%), and m_Φ is the mid-point of each class interval (Φ).

$$\Phi_\sigma = \sqrt{\sum f(m_\Phi - \Phi_x)^2},$$

(3)

where Φ_σ is the sorting (Φ).

Using wind data from June 2012 to April 2013, drift potential (DP) was calculated. DP in vector units (VU) is an important index for measuring regional aeolian activity intensity. Fryberger's formula for calculating DP is widely used in regional aeolian activity and dune morphology studies. Fryberger (1979) simplified Lettau's sand transport equation to:

$$DP = V^2(V - V_t)t,$$

(4)

where V is wind velocity (knot/h) above threshold V_t , V_t is threshold velocity at 10-m height (11.66 knot/h) (Liao et al., 2010), and t is the frequency (%) of sand-driving wind expressed as a percentage of total time. The direction and magnitude of vector resultants of drift potentials from 16 compass directions are termed resultant drift direction (RDD) and resultant drift potential (RDP), respectively. RDP/DP serves as an index of wind directional variability.

Sixteen seif dunes were selected for movement analysis using remote sensing images from 1965 and 2015. Dune crest locations were mapped to determine extension and migration. The measurement method is illustrated in Figure 5 [Figure 5: see original paper]. Longitudinal migration of dune tails has rarely been investigated, while longitudinal extension of dune tips is typically termed "elongation" (Hu et al., 2019). To measure average lateral migration rate, "across-dune transects" were drawn at 10-m intervals, and the locations where dune crests intersected these transects were measured and averaged (Rubin et al., 2008).

3.1 Drift Potential

DP and RDP distributions from meteorological stations are calculated and shown in Figure 6 [Figure 6: see original paper]. Annual DP in the study region was 122.37 VU, indicating a low wind energy environment according to Fryberger's classification. DPs in WNW and ENE directions were dominant, accounting for 23.16% and 26.58% respectively, with a 135.00° angle between the two primary DP directions. DP was highest from April to July, comprising 65.14% of annual DP, with April showing the maximum at 35.50 VU.

Annual RDP was 45.60 VU and annual RDD was 186.15° . Monthly RDD ranged from 89.43° to 239.92° . RDD in February, March, April, August, and September ranged from 181.00° to 239.92° , while in other months it ranged from 89.43° to 171.13° .

RDP/DP, measuring wind directional variability, is classified as: low (0.0–0.3), intermediate (0.3–0.8), and high (>0.8) (Fryberger, 1979). Annual RDP/DP in the study region was 0.37, classified as intermediate directional variability associated with an obtuse bimodal wind regime. Fryberger (1979) found that linear dune wind environments exhibit greater directional variability of effective winds (lower RDP/DP) than barchanoid dune environments for a given DP.

3.2.1 Orientation

Dune orientations relate to the resultant or vector sum of sand transport (Fryberger, 1979). Seif dunes are usually parallel to the RDD of effective winds in the surrounding environment. Figure 7 [Figure 7: see original paper] shows that 93.92% of dunes in the study area are oriented at 168.75° – 213.75° , coinciding with an RDD of 186.15° .

3.2.2 Length and Spacing of Seif Dunes

Figure 8 [Figure 8: see original paper] shows distributions of seif dune length and spacing. Seif dune lengths ranged from 51.68 to 1,932.11 m with a mean of 344.91 m (Fig. 8a). The number of seif dunes decreased as length increased, with dunes shorter than 400 m comprising 73.96% of the total. Nine transects perpendicular to seif dune orientation were selected to analyze spacing (Fig. 2 [Figure 2: see original paper]). Spacing ranged from 32.34 to 319.77 m with a mean of 93.39 m (Fig. 8c), concentrated mainly at 0–150 m (91.04% of dunes). Average length and spacing of raked linear dunes in the northern Kumtagh Desert were 4,271 m and 1,132 m respectively (Wu, 2012).

Cumulative frequency plots of dune length and spacing provide statistical identification of multiple populations (Ewing et al., 2006). We constructed cumulative frequency plots (Fig. 8b and d) following Ewing et al. (2006). The x-axes in Figure 8b and d represent the reciprocal of the Gaussian cumulative distribution of dune length and spacing, respectively, while y-axes represent logarithmic values (base 10). Straight-line data indicate a single population resulting from one

mechanism, whereas inflection points dividing data into multiple populations suggest multiple mechanisms. Both dune length and spacing data in the study region formed single populations (Fig. 8b and d), indicating similar development environments and processes.

3.2.3 Topography

Topography of the upwind tail, middle part, and downwind tip of a typical seif dune (length: 1,250 m) was measured in October 2016 (Figs. 4 and 9 [Figure 4: see original paper] [Figure 9: see original paper]). Results are shown in Figures 10 and 11 [Figure 10: see original paper] [Figure 11: see original paper]. Widths of W1, W2, and W3 in the upwind tail were approximately 75.86, 71.65, and 60.80 m respectively, with a mean of 69.44 m. Widths of W4, W5, and W6 in the middle part were approximately 42.93, 40.66, and 38.17 m respectively, averaging 40.59 m. Widths of W7, W8, and W9 in the downwind tip were approximately 19.26, 15.27, and 12.47 m respectively, averaging 15.67 m. Generally, seif dune widths narrow from upwind tail to downwind tip.

Relative height in the upwind tail increased from upwind to downwind, with heights of approximately 0.87, 1.55, and 2.09 m at W1, W2, and W3 respectively. Height in the downwind tip decreased from upwind to downwind, with heights of approximately 0.80, 0.59, and 0.36 m at W7, W8, and W9 respectively. Heights in the middle part remained stable from upwind to downwind, at approximately 2.34, 2.88, and 2.57 m at W4, W5, and W6 respectively. Average heights in the upwind tail, middle part, and downwind tip were 1.50, 2.60, and 0.58 m respectively. Generally, seif dune height was highest in the middle part, followed by the upwind tail, and lowest in the downwind tip.

3.3 Grain Sizes

Sediments from a typical dune consisted largely of sand (very coarse, coarse, medium, fine, and very fine). Sand content ranged from 97.46% to 99.69% (Fig. 12 [Figure 12: see original paper]). Granule and pebble content in the upwind tail was approximately 1.04%, with almost none present elsewhere. Very coarse sand content was approximately 28.42% in the upwind tail, compared to 0.01%–8.94% in the middle part and downwind tip. Soil aggregates and particles >840 μm are generally considered non-erodible by wind (Chepil, 1942). Higher non-erodible fraction content in the upwind tail indicates serious wind erosion in this part.

Medium and fine sand contents in the upwind tail were only approximately 4.64% and 10.47% respectively, but were much higher in the middle part and downwind tip. Very fine sand content was 27.68% in the upwind tail and 18.11%–20.95% in the middle part (average of middle parts 1–4) and downwind tip. Silt and clay content was only 1.50% in the upwind tail but higher in the middle part and downwind tip.

Mean grain size became finer from upwind to downwind (Fig. 13 [Figure 13: see original paper]), with mean size of 1.29Φ in the upwind tail, $1.64\text{-}1.90 \Phi$ in the middle part, and 2.15Φ in the downwind tip. Sorting improved from upwind to downwind, with a sorting value of 1.59Φ (poor sorting) in the upwind tail, $0.88\text{-}1.21 \Phi$ (moderate to poor sorting) in the middle part, and 0.70Φ (moderately well sorted) in the downwind tip. Mean grain size and sorting relate to sand source, transport distance, and wind regime. Generally, longer wind transport produces finer grain size and better sorting. Granularity results from this typical seif dune indicate sand source location and transport direction, suggesting that seif dune sediments in the study region may be transported from north to south.

3.4 Movement of Seif Dunes

Sixteen seif dunes were selected for movement analysis using 1965 and 2015 remote sensing images (Fig. 14 [Figure 14: see original paper]; Table 1) with the measurement method shown in Figure 5 [Figure 5: see original paper]. Average length of the 16 seif dunes was 647.19 m in 1965 and 893.91 m in 2015, representing an average increase of 246.72 m at a rate of 4.93 m/a. The mean longitudinal migration rate of dune tail parts was approximately 4.63 m/a along seif dune orientations from 1965 to 2015. Longitudinal migration of dune tails has rarely been reported. The mean longitudinal extension rate of dune tips (elongation rate) was approximately 9.55 m/a from 1965 to 2015 along seif dune orientations.

Lateral migration directions of the 16 selected seif dunes were not consistent—some migrated westward while others migrated eastward. We defined westward migration as negative and eastward as positive. The mean lateral migration vector was approximately 0.11 m/a toward the west (-0.11 m/a), but the mean amplitude of lateral migration was 0.53 m/a when ignoring direction.

4 Discussion

Active sand seas occur in areas receiving <250 mm annual precipitation, yet dunes can form in any climatic regime where bare sand is exposed and winds are strong enough to entrain sand, such as coastal dunes in humid tropical climates (Pye and Tsoar, 2009). The study region has an annual temperature of approximately 11.69°C and annual precipitation of about 36.19 mm, with extremely arid climate and sparse vegetation cover—conditions that facilitate aeolian process development.

Dunes result from wind-sand surface interactions, with sediment and wind characteristics playing important roles in determining dune type, size, and spacing (Lancaster, 1995; Zhang et al., 2019). Two prevalent conceptual models describe the transition from symmetric barchan to seif dune under bidirectional winds (Bagnold, 1941; Tsoar, 1984). In Bagnold's model, a steady gentle wind forms the original barchan, and a storm wind from an oblique direction creates asymmetry by extending the horn nearest the strong wind. In Tsoar's model, a strong

storm wind forms the barchan, and a secondary gentle wind from another direction creates asymmetry by extending the horn farthest from the gentler wind (Tsoar and Parteli, 2016).

Our investigation of seif dune formation further validates this theory (Fig. 15 [Figure 15: see original paper]). In a bidirectional wind regime, one horn of barchan dunes elongates, and over time, barchan dunes transform into seif dunes (Bagnold, 1941; Tsoar, 1984). DPs in the two dominant ENE and WNW directions were 32.52 and 28.34 VU respectively—forces essentially equal and difficult to classify as strong versus gentle. Additionally, slip faces of symmetrical barchan dunes in the study region were not unidirectional and even occurred in opposite directions, determined by the dominant direction since barchan formation began. Field investigations and satellite images could not definitively identify extending horns of asymmetric barchans or determine whether barchan-seif transitions followed Bagnold's or Tsoar's model. Bidirectional winds, dune collision, and inclined topography influence can lead to barchan asymmetry (Bourke, 2010; Lv et al., 2016). However, asymmetric barchans transform to seif dunes only when the divergence angle between the two main wind directions is 90.00° (Parteli et al., 2014; Tsoar and Parteli, 2016). The angle between the two primary DP directions in the study region was 135.00° .

The seif dune field in the eastern Kumtagh Desert margin is located beside seasonal rivers (Fig. 2 [Figure 2: see original paper]). Seasonal river behavior causes significant fluctuations in riverbed surfaces. Desiccation can uncover riverbed sediments, intermittently exposing them to aeolian erosion and dust generation (Montes et al., 2017; Wang et al., 2019). Wind-transported sand particles may deposit when wind speed drops, vegetation is present, topography changes, or through other mechanisms. We observed dune development stages beginning with dome-shaped dunes. Under one bidirectional wind, sand eroded from the windward side and deposited on the leeward side, steepening the leeward slope and causing avalanches (leeward slope angle approximately 34.00°), forming a barchan dune. Initially, barchan dune horns were typically symmetrical, but bidirectional winds transformed symmetrical barchans into asymmetric forms. Through interaction of the two wind directions, seif dunes formed and began developing.

Hunter et al. (1983) classified linear dunes by the angle between their trend and long-term resultant sand-transport direction: longitudinal dunes deviate $<15.00^\circ$, oblique dunes deviate by 15.00° – 75.00° , and transverse dunes deviate by 75.00° – 90.00° . According to Hunter et al. (1983), dunes in the study region are mainly longitudinal. McKee and coworkers (McKee, 1979) classified dunes by shape and slip face number into five major types: crescentic, linear, reversing, star, and parabolic, each with simple, compound, and complex varieties. Simple dunes are basic forms, compound dunes consist of two or more overlapping or superimposed dunes of the same type, and complex dunes occur where two dune types are superimposed or merged. According to McKee (1979) and Lancaster (1982), dunes in the study region (Fig. 16a [Figure 16: see original paper])

are simple linear dunes. Linear dunes in the northern Kumtagh Desert (Fig. 16b [Figure 16: see original paper])—the raked linear dunes—are complex linear dunes composed of primary ridges and subsidiary ridges nearly perpendicular to primary ridges (Dong et al., 2010). Primary ridges of raked linear dunes in the northern Kumtagh Desert generally align from 220.00° to 235.00° , while seif dune orientations in this study region mainly range from 168.75° to 213.75° . Avalanche orientations of seif dunes are nearly perpendicular to dune orientation, whereas avalanche orientations of subsidiary ridges in raked linear dunes are parallel to primary ridge orientations. Morphological differences between linear dunes in northern and eastern Kumtagh Desert result mainly from wind regime differences. The angle between two primary wind directions is acute in the northern Kumtagh Desert but obtuse in the eastern desert. RDP/DP and RDD in the northern Kumtagh Desert are $0.48\text{--}0.55$ and $33.00^\circ\text{--}44.00^\circ$ (Dong et al., 2010), respectively, compared to 0.37 and 186.15° in the eastern desert.

Seif dune dynamic processes include longitudinal elongation, dune summit displacement, lateral migration, lateral widening, and vertical growth (Bagnold, 1941; Craddock et al., 2015). The mean longitudinal extension rate of seif dune tips (elongation rate) was approximately 9.55 m/a along dune orientations from 1965 to 2015. Seif dune elongation rates were 17 m/a in the northern Qaidam Basin (Zhang et al., 2017) and 12.2 m/a in Egypt' s Sinai Desert (Tsoar, 1983).

The greatest controversy concerns whether seif dunes exhibit lateral migration. Bagnold (1941) believed linear dune lateral migration rates were relatively small. Rubin and Hunter (1985) indicated linear dunes had minor lateral migration, producing sedimentary structures unlike those Bagnold (1941) predicted, leading to misinterpretation as other dune types. Consequently, linear dunes are common in modern deserts but their deposits are rarely identified in aeolian sandstones. The mean lateral migration vector of seif dunes in the study region was approximately 0.11 m/a toward the west (-0.11 m/a), but the mean amplitude was 0.53 m/a when ignoring direction. Studies in the Qaidam Basin, China (Hesp et al., 1989), Western Sinai Desert, Egypt (Rubin et al., 2008), and Tengger Desert, China (Zhang et al., 2010) indicated seif dunes have lateral movements at annual rates of approximately $0.50\text{--}3.00$ m/a. However, some scholars believe linear dunes have no lateral migration (Livingstone, 2003; Roskin et al., 2014). When monitoring large, complex, slow-moving dunes, topographic profiles are temporally and spatially restricted; repeated multi-dune surveys are more spatially representative but temporally limited, while stratigraphic cross-sections provide more complete temporal histories but are spatially limited (Rubin et al., 2008).

5 Conclusions

The Kumtagh Desert has a low wind energy environment with an obtuse bimodal wind regime according to Fryberger' s classification. DPs in WNW and ENE directions were dominant, accounting for 23.16% and 26.58% of measurements respectively, with a 135.00° angle between the two primary DP directions.

Seif dune orientations in the study region mainly ranged from 168.75° to 213.75° , parallel to the annual RDD (186.15°). Dune lengths ranged from 51.68 to 1,932.11 m with a mean of 344.91 m, and spacings ranged from 32.34 to 319.77 m with a mean of 93.39 m.

Average widths of typical seif dunes in the upwind tail, middle part, and downwind tip were 69.44, 40.59, and 15.67 m respectively, narrowing from upwind tail to downwind tip. Average heights were 1.50, 2.60, and 0.58 m respectively, with highest elevation in the middle part, followed by the upwind tail, and lowest in the downwind tip.

Mean grain size became finer from upwind tail to downwind tip, and sorting improved along the same gradient. Based on granularity results, seif dune sediments in the study region may be transported from north to south. Higher non-erodible fraction content in the upwind tail indicates serious wind erosion in this part.

The average rate of seif dune length increase was 4.93 m/a from 1965 to 2015. Mean longitudinal migration rate of dune tails and mean longitudinal extension rate of dune tips (elongation rate) were 4.63 and 9.55 m/a respectively along dune orientations from 1965 to 2015. The mean lateral migration vector was approximately 0.11 m/a toward the west (-0.11 m/a), but the mean amplitude of lateral migration was 0.53 m/a when ignoring direction.

The seif dune field in the eastern Kumtagh Desert margin over gravel desert surfaces is distributed mainly beside seasonal rivers, which provide sediments for aeolian erosion and deposition. The seif linear dune field can initially form beside seasonal rivers and then expand downwind.

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References

- Bagnold R A. 1941. *The Physics of Blown Sand and Desert Dunes*. London: Methuen, 222-234.
- Besler H, Lancaster N, Bristow C, et al. 2013. Helga' s dune: 40 years of

dune dynamics in the Namib Desert. *Geografiska Annaler: Series A, Physical Geography*, 95(4): 361–368.

Bourke M. 2010. Barchan dune asymmetry: Observations from Mars and Earth. *Icarus*, 205(1): 183–197.

Bristow C S, Bailey S D, Lancaster N. 2000. Sedimentary structure of linear sand dunes. *Nature*, 406(6791): 56–59.

Chepil W S. 1942. Measurement of wind erosiveness of soils by dry sieving procedure. *Scientific Agriculture*, 23: 154–160.

Craddock R A, Tooth S, Zimbelman J R, et al. 2015. Temporal observations of a linear sand dune in the Simpson Desert, central Australia: Testing models for dune formation on planetary surfaces. *Journal of Geophysical Research Planets*, 120(10): 1–15.

Dong Z B, Qu J J, Wang X M, et al. 2008. Pseudo-feathery dunes in the Kumtagh Desert. *Geomorphology*, 100(3–4): 328–334.

Dong Z B, Wei Z H, Qian G Q, et al. 2010. “Raked” linear dunes in the Kumtagh Desert, China. *Geomorphology*, 123(1–2): 122–

Ewing R C, Kocurek G, Lake L W. 2006. Pattern analysis of dune-field parameters. *Earth Surface Processes and Landforms*, 31(9): 1176–1191.

Fryberger S G. 1979. Dune forms and wind regime. In: McKee E D. *A Study of Global Sand Seas*. Washington: United States Geological Survey, 137–169.

Hesp P, Hyde R, Hesp V, et al. 1989. Longitudinal dunes can move sideways. *Earth Surface Processes and Landforms*, 14(5): 447–

Hu F G, Yang X P, Li H W. 2019. Origin and morphology of barchan and linear clay dunes in the Shuhongtu Basin, Alashan Plateau, China. *Geomorphology*, 339: 114–126.

Hunter R E, Richmond B M, Alpha T R. 1983. Storm-controlled oblique dunes of the Oregon coast. *Geological Society of America Bulletin*, 94(12): 1450–1465.

Lancaster N. 1982. Linear dunes. *Progress in Physical Geography*, 6(4): 475–504.

Lancaster N. 1995. *Geomorphology of Desert Dunes*. New York: Routledge, 1–264.

Liao K T, Qu J J, Tang J N, et al. 2010. Activity of wind-blown sand and the formation of feathered sand ridges in the Kumtagh Desert, China. *Boundary-Layer Meteorology*, 135: 333–350.

Livingstone I. 2003. A twenty-one-year record of surface change on a Namib linear dune. *Earth Surface Processes and Landforms*, 28(9): 1025–1031.

- Lü P, Narteau C, Dong Z B, et al. 2017. Unravelling raked linear dunes to explain the coexistence of bedforms in complex dunefields. *Nature Communications*, 8: 14239, doi: 10.1038/ncomms14239.
- Lv P, Dong Z B, Narteau C, et al. 2016. Morphodynamic mechanisms for the formation of asymmetric barchans: improvement of the Bagnold and Tsoar models. *Environmental Earth Sciences*, 75(3): 1-9.
- McKee E D. 1979. Introduction to study on global sand seas. In: McKee E D. *A Study of Global Sand Seas*. Washington: United States Geological Survey, 1-19.
- McManus J. 1988. Grain size determination and interpretation. *Techniques in Sedimentology*, 408: 112-116.
- Montes A, Rodríguez S S, Domínguez C E. 2017. Geomorphology context and characterization of dunefields developed by the southern westerlies at drying Colhué Huapi shallow lake, Patagonia Argentina. *Aeolian Research*, 28: 58-70.
- Parteli E, Durán O, Bourke M, et al. 2014. Origins of barchan dune asymmetry: Insights from numerical simulations. *Aeolian Research*, 12: 121-133.
- Parteli E J R, Orenco D, Haim T, et al. 2009. Dune formation under bimodal winds. *Proceedings of the National Academy of Sciences of the United States of America*, 106(52): 22085-22089.
- Pye K, Tsoar H. 2009. *Aeolian Sand and Sand Dunes*. Berlin: Springer-Verlag, 153-155.
- Qu J J, Liao K T, Dong G R, et al. 2011. Feathered sand ridges in the Kumtagh Desert and their position in the classification system. *Science China Earth Sciences*, 54(8): 1215-1225.
- Roskin J, Dan G B, Katra I. 2014. Last millennium development and dynamics of vegetated linear dunes inferred from ground-penetrating radar and optically stimulated luminescence ages. *Sedimentology*, 61(5): 1240-1260.
- Rozier O, Narteau C, Gadal C, et al. 2019. Elongation and stability of a linear dune. *Geophysical Research Letters*, 46(24):
- Rubin D M, Hunter R E. 1985. Why deposits of longitudinal dunes are rarely recognized in the geologic record. *Sedimentology*, 32(1): 147-157.
- Rubin D M, Tsoar H, Dan G B. 2008. A second look at western Sinai seif dunes and their lateral migration. *Geomorphology*, 93(3-4): 335-342.
- Srivastava A, Durcan J A, Thomas D S G. 2019. Analysis of late Quaternary linear dune development in the Thar Desert, India. *Geomorphology*, 344: 90-98.
- Tsoar H. 1983. Dynamic processes acting on a longitudinal (seif) sand dune. *Sedimentology*, 30(4): 567-578.

Tsoar H. 1984. The formation of seif dunes from barchans—a discussion. *Z Geomorph N F*, 28(1): 99-103.

Tsoar H, Blumberg D G, Stoler Y. 2004. Elongation and migration of sand dunes. *Geomorphology*, 57(3-4): 293-302.

Tsoar H, Parteli E J R. 2016. Bidirectional winds, barchan dune asymmetry and formation of seif dunes from barchans: a discussion. *Environmental Earth Sciences*, 75(18): 1237.

Wang X M, Dong Z B, Qu J J, et al. 2003. Dynamic processes of a simple linear dune—a study in the Taklimakan Sand Sea, China. *Geomorphology*, 52(3): 233-241.

Wang Y, Yan P, Han G, et al. 2019. Sand source and formation mechanism of riverine sand dunes: a case study in Xiangshui River, China. *Journal of Arid Land*, 11(4): 525-536.

Wang Z T, Sun Q F, Ren X Z, et al. 2009. Pseudo-feathery dunes in the Kumtagh desert reclassified as linear dunes and zibars. *Aeolian Research*, 1(1-2): 87-89.

Wu J F. 2012. Geomorphological patterns in a linear dune field and ages of the linear dunes in the northern Kumtagh Desert, northwest China. *Environmental Earth Sciences*, 66(8): 2449-2457.

Xu Z W, Lu H Y, Zhao C H, et al. 2011. Composition, origin and weathering process of surface sediment in Kumtagh Desert, Northwest China. *Acta Geographica Sinica*, 21(6): 1062-1076.

Zhang K C, Kai K, Qu J J, et al. 2010. Formative environment and dynamic process of a simple linear sand dune. *Arid Land Geography*, 33(3): 340-345. (in Chinese)

Zhang W M, Tan L H, An Z S, et al. 2019. Morphological variation of star dune and implications for dune management: a case study at the Crescent Moon Spring scenic spot of Dunhuang, China. *Journal of Arid Land*, 11(3): 357-370.

Zhang Z C, Dong Z B, Qian G Q, et al. 2017. Formation and development of dunes in the northern Qarhan Desert, central Qaidam Basin, China. *Geological Journal*, 53(3): 1123-1134.

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