Environmental dynamics of a star dune

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Abstract:

Star dunes, the largest aeolian bedforms in the sand seas of the world, are usually distributed within specific geographical areas that have multi-directional wind regimes. However, relatively few studies have focused on the environmental factors that impart such great volumes of sand to these dunes. Specifically, verification of the developmental processes of star dunes through long-term monitoring is scarce. In this study, by observing 3-D airflow fields and long-term dune dynamics, we demonstrate how topographic barriers, which generate vertical airflow and local air circulation, control the development of a star dune on Mingsha Mountain in Dunhuang, China. Results show that airflow stagnation and deflection caused by topography is one of the major mechanisms for the formation of star dunes. In our study, topographic barriers contribute to the development of intensive vertical airflow dominated by easterly winds. This intensive vertical airflow is one of the main driving mechanisms of the upward growth of mega-dunes. Vertical airflow is the strongest developed airflow reported in available data on aeolian geomorphology. In addition, star dunes are usually distributed in areas where the local air circulation is strong. The results of long-term dune dynamics verify that local air circulation, which forms three wind directions with the regional wind regime, contributes to the maintenance and

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development of star dunes. Our study indicates that complex mega-dunes are products of topographic barriers, which facilitate their recognition in aeolian geomorphology. We introduce a new evolution pattern of star dunes under the influence of local environment and topographic barriers.

Keywords: Star dune; Topographic barriers; Dune dynamics; Dunhuang

1. Introduction

Star dunes are the largest aeolian bedforms in many sand seas and may reach heights of more than 300 m (Cooke and Warren, 1973; Wilson, 1973; Lancaster, 1989a). They contain a greater volume of sand than any other dune type (Wasson and Hyde, 1983; Yang et al., 2011) and seem to occur in areas that represent depositional centers (Mainguet and Callot, 1978; Lancaster, 1983; Dong et al., 2004). Star dunes, with their tall bodies, special morphology, balanced development, and relatively limited migration, are usually distributed in specific geographical areas that have multi-directional wind regimes (Fryberger, 1979). They grow vertically as they accumulate sand brought in from numerous directions (Lancaster, 1989a). Their near-surface flow fields and sedimentary structures are also complex (Nielson and Kocurek, 1987; Lancaster, 1989a, b; Qu et al., 1992; Zhang et al., 2000), and their movement is different from those of transverse and longitudinal sand dunes, that is, it is stable with minimal movement (Breed and Grow, 1979; Qu et al., 1992; Zhang et al., 2000; Wang et al., 2005). Thus, star dunes have a unique position in the research field of aeolian geomorphology.

A close association between topographic barriers and the occurrence of star dunes has been observed (Zhu et al., 1981; Mainguet and Chemin, 1983; Lancaster, 1989b; Pye and Tsoar, 1990; Yan et al., 2001). The main effects of topographic barriers are probably an increase in the complexity of regional wind flow and the generation of secondary flows through differential surface heating (Lancaster, 1989b). Topographic barriers also create traps for sand transport, leading to the accumulation of thick sand deposits that are associated with the occurrence of star dunes (Lancaster,

1989b). Previous studies on the effect of topographic barriers on dune formation have primarily concentrated on simple dunes, such as echo and climbing dunes (Tsoar, 1983b). Topographic barriers can have a significant effect on the size, shape, and orientation of dunes, regardless of type or variety. The formation of star dunes also has some bearing on topographic barriers (Lancaster, 1989b; Qu et al., 1992). Recently, a numerical simulation group showed that soil topography can also affect the shape of barchan dunes (Parteli et al., 2014a). The group also indicated that obstacles can be used to induce dune formation in the combat against desertification (Parteli et al., 2014b). However, historically, the long-term dynamics of star dunes under such wind regimes has been difficult to investigate systematically in the field because of their size, and thus an extensive study on star dunes has not yet been conducted (Breed and Grow, 1979; Mader and Yardley, 1985; Nielson and Kocurek, 1987; Pye and Tsoar, 1990; Wang et al., 2005; Zhang et al., 2012). To date, relatively limited information has been published regarding how environmental factors (e.g., topographic barriers and local air circulation) cause star dunes to contain such large sand volumes (Lancaster, 1989b; Zhang et al., 2000; Andreotti et al., 2009; Yang et al., 2011).

Star dunes, as products of sand deposition, are usually distributed in a unique sedimentary environment. Consequently, conventional weather anemometers cannot accurately measure the influence of environmental factors, such as vertical airflow. Specifically, verification of the developmental processes of star dunes through long-term monitoring is scarce. Star dunes remain one of the least-studied dune types.

In this paper, we present field observations of vertical airflow, local air circulation, and long-term dynamics (1963–1985 and 1985–2004) of a giant star dune on Mingsha Mountain in Dunhuang, China. Special attention is paid to the effects of vertical airflow, local air circulation, and topographic barriers on the formation and development processes of the star dune.

2. Aeolian environment

The study area is located on Mingsha Mountain in the Crescent Moon Spring scenic area located approximately 5 km south of the city of Dunhuang, a famous historical and cultural city in Gansu Province, China (40.09° N, 93.67° E). This area is famous for its unique natural landscape variously described as “spring mirroring sand hills” and is considered an outstanding tourism resource in the northwest arid region of China. The specifically monitored star dune, with a relative height of 90 m, is located at the northern edge of the Mingsha Mountain dune field and north of the Crescent Moon Spring. This star dune has three arms radiating from the central peak and extending to the N (5°), SE (140°), and WSW (250°). The two adjacent arms constitute the E, S, and WNW dune sides. The E side is a typical avalanche face at angles of 25°–32°, with a slope length of 386 m, and a gently sloping plinth ahead of this side. The S and N sides have respective slope angles of 15°–30° and 20°–30° and respective slope lengths of 266 and 209 m (Fig. 1).

Place Fig. 1 here

Mingsha Mountain is 10–15 km wide from north to south and approximately 30 km from east to west. It is an aeolian depositional landform composed of complex linear dunes, star dunes, and complex mega-dunes, all of which are superimposed on low bedrock hills. Mingsha Mountain is approximately 1,250–1,600 m a.s.l, with a relative height of about 300 m (Fig. 1).

The recorded mean yearly precipitation at the meteorological station (40°08'N, 94°47'E) in Dunhuang City is approximately 39.7 mm, mainly falling between June and August and equaling 64% of the annual amount. However, the annual potential evaporation is approximately 2465 mm, which is almost 62 times that of the precipitation.

The regional environment of Mingsha Mountain was described by Zhang et al. (2000). The star dune in this area was formed by three wind directions. The 2014 wind data at the dune top were used to calculate the drift potential according to the method reported by Fryberger (1979). The annual DP at the dune crest was 221.6 VU.

A clear three-directional wind regime existed, with a primary peak in the western direction (WSW, W, WNW, NW) (75.0 VU), a secondary peak in the southern direction (SE, SSE, S, SSW) (73.1 VU), and a third peak in the eastern direction (NNE, NE, ENE, E, ESE) (20.7VU). According to Fryberger's classification of the wind environment standard, which reflects the complexity of wind regimes, this wind regime belongs to a moderate wind-energy environment with a directional variability (resultant DP/DP) of 0.45 (Fig. 2). Westerly winds mainly prevailed in winter, easterly winds were the dominant wind directions in spring and summer, and southerly winds occurred mainly at midnight throughout the year, especially during the months of October to February. The regional wind regime was mainly characterized by easterly and westerly winds. Field observations atop the Mogao Grottoes, 1.2 km southeast from the monitored star dune, have shown that the easterly winds are stronger than the westerly winds (Zhang et al., 2000; 2014). Given that the mega-dune developed in the piedmont area, the strength of easterly winds varied in different locations of mountain front; here, easterly winds are the weakest wind direction in the study area. Southerly winds are a critical local circulation in this area (Qu et al., 1992; Zhang et al., 2000; Wang et al., 2005), and with high frequency and long duration, they constitute the three wind directions with the regional wind regime, thus contributing to the development of star dunes.

Place Fig. 2 here

3. Methods

The wind profiles over the dune sides of the star dune were measured by HOBO anemometers with four wind cups at heights of 0.2, 0.5, 1.0, and 2.0 m and one wind vane at a height of 2 m above the dune surface. Wind speeds were collected at 1 min. intervals. Five 3-D ultrasonic anemometers (Young Model 81000) were also used to measure 3-D wind velocity at a frequency of 1 Hz and a height of 3 m (Fig. 3). The 3-D wind velocity refers to the resultant u (horizontal streamwise), v (horizontal spanwise), and w (vertical) wind components, including 3-D velocity magnitude,

azimuth angle, and flow elevation angle. Azimuth angle refers to the angle in the horizontal $u-v$ plane between the incoming wind vector and the geographical north. Flow elevation angle refers to the angle between the 3-D wind vector and the horizontal $u-v$ plane (-90° – 90°). The measurement period was from November 2013 to December 2014.

Place Fig. 3 here

Aerial photographs in 1985 and 2004 were processed by a digital photogrammetric workstation (JX-4C, Beijing Geo-Vision Tech. Co. Ltd., China). A digital elevation model (DEM) with a cell size of $1\text{ m} \times 1\text{ m}$ was then created. The digital cartographic dataset of the elevations in 1963 and 2008 was supplied by the Center of Mapping Geography Information in Gansu Province, China. We processed the DEM data and the digital cartographic dataset of the elevations by using the arithmetic operation in ArcGIS 9.3 (ESRI, USA), as well as analyzed dune erosion and deposition by using Surfer 8.0 software (Golden Software, USA). The movement characteristics of dune crestlines were also analyzed.

4. Results

4.1 Wind flow patterns

Wind flow over the star dune could be divided into transverse and longitudinal airflows, which functioned together to form different dune arms and sides. Transverse airflow (easterly winds) converged sand streams in the windward slope and diverged near the crest, where sands accumulated and caused the vertical growth of the southeast ridge. Longitudinal airflow (westerly winds) transported sand obliquely along a stoss or lee slope and induced the migration of the north and southeast crestlines.

4.1.1 Effect of easterly winds

In periods of easterly winds, the development of strong vertical airflows was the

main characteristic of the flow field of the studied star dune. In the piedmont area, a mega-dune barrier contributed to the decrease in wind speed, and airflow was impeded and climbed along the side of the mega-dune, resulting in the development of a strong vertical airflow. For example, the process of easterly winds (selected at 6:00 a.m.–6:30 a.m. on March 19, 2014) flowing over the E side with a reference average wind velocity of 11.3 m s^{-1} at 2 m above the ground surface and a wind direction of 56.9° , is shown in Fig. 4. The results showed that the strength of the vertical airflow was closely related to the locations on the E side. The 60 s running average vertical wind velocities of the lower, middle, and top locations of the E side (see Fig. 3) were 3.50, 6.23, and 3.59 m s^{-1} , respectively; the corresponding 3-D wind speeds were 8.52, 12.78, and 11.23 m s^{-1} , respectively. The maximum instantaneous vertical wind speeds reached 6.84, 9.18, and 9.26 m s^{-1} . Thus, the above locations of the E side corresponded to the vertical airflow initiation, development, and recession zones, respectively, and were similar to the corresponding locations of Zones A, B, and C reported by Wiggs et al. (1996). The vertical airflow in our study was the strongest developed airflow reported in the available data in literature (Walker et al., 2009).

Place Fig. 4 here

The development strength of vertical airflows could also be reflected from the incident and elevation angles of the flow. Incident angle, the angle between the wind direction and the crestline, is an important factor for determining the development of vertical airflow. Flow elevation angle is a direct factor that reflects the intensity of vertical airflow. The flow elevation angles at the lower and middle locations of the E side were 20° – 26° and 26° – 32° , respectively (Fig. 5). These angles showed a positive correlation with the incident angle of flow. In this case, the mega-dune barrier governed by the windward transverse airflow was the main dynamic mechanism of the well-developed vertical component, which was the result of the strong effects of streamline compression. Thus, the vertical lift toward the crest played a significant

role in the transport of sand particles from the toe of the E side to the crest. Sand deposition occurred near the leeward slope, which is critical for the increase in height of star dunes.

Place Fig. 5 here

Vertical velocity was strengthened by the mega-dune barrier, while the corresponding horizontal wind speed was amplified. Fig. 6a shows that during easterly winds, wind speeds at the bottom of the E side decreased by 20%–30% compared with the reference wind speed because of the barrier effect of the mega-dune's east side. By contrast, wind speeds increased toward the top of the star dune by 1.5–2.4 times at the upper one-third section of the E side, and then reached a maximum near the top of the mega-dune. However, wind speeds in the lee side near the crestline decreased to two-fifths of the reference wind speed, and a reversed helical vortex occurred (Lancaster, 1989a; Wang et al., 2005). In 3-D space, the direction of the rotating vortex was perpendicular to the crestline of the south arm. The convergence of the forward and reverse sand transports on the windward side and leeward accelerating zone heightened the star dune crest. Fig. 6b shows that the wind profile from wind speeds at 0.2, 0.5, 1.0, and 2 m at the lower part of the slope followed a logarithmic law. However, when airflow reached the upper one-third section of the slope surface, the wind speed at the 2 m height was roughly the same as that at the 1 m height because of the development of a strong vertical velocity, which formed a typical stagnant layer. The difference in wind speeds at the near-surface heights of 0.2 and 0.5 m increased with the dune height, indicating that the near-surface friction velocity increased.

The airflow produced by easterly winds had a specific impact on the south side of the star dune. As a result of the “funneling” between the mega-dunes, the airflow was accelerated, and the wind speeds at the bottom of the south side were second only to those near the crest line. The wind speeds could increase by 1.4 times with an average direction of 129°–151° (Fig. 6a).

Place Fig. 6 here

Fig. 7 shows the annual DP controlled by the easterly winds at different locations of the studied star dune. We selected wind speeds $>5 \text{ m.s}^{-1}$ and directions of 20° – 90° as the initial values of the easterly winds, as well as selected synchronous wind speeds at different locations. Owing to the vortex effect at the dune top, we did not select the DP at the top of the mega-dune but that at the upper one-third section of the E side to represent the annual DP of easterly winds. The annual DP was 29.7 VU, accounting for 13% of the total annual DP. The annual DP in 2014 also showed that the amplification effect of easterly winds was mostly pronounced. For example, the DP at the toe of the E side was only 2.9 VU, and wind speeds ranged mainly from 5 m.s^{-1} to 9 m.s^{-1} ; however, it increased to 29.7 and 9.2 VU at the upper one-third section and at the top, which were respectively 10.2 and 3.2 times that at the toe. The main wind speed ranges were 9–11 and $>11 \text{ m.s}^{-1}$, respectively.

Place Fig. 7 here

The wind flow pattern of easterly winds presented the similar flow pattern reported by Wiggs et al. (1996), that is, the concave streamline curvature presented at the toe, wind speed decreased, convex streamline curvature occurred with significant wind speed acceleration at the windward slope, and airflow diverged near the crest.

4.1.2 Effect of westerly winds

In the piedmont area, different wind directions exerted variable impacts on dune development. Compared with the vertical airflow velocities of easterly winds, the vertical airflow velocities of westerly winds were relatively weak. The incident angle between the westerly winds and the WSW ridge line was less than 30° – 40° ; thus, this airflow could be called the longitudinal airflow (Tsoar, 1983a; Wang et al., 2005). Fig. 8 shows the process of westerly winds over the S and WNW sides at 4:00 a.m.–4:30 a.m. on April 30, 2014 with a reference average wind velocity of 4.5 m s^{-1} at 2 m above the ground surface and a 192.7° direction. The results showed that the 60 s

running average vertical velocities on the S and WNW sides were 0.94 and 1.69 m.s^{-1} , respectively. A positive linear correlation was found between the 3-D wind and its vertical component ($R^2 = 0.84\text{--}0.97$) (Fig. 9). When the incident angle between the westerly wind and the north crestline ranged from -20° to 20° , the flow elevation angle changed from -2° to 16° . The incident angle for the south slope was $0^\circ\text{--}30^\circ$, and the flow elevation angle ranged from 7° to 16° . Therefore, flow elevation angle increased with incident angle. Under the effect of longitudinal airflow, the vertical airflow vector also occurred on both the S and WNW sides, a result that was consistent with the results of the near-surface flow field of a longitudinal dune reported by Tsoar et al. (1985) and Bristow et al. (2000).

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Place Fig. 9 here

In periods of westerly winds, we selected wind directions ranging from 200° to 270° and wind speeds greater than those at the lower part of the WNW side as the initial values of the westerly winds. We also selected synchronous winds at different monitoring points on the three sides. The annual DP at the top of the mega-dune was 60.6 VU , accounting for 27% of the total annual DP, which was twice that of the easterly winds. Westerly winds also had a strong amplification effect. The annual DP changed from 12.7 VU at the toe to 28.9 VU at the upper one-third section of the WNW side, and it reached 60.6 VU at the top. WNW- and S-slope airflows along the slope converged at the top under the influence of westerly winds. The DPs at the upper one-third section of the south side and the top were 30.5 (3-D wind data) and 23.3 VU , which were 2.4 and 1.8 times those of the toe, respectively (Fig. 10).

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The difference between the longitudinal and transverse airflows over the studied mega-dune was significant. The longitudinal airflow was less affected by the mega-dune barrier. The westerly wind speeds at the toe of the WNW side did not

decrease but increased, and they could be amplified to 1.2 times that of the reference wind speed. The westerly wind speed then rapidly increased with the height of the WNW side, reaching a maximum near the crestline, where wind speeds were amplified to 2.0 times of the reference wind speeds. Meanwhile, the wind speeds of the airflow on the lee side (the south side) decreased, reaching the minimum at the toe of the south side, with a value of 80% of the reference wind speeds (Fig. 11a). Furthermore, our observations showed that the turbulence intensity of the westerly winds acting on the WSW arm was stronger than that of the transverse airflow on the SE- and N arms. When the airflow accelerated or decelerated, the wind speeds at heights of 0.5, 1, and 2 m did not follow the logarithmic law (Fig. 11b).

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4.2. Long-term star dune dynamics

The long-term dynamics of star dunes were critical to revealing and verifying near-surface airflow under different wind directions. First, the dune dynamics over a timescale of decades (1963–1985) further demonstrated that the vertical airflow of easterly wind was a dynamic mechanism of the upward growth of star dunes. During the 12 years between 1963 and 1985, the maximum deposition thickness of the SE arm was 16 m with a deposition rate of 1.33 m a^{-1} . This zone was mainly distributed at the upper one-third section of the SE arm (Fig. 12a). Prior to the 1980s, only farmland with sporadic shrub surrounded Mingsha Mountain. However, the large-scale construction of fruit trees and shelter forest around Mingsha Mountain after the 1980s strongly influenced the strength of easterly winds (Pang et al., 2014). The construction of fruit trees and shelter forest likewise resulted in the deficiency of sand supply, which also played an important role in the upward growth of star dunes. Thus, the maximum deposition thickness of the southeast arm was 8 m, and the height of the dune crest increased by 3 m between 1985 and 2004 (Fig. 12b), indicating that the original vertical airflow before the 1980s was apparently stronger than that measured in the 2000s.

Place Fig. 12 here

Second, the results of dune dynamics further revealed that the prolongation of star dunes was apparent. Wind erosion mainly occurred on the stoss WNW side, and sand deposition occurred on the leeward sides (E and S). During the periods of 1963–1985 and 1985–2004, the respective maximum erosion depths of the WNW side were 13 and 2 m. The ridge line of the southeast arm moved 7.6–27 m and 8–10 m to the east in 1963–1985 and 1985–2004, respectively, and the variation in the north arm was relatively insignificant (Fig. 12). This phenomenon indicated that the surrounding environment mentioned above also strongly influenced the strength of the westerly winds. Significant differences existed in the variation process of airflow over dune sides for the transverse and longitudinal airflows.

Third, the results of dune dynamics illustrated that the local air circulation–southerly winds played a significant role in the development of the star dune. Prior to the 1980s, religious temples were sporadically distributed on the terrace south of the Crescent Moon Spring, and the original airflow field of the monitored mega-dune was not greatly affected by the presence of those temples. The entire south side was mainly dominated by wind erosion from 1963 to 1985. The maximum erosion depth reached 20–23 m with an annual average erosion rate of $1.66\text{--}1.92\text{ m a}^{-1}$ (Fig. 12a). However, some pavilions rebuilt in the 1990s hindered the channel of southerly winds and lessened the strength of the downhill southerly winds. Such outcomes, in turn, destroyed the original near-surface stream and gave rise to a change from wind erosion to sand deposition at the south side. The sand deposition thickness from 1985 to 2004 was 24 m, and sand was deposited at a rate of 1.1 m a^{-1} ; deposition mainly occurred at one-third the height of the south side (Fig. 12b). The phenomenon of erosion in the south side being converted into deposition indicated that the original southerly winds should be markedly stronger than those observed in this study. The airflows downward along the E side resulted in wind erosion that mainly occurred in areas below two-thirds the height of the E side, with maximum erosion depths of 17 and 6 m from the periods 1963–1985 and 1985–2004, respectively (Fig. 12).

5. Discussion

Topographic barriers that control the development of star dunes can be divided into three scales, the first of which is the mesoscale Mingsha Mountain. Easterly winds are the primary winds that form similar wind shadows in front of Mingsha Mountain. The front of Mingsha Mountain is an essential environmental condition for star dune development; in China, a common characteristic of star dunes is that they develop in front of mountains (Zhu et al., 1981; Qu et al., 1992). The general terrain characteristic of the study area is a transition zone between Sanwei Mountain and Mingsha Mountain, forming a typical col topography. On the one hand, the unique topographic barrier conditions caused a decrease in wind speed and an accumulation of airflow, resulting in the sand accumulation being closely related to the piedmont airflow structure (Sharp, 1966; Andrews, 1981; Tsoar, 1983b). For example, an anemometer was installed approximately 800 m to the east of the monitored star dune (Fig. 3, location A). According to its 10-min average wind speed from May 2011 to April 2012, easterly winds (NE, ENE, E, ESE, and SE) accounted for 5.81% of the total driving winds in frequency, of which the wind frequencies at various speed ranges were $>11 \text{ m.s}^{-1}$ (0.31%), $9\text{--}11 \text{ m.s}^{-1}$ (0.78%), $7\text{--}9 \text{ m.s}^{-1}$ (1.70%), and $5\text{--}7 \text{ m.s}^{-1}$ (3.01%). At the leading edge of the south of the monitored star dune, the results of the wind regime from the anemometers (Fig. 3, location B) revealed that the 10-min average wind speed was decreased by 40%–50%, and the frequency of the driving winds decreased to 1.38% compared with that at anemometer A. At anemometer B, the wind frequencies at various speed ranges were $>11 \text{ m.s}^{-1}$ (0), $9\text{--}11 \text{ m.s}^{-1}$ (0.02%), $7\text{--}9 \text{ m.s}^{-1}$ (0.29%), and $5\text{--}7 \text{ m.s}^{-1}$ (1.16%). Thus, the unique topographic barrier could change the original wind regime. *In situ* easterly winds became the weakest among the three directions at the monitored mega-dune under the influence of topographic barriers. On the other hand, the generation of local air circulation is another main contribution of topographic barriers. The downhill flow of southerly winds is strong, and thus plays an important role in the development of star dunes. For example, the downhill airflow constituted SE and SSE winds at the dune

top, and their total annual DP was 27.3 VU with wind speeds of 7–11 m s⁻¹, accounting for 73% of the total value of southerly winds (Fig. 2). Although the downhill southerly winds were strong, they were usually neglected. The generation of local air circulation–southerly winds was largely determined by the different locations of Mingsha Mountain. For example, meteorological data from Mogao Grottoes, which is located at the edge of Mingsha Mountain and adjacent to the study area, show three wind directions. Additionally, the frequency of the southerly winds less than the threshold velocity was 39.9%, and 59.2% of the wind speeds ranged from 5 m.s⁻¹ to 8 m.s⁻¹, while wind speeds >8 m s⁻¹ account for only 1.5% (Zhang et al., 2000). However, the meteorological data of Dunhuang City show only two main wind directions, which lack the southerly wind (Qu et al., 1992). Generally, weather station data lack local air circulation, and its effect on the development of star dunes is neglected, which is a main reason the star dune is the least-studied dune type.

Mega-dunes, as secondary topographic barriers, play a significant role in the development of vertical airflow vectors. Vertical velocity amplification is an outstanding feature of easterly winds and a main dynamic mechanism of the upward growth of star dunes. When airflow climbs along the side of the star dune, the well-developed vertical airflow vector only occurs during easterly winds (windward transverse airflow), and the development of the vertical airflow is dominated by the incident angle between the airflow and the crestline.

Star dunes are often formed in areas with certain micro-reliefs, such as unaka, and bench terraces, or close to mountain ridges (Wilson, 1973; Breed and Grow, 1979; Zhu et al., 1981; Lancaster, 1983; Qu et al., 1992). For example, at the edge of Mingsha Mountain, the Yumen group (Q₁¹) and brown mingled with taupe sandstone, clay, and glutenite alluvium (Q₂¹) formed by glaciofluvial activity exhibit a sidestep shape from north to south with an east–west strike. The topographical relief of Mingsha Mountain is mainly controlled by the underlying terrain, and the morphology of the star dunes inherits traces of the ancient terrain while also following the characteristics of modern aeolian landforms. Our field reconnaissance indicated that the underlying terrain, sporadically exposed at the bases of mega-dunes, is composed

of alluvial, lacustrine-alluvial, or river-bed sediments, which mainly contain clay and loam deposits. Pavilions adjacent to the mega-dunes south of the Crescent Moon Spring are built on the alluvial layer with an exposed height of 10–15 m. The residual strata, with a height of 20–30 m from the washout of Danghe River, are exposed approximately 8 km west of the monitored star dune. Thus, the bases of the mega-dunes on Mingsha Mountain are similar to a “rock core,” verifying the assumptions of early researchers that a rock core underlies mega-dunes (Zhu et al., 1981; Mckee, 1982; Yang et al., 2011). The rock core lays a foundation for further sand deposition and is a trigger for them to develop to a certain height. Sand accumulation promotes the development of vertical velocity and an airflow amplification effect, such that the mutual feedback between mega-dune development and airflow increases. Nielson and Kocurek (1987) argued that only when the dune size reaches a “minimum survival size” will it produce a secondary airflow so that the pyramidal shape can be maintained and grow in volume at the same time. As a result, sand dunes can withstand the influence of wind changes. In this sense, the expansive plinth controlled by the underlying terrain may play the role of “minimum survival size” in the process.

Field observations have confirmed that star dunes are one deformation form of transverse dunes (Lancaster, 1989a; Zhang et al., 2000). However, recent numerical simulations have indicated that the morphology of star dunes results from the combination of individual longitudinal dunes (Zhang et al., 2012). Based on the preceding field observation results, we propose a new model of star dunes governed by the local environment. The formation and evolution processes include the following three stages:

- The westerly and southerly winds, which are governed by Mingsha Mountain, are the two predominant strong winds in the area. The first phase is the formation of a WSW–ENE-oriented small longitudinal ridge. A small avalanche E face usually occurs in front of the longitudinal ridges, similar to transverse dunes. When the height of the avalanche face is less than a specific size, the effect of easterly winds is relatively weak (Fig. 13a).

- The second phase occurs when the extension movement of the longitudinal sand ridge encounters and climbs terrain obstacles from the WSW to ENE direction, while the plinth expands under the influence of the underlying terrain. The front of the sand ridge also widens and becomes higher. When the dune body reaches the so-called minimum survival size, the vertical airflow of the easterly winds is intensified. The effect of easterly winds on the avalanche E face is gradually enhanced, and the typical avalanche face then evolves into the E side. The SE ridge line of the E side gradually extends and develops to form the SE arm. Southerly winds (downhill winds) form airflow around the E side, causing the N ridge extend gradually to become a sand arm. The N and SE arms and the dune top link to become linking arms, thus forming a typical small star dune (Fig. 13b).
- Over time, a third stage occurs. With the development of the star dune formation, its mutual feedback with airflow further strengthens. Under the influence of westerly wind, the base of the star dune further enlarges. The dune height increases, causing the acceleration of vertical flows. The acceleration of vertical flow will give rise to a stronger lee-side circulation, reinforcing the tendency for dune upward growth. The star dune gradually evolves into a mega-dune (Fig. 13c).

Place Fig. 13 here

6. Conclusion

Through the integrated approach of combining observations of wind flow patterns with long-term monitoring of dune landform variation, we successfully obtained the observation evidence that wind deflection caused by topography is one of the major mechanisms for the formation of star dunes. Vertical velocity and local air circulation dominated by topographic barriers are important environmental factors controlling the development of star dunes. Mega-dunes are usually considered an outcome of environmental change (Lancaster, 1990; Chen et al., 2004), but this is not the only dominant factor. Instead, we verified that star dunes can also be products of vertical lift of airflow and local air circulation. Vertical velocity is one of the driving

factors for the height growth of mega-dunes. Local air circulation, which constitutes three wind directions with a regional wind regime, contributes to the maintenance and development of star dunes. Thus, topographic barriers not only play a crucial part in the formation of simple dunes, such as echo and climbing dunes, but also exert an important role in the formation of mega-dunes. The developing mechanisms of complex mega-dunes controlled by topographic barriers will eventually stimulate new thinking in the computational simulation of mega-dune development in the future.

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Fig. 1 Location map of the studied star dune in Dunhuang, China.

Fig. 2 DP at different locations of the star dune in 2014.

Fig. 3 The layout of HOBO and 3-D ultrasonic anemometers and wind roses at locations A and B

Fig. 4 Time series of horizontal and vertical wind speeds (the bold line represents the 60 s running mean) and sand-driving wind rose (3-D speed) at different locations of the E side during easterly winds.

Fig. 5 Relationship between incident angle and flow elevation angle during easterly winds on the E side.

Fig. 6 Variation in wind speed along the cross-section of the monitored dune (a) and near-surface wind profiles during easterly winds (b).

Fig. 7 DP under easterly winds at different dune locations in 2014.

Fig. 8 Time series of horizontal and vertical wind speeds (the bold line represents the 60 s running mean) and sand-driving wind rose (3-D speed) at the two-thirds upper WNW and S sides during westerly winds.

Fig. 9 Relationship between incident angle and flow elevation angle on the north and south sides during westerly winds.

Fig. 10 Variation in wind speeds in the cross-section of the monitored mega-dune during westerly winds (a) and near-surface wind profile (b).

Fig. 11 DP under westerly winds at different dune locations in 2014.

Fig. 12 Long-term dynamics of the monitored star dune during different periods (a: 1963–1985; b: 1985–2004). Positive contour interval value indicates deposition and negative erosion.

Fig. 13 Evolution model of the star dune: (a) formation of a WSW–ENE-oriented small longitudinal ridge, (b) formation of a typical small star dune, (c) star dune evolving into a mega-dune.

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