J Arid Land (2014) 6(3): 255–263
doi: 10.1007/s40333-013-0245-0
jal.xjegi.com; www.springerlink.com/40333

Quantitative analysis on the dynamic characteristics of megadunes around the Crescent Moon Spring, China

YingJun PANG[1,2], JianJun QU[1,2,3*], KeCun ZHANG[1,2,3], ZhiShan AN[1,2,3], QingHe NIU[1,2,3]

[1] Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China;
[2] Dunhuang Gobi and Desert Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Dunhuang 736200, China;
[3] Gansu Center for Sand Hazard Reduction Engineering and Technology, Lanzhou 730000, China

Abstract: The Crescent Moon Spring is a precious natural heritage. However, the dynamic characteristics of megadunes around the Crescent Moon Spring are not well known. This paper quantitatively studied the characteristics and changes of megadunes around the Crescent Moon Spring by interpreting aerial photographs taken in 1985 and 2004 and analysing the dune crestlines and the wind data collected from 2011 to 2012. Results revealed that pyramid dunes were formed by a complex wind regime. The Crescent Moon Spring was not buried by shifting sands because of the stable wind regime and relative stability of pyramid dunes. The crestlines of the dunes around the spring moved northward between 1985 and 2004. The south-facing slip faces were also exposed to wind erosion, whereas the other faces were under deposition, thus indicating that the southerly wind was relatively enhanced. Limiting the scale of tall windbreaks and architectures in the Dunhuang oasis at the north of the spring was necessary to maintain the dynamic equilibrium of the wind regime and sand transport.

Keywords: Dunhuang city; Crescent Moon Spring; pyramid dunes; dynamic characteristics; erosion and deposition

Citation: YingJun PANG, JianJun QU, KeCun ZHANG, ZhiShan AN, QingHe NIU. 2014. Quantitative analysis on the dynamic characteristics of megadunes around the Crescent Moon Spring, China. Journal of Arid Land, 6(3): 255–263. doi: 10.1007/s40333-013-0245-0

The Crescent Moon Spring (Fig. 1), which is located 5 km south of the arid Dunhuang city, Gansu province, Northwest China, is embraced by the rolling sand dunes of the Mingsha Mountain (also named as "Singing Sand Mountain"). Spring water is dreamily lucid at dawn, and the dunes produce sounds similar to melodies on sunny days. These sites are important tourism resources and are considered precious natural heritage areas in Dunhuang. The earliest written records on the Mingsha Mountain and Crescent Moon Spring can be found in the writings of the Eastern Han Dynasty (25 AD to 220 AD). The Mingsha Mountain is known for the ability of the night wind to blow up the sand and to restore the mountain to its natural shape. This miraculous phenomenon was recorded in the ancient archive *Annals of Yuanhe County*. The Chinese ancients recognized that the harmonious coexistence of the Crescent Moon Spring and Mingsha Mountain is related to unique regional atmospheric circulation. The spring has not been buried by the shifting sand for thousands of years. The relative stability of the pyramid dunes (Nielson and Kocurek, 1987) is also one of the causes of this phenomenon.

Zhang et al. (2012) investigated the spatial patterns of the sand-driving wind, sand drift potential (DP) and dominant sand-transporting orientations based on 2008–2009 wind data from seven meteorological stations around the Crescent Moon Spring. They indicated that northerly wind is uncommon in the Crescent Moon Spring and that the northward movement of the megadunes at the south of the Crescent Moon Spring threatens the survival of the spring. An et al. (2013) monitored the height of the seven typical feature points of the megadunes surfaces around the Crescent

*Corresponding author: JianJun QU (E-mail: qujianj@lzb.ac.cn)
Received 2013-05-06; revised 2013-06-02; accepted 2013-06-28

Fig. 1 Crescent Moon Spring

Moon Spring from April 2008 to October 2010. They found that the maximum and minimum fluctuation ranges were 2.6 and 1.3 m, respectively. Studies on the formation (Wang, 2009; Yin and Wei, 2010), water table decline (Ding and Gong, 2004; Yue et al., 2007) and protection (Yang and Zhang, 2003; Dong and Bian, 2004) of the Crescent Moon Spring have also been conducted recently by local and foreign researchers. However, a quantitative analysis on the morphological variation of the megadunes and their effect on the Crescent Moon Spring is lacking. The dunes at the north and south sides of the spring have recently started to move towards the spring. This movement threatens the survival of the spring and has attracted the attention of relevant government agencies. Therefore, quantitatively evaluating the change of morphology and assessing the stability of the meg- adunes around the Crescent Moon Spring are important.

This paper quantitatively studied the characteristics and changes of the megadunes around the Crescent Moon Spring by interpreting the aerial photographs taken in 1985 and 2004, observing the dune crestlines and analysing the wind data collected from 2011 to 2012. This study is not only theoretically significant for studies on the dynamic process of megadunes but also provides scientific guidance to protect the natural heritage.

1 Study area

The Crescent Moon Spring (40°05′12.94″N, 90°40′16.71″E) is located at the west of the Hexi Corridor, the southern edge of the Dunhuang Basin and within the Danghe River and Xishui Valley alluvial fans and bordered the Sanwei Mountain (Fig. 2). The key factors in the formation of the spring are loose geological structures, low-lying terrain conditions and high regional water levels. Tectonic movement and water and wind geological processes are intrinsic and extrinsic dynamic conditions, respectively (Yin and Wei, 2010). The mean annual precipitation is less than 40 mm. The annual potential evaporation is high and reaches 2,488 mm. The study area is subject to the continental arid climate. The DP is 161.8 VU and is predominated by the NE, WSW, ENE and SW winds at 42, 34.1, 31.5 and 22 VU, respectively. The wind regime belongs to a low wind-energy environment with a directional variability (RDP/DP) of 0.02 according to the Fryberger's classification of the wind environment standard, which reflects the complexity of the wind regimes (Fig. 3).

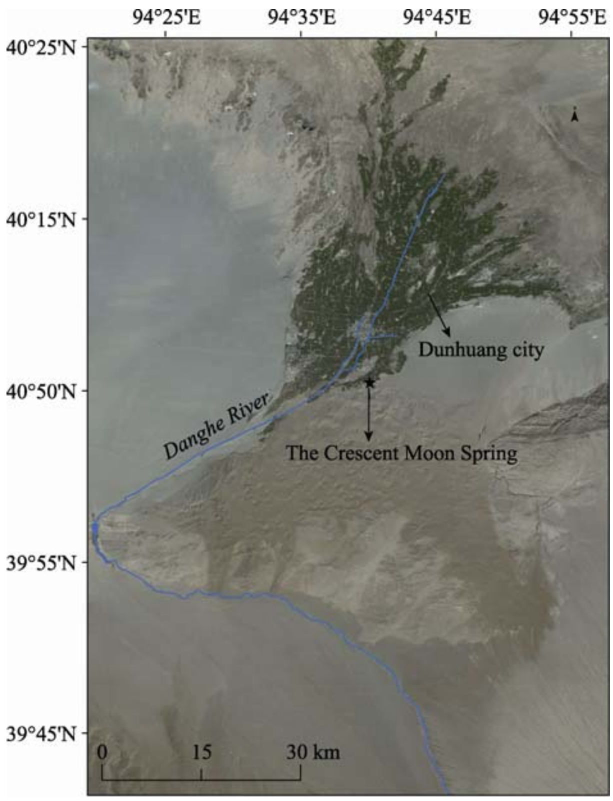

Fig. 2 Location of the Crescent Moon Spring

The Crescent Moon Spring lies at the edge of the Mingsha Mountain. The surrounding terrain is complex (Fig. 4). Area I is a big spring bay where the Crescent Moon Spring and buildings constructed in ancient styles (Moon Spring Pavilion, Thunder-hearing Veranda, Ink Cloud Pool and Mountain Gate) are located. Area II is a small spring bay that is under a wind-erosion depression among megadunes that con-

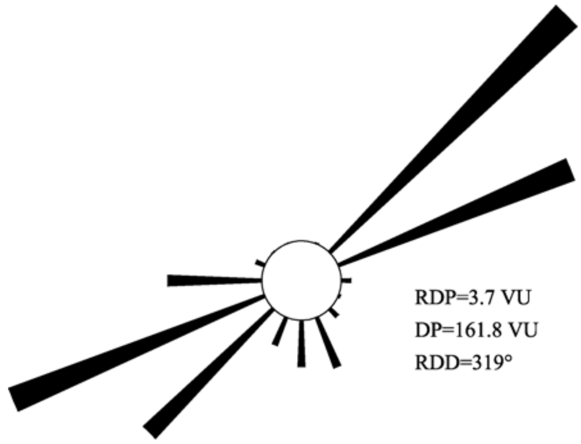

Fig. 3 Sand-drift potential rose in the Crescent Moon Spring (May 2010 to May 2012). DP, drift potential; RDP, resultant drift potential; RDD, resultant drift direction.

Fig. 4 Schematic of the division of the Crescent Moon Spring

tains an artificial lake, administrative area and flower garden. Area III is a relatively flat area with a Gobi surface and low dunes. Areas IV and V are pyramid dunes 100 and 170 m high above the ground of the spring, respectively, with three arms oriented approximately S–N, ENE–WSW and NNW–SSE. Slip faces are located between arms. Area VI is a longitudinal dune 130 m above the ground of the spring with an orientation of SSE–NNW. Area VII contains complex pyramid dune chains that are 150 m high.

The material composition of the megadune surfaces is dominated by fine sand (51.26%), medium sand (29.49%) and coarse sand (15.35%); very fine sand and silt are scarce (Table 1).

2 Method

Aerial photographs in 1985 and 2004 were processed by using a digital photogrammetric workstation (JX-4C, Beijing Geo-Vision Tech. Co. Ltd., China). The photographs were used as information resources to perform interior orientation, relative orientation, absolute orientation, epipolar image resampling, image correlation and feature matching. A digital elevation model (DEM) with a cell size of 1 m×1 m was then created. JX-4C is a set of semi-automatic digital photogrammetric workstation with great human–computer interaction and strong product quality control that are combined with the operating experience of the production. This system is mainly used to produce various scales of the DEM, digital orthophoto map and digital line graph. The DEM is a digital cartographic/geographic dataset of the elevations in xyz coordinates. We processed DEM data by using the arithmetic operation in Arcgis 9.3 to analyze the slope erosion and deposition. We then extracted the dune crestlines by the hydrological analysis method (Tang and Yang, 2010) and analyzed the migration characteristics of these crestlines. The dune crestlines around the Crescent Moon Spring were also measured by the total station (Leica TS06, accuracy: 1.5 mm+2 ppm) provided by Leica Geosystems AG (Switzerland) in July, September and November 2011 and October 2012. The movement characteristics of the dune crestlines were also analyzed combined with the contemporaneous wind speed and wind direction data.

Table 1 Sand grain size distribution in the Crescent Moon Spring

	Coarse sand (mm)	Medium sand (mm)	Fine sand (mm)	Very fine sand (mm)	Silt (mm)
Grain size distribution	1.00–0.40 (15.35%)	0.40–0.25 (29.49%)	0.250–0.125 (51.26%)	0.125–0.063 (3.77%)	<0.063 (0.15%)

Note: *n*=70, where *n* is the number of samples.

3 Results

3.1 Erosion and deposition in slip faces of dunes during 1985–2004

Figure 5 and Table 2 show that 82.4% of the S slip face (1) of the pyramid dune at the north of the Crescent Moon Spring experienced wind erosion during 1985–2004, with average and maximum erosion depths of approximately 7.3 and 18.1 m, respectively. The deposition mainly occurred in the upper and middle parts of the slip face, the average and maximum depositional thickness being about 5.3 and 18.5 m, respectively. The average erosion depth of the entire S slip face (1) was roughly 5.1 m. The wind-erosion area of the E slip face (2) was approximately 34.6%, and the average and maximum erosion depths were roughly 1.9 and 8.5 m, respectively. The erosion mainly occurred at the bottom. A total of 65.4% of the E slip face (2) experienced deposition, and the average and maximum depositional thicknesses were approximately 7.7 and 20.1 m, respectively. The deposition mainly occurred in the upper and middle parts of the slip face. The average depositional thickness of the entire E slip face (2) was about 4.4 m. The W slip face (3) was depositional. The average depositional thickness of the entire slip face was roughly 4.3 m. The depositional area was approximately 87.1%, with average and maximum depositional thicknesses of roughly 5.4 and 16.2 m, respectively.

The erosion and deposition of the pyramid dune at the west of the Crescent Moon Spring are similar to the erosion and deposition at the north, i.e. the S slip face (4) was erosional. The average erosion depth of the entire slip face (4) was approximately 15.4 m, which was 10.3 m deeper than the S slip face (1) of the pyramid dune at the north of the Crescent Moon Spring. The erosional area was approximately 93.3%, with average and maximum erosion depths of 16.7 and 55 m, respectively. The E and W slip faces (5 and 6) were depositional. The average depositional thicknesses of the entire slip faces were approximately 6.1

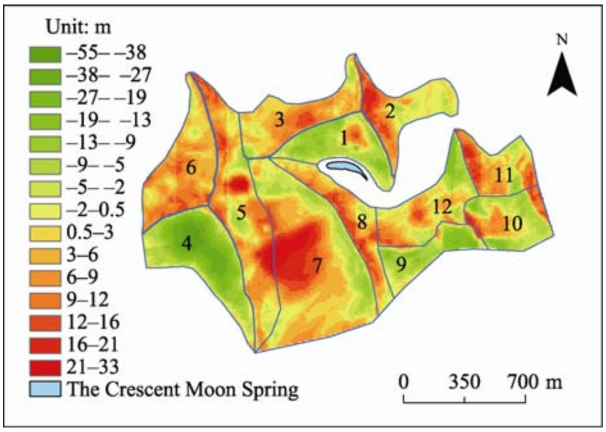

Fig. 5 Erosion and deposition of the dunes around the Crescent Moon Spring during 1985–2004. Numbers 1–12 indicate different slip faces.

Table 2 Erosion and deposition statistical data during 1985–2004

Slip face	Erosion				Deposition				Total (+ deposition; – erosion)	
	Max (m)	Mean (m)	Ratio (%)	Volume (m^3)	Max (m)	Mean (m)	Ratio (%)	Volume (m^3)	Volume (m^3)	Unit area (m)
1	18.1	7.3	82.4	842,013	18.5	5.3	17.6	132,081	–709,932	–5.1
2	8.5	1.9	34.6	82,733	20.1	7.7	65.4	647,095	564,362	4.4
3	10.6	3.0	12.9	60,996	16.2	5.4	87.1	730,776	669,780	4.3
4	55.0	16.7	93.3	3,466,636	7.9	2.4	6.7	35,443	–3,431,193	–15.4
5	12.3	2.8	19.1	148,330	32.8	8.2	80.9	1,872,988	1,724,659	6.1
6	6.0	1.7	5.6	18,293	18.2	6.2	94.4	1,133,236	1,114,943	5.7
7	12.8	4.1	31.1	584,996	28.0	8.3	68.9	2,641,015	2,056,019	4.4
8	7.0	1.9	16.9	42,405	18.4	7.2	83.1	772,031	729,626	5.6
9	22.8	8.8	88.7	768,428	16.4	4.7	11.3	52,450	–715,977	–7.3
10	19.4	6.0	60.1	477,785	19.2	7.1	39.9	373,521	–104,264	–0.8
11	10.7	3.6	25.4	99,287	18.6	7.6	74.6	613,380	514,094	4.7
12	16.9	5.5	43.3	385,183	16.6	5.0	56.7	462,110	76,927	0.5
Total				6,977,085				9,466,126	2,489,045	1.1

and 5.7 m, which were 1.7 and 1.4 m thicker than those of the E and W slip faces (2 and 3) of the pyramid dune at the north of the Crescent Moon Spring, respectively. For the E and W slip faces (5 and 6), the depositional areas were roughly 80.9% and 94.4%, with average depositional thicknesses of 8.2 and 6.2 m, and the maximum depositional thicknesses of 32.8 and 18.2 m, respectively.

A total of 68.9% of the S slip face (7) of the longitudinal dune at the south of the Crescent Moon Spring was depositional. The depositional area mainly occurred at the bottom of the slip face, with average and maximum depositional thicknesses of approximately 8.3 and 28 m, respectively. The erosional area mainly occurred at the upper area, with average and maximum erosion depths of approximately 4.1 and 12.8 m, respectively. The average depositional thickness of the entire slip face (7) was approximately 4.4 m. This phenomenon was caused by the higher wind velocities and sand transport rates in the crestal area than in the plinths. The depositional area of the slip face (8) was 83.1%, with average and maximum depositional thicknesses of approximately 7.2 and 18.4 m, respectively. The average depositional thickness of the entire slip face (8) was approximately 5.6 m.

The erosional area of the slip face (9) of the pyramid dune chains at the east of the Crescent Moon Spring was roughly 88.7%, with average and maximum erosion depths of approximately 8.8 and 22.8 m, respectively. The average erosion depth of the entire slip face (9) was roughly 7.3 m. A total of 60.1% of the slip face (10) was erosional, with average and maximum erosion depths of approximately 6 and 19.4 m, respectively. In the depositional area, the average and maximum depositional thicknesses were approximately 7.1 and 19.2 m, respectively. The average erosion depth of the entire slip face (10) was approximately 0.8 m. A total of 74.6% of the slip face (11) was depositional, with average and maximum depositional thicknesses of approximately 7.6 and 18.6 m, respectively. The average depositional thickness of the entire slip face (11) was approximately 4.7 m. When the NE wind blows into the valley surrounded by dunes, the wind speed increases. Therefore, the erosional area of the slip face (12), which was mainly located in the north and accounted for 43.3% of the total slip face area, had average and maximum erosion depths of approximately 5.5 and 16.9 m, respectively. The depositional area mainly occurred in the south with average and maximum depositional thicknesses of approximately 5.0 and 16.6 m, respectively. The average depositional thickness of the entire slip face (12) was approximately 0.5 m.

Dune surfaces undergo constant erosion, deposition and neither erosion nor deposition (Tsoar and Blumberg, 2002). The erosion and deposition of the dunes around the Crescent Moon Spring generally had obvious regularity. The S slip faces of the dunes were almost erosional, whereas the other slip faces were depositional. The erosion and deposition changes of the dune surfaces were mainly affected by wind velocity, wind direction, turbulent fluctuation, sand supply and sand grain size distribution. A close correlation existed between the patterns of erosion/deposition and wind velocity/direction (Lancaster, 1989). The erosional slopes in all directions experienced accelerated or divergent winds. Rapid and large-volume deposition occurred on the lee-side avalanche faces, where velocities rapidly decreased by flow separation. Slow deposition also occurred in areas where the sand transport rates decreased downwind because of flow convergence or local flow expansion. The erosion and deposition distribution map (Fig. 5) shows that the southerly winds were relatively stronger between 1985 and 2004.

3.2 Migration of dune crestlines during 1985–2004

The migration of the crestlines of the pyramid dunes at the north and west of the Crescent Moon Spring was similar (Fig. 6). During the monitoring period of 1985–2004, the SSE crestlines (A and D) migrated 12.1 and 6.8 m in the ENE direction, respectively, whereas the WSW crestlines (C and F) migrated 16.1 and 19.1 m in the NNW direction, respectively. The upper and lower parts of the N crestline of the pyramid dune at the north of the Crescent Moon Spring (B) migrated 2.9 m in the E direction and 4.3 m in the W direction, respectively. The N crestline of the pyramid dune at the west of the Crescent Moon Spring (E) migrated 9.2 m in the W direction. The migration directions of the SSE, WSW and N crestlines of the pyramid dunes on the west of the Crescent Moon Spring (D, E and F) were in accordance with those of the crestlines of the pyramid dunes at the north of the Crescent Moon Spring (A, B and C). However, the migration distances had slight differences.

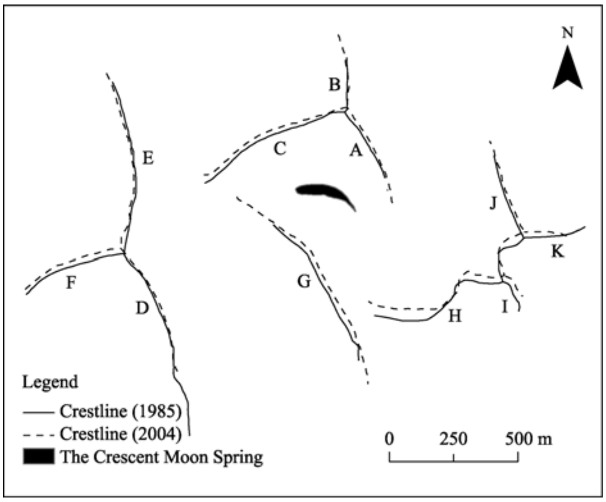

Fig. 6 Migration of dune crestlines around the Crescent Moon Spring during 1985–2004. A–K indicate the crestlines of different directions.

The crestline of the longitudinal dune (G) at the south of the Crescent Moon Spring migrated 16 m in the ENE direction. The crestline was approximately parallel to the SSE crestlines of the pyramid dunes at the north and west of the Crescent Moon Spring (A and D). The migration directions were almost the same, but the migration distance was 3.9 and 9.2 m longer than SSE crestlines of the pyramid dunes at the north and west of the Crescent Moon Spring, respectively.

The western part of the WSW crestline of the pyramid chains (H) was oriented W–E and had a maximum migration distance of 42.2 m in the N direction. The eastern part was oriented W–E and migrated 28.1 m in the N direction. The middle part was oriented SW–NE and had no distinctive migration. The SE crestline (I) migrated 22.7 m in the ENE direction. The NNW crestline (J) migrated 9.5 m in the ENE direction. The migration distances of the E crestline (K) decreased from west to east, and the western part migrated 16.6 m in the N direction.

The crestlines had obvious migrations in the N direction, except for the N crestlines of the pyramid dune at the north and west of the Crescent Moon Spring (B and E), and were parallel before and after the movement. This result was in accordance with those in the Dunhuang Mogao Grottoes, China (Wang et al., 2005).

The summit of the pyramid dune at the north of the Crescent Moon Spring migrated 20.3 m in the NNE direction and increased by 2 m in height. The summit of the pyramid dune at the west of the Crescent Moon Spring migrated 21.7 m in the NNW direction and increased by 4.9 m in height. The southern summit of the pyramid dune chains at the east of the Crescent Moon Spring migrated 27 m in the NNE direction and decreased 3.9 m in height. The northern summit migrated 22.1 m to the north and decreased 6.3 m in height. All summits moved in an N direction.

3.3 The short-term migration of dune crestlines

The winds were predominantly NE, ENE and WSW (Fig. 7a) during the monitoring period from 6 July 2011 to 3 September 2011. The rose diagram for this period revealed that the DP was 170.4 VU with a resultant drift direction (RDD) of 270.1°. The SSE crestline of the pyramid dune at the north of the Crescent Moon Spring migrated 2.4 m to the SW. The upper part of the N crestline migrated 0.6 m to the WSW, and the lower part migrated 1.4 m to the NE. The WSW crestline migrated 3.5 m to the NW. The summit migrated 3.6 m to the NNW and increased by 0.7 m in height (Fig. 8). The western part of the longitudinal dune crestline at the south of the Crescent Moon Spring migrated 2.4 m to the SSW. The eastern part migrated 1.7 m to the NE.

The winds were predominantly NE and ENE (Fig. 7b) during the monitoring period from 3 September 2011 to 7 November 2011. The rose diagram for this period showed that the DP was 77.9 VU with an RDD of 235.9°. The SSE crestline of the pyramid dune at the north of the Crescent Moon Spring migrated 0.9 m to the SW. The upper part of the N crestline migrated 0.1 m to the WSW, and the lower part migrated 0.3 m to the NE. The WSW crestline migrated 1.2 m to the SE. The summit migrated 2.8 m to the S and increased by 0.5 m in height (Fig. 8). The western part of the longitudinal dune crestline at the south of the Crescent Moon Spring migrated 1.2 m to the SSW. The eastern part had no obvious migration.

The winds were predominantly NE, WSW, SW and

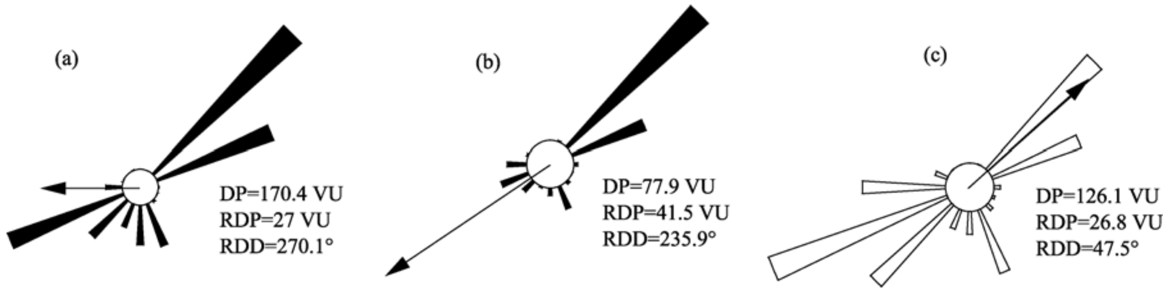

Fig. 7 Sand-drift potential roses for the monitoring period. (a), 6 July 2011 to 3 September 2011; (b), 3 September 2011 to 7 November 2011; (c), 7 November 2011 to 21 October 2012

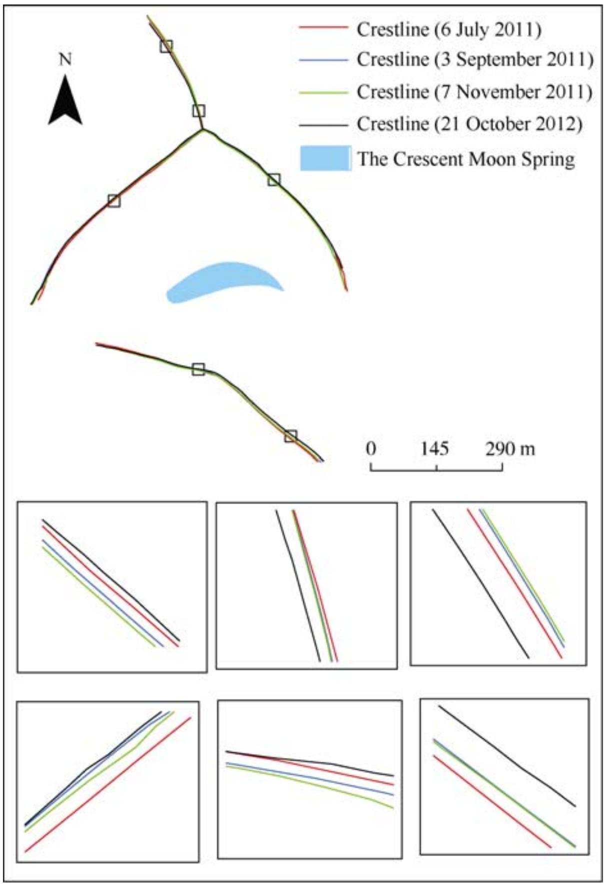

Fig. 8 Short-term migration of the dune crestlines around the Crescent Moon Spring

ENE (Fig. 7c) during the monitoring period from 7 November 2011 to 21 October 2011. The rose diagram for this period showed that the DP was 126.1 VU with an RDD of 47.5°. The SSE crestline of the pyramid dune at the north of the Crescent Moon Spring migrated 4.1 m to the NE. The N crestline migrated 4.8 m to the WSW. The WSW crestline migrated 1.8 m to the NW. The summit migrated 3.3 m to the NW and decreased by 0.6 m in height (Fig. 8). The crestline of the longitudinal dune at the south of the Crescent Moon Spring migrated 3.9 m to the NNE.

The wind velocities in the crestal ridges of the pyramid dunes were generally higher than those at the middle and bottom of the slopes (Zhang et al., 2000). Thus, most erosion and deposition occurred on the crestal ridges of the pyramid dunes (Sharp, 1966). The crestline migrations of the pyramid dunes were highly correlated with the wind velocities and directions during the monitoring period. A comparison of the migrations of the crestlines and wind regime from the same period revealed that the direction of the crestline migration was consistent with the direction of the component of the resultant drift potential along the direction perpendicular to the crestline. The above characteristics were obvious, particularly for the SSE, WSW crestlines of the pyramid dune at the north of the Crescent Moon Spring and the longitudinal dune at the south of the Crescent Moon Spring.

4 Discussion

The Crescent Moon Spring and its surrounding megadunes coexist harmoniously and have not been buried by shifting sand, thus indicating the excellent stability of the megadunes. The equation for the velocity of dune movement (D=Q/rh; D, the velocity of dune movement; Q, sand transport amount; r, sand bulk density; h, dune height) (Wu, 1987) revealed that the velocity of the dune movement was inversely proportional to the dune height, i.e. a higher dune leads to slower dune movement. The DP at the Crescent Moon Spring was 161.8 VU, but the RDP was considerably low at 3.7 VU. The dune height was large, thus causing the dune around the Crescent Moon Spring to move slightly. The Crescent Moon Spring is in the Sanwei Mountain piedmont and has three group winds (NE–ENE, SSE–SSW and SW–W), which provide advantages in the formation of stable high pyramid dunes (Wilson, 1973; Breed and Grow, 1979; Fryberger and Dean, 1979; Zhu et al., 1981; McKee, 1982; Lancaster, 1983; Lang et al., 2013). Previous studies suggested that the pyramid dunes were typical sand dunes in the role of multi-directional winds and could be considered bare dunes. However, they swung back and forth with slight movement, thus leading to the stability of the pyramid dunes (Wu, 2009). The observation of the dune crestlines around the Crescent Moon Spring in July, September and November 2011 and October 2012 suggested that the dune crestlines swung back and forth with changing RDD during the monitoring period. The movements were not always towards the same direction. This is the key to the harmonious coexistence of the Crescent Moon Spring and megadunes.

The dynamic changes of the dunes were mainly manifested in the migration (most obvious in the crestlines and toelines), erosion and deposition in the slip faces. The dynamic changes of the dunes were related to the wind regime, sand source supply, underlying surface, and so on. The erosion and deposition of each part of the dune was fundamentally a function of their sediment budget. The comparison of the aerial photographs taken in 1985 and 2004 revealed that the crestlines of the dunes around the Crescent Moon Spring moved towards the north. The south-facing slip faces were in a state of wind erosion, whereas the others were in a state of deposition, thus indicating that the southerly wind was relatively enhanced. This enhancement may stem from the increase of the southerly winds or the weakening of the northerly winds because of the expansion of the Dunhuang Oasis at the north of the Crescent Moon Spring. Therefore, to maintain the stability of the megadunes around the Crescent Moon Spring, we should limit the scale of tall windbreaks and architectures, which can increase the strength of northerly winds, recover the dynamic equilibrium of the wind regime and sand transport, and prevent dunes from migrating substantially towards one direction and threatening the survival of the Crescent Moon Spring.

5 Conclusions

Pyramid dunes are formed by complex wind regimes. The Crescent Moon Spring was not buried by shifting sand because of the stable wind regimes and relative stability of the pyramid dunes.

From 1985 to 2004, the northerly wind was weakened because of the expansion of the Dunhuang Oasis at the north of the Crescent Moon Spring, which further led to the northward moving of megadunes around the spring. The moving of the megadunes could be observed in two aspects: the northward shifting of the dune crestlines, and the wind erosion status of the south-facing slip faces but deposition status of other dune faces.

Acknowledgements

This work was funded by the National Key Technology R&D Program of China (2013BAC07B02), the National Natural Science Foundation of China (41071009), and the West Light Foundation of Chinese Academy of Sciences (29Y128841).

References

An Z S, Zhang K C, Wang X L, et al. 2013. Dynamic monitoring of sand hill and wind-blown sand environment in the scenic spots of Crescent Moon Spring in Dunhuang, China. Journal of Arid Land Resources and Environment, 27(3): 115–120.

Breed C S, Grow T. 1979. Morphology and distribution of dunes in sand seas observed by remote sensing. In: McKee E D. A Study of Global Sand Seas. U.S. Geological Survey, 253–302.

Ding H W, Gong K C. 2004. Analysis of the reasons and countermeasures for the decline in the water level of the Crescent Moon Spring near Dunhuang. Hydrogeology & Engineering Geology, 31(6): 74–77.

Dong J H, Bian Z F. 2004. Proposal for the protection of natural heritage of Singing Sand Mountain and Crescent Moon Spring in Dunhuang City, China. Journal of Natural Resources, 19(5): 561–566.

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

Lancaster N. 1983. Controls of dune morphology in the Namib sand sea. Developments in Sedimentology, 38: 261–289.

Lancaster N. 1989. The dynamic of star dunes–an example from the gran desierto, Mexico. Sedimentology, 36(2): 273–289.

Lang L L, Wang X M, Hasi E, et al. 2013. Nebkha (coppice dune) formation and significance to environmental change reconstructions in arid and semiarid areas. Journal of Geographical Sciences, 23(2): 344–358.

McKee E D. 1982. Sedimentary structures in dunes of the Namib desert, south west Africa. Geological Society of America Special Papers, 188: 1–2.

Nielson J, Kocurek G. 1987. Surface processes, deposits, and development of star dunes-Dunmont dune field, Califoria. Geological Society of America Bulletin, 99 (2): 177–186.

Sharp R P. 1966. Kelso dunes, Mojave Desert, California. Geological Society of America Bulletin, 77(10): 1045–1074.

Tang G A, Yang X. 2010. Spatial analysis experiment course of ArcGIS geographic information system. Beijing: Science Press, 92–96.

Tsoar H, Blumberg D G. 2002. Formation of parabolic dunes from barchan and transverse dunes along Israel's Mediterranean coast. Earth Surface Processes and Landforms, 27(11): 1147–1161.

Wang J P. 2009. Geological causes and the protection of Lake Grescent Moon Spring in Dunhuang. Water Sciences and Engineering Technology, doi: 10.3969/j.issn.1672-9900.2009.04.013.

Wilson I G. 1973. ERGS. Sedimentary Geology, 10(2): 77–106.

Wang T, Zhang W M, Dong Z B, et al. 2005. The dynamic characteristics and migration of a pyramid dune. Sedimentology, 52(3): 429–440.

Wu Z. 1987. Aeolian Landform. Beijing: Science Press, 157–166.

Wu Z. 2009. Sandy Deserts and Its Control in China. Beijing: Science Press, 142–152.

Yang J C, Zhang C. 2003. The selection of leaking-flow fields mathematical model and harnessing program in Yueya spring. Northewest Water Resources & Water Engineering, 14(3): 25–28.

Yin N W, Wei Y T. 2010. The analysis on the formation of the Crescent Moon Spring. Groundwater, 32 (2): 20–22.

Yue F, Dong J H, Wen X Q. 2007. The decadent reason and countermeasure of Crescent Moon Spring view of Dunhuang City. Research of Soil and Water Conservation, 14(2): 200–206.

Zhang K C, Niu Q H, Qu J J, et al. 2012. Analysis of wind-blown sand environment in the Singing Sand Mountain & Crescent Moon Spring scenic spot in Dunhuang, China. Journal of Desert Research, 32(4): 896–900.

Zhang W M, Qu J J, Dong Z B, et al. 2000. The airflow field and dynamic processes of pyramid dunes. Journal of Arid Environments, 45(4): 357–368.

Zhu Z D, Chen Z P, Wu Z, et al. 1981. Study on Aeolian Sand Landforms of Taklimakan Desert. Beijing: Science Press, 27–55.