

Geomorphological patterns in a linear dune field and ages of the linear dunes in the northern Kumtagh Desert, northwest China

Jinfeng Wu · Feng Guo

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Abstract The unique linear dunes in the northern Kumtagh Desert of northwest China have inspired enthusiastic debate among aeolian geomorphologists over their origins and classification. Their uniqueness lies not only in their morphology, but also in their geomorphological patterns. In this paper, the geomorphological patterns and ages of the linear dunes in the northern Kumtagh Desert are analyzed using the pattern analysis method that was recently adopted by geomorphologists. The analysis suggests that these linear dunes have developed since 13 ka BP, during the late part of the most recent deglaciation stage, when the region's dry climate was favorable for dune formation. The differences in dune construction time within this region result from the complex factors that control their formation and spatial variations in the local environment, but these factors were not strong enough to prevent us from estimating the dune age recorded by the geomorphological patterns with acceptable precision. It is also suggested that the pattern analysis method can be used to estimate dune ages in the absence of more reliable dating methods.

Keywords Aeolian geomorphology · Dune age · Geomorphological patterns · Linear dunes · Pattern analysis

Introduction

The Kumtagh Desert in northwest China, whose name is derived from the Uighur word for “sand hills”, lies in the

eastern part of the Tarim Basin and south of Lop Nur, in the northern foothills of the Altyn Mountains (Fig. 1). Its western part administratively belongs to Ruoqiang County of the Xinjiang Uygur Autonomous Region, and the eastern part belongs to Dunhuang County of the Gansu Province. The desert extends up to 120 km from the north to south and up to 350 km from the east to west. It lies between 90°27'E and 94°52'E and between 39°00'N and 40°47'N, covering an area of 22,800 km², and is the fourth largest desert composed of mobile dunes in China (Dong et al. 2010a).

Due to the region's harsh natural environment, desert scientists have done little work in the Kumtagh Desert. Until 2005, few in-depth scientific investigations had been conducted to unveil the desert's secrets (Wang et al. 2005; Dong et al. 2009). However, due to the lack of research, key scientific questions about the Kumtagh Desert remain to be resolved. For example, the Kumtagh Desert has a range of complex dunes, with more than ten types being proposed (Dong et al. 2009). The linear dunes in this desert cover an area of about 3,400 km², accounting for 14% of the total area (Dong et al. 2009). In the northern part of the desert, linear dunes have become the subject of debate among aeolian geomorphologists, who do not yet agree on the classification of these dunes, let alone on their formation mechanisms. The terms that have been proposed for these dunes include feather-like dunes, pseudo-feathery dunes and raked linear dunes (Qu et al. 2007; Dong et al. 2008, 2010b).

Owing to a lack of reliable data, questions about the formation mechanisms and ages of the linear dunes could not be convincingly answered. In the present study, an attempt is made to look for a reliable method and obtain reliable data that would enable the estimate of the formation time of the linear dunes in the northern Kumtagh

J. Wu (✉) · F. Guo
College of Tourism and Environment,
Shaanxi Normal University, No. 199, South Changan Road,
Xi'an, Shaanxi Province 710062, China
e-mail: jfwu@snnu.edu.cn

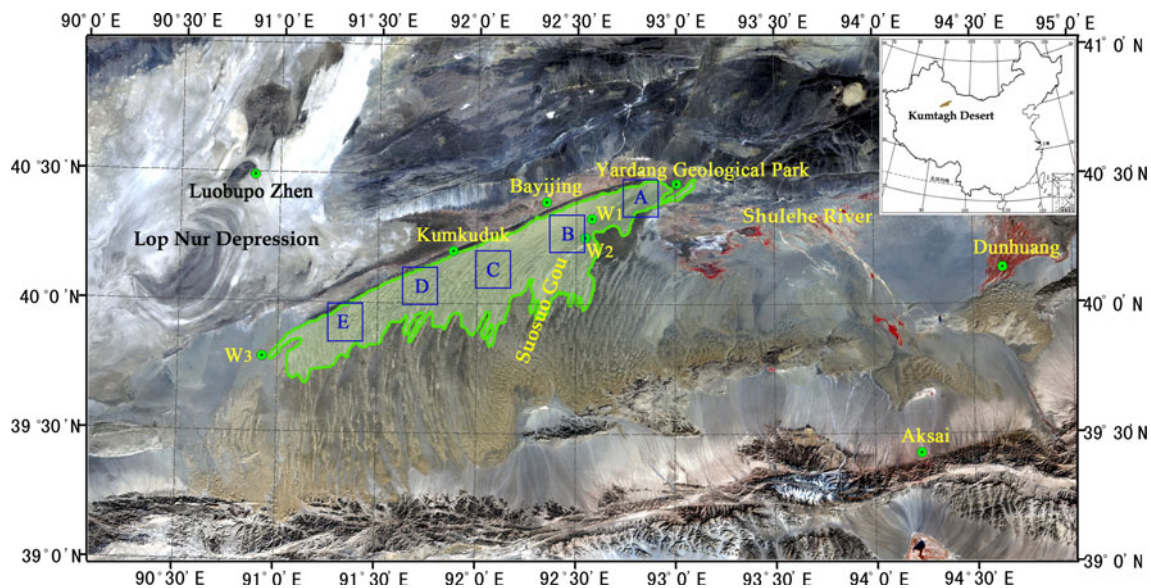


Fig. 1 Geographical location of the area of linear dunes and the five sample plots in the northern Kumtagh Desert

Desert, with the goal of helping to resolve some of the controversies over these dunes. To do so, geomorphic pattern analysis is applied, a method that has been increasingly used in dune geomorphology in recent years (Ewing et al. 2006).

“Geomorphic patterns” refer to the spatial organization of geomorphic types such as dunes, which are visually evident as various patterns. The nature of these patterns has been a concern for landscape ecologists since the 1990s (Hallet 1990). On the earth, every kind of geomorphology has unique geomorphological patterns, and dunes are no exception to this rule (Werner 1999). Geomorphic patterns are generally considered to result from the internal self-organizing factors that govern complex systems (Werner 1995). Of the many geomorphic patterns that exist, the patterns of dunes are both common and relatively simple, making dunes easy to study. Hence, dunes are considered to be a typical case of spatial self-organization in geomorphology (Hallet 1990).

However, the complexity of the factors that underlies geomorphic patterns increases the complexity of dune geomorphology. Even a simple dune type can possess a complicated geomorphic pattern, increasing the difficulty of studying its geomorphology. The dispute over the origin and classification of linear dunes in the northern Kumtagh Desert has resulted from their peculiar geomorphic patterns. The existing primary research suggests that these dunes lack the clear relationship between height and spacing that is exhibited by most other linear dunes (Dong et al. 2010b).

Dune patterns are considered the cumulative sum of dynamics beginning with fluid flow and grain transport.

Specifically for dune fields, pattern elements such as crest length, spacing and defect density are thought to evolve as a function of time. This exciting new understanding has the potential to completely alter the way in which we think about aeolian bedforms, their patterns, flow regime and fluid dynamics. Researchers are pursuing the geomorphic backstripping of dune-field patterns to understand their construction (Ewing et al. 2006).

Study methods

The aim of the present research was to apply pattern analysis (Ewing et al. 2006) to analyze the parameters of dune patterns measured from satellite images. Specifically, the goal was to analyze the probability distributions and spatial variation in these parameters to support a discussion of the factors influencing the dune characteristics and to provide an estimate of the age of investigated dunes. A study of dune patterns must begin by identifying the parameters that can be used to quantitatively represent the geomorphic patterns of the dunes. For instance, in landscape ecology, spatial pattern analysis is widely used, and the frequently used quantitative parameters include plaque area, density, shape and segregation.

Various types of remote-sensing images are useful for studies of large areas because they provide reliable data for studying geomorphic patterns, faster and at lower cost than would be possible through field surveys. The present analysis of the linear dunes of the northern Kumtagh Desert was therefore based on satellite remote-sensing images. When selecting the dune parameters that would be used for

characterization of the geomorphic patterns, two criteria were used: first, the parameters must allow objective, detailed assessment of the geomorphic patterns, and second, the parameters must be easily and accurately measured using remote-sensing images.

Based on these criteria and the experience of previous researchers (e.g., Ewing et al. 2006), the following parameters were selected: dune crest length, spacing (i.e., the mean distance between crests), orientation, and defect density. These parameters are illustrated in Fig. 2, but the meaning of “defect” and “defect density” should be clarified. “Defects” refer to the breaking points or end points of a dune, and the defect density refers to the number of pairs of defects (N) per unit of dune crest length (L); that is, $\rho = N/L$ (Werner and Kocurek 1999). For a given area, L is the sum of the lengths of all dunes in the area, and N is the total number of defects in this area. To obtain quantitative data on these parameters of the dunes’ geomorphic pattern, the methods used are described in the following.

First, Landsat ETM+ satellite images of the linear dune area in a month in 2008 were acquired, with a spatial resolution of 30×30 m. Then the abovementioned parameters were measured using version 9.2 of the ArcGIS software (ESRI, Redlands, CA, USA). To reveal the spatial variation in these pattern parameters, the area of linear dunes was divided into an 8×8 km grid, with a total of 13 rows from east to west and 23 lines from north to south. In the resulting grid, linear dunes occupied 99 of the 299 cells. Within each cell that contained linear dunes, the crest length, dune spacing, dune orientation and number of defect pairs were calculated and the defect density was measured.

To support this analysis, the dune crest lines were manually identified and traced (Fig. 3). Based on data from all cells in the grid that contained linear dunes, a cumulative probability curve for the dune crest lengths and spacings was derived. Using ArcGIS’s inverse distance-weighted interpolation algorithm, contour maps for the mean dune crest length, spacing and defect density were developed to support our analysis of how the pattern parameters changed spatially.

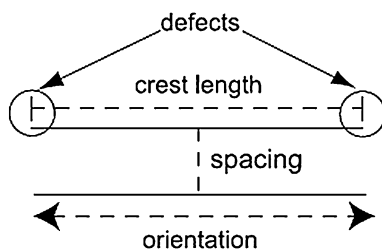


Fig. 2 Illustration of the pattern parameters used in the measurements of the geomorphic patterns of linear dunes

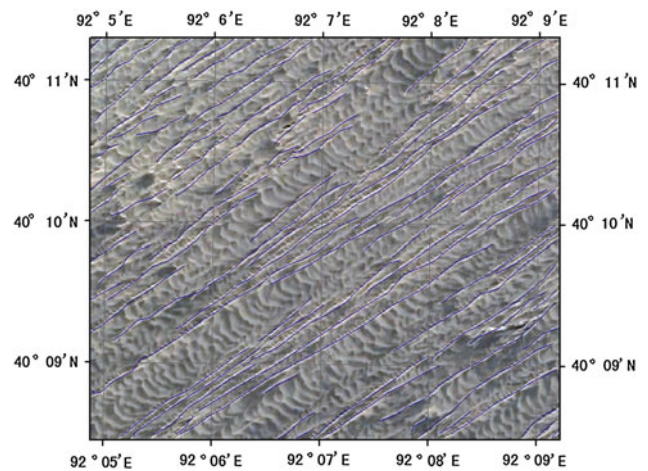


Fig. 3 An example of the dune crest lines identified and traced manually in the ETM+ images using ArcGIS

To analyze the main factors that influenced the pattern parameters, five sample plots that covered the full east–west extent of the linear dune area were selected (Fig. 1, locations A–E). The size of each sample plot was 16×16 km. Table 1 summarizes the locations and geomorphology of these areas.

Results and discussion

Dune crest length and spacing

A logarithmic cumulative probability curve for dune crest lengths and spacing offers a statistical method for recognizing the formation mechanism responsible for a dune’s geomorphic pattern. The theoretical basis for this analysis is the central limit theorem of statistics and the defect dynamics aspects of the system theory. The central limit theorem states that the probability distribution of a variable that results from many independent and additive events will be a normal (Gaussian) distribution. In the analysis of dune geomorphic patterns, Ewing et al. (2006) extended the central limit theorem in three ways: they used the cumulative frequency to replace the probability; they replaced the logarithmic frequency plot with a plot of the logarithm of the cumulative frequency, which means that the central limit theorem is used in multiplying events; and they assumed that the data were only sufficiently reliable when the data produced a logarithmic normal distribution.

If the geomorphic data acquired for the dunes is the result of a single mechanism, the entire collection of the data will form a line that can be represented by a mean and a standard deviation. More generally, the acquired data result from many mechanisms, and the sample data can be classified into multiple groups. These groups have their

Table 1 Locations and characteristics of the linear dunes in the five sample areas (A–E) shown in Fig. 1

Sample area	Geographical center	Geomorphic features	Mean crest length (m) and range	Mean spacing (m) and range	Mean orientation (°clockwise from north) and range
A	92°49.2'E, 40°25.2'N	Located in the northeastern Kumtagh Desert, facing Yardang Geological Park. The northern part of this area includes yardang geomorphology at the edge of the desert. There are two flat interdune areas in the central and southern parts of the area, as well as crescent dunes and transverse dunes developing in some sections where rich sand sources are present	4,912 (14–15,500)	1,294 (234–3,519)	39 (18–70)
B	92°27.0'E, 40°16.2'N	Linear dunes are concentrated in this area. The southern part of the area includes the Suosuo Gou with a seasonal river. There are wide, flat interdune areas in the southeast. The dune spacing is small from south to north, but the length increases in this direction	7,144 (39–36,222)	1,029 (165–4,120)	36 (14–50)
C	92°4.8'E, 40°7.8'N	This is an area of concentrated dunes underlain by ancient rivers. The linear dunes tend to be atypical from north to south, but to transit to southern dune areas	3,495 (9–10,540)	1,279 (174–4,721)	42 (27–70)
D	91°42.0'E, 40°3.0'N	The northern part of this area is at the edge of the Lop Nur Depression, with a few areas in which yardang geomorphology is developing. From north to south, linear dunes are increasingly atypical, tending to evolve into other types of dunes. The dunes' length and spacing decrease from north to south. There are many ancient rivers underlying the developing dunes	5,096 (1,129–17,469)	1,616 (233–3,755)	44 (30–62)
E	91°19.8'E, 39°54.6'N	This area is located in the southwestern part of the linear dune area. The northern part is at the edge of the Lop Nur Depression, with a few areas in which yardang geomorphology is developing. From north to south, linear dunes are increasingly atypical, tending to evolve into other types of dunes. The dunes' length and spacing decrease from north to south	3,043 (784–11,044)	909 (219–4,220)	53 (11–80)

own means and standard deviations. Therefore, a sample consists of many lines, each of which represents a different group.

Based on this theoretical framework, Ewing et al. (2006) studied the pattern parameters of dunes in the White Sands area of New Mexico, the Algodones area of California, the Agneitir area of Mauritania and the Namib area of Namibia. They found that for simple dunes, the pattern parameters formed a single group in the logarithmic cumulative probability plot, whereas the parameters for compound and complex dunes formed several groups in the logarithmic cumulative probability plots.

In the area of linear dunes in the northern Kumtagh Desert, the length of 1,273 linear dunes was measured and an average length of 4,271 m, with a standard deviation of 3,823 m was calculated. The logarithmic cumulative probability plot (Fig. 4a) reveals three sections. The length of the dunes in the first group is shorter than 40 m, and this group represents the extended arms of asymmetrical barchan dunes evolving into linear dunes. Strictly speaking, these dunes should not be called linear dunes and may

instead represent a precursor stage of true linear dunes. In fact, even the well-developed linear dunes in the north of Kumtagh Desert have the clear vestiges of asymmetrical barchans, so that they are termed raked linear dunes (Dong et al. 2010b). This type accounted for less than 10% of the dunes. The second group's length ranged between 40 and 800 m, and represented true linear dunes that were formed as a result of the connection of the extended arms of barchan dunes. The dunes in this group are generally straight. They account for less than 30% of the dunes. The third group's length was longer than 800 m, with the longest dunes extending beyond 10 km. This type accounted for the majority of the linear dunes, accounting for more than 60% of the dunes, and represented fully developed linear dunes. These dunes developed from the linkage of a large number of barchan dunes, with remarkable trace of barchan dunes.

Based on the research of Werner and Kocurek (1999) and Ewing et al. (2006), evolution of linear dunes appears to be a process of extension of the crest line. Figure 5 is an isopleth map of the mean crest length. As a whole, crest

Fig. 4 Cumulative probability plots for the (a) crest length and (b) dune spacing

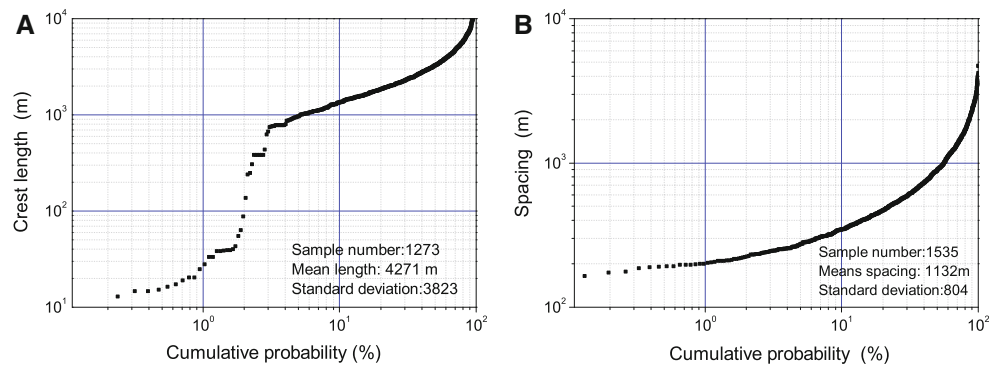
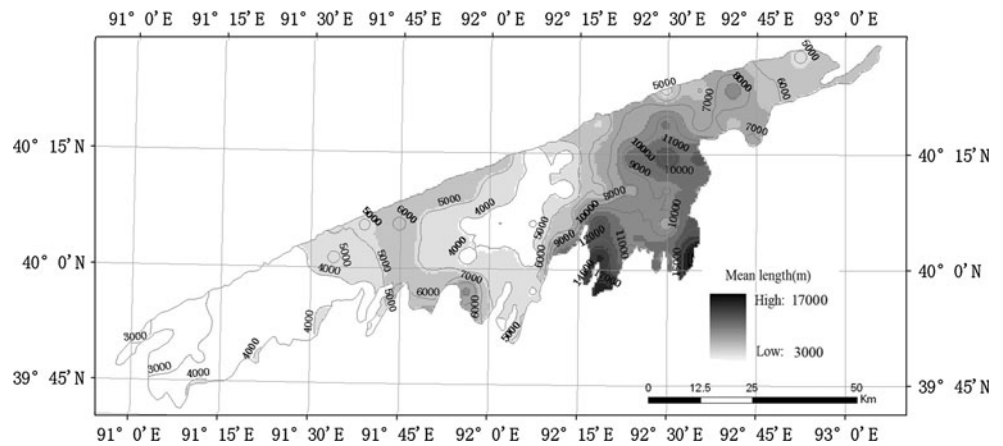


Fig. 5 Isopleth plot of the mean dune crest length

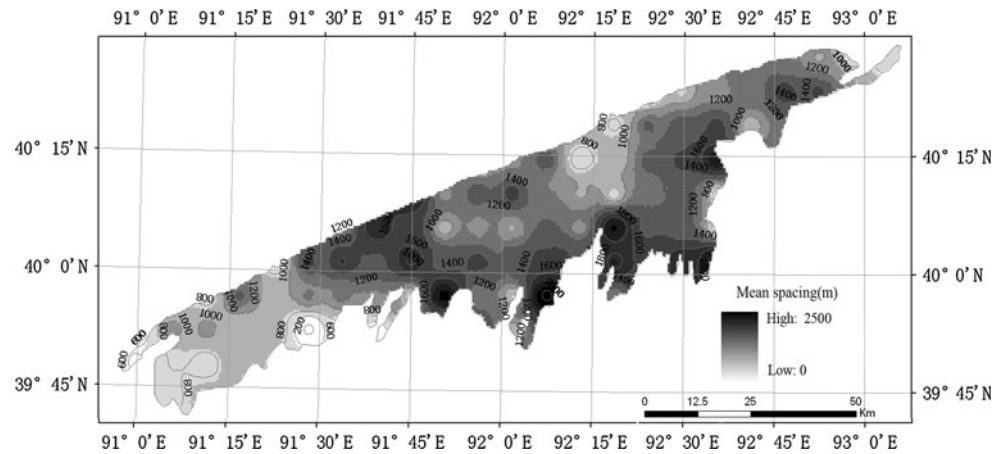


length tends to decrease on moving from the northeast to the southwest, suggesting that the age of the linear dunes decreases on moving from the northeast to the southwest. However, this trend is disrupted by the presence of an area with low mean lengths in the central part of the study area and by an area with a high mean length in the eastern central part of the study area. To analyze the possible causes for the spatial patterns of crest length, the average dune crest length in the five sample plots are summarized in Table 1, and the local wind regimes are analyzed. The wind regime is typically a dominant factor that controls the dune crest length. The wind energy in the linear dune areas decreases from northeast to southwest, and the wind direction becomes increasingly complex. The northeastern part of the study area shows an acute bimodal pattern, with a directional variability index of about 0.5, whereas the southwestern part shows a blunt bimodal pattern, with a directional variability index of about 0.4. Hence, the wind regime becomes decreasingly suitable for the development of linear dunes toward the southwest.

The break in the overall trend for dune crest length shown in Fig. 5 may have resulted from the presence of underlying ancient rivers, which affect the topography. By comparing Fig. 5 with the geomorphological characteristics of the five sample plots (Table 1), it can be seen that the central area with a low mean crest length is roughly

equivalent to sample plot C, and represents an area with a high concentration of underlying ancient stream channels. The appearance of these channels suggests that the extension of the linear dunes may be stopped by the channels. In contrast, as for the activities of old stream channels, their neighboring linear dunes form relatively late, so the length of the linear crest line is rather short. The mean dune crest length in sample plot A is shorter than that in sample plot B, because sample plot A is at the northern edge of the desert and the crest line has to be discontinued.

Dune spacing is also regarded as an important parameter of the geomorphic pattern. Werner and Kocurek (1999) thought that spacing was a function of dune age, the initial conditions under which the dunes formed and evolved, and defect activities. In the current study area, the spacing of 1,535 pairs of dunes was measured, and the mean spacing of 1,132 m (with a standard deviation of 804 m) was found to be less than the mean spacing of the compound linear dunes, but greater than that of the superimposed linear dunes on compound linear dunes in the Aneitir Desert in Mauritania and the Namib Desert in Namibia (Ewing et al. 2006). The logarithmic cumulative probability plot (Fig. 4b) is a continuous and smooth curve. The graph therefore reveals no distinct groups. The isopleth map for dune spacing (Fig. 6) displays a similar pattern to the crest length isopleth map (Fig. 5); for instance, the locations

Fig. 6 Isopleth map for dune spacing

Site	Spring	Summer	Autumn	Winter	Annual
W1	DP=30 RDP=4.7 RDD=117° RDP/DP=0.16	DP=114 RDP=59 RDD=26° RDP/DP=0.52	DP=167 RDP=99 RDD=27° RDP/DP=0.60	DP=53 RDP=39 RDD=59° RDP/DP=0.72	DP=363 RDP=192 RDD=35° RDP/DP=0.53
W2	DP=25 RDP=3.7 RDD=202° RDP/DP=0.14	DP=83 RDP=36.39 RDD=38° RDP/DP=0.44	DP=122 RDP=64 RDD=36° RDP/DP=0.53	DP=47 RDP=33 RDD=68° RDP/DP=0.69	DP=277 RDP=127 RDD=45° RDP/DP=0.46
W3	DP=24 RDP=84 RDD=40° RDP/DP=0.39	DP=67 RDP=15 RDD=197° RDP/DP=0.63	DP=92 RDP=52 RDD=35° RDP/DP=0.56	DP=34 RDP=9.3 RDD=76° RDP/DP=0.27	DP=217 RDP=84 RDD=40° RDP/DP=0.39

Fig. 7 Wind regime of the linear dune area. (DP is the drift potential, RDP is the resultant drift potential, RDD is the resultant drift direction, and RDP/DP is the directional variability index)

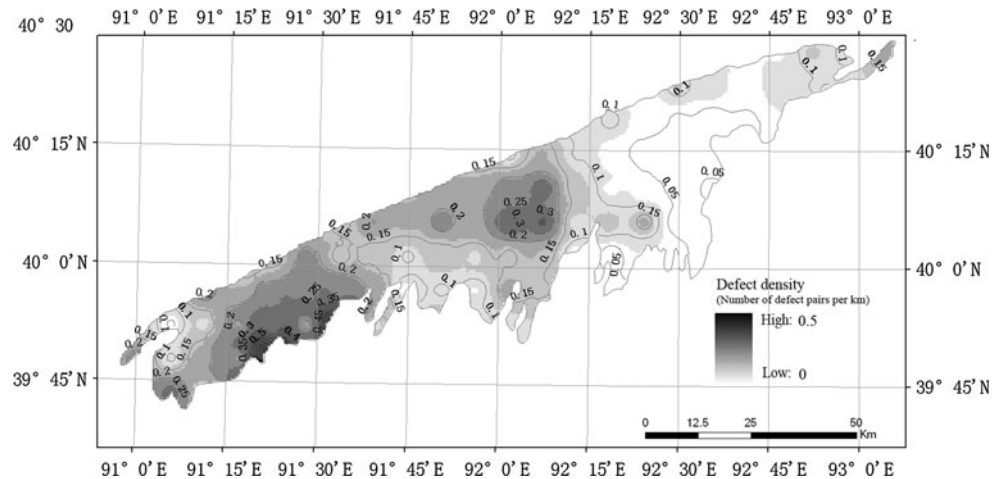
with high and low mean spacings are similar in the two maps, but are not well correlated, and there is a poor correlation between the average spacing and average crest length in the five sample plots (Table 1).

Dune orientation and defect density

Ewing et al. (2006) reported that the orientation of dunes tends to be consistent with their evolution. Table 1 shows that dune orientation ranged from 11° to 80°. Moving from

northeast to southwest, the range of the orientation generally increases, and the average orientation rotates the clockwise wind regime that becomes increasingly complex from northeast to southwest (Fig. 7). However, because of inconsistencies in the wind regime, there is a poor correspondence between the trends for dune spacing, orientation and crest length, indicating that the factors that control dune formation are complicated. The relationship, obtained for White Sands in New Mexico, the Algodones in California, the Agneitir in Mauritania and the Namib in

Fig. 8 Isopleth map for defect density



Namibia between the crest length, spacing and orientation of dunes that formed under similar conditions suggests that longer dune crests with wider spacing lead to a narrower range of orientations (Ewing et al. 2006).

The defect density parameter is a relatively independent dynamical variable (Ewing et al. 2006). Defect dynamics suggests that the changes in the parameters of dune geomorphic patterns result from changes in the defect characteristics (Werner and Kocurek 1999). Because the defects (here, the end points of the dunes) are always lower than the dune crest, they move more quickly. During this motion, they often combine with other bedforms, leading to extension of the crest and widening of dune spacing. The defect density of the linear dunes in the northern Kumtagh Desert is small (less than 0.25/km), and the mean is 0.14/km. In other words, there is a defect pair roughly every 7 km, which means one defect every 3.5 km. This is close to the average length of the dune crest (4,271 m). This suggests that the linear dunes are generally fully developed, though they are shorter than the compound linear dunes in the Agneitir Desert in Mauritania, and the Namib Desert in Namibia, whose mean length exceeds 10,000 m (Ewing et al. 2006).

The spatial variation in defect density (Fig. 8) appears to be the inverse of the pattern for crest length and poorly correlated with the spacing. This is because defect density and crest length are two sides of the same issue. By definition, the longer the dune length, the smaller is the defect density. Although the correlation between defect density and dune spacing is poor, both can still reflect inverse trends; that is, regions with a high defect density roughly correspond to areas with a small spacing, whereas areas with a low defect density basically correspond to areas with wide spacing.

The southwestern part of the area of linear dunes and the downstream areas of the Suosuo Gou, where underlying stream channels are concentrated, are two areas with high

defect density, and the linear dunes in these areas are therefore poorly developed. There is a poor spatial correlation between defect density and dune spacing; on the one hand, this reflects the complexity of the factors that govern dune formation and evolution (i.e., spatial variability in these factors), and on the other hand, this shows the inconsistency of their changes. Defect dynamics suggests that the changes in spacing should lag behind the changes in defects (Werner and Kocurek 1999).

Dune formation date

Based on the theory of self-organizing complex systems, particular geomorphic patterns will appear during a specific development period; that is, the form of a pattern is a function of the formation date and the elapsed time since that date (Ewing et al. 2006). Werner and Kocurek (1999) suggested, based upon their defect dynamics model, that as a result of the links between and disappearance of defect pairs, dune spacing grows logarithmically with increasing time; on this basis, they established a function that described the changes in dune spacing and defect density over time (Fig. 9).

Based on the dune geomorphic pattern parameters and optically stimulated luminescence dating results from several deserts in southern Africa and parts of North America, Ewing et al. (2006) discovered a good correlation between dune crest length, dune spacing and defect density and the time elapsed since dune formation began (Fig. 9). These relationships were comparable to those developed by Werner and Kocurek (1999). Based on these relationships, both research groups were able to estimate the formation dates of dunes with a range of sizes in Africa’s Namib Desert. Given that, currently, there no other reliable method to estimate dune formation time, we used Ewing et al.’s fitting curve to estimate the approximate formation date of the northern Kumtagh Desert’s linear dunes. Figure 9

Fig. 9 The relationships between (a) dune crest length, (b) spacing and (c) defect density and the time elapsed since dune formation began

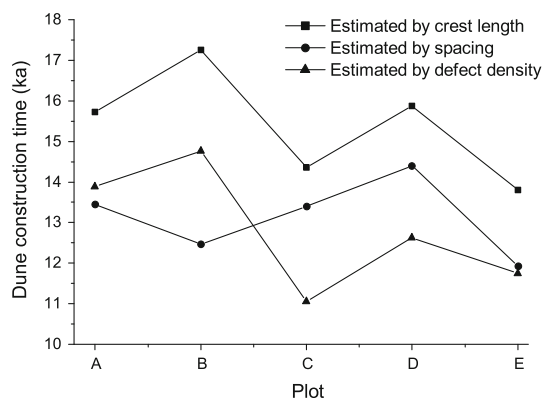
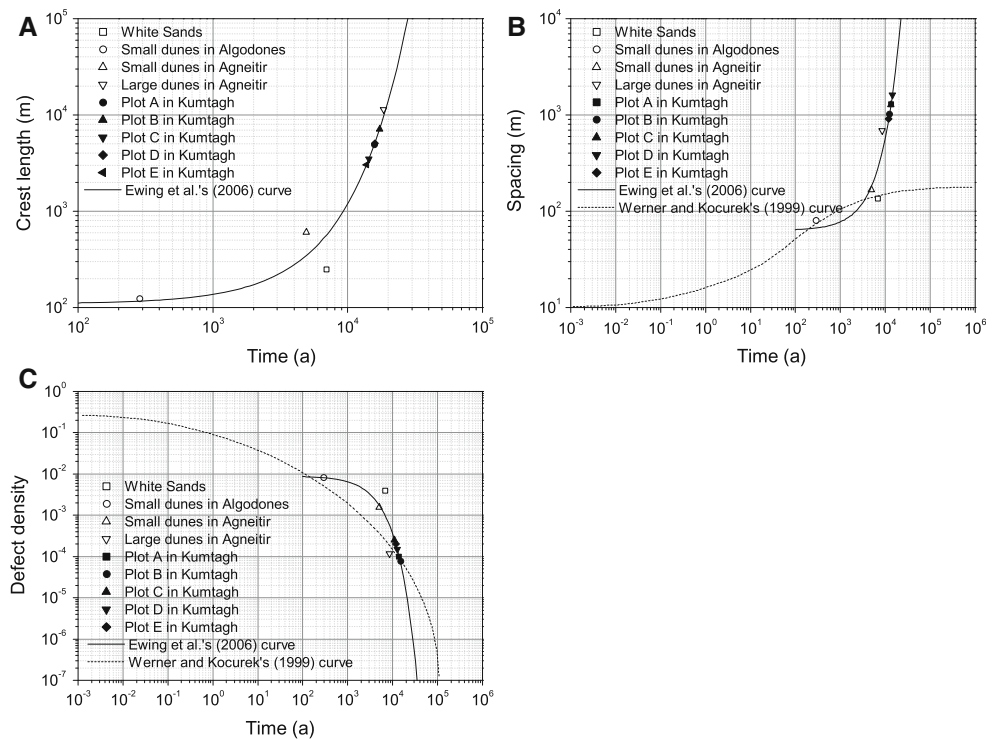


Fig. 10 Estimated formation date of the linear dunes in the northern Kumtagh Desert based on their crest length, spacing and defect density

shows that the fit between our data and Ewing et al.'s curves was generally good. Based on this result, we estimated the formation time of the northern Kumtagh Desert's linear dunes based on the three parameters (Fig. 10).

Figure 10 shows that the estimated formation date differs by up to 5.5 ka BP among the three geomorphic pattern parameters. Using the dune crest data, the linear dunes appear to have formed between 13.8 and 17.3 ka BP, with an average of 15.4 ka BP. In contrast, the dune formation time based on dune spacing and defect density was closer, with ranges of 12–14.4 ka BP (and an average of 13.1 ka BP) and 11.8–14.8 ka BP (and an average of 12.8 ka BP), respectively.

Werner and Kocurek (1999) suggested that dune spacing and defect density were the parameters that best represented dune geomorphic patterns. Their research therefore emphasizes the relationships between dune spacing, defect density and formation time. In the linear dunes of the northern Kumtagh Desert, the dune formation time estimated based on spacing and defect density was relatively close, and this supports Werner and Kocurek's opinion. On this basis, the formation of the dunes in our study area began about 13 ka BP (ranging from 12.8 to 13.1 ka BP), which corresponds to the end of the last deglaciation (16–12 ka BP), when central Asia was drying and became a more arid zone, which would promote the development of aeolian sands (Zheng et al. 2006). This is supported by the records of climate change preserved in the Bositen Lake sediments (Chen et al. 2006). These records, based on the depositional age, spore and pollen data, carbonate contents, grain size distribution and other proxy indicators in a drill core, show that from the last deglaciation to the early Holocene epoch, central Asia became increasingly dry; lakes dried out and aeolian deposits prevailed. Although the Holocene epoch, since about 8 ka BP, has been characterized by a comparatively humid climate, the Kumtagh Desert has remained dry, even during the wettest stage of the late Holocene. In addition, after the Han and Tang dynasties (ca. 200 BC), and especially since the Ming and Qing dynasties (ca. 1300 AD), water consumption for irrigation and domestic use has increased rapidly in northern China. As a result, discharge in the Shule River's

midstream and downstream reaches has greatly decreased; wetlands gradually dried up, and deserts have gradually encroached on agricultural areas as the region's ecological environment worsened (Zheng et al. 2006).

Based on the results of our study, we hypothesize that the linear dunes of the northern Kumtagh Desert have formed continuously since the last deglaciation. Research on the yardang geomorphology in the northeastern part of the area of linear dunes suggests that they formed during the Holocene epoch, about 8 ka BP, which is later than the start of formation of the linear dunes (Dong et al. 2012). This provides evidence of the development of an aeolian sand environment in the Kumtagh Desert during the Holocene epoch.

Figure 10 suggests different dates for the start of dune formation in different parts of the study area. This may have resulted from differences in the wind regime (Fig. 6), which strongly influence the development of aeolian geomorphology, but differences in the underlying topography and other factors would also have affected dune initiation and evolution. For example, the effects of sudden floods produced after a rainfall in areas near the mountains would lead to the development of broad, flat, sedimentary bodies with a high component of coarse materials in some parts of the northeastern and central linear dune area. However, these factors do not fundamentally influence the dunes' overall geomorphic patterns and evolutionary trends, so the geomorphic pattern of the dunes records important information about their formation date.

It is important to note that the dune formation date does not necessarily represent the desert's formation date. The deserts are likely to have developed before the dunes. Because dunes in different stages form and disappear over time, the estimated dune formation times in this study probably represent the latest dates when dune formation began.

Conclusions

In this paper, a geomorphic pattern analysis method based on the theory of self-organization of complex systems is applied to analyze the geomorphic pattern parameters of linear dune areas in the northern Kumtagh Desert. In addition, the dates when dune formation began are estimated using Ewing et al. (2006)'s empirical relationship between dune formation time and geomorphic pattern parameters, using data from the present study as inputs. The results suggest that the linear dunes in the study area formed after the last deglaciation, beginning at least 13 ka BP. During the Holocene epoch, the climate changed from dry to relatively humid, but the Kumtagh Desert remained extremely dry. Since at least 2000 BP, human activities

have greatly decreased the flows of water entering the Kumtagh Desert, and the linear dunes have therefore developed continuously since the last deglaciation. Regional differences in the dates when dune formation began reflect the complexity of and regional difference in the factors that affect dune development, but have not fundamentally influenced the date of dune formation recorded by the dune geomorphic patterns. Therefore, the present estimation of these dates appears reliable, even if the actual dates are only approximations. The results also show that even though current dating techniques cannot reliably determine the date when dune formation began, geomorphic pattern analysis is a useful technique for providing reliable approximations of this date.

References

- Chen F, Huang X, Yang M, Yang X, Fan Y, Zhao H (2006) Westerly dominated Holocene climate model in arid central Asia—case study on Bosten Lake, Xinjiang, China. *Quat Sci* 26(6):881–887 (in Chinese with English abstract)
- Dong Z, Qu J, Wang X, Qian G, Luo W, Wei Z (2008) Pseudo-feathery dunes in the Kumtagh Desert. *Geomorphology* 100: 328–334
- Dong Z, Qu J, Lu J, Qian G, Luo W, Wang X, Zhou Q, Wang XM (2009) Geomorphic map of the Kumtagh Desert. Science Press, Beijing (in Chinese with English abstract)
- Dong Z, Qian G, Yan P, Su Z (2010a) Gravel bodies in the Kumtagh Desert and their geomorphological implications. *Environmental Earth Sciences* 59:1771–1779
- Dong Z, Wei Z, Qian G, Zhang Z, Luo W, Hu G (2010b) “Raked” linear dunes in the Kumtagh Desert, China. *Geomorphology* 123: 122–128
- Dong Z, Lv P, Lu J, Qian G, Zhang Z, Luo W (2012) Geomorphology of yardangs in the Kumtagh Desert. *Geomorphology* 139–140: 145–155
- Ewing RC, Kocurek G, Lake LW (2006) Pattern analysis of dune-field parameters. *Earth Surf Proc Land* 31:1176–1191
- Hallet B (1990) Spatial self-organization in geomorphology: from periodic bedforms and patterned ground to scale-invariant topography. *Earth-Sci Rev* 29:57–75
- Qu J, Liao K, Zu R, Xia X, Jing Z, Dong Z, Zhang K, Yang G, Wang X, Dong G (2007) Study on formation mechanism of feather-shaped sand ridges in the Kumtagh Desert. *J Desert Res* 27(3):349–353 (in Chinese with English abstract)
- Wang J, Liao K, Youhao E, Su Z, Zhai X, Liu H, Tang J, Ding F, Zhang J, Zhang Q (2005) Some results of the scientific expeditions in the Kumtagh Desert. *Gansu Sci Technol* 21(10): 6–8, 222 (in Chinese)
- Werner BT (1995) Eolian dunes: Computer simulation and attractor investigation. *Geology* 23:1100–1107
- Werner BT (1999) Complexity in natural landform patterns. *Science* 284:102–104
- Werner BT, Kocurek G (1999) Bedform spacing from defect dynamics. *Geology* 27:727–730
- Zheng G, Yue L, He J, Wang J, Zhang Y (2006) Grain-size characteristics of the sediments at palaeoswamp in Anxi County in downstream of Shulehe River during Holocene and its paleoclimatic significance. *Acta Sedimentol Sin* 24(5):732–739 (in Chinese with English abstract)