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Preliminary studies on the large-scale geomorphic patterns of the complex longitudinal sand ridge zone in the Taklimakan Desert

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Through analysis of satellite images from Google Earth, this article expounds the characteristics of large-scale geomorphic patterns of the complex longitudinal sand ridge zone in the Taklimakan Desert, and reduces the large-scale geomorphic patterns to six types: parallel pattern, "日" character-shaped and "乡" character-shaped pattern, comb-shaped pattern, fork-shaped pattern, toe-shaped pattern and miscellaneous pattern. And according to the large-scale geomorphic pattern type (or composition of pattern types) as well as some other factors, the article divides the complex longitudinal sand ridge zone into 55 subzones. Lastly, aiming at the genetic problems of the large-scale geomorphic patterns, the article suggests three connective types of the sand ridges in the complex longitudinal sand ridge zone, i.e., connecting or intersecting after natural elongation, connecting in a narrow place and connecting with the aid of intermediary.

Taklimakan Desert, complex longitudinal sand ridges, large-scale geomorphic pattern, subzone, Google Earth

The physiognomy of the Taklimakan Desert's hinterland, where the Tarim Desert Highway traverses, is mainly characterized by the alternant distribution of high complex longitudinal sand ridges (or sand dunes) and inter-ridge (or inter-dune) areas[1].

The geomorphic scale of the complex longitudinal sand ridge zone (CLSRZ) can be generally subdivided into three grades: the first grade is large scale, just like the complex longitudinal sand ridges (CLSRs); the second grade is medium scale, like the barchan or barchan chain; the third grade is small scale, like sand ripple[1]. Till recently, researches on the aeolian landform of the CLSRZ in the Taklimakan Desert and the sand calamities along the Tarim Desert Highway are mainly concentrated on the medium and small scale[2−19]. But in fact, the differences of large-scale geomorphic patterns distributed in the CLSRZ are more evident than those of the medium- and small-scale.

It is easy to understand that the large-scale geomorphic patterns decide on the evolution of aeolian landform and the occurrence and development of sand disasters together with their distribution law. This is because when the regional wind regime acts on the high and large CLSRs, it will impact the air current (flow field) near the ground surface and then make the latter distinctly changed, thus produce secondary circulating system, and also influence the dynamic processes of those longitudinal sand ridges that lie in the inter-ridge depressions[7]. Similarly, different large-scale geomorphic patterns can also produce the analogous different influences to the near ground surface flow field. So, what kind of influence they can produce on the near ground surface flow field? How do these large-scale geomorphic pattern types form and how will they de-

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velop? Obviously, the understanding of these questions will not only help us to better understand the formation, distribution and evolution law of the overall CLSRZ's aeolian landforms and the highway sand disasters, but also can be used as references to the large-scale geomorphic pattern research of other regions in the Taklimakan Desert, thus making contributions to the development of geomorphology of wind-drift sand.

There are many problems relevant to the large-scale geomorphic patterns of the CLSRZ, and the large-scale geomorphic pattern types are the most fundamental and necessary to know. As to the large-scale geomorphic pattern of this region, there was a classification in the literature which roughly divided the sand ridges into two types according to the forms of the CLSRs themselves and the lesser-grade sand dunes superimposed on them as well as the forms of the sand dunes (or sand ridges) in the inter-ridge areas[20]. But until now, there is still no classification about the large-scale geomorphic patterns in the CLSRZ. This article investigates the characteristics of large-scale geomorphic patterns in the Taklimakan Desert's CLSRZ mainly through analyzing the satellite images, and attempts to classify the patterns and to zone the CLSRZ.

The meanings of so-called large-scale geomorphic pattern in this article are the forms of spatial distribution of large- or medium-scale geomorphic landforms and the forms of horizontal composition and distribution among the landforms. These landforms include the complex longitudinal sand ridges (or sand ridge chains), the inter-ridge areas, the obstructive transverse sand ridges partitioning the inter-ridge areas, the linear sand dunes (or dune groups) in the inter-ridge areas, and so on.

1 Method

Due to the comparatively high resolution of the images on Google Earth — normally within 30 m, in some places even less than 1 m, it is very convenient to perform all the analyses and manipulation in this article such as zooming in or zooming out the images, adding annotations and the like. Still more, on Google Earth there are altitude data which are offered for reference to match the images. So this article carries out the study by use of Google Earth.

Google Earth is a kind of on-line electronic map for search service. It is a kind of software of virtual terrestrial globe. It arranges satellite images, aerial photographs and GIS on a three-dimensional model of the globe so that it can support various services for users such as browsing the landscape, searching for and inquiring about geographical information, navigating automobiles and so on (see http://earth.google.com). The various information offered by Google Earth, such as considerably detailed satellite images, three-dimensional pictures, etc., can also be helpful for the scientific researchers to carry out their relevant work.

Based on the geomorphic characteristics of the areas along and near the Tarim Desert Highway which are reflected from the satellite images on Google Earth, this article aims at analyzing and summarizing the large-scale geomorphic pattern types in the CLSRZ in view of morphology and zoning the CLSRZ into subzones according to the differences of spatial distribution of large-scale geomorphic patterns. The procedure of mapping subzones of the CLSRZ is: first, roughly drawing the subzone boundaries with Google Earth; then, storing the result as an image file; and lastly, registering and vectoring this image file under the GIS software. The topographic sketch maps are drawn according to the altitude information on Google Earth.

2 Large-scale geomorphic pattern types of compound longitudinal sand ridges

The satellite images display that the large-scale landforms in the Taklimakan CLSRZ form various horizontal patterns, along with the differences of different regions' ground surface, conditions of wind field and developing stages of the CLSRs. Through the preliminary analysis, according to the implication of the large-scale geomorphic pattern as stated before in this article, we can ideally summarize some comparatively typical shapes of the distribution and combination of various large-sacle and medium-scale landforms in the CLSRZ, at least, into 6 pattern types, including 'parallel', '日 character-shaped and 乡 character-shaped', 'comb-shaped', 'fork-shaped', 'toe-shaped' and 'miscellaneous':

(1) Parallel pattern: As shown in Figure 1(a), the sand ridges or sand ridge chains are parallel to each other and elongate somewhat distantly. The longest chain may reach over 30 km. The distance between ridges is generally 0.5—3.5 km, and more frequently 1.4—2.2 km.

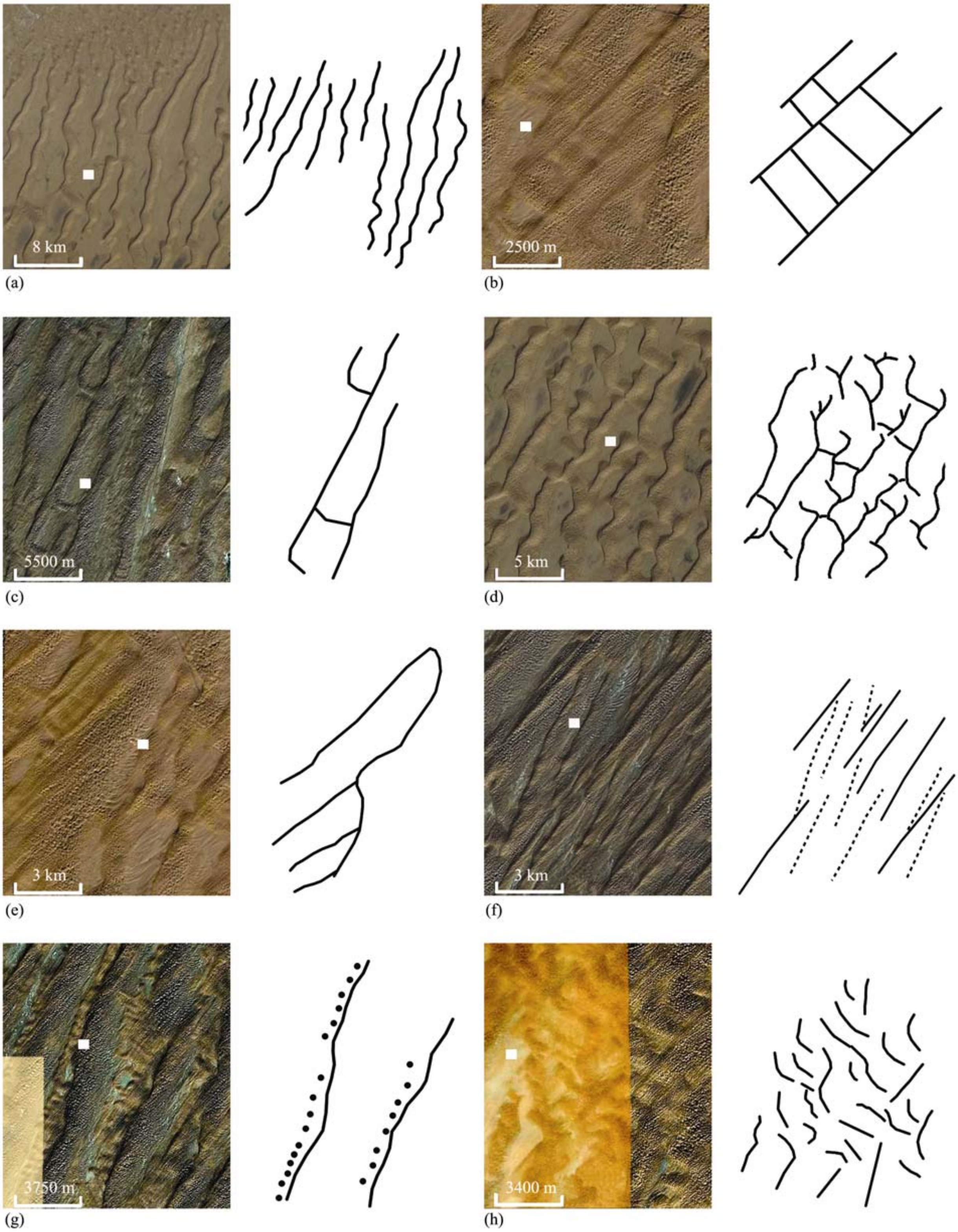

Figure 1 The large-scale geomorphic pattern types of the CLSRZ. The real lines represent the crest lines of sand ridges; in (f), the dotted lines represent the crest lines of a group of sand ridges which belong to another strike; in (g), the black spots represent dome-shaped sand dunes.

(2) '日' character-shaped and '乡' character-shaped patterns: As shown in Figure 1(b), (c), (d), two adjacent CLSRs are connected by one or more transverse sand ridges. The transverse sand ridges are normally relatively distant from each other, and their lengths are usually much shorter than those of the inter-ridge areas. However, within some regions such as the region between the highway and the lower reaches of the Niya River, many transverse sand ridges, which bear the lengths near or even larger than those of inter-ridge areas, also can be seen. Figure 1(b), (c) can be called the most 'standard' '日' character-shaped and '乡' character-shaped patterns: the strikes of the CLSRs are straight, the spatial combination and layouts among the CLSRs and those of between the CLSRs and the inter-ridge obstructive transverse dunes are clear and regular. But the more frequent phenomena are those in Figure 1(d). The '日' character-shaped pattern is mingled and combined with the '乡' character-shaped pattern. The strikes of the CLSRs become curved. The inter-ridge areas are either closed by the transverse obstructions or not. The spatial combination and layouts among the CLSRs and those of between the CLSRs and the inter-ridge obstructive transverse dunes are comparatively irregular or even somewhat disordered.

(3) Comb-shaped pattern: As shown in Figure 1(e), the strike of the 'comb teeth' formed by the densely arrayed longitudinal sand ridges points to the resultant sand transport direction. The inter-ridge areas among the "comb teeth" become narrow and small. The windward "head parts" of the sand ridges are connected with each other and thus a unified transverse (or nearly transverse) sand ridge——"comb ridge" forms.

(4) Fork-shaped pattern: As shown in Figure 1(f), two groups of CLSRs with cross strikes at acute angles intersect and divide the same area. The cross angle is normally between 11°—23°, a few of them may reach 53°.

(5) Toe-shaped pattern: As shown in Figure 1(g), adjacent to the western edges of the CLSRs, there are normally multiple dome-shaped sand dunes which connect with the CLSRs and are comparatively regularly arranged one after another along the CLSRs. The eastern edges of the CLSRs are mostly not distinct and there are many simple linear dunes frequently beside them.

(6) Miscellaneous pattern: As shown in Figure 1(h), it is difficult to estimate which ones of the transverse sand ridges or the longitudinal sand ridges are more dominant because their overall layout is disordered and unclear. For the positions of the satellite images see Table 1.

Table 1 The positions of the satellite images in this article

Code of image	Position	Code of image	Position
Figure 1(a)	40°11′35.47″N, 84°47′30.95″E	Figure 1(h)	38°37′0.09″N, 83°48′55.23″E
Figure 1(b)	39°10′19.93″N, 83°27′48.51″E	Figure 3(a)	40°15′43.30″N, 84°29′15.47″E
Figure 1(c)	38°10′16.65″N, 83°04′19.73″E	Figure 3(b)	39°53′36.23″N, 84°21′18.52″E
Figure 1(d)	39°57′22.02″N, 84°52′46.24″E	Figure 3(c)	40°03′32.91″N, 84°24′18.92″E
Figure 1(e)	39°12′51.03″N, 83°25′39.18″E	Figure 3(d)	39°53′07.66″N, 84°26′16.64″E
Figure 1(f)	39°24′46.94″N, 82°47′42.32″E	Figure 3(e)	39°51′24.50″N, 83°44′17.32″E
Figure 1(g)	38°36′19.31″N, 82°58′54.71″E	Figure 3(f)	39°02′04.21″N, 82°30′26.93″E

All the images are from Google Earth and all the images' upright side is upright north; the geographic coordinates in the table show the positions where the white quadrangles are marked in the figures.

3 The regional differentiation of large-scale geomorphic patterns in the CLSRZ

Owing to the distinct differences of various large-scale geomorphic pattern types (or their compositions) within everywhere of the CLSRZ, we are able to divide the whole zone into some different subzones, and thus can understand the characteristics of large-scale geomorphic patterns of the whole zone clearly and comprehensively. Consequently, we have drawn a small-scale map showing the zoning of the CLSRZ according to the large-scale geomorphic patterns and the main large-scale geomorphic pattern types of various zones.

Being aware that the CLSRs in this region are mainly distributed in the area between 82°E—85°E[20], this article selected this scope as the mapping area. We attempted to zone this region into 55 subzones (Figure 2). The zoning mainly was on the basis of the differences of large-scale geomorphic pattern types (or their compositions). And simultaneously we also considered many other factors such as the widths and lengths of inter-ridge areas, the shapes of ridges, the heights of ridges, the strikes of ridges, the regularity of layout of ridge bodies, the definition of ridge margins (or inter-ridge areas), presence or absence of the fluvial traces (distinct or not), vegetation condition, and so on. The general principles of zoning are as follows: firstly, the difference of large-scale geomorphic pattern types (or their compo-

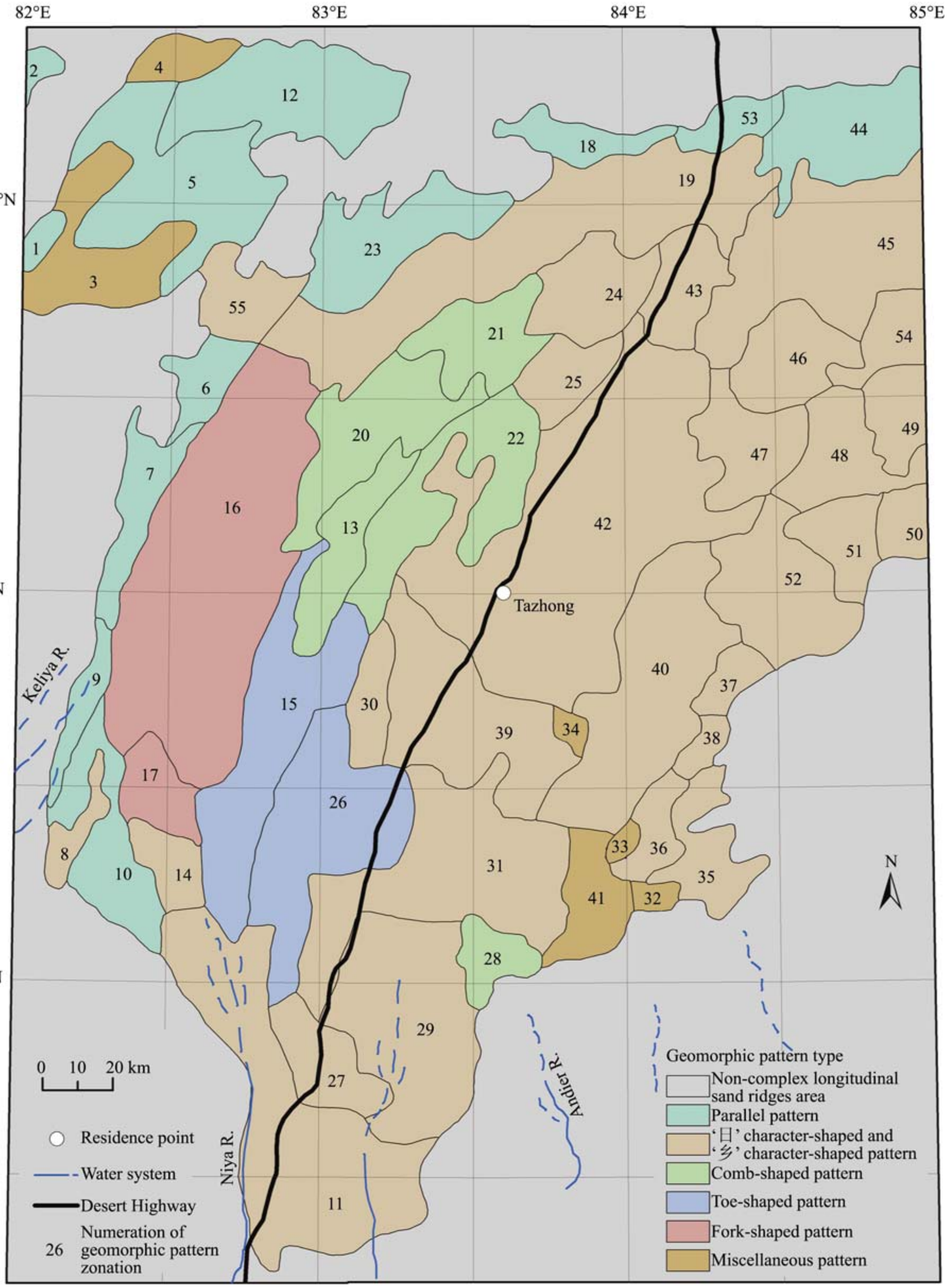

Figure 2 The zoning of the CLSRZ according to the large-scale geomorphic patterns and the main large-scale geomorphic pattern types of various sub-zones.

sitions) is taken as the main referenced factor; secondly, if there is no difference in the main referenced factor basically, then other factors will be considered, but they will be treated on the same level without specifying their priorities in advance, and the factor which can make the subzone most distinctly different from the surrounding contiguous areas will be taken as the main factor; thirdly, the areas already zoned should possess consistency in themselves in the characteristics of images, but obviously differ from surrounding contiguous areas; lastly, the area of each subzone should be large enough, so as not to make the picture-patches of the map too meticulous or too crowded.

All the characteristics of each subzone are briefly described in Table 2.

From Figure 2 and Table 2, it is very clear that the distributions of the large-scale geomorphic patterns within the CLSRZ everywhere not only have distinct differences but also obey some laws, concretely speaking as follows:

(1) The parallel pattern mainly consists in the northern and western margin of the CLSRZ, and is the most typical in the northern margin of the desert, which adjoins the area of dome-shaped sand dunes;

(2) '日' character-shaped and '乡' character-shaped pattern mainly consist in the central eastern part and southern part of the CLSRZ, and they are the two most prevalent pattern types;

(3) Comb-shaped pattern can be seen mainly at the lower reaches of the Keliya River and the lower reaches of the Niya River on the west of the highway and also the area between them. It is particularly concentrated in the central part of the CLSRZ and at the area of western side of the highway;

(4) Fork-shaped pattern can be seen mainly at the lower reaches of the Niya River and in the area between the lower reaches of the Niya River and of the Keliya River;

(5) Toe-shaped pattern can be seen mainly at the southern part of the CLSRZ. It is more typical on the south of N39° and at the area between the highway and the lower reaches of the Niya River.

(6) Miscellaneous pattern can be seen mainly at the marginal areas of the CLSRZ's SE part and NW part.

It is not difficult to understand that the differentiation of these large-scale geomorphic patterns of the CLSRZ may have its peculiar formation mechanism. The formations, configurations and presences of the patterns should have some direct relations with the wind fields of the areas where the patterns are located, and also with the ground surface conditions just before the patterns originated, such as relief, distribution of vegetation, distribution of embryonic form sand ridge or sand dune, etc. Some may be possibly related with the current evolutionary stages of the geomorphic patterns themselves. For example, the reason why the miscellaneous pattern is mainly located at the marginal area of the CLSRZ, is very likely related to its special location, which lies in the transitional areas between the CLSRZ and other geomorphic zones and where the wind direction is complex and relatively unstable; whereas the fork-shaped pattern generally has distinct fluvial traces, thus it is very likely formed by the double functions of water flow and wind.

Obviously, the conveyance of wind-drift sand and the movement of sand dunes are different in different large-scale geomorphic pattern types, and they also have different influences on the formation and distribution of the highway sand disasters. For example, as for the highway which is basically parallel to the strikes of CLSRs, the sand disasters in the inter-ridge areas of the parallel pattern are generally lesser, compared with those of other geomorphic patterns. Therefore, it is of great significance for clarifying the regional distribution of the CLSRZ's large-scale geomorphic pattern types, which not only can promote the researches on the formation and evolution mechanism of desert landforms and also can deepen the studies of highway sand disasters so as to lead people to avoid the calamities effectively and gain the advantages.

4 Formation of the large-scale geomorphic patterns in the CLSRZ

The geneses of sand dunes of diversified shapes are identical with or similar to those of large-scale geomorphic patterns in the CLSRZ in many aspects. So under certain conditions, we can infer the results of the latter from those of the former. For the geneses of various sand dunes, although a variety of theories or hypotheses have been proposed[18−29], such as the doctrine of suffocation of airflow[25,26] and of wave-like motion of airflow[27] for transverse sand dunes (Scorer, et al.), and the doctrine of tectonic control (Makyev)[26,27], of erosion of water flow (Geller, et al.)[27], of evolution of shrub-covered dunes (Glasimov)[27,28], of resultant wind (Bag-

Table 2 Characteristics of the subzones in the CLSRZ

Subzone coding	Main large-scale geomorphic pattern	Other characteristics
1	parallel	The ridge bodies (RBs) and the strikes of the ridges (TRs) are not very clear. The ridges are relatively straight. The widths of the inter-ridge areas (WIRAs) are 0.7－0.9 km, close to that of the ridges (WRs), and the heights of the ridges (HRs) are merely 1－3 m.
2	parallel	The TRs are comparatively clear, and the prolongations of the ridges are obvious. The HRs are all below 5 m, merely 1－3 m in general. The WIRAs are 0.5－0.8 km, slightly wider than the WRs.
3	miscellaneous	The RBs are not completely shaped up yet. The total area of the complex longitudinal sand ridges (CLSRs) is equal to or less than that of non-CLSRs. The edges of the ridges are blurry and the TRs, which intermix with those of non-CLSRs, are not clear at all. The WIRAs are 0.4－0.6 km and the HRs are all under 5 m, merely 1－3 m commonly, which slightly show the characteristics of longitudinal dunes.
4	miscellaneous	Similar to No.3 subzone. Its RBs and TRs are clearer than those of No.3 subzone, but not so clear as those of No.1 subzone. The WIRAs are 0.8－1.7 km.
5	parallel	Often intercalated with miscellaneous geomorphic pattern. The RBs are relatively straight, and the RBs and TRs are clearer than those of No.1 subzone, but the edges of the RBs are still comparatively blurry. The HRs are under 5 m, merely 1－3 m commonly. The WIRAs are 0.3－1 km, close to or appreciably wider than the WRs.
6	parallel	This subzone lies at the eastern side of lower reaches of the Keliya River. The fluvial traces are clear. The inter-ridge areas (IRAs) are uneven and mostly incised by old river channels. The RBs are slender, and the WIRAs are 1.2－2.4 km, 3－5 times as wide as the WRs. The HRs are from several meters to more than 20 m. There are many areas of small-scale comb-shaped geomorphic pattern in the complex obstructive transverse dunes in the IRAs. But the obstruction is often not complete and the connectivity among the ridges is usually good.
7	parallel	Similar to No.6 subzone. But the HRs decrease apparently, which are less than 5 m in general. The RBs are narrow, short and much sparser. The ridge chains are often disconnected and discontinuous along their lengths. The WIRAs are 0.4－1.8 km.
8	‘日’ character-shaped and ‘乡’ character-shaped	The ridges are sparse, low and unconspicuous. The HRs are below 5 m. There are many dome-shaped dunes, with up to about 20 m in height. The traces of the past fluvial process can be dimly discerned. The inter-ridge obstructive dunes are not obvious and the WIRAs are 0.6－1.6 km.
9	parallel	This subzone lies at the eastern side of lower reaches of the Keliya River. In the IRAs, the traces of the modern fluvial process are obvious, and there is much vegetation. The HRs are relatively high and can be up to about 15 m. The RBs are slender and straight. The ridge chains are often disconnected and discontinuous along their lengths. The WIRAs are 0.6－2.4 km.
10	parallel	There are many dome-shaped dunes and beads-string-like dunes formed by the connection of dome-shaped dunes. The shape of each dome-shaped dune is still clear. The HRs are mostly 10－20 m, sometimes over 30 m. In the IRAs, the traces of the past fluvial process can be discerned to a certain extent. The WIRAs are 0.4－2.6 km, and the IRAs are mostly not closed up. There are unconspicuous obstructive transverse dunes in some areas.
11	‘日’ character-shaped and ‘乡’ character-shaped	This subzone lies near the North Minfeng Upheaval and between the Niya River and the Yatongguzi River. This subzone is apparently affected by the modern fluvial process, which makes the alignment of the ridges disturbed and disordered, and makes the RBs look like plaits or twists. The RBs are commonly formed by the connection of short, small and near NE-SW strike sand ridges in the direction of near N-E or NW-SE. The HRs are commonly 10 m to over 20 m, a few over 30 m. There is a parallel geomorphic pattern in some parts. The WIRAs are 0.3－1.7 km.
12	parallel	The RBs are gracile and relatively straight. The IRAs are open and range from 0.6－2.7 km in width, which are 3－6 times as wide as the RBs. The HRs are mostly several meters, a few up to about 10 m.
13	comb-shaped	In the next place is ‘日’ character-shaped and ‘乡’ character-shaped pattern. The traces of old river channels are obvious. The WIRAs are 0.3－1.2 km, the proportion of the IRAs is far smaller than that of the RBs, and the IRAs are mostly divided into triangular bits. The HRs are commonly 10 m to over 20 m, a few over 40 m.
14	‘日’ character-shaped and ‘乡’ character-shaped	In the next place are fork-shaped and comb-shaped geomorphic patterns. The patterns are comparatively disordered as a whole. This subzone lies at the lower reaches of the Niya River and there are many beadlike dunes in it. The fluvial traces are obvious, and landforms composed of earth-like fluvial-lacustrine deposits such as patterned ground or small yardangs, are often seen in the IRAs. The ridges are relatively dense, the IRAs are narrow and the WIRAs are 0.2－0.7 km. The HRs are commonly under 10 m, a few close to 20 m.
15	toe-shaped	In the next place are comb-shaped and ‘日’character-shaped and ‘乡’ character-shaped patterns. The vestiges of the past fluvial process are obvious and there are many old river channels. Affected by the incision of water flow, disorder goes with orderliness in the pattern as a whole. The RBs are relatively dense, the IRAs are mostly narrow and comparted, and the WIRAs are 0.2－1 km. The HRs are commonly around 10 m, the highest up to about 20 m. There are a few bead-like dunes in the southern area.
16	fork-shaped	Comb-shaped geomorphic pattern also appears in partial areas, especially in the northeastern and southern parts. The vestiges of the past fluvial process can be discerned to a certain extent. The direction of fluviation has an acute angle with that of dominant wind and the RBs are mostly divided into sections by the fluviation. The WIRAs are 0.2－2.5 km, most of which are 0.6－1.6 km. The IRAs controlled by winds are relatively narrow, dense and regular, whereas the IRAs controlled by water flow are obviously wide and comparatively irregular. The HRs are commonly several meters to over 20 m, the highest close to 40 m. The HRs in the north are mostly higher than those in the south, and the HRs controlled by winds are mostly higher than those controlled by water flow.

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Subzone coding	Main large-scale geomorphic pattern	Other characteristics
17	fork-shaped	In the next place is the comb-shaped geomorphic pattern. The pattern is orderly as a whole. The HRs are mostly several meters to more than 10 m, the WIRAs are 0.2－1.6 km. The rest characteristics are similar to those of No.14 subzone.
18	parallel	This subzone lies at the northern verge of the CLSRZ, proximately to the area of complex dome-shaped dunes on the north side. Most of the ridges are beadlike dunes and the ridge chains are often disconnected along their lengths. The IRAs are wide and the WIRAs are 0.8－3.3 km, which can be 4 times as wide as the RBs. The HRs are commonly over 20 m, the highest over 40 m.
19	'日'character-shaped and '乡' character-shaped	The ridges are relatively straight, short and narrow. The IRAs look a little disordered, but still relatively wide, and the WIRAs are 0.8－2.2 km, the widest of which is 2.8 km, which can be 2－3 times as wide as the WRs. The HRs are mostly over 20 m, the highest around 50 m. The HRs in the south are higher than those in the north. There are also a few dome-shaped dunes in this subzone.
20	comb-shaped	In the next place are fork-shaped and '日' character-shaped and '乡' character-shaped geomorphic patterns. The vestiges of past fluviation can be dimly discerned. The IRAs are relatively wide and distinct, but they often do not extend lengthways too far. The WIRAs are 0.3－1.7 km. The HRs are commonly over 20 m, the highest over 50 m.
21	comb-shaped	Similar to No.20 subzone. But the ridges are much denser. The IRAs are narrow, sparse and not evident. The WIRAs are 0.2－0.9 km, a few of which can reach 1.7 km. The HRs are commonly over 20 m, the highest over 40 m.
22	comb-shaped	In the next place is the '日' character-shaped geomorphic pattern. The IRAs are mostly narrow, sparse and unconspicuous, and the WIRAs are 0.4－1.4 km. The HRs are mostly 10－30 m, the highest over 40 m.
23	parallel	The ridge chains mostly have gaps. The ridges are mostly straight, short and narrow, like tadpoles in shape. The IRAs are wide, and the WIRAs are 1.2－2.5 km, 2－3 times as wide as the WRs. The HRs are commonly over 20 m, the highest around 4 m.
24	'日' character-shaped and '乡' character-shaped	Similar to No.19 subzone. But the IRAs are narrower, shorter and more disordered than those in the latter. WIRAs are 0.6－2.4 km, and the HRs are mostly over 30 m, the highest over 50 m.
25	'日' character-shaped and '乡' character-shaped	There are some beadlike sand ridges. The IRAs are relatively disordered, and the WIRAs are 0.7－1.7 km. The HRs are mostly over 30 m, the highest over 60 m. There is also a fork-shaped geomorphic pattern in some areas.
26	toe-shaped	The "toes" are slightly not clear. there is also '日' character-－shaped and '乡' character-shaped geomorphic patterns in some areas. There are many fluvial traces. The HRs are mostly 10－30 m, a few over 30 m. The WIRAs are 1.4－2.2 km, a few only 0.7 km.
27	'乡' character-shaped	There is a parallel geomorphic pattern in partial areas. The ridges appreciably curve like snakes, the TRs is close to NW-SE and the array of the ridges is regular on the whole. There are obvious fluvial traces in the IRAs. The WIRAs are 0.6－2.7 km, 0.5－3 times as wide as the WRs., and the WIRAs in the north are wider than in the south. The HRs are mostly 15－30 m.
28	comb-shaped	This subzone lies at the lower reaches of the Andier River. There are many new and old channels formed by fluviation, and there are some sporadic patches of vegetation in partial channels. The RBs are wide and low, and the HRs are generally under 20 m. The borderlines between the ridges and the IRAs are not distinct. The IRAs are relatively disordered, and the WIRAs are 0.5－1.3 km.
29	'乡' character-shaped	It lies at the lower reaches of the Yatongguzi River. There is parallel geomorphic pattern in some parts. The fluvial traces are clear, and the vegetation , which covers like strips in channels of the IRAs in the middle area, is exuberant. The WIRAs are 0.6－2.3 km. The array of the ridges is slightly actinomorphic and relatively regular. The HRs are several meters to over 20 m.
30	'乡' character-shaped	The IRAs are wide and evident, and extend lengthways for comparatively long distances. The WIRAs are 0.8－2 km, 1－1.5 times as wide as the WRs. In partial areas, the geomorphic pattern is close to the parallel pattern. The array of the ridges is relatively regular and the ridges are comparatively straight. The HRs are mostly 20－30 m, a few close to 40 m.
31	'日'character-shaped and '乡' character-shaped	The geomorphic pattern is close to the parallel pattern in many areas. The array of the ridges is relatively regular and the ridges are comparatively straight. The IRAs are wide and evident, and the WIRAs are 0.5－3 km, mostly 1.1－2.2 km, 1－2 times as wide as the WRs. The HRs are 20－40 m.
32	miscellaneous	The IRAs are few and unclear, and the WIRAs are 0.5－1.4 km. The HRs are within 20 m, mostly around 10 m.
33	miscellaneous	The IRAs are few and unclear, and the WIRAs are 0.4－0.8 km. The HRs are within 20 m, mostly several meters.
34	miscellaneous	The IRAs are few and unclear, and the WIRAs are 0.4－0.9 km. The HRs are about 20 m, a few close to 40 m.
35	'乡' character-shaped	The array of the ridges is relatively regular. The ridge chains have many turns and each section of a chain is relatively short. The IRAs mostly are comparatively wide, and mostly extend for relatively short distances. The WIRAs are 0.4－2.3 km, 0.5－4 times as wide as the WRs. The HRs are 20－50 m.
36	'乡' character-shaped	The array of the ridges is relatively disordered. The TRs are close to N-E. The WIRAs are inconsistent and are 0.3－2.2 km. The HRs are several meters to over 50 m.

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(*Continued*)

Subzone coding	Main large-scale geomorphic pattern	Other characteristics
37	‘日’character-shaped and ‘乡’ character-shaped	The TRs are close to N-E. Some edges of the ridges are not clear. The WIRAs are 0.8—2.1 km, equal to or slightly wider than the WRs. The IRAs extend relatively far. The HRs are 20—60 m.
38	‘日’character-shaped and ‘乡’ character-shaped	The IRAs are disordered but still relatively clear, and mostly are divided into small patches. The WIRAs are 0.4—1.9 km. The orientation of the ridges swings around the very north direction because of the curving of the ridges. The HRs are 30—60 m.
39	‘日’character-shaped and ‘乡’ character-shaped	There are also relatively plentiful areas of comb-shaped pattern and a small quantity of areas of toe-shaped pattern, so that the total geomorphic pattern looks appreciably disordered. The east-side edges of the ridges are mostly not clear. The IRAs are mostly close to prolate ellipses in shape, and the WIRAs are 0.3—1.7 km, close to the WRs. The ridges are relatively high and the HRs are generally up to 30—40 m.
40	‘日’character-shaped and ‘乡’ character-shaped	There are also relatively plentiful areas of comb-shaped pattern. The IRAs are narrow, sparse and unconspicuous, and the WIRAs are 0.6—1.7 km. The connections of the ridges are unclear, and the ridge chains extend for relatively short distances. The HRs are 20—50 m.
41	miscellaneous	It is intercalated with a comb-shaped pattern. The TRs are variational, the WRs are inconsistent and the shapes of the ridges are irregular. The IRAs are relatively big, and the WIRAs are 0.4—1.9 km. The HRs are several meters to 20 m.
42	‘日’character-shaped and ‘乡’ character-shaped	There is a small quantity of areas of the comb-shaped pattern in some parts. The TRs are relatively clear and consistent, but the east-side edges of the ridges are mostly coarse and unconspicuous. The WRs are even comparatively. The IRAs mostly look like peanuts or near prolate ellipses in shape. The WIRAs are 0.6—2 km, close to the WRs. The ridges are relatively high and the HRs are mostly over 30 m, the highest around 50 m.
43	‘日’ character-shaped and ‘乡’ character-shaped	Similar to No.42 subzone. But the IRAs here are relatively wide and long, and the WIRAs are 0.6—2 km, mostly over 1 km. The ridges are sparse comparatively and the HRs are mostly higher than those in No.42 subzone, quite a few over 60 m.
44	parallel	The ridge chains curve slightly like earthworms and the curvatures of the ridges increase from north to south. The boundaries of the ridges are very clear and the alignment of the ridges is relatively regular. The WRs have a gradually increasing trend from west to east and from north to south. The IRAs are open, and the WIRAs are 0.8—3.7 km, mostly between 1.5 km and 2.5 km, over 2 times as wide as the WRs. The ridges are high and the HRs are mostly over 40 m, some even over 60 m.
45	‘日’ character-shaped and ‘乡’ character-shaped	Adjacent to the southern side of No.44 subzone. Most edges of the ridges are clear. The ridge chains are dense and most of them curve. In the ridge chains, the north ends of many ridges are like commas in shape. The TRs are slightly disordered and gradually turn to the west direction from the SW part to the NE part. The IRAs are mostly like long or super-long beanpods in shape. The WIRAs are 0.5—3 km, mostly 0.8—1.8 km, which narrow evidently compared with those of No.44 subzone and are close to or slightly wider than the WRs. The HRs are close to or slightly lower than those of No.44 subzone.
46	‘日’ character-shaped and ‘乡’ character-shaped	Adjacent to the southern side of No.45 subzone. The ridges slightly curve but are relatively somewhat straight compared with those of No.45 subzone. The boundaries of the ridges are mostly unclear. The WRs narrow compared with those of No.45 subzone. Each section of the ridge chains also narrows and is evidently shorter than that in No.45 subzone. The IRAs are like beanpods in shape. The WIRAs are narrower than those of No.45 subzone, and are 0.4—2.2 km, mostly 1.1—1.8 km, close to the WRs. The ridges are high and the HRs are similar to those of No.45 subzone.
47	‘乡’ character-shaped	Adjacent to the southern side of No.46 subzone. The boundaries of the ridges are much more unclearer than those of No.46 subzone. The ridges curve slightly and the TRs are close to the very north direction. The WRs rifely widen and are close to those of No.46 subzone. The WRs are mostly wider than or close to the WIRAs. The IRAs look much narrower and closer, and are mostly like beanpods or cucurbits in shape. The WIRAs are 0.4—2.5 km, mostly between 0.8 km and 1.5 km. The ridges are high and the HRs are similar to those of No.46 subzone.
48	‘乡’ character-shaped	The ridge chains curve and each section of them is like short burls in shape. The boundaries of the ridges are relatively clear and the TRs are close to the very north direction. The IRAs are relatively open, and the WIRAs are 0.4—2.7 km, mostly 0.9—2 km, close to those of No.45 subzone. The ridges are high, and the HRs are close to or slightly lower than those of No.47 subzone.
49	‘日’ character-shaped and ‘乡’ character-shaped	Similar to No.54 subzone. But the ridges thicken and the boundaries of them are much unclearer, the WRs and WIRAs all narrow and the sizes of the ridges decrease. The WIRAs are 0.3—1.4 km, mostly 0.5—0.7 km. The overall geomorphic pattern is slightly like grids because of the IRAs' being partitioned and broken into pieces. The HRs lower further and are mostly within 20 m.
50	‘日’ character-shaped and ‘乡’ character-shaped	Due to the closeness between the lengths and the widths of the IRAs, the overall geomorphic pattern is very close to grids. The boundaries of the ridges are relatively blurry. The ridge chains curve and each section of them is short and wide. The ridge chains are dense and the holistic strike of them is close to the very north direction. The IRAs are all partitioned into small rhombic patches. The WIRAs are 0.4—1.9 km. The total area of the RBs is evidently bigger than that of the IRAs. The HRs increase evidently compared with those of No.49 subzone, generally around 30 m, the highest over 50 m.
51	‘日’ character-shaped and ‘乡’ character-shaped	The lengths and widths of the ridges are close to those of No.48 subzone. But the alignment of the ridges is relatively disordered. The strikes of most ridges are close to the very north direction and the strikes of a few ridges in the southwest are close to NW-SE direction. The WIRAs are 0.4—2.5 km, and the IRAs are mostly smaller than those of No.48 subzone. The ridges are high and are mostly over 40 m or even over 50 m.

(*To be continued on the next page*)

(*Continued*)

Subzone coding	Main large-scale geomorphic pattern	Other characteristics
52	'乡' character-shaped	There is a parallel geomorphic pattern in some parts. The ridge chains are relatively straight and align comparatively regularly. The strikes of the ridge chains are close to or slightly inclined to the very north direction. The WRs are relatively even, and the boundaries of the ridges are clear. The IRAs are wide and distinct, and the WIRAs are 0.3—2.8 km, mostly 1—2 km, generally wider than the WRs. The ridges are high and are similar to those of No.51 subzone.
53	parallel	It lies at the northern edge of the CLSRZ, similar to No.18 subzone. Most of the ridges are beadlike dunes, and among them there are also some isolated complex dome-shaped dunes. The IRAs are wide and the WIRAs are 0.6—4.5 km, 2—5 times as wide as the WRs. The HRs are 10 m to over 40 m.
54	'日' character-shaped and '乡' character-shaped	The ridges are relatively straight and the boundaries of the ridges are blurry. The IRAs are comparatively wide, the WIRAs are 0.2—1.8 km and there are many linear dunes in the IRAs. The HRs are generally lower than those of adjacent No.45, No.46 and No.48 subzones, commonly within 40 m and the HRs in the south are lower than in the north.
55	'日' character-shaped and '乡' character-shaped	It lies at the eastern side of the lower reaches of the Keliya River and the fluvial traces are evident. The ridge chains are mostly like bamboo sections in shape, the NE end of each "section" is relatively wide and thick, and the "sections" taper to the SW direction. The WIRAs are 0.7—2 km, 1—4 times as wide as the WRs. But the IRAs are mostly partitioned into several sections by the transverse sand ridges. The HRs are several meters to over 20 m.

nold)[23,27], and of roll-vortex (Hanna, etc.)[26,27] for longitudinal sand dunes, as well as the theory of lateral movement and evolution of simple linear dunes for complex longitudinal sand ridges[19], all of these theories or hypotheses can not be generally accepted yet so far[27], so do the theories for the CLSRs in the Taklimakan Desert. The explanations are still divergent. Among them, the doctrine of resultant wind[5], of prevailing wind[26] and of the control of buried ridged landform[1], are representative.

Compared with the geneses of various kinds of sand dunes, the problem of large-scale geomorphic patterns in the CLSRZ is much more complicated because it involves the large, medium and small scales at the same time. However, this paper tries to provide some possible clues for this problem from the analysis of satellite images.

By analyzing the satellite images and the topographic sketch maps, we think that the connections between the sand ridges (or sand dunes) in the CLSRZ are the most important ways for the formation of large-scale geomorphic patterns. The specific connection modes are mainly as follows:

(1) The connection or convergence after natural elongation. It often occurs when the strikes of two adjacent sand ridges (or sand dunes) have a certain angle or the extension lines of resultant sand transport directions of two sand ridges (or sand dunes) are nearly superposed. Dome-shaped sand dunes or relatively short and small sand ridges may even develop into longer and bigger sand ridges in this way. It can be seen frequently in the CLSRZ. As shown in Figure 3(a), the northern edge of the desert at the south of the old riverbeds of the Tarim River is the most typical case. (What should be clarified is that, the dome-shaped sand dunes mentioned above include the resembling dome-shaped sand dunes. The so-called resembling dome-shaped sand dunes mean various kinds of non-typical (round or oval) dome-shaped sand dunes, such as sand dunes with raindrop-shaped, short-spindle-shaped or tadpole-shaped as well as sand dunes with the shapes between those of dome-shaped dune and barchan (or sand ridge)). Another example is the connection of two groups of sand ridges with acute angles in strikes in fork-shaped pattern, as shown in Figure 1(f).

(2) The connection at narrow parts. The adjacent sand ridges naturally connect each other after expanding vis-à-vis transversely where they are very close and the inter-ridge area is too narrow, as shown in Figure 3(b). But it is scarce.

(3) The connection through intermediaries. This is the most common way of forming the large-scale geomorphic patterns in the CLSRZ. It controls the formation of most transverse sand ridges which connect the CLSRs, and also affects the process of formation of much huge and long CLSRs through union of some longitudinal sand ridges end to end. In this process, the connection of two sand ridges relies mainly on an intermediary between them to complete. The intermediary extends to the adjacent sand ridges in both or one side (of course, there may also exist the extension of sand ridges to the intermediary from both sides of it), and it eventually links them together. The most familiar intermediary is the very dome-shaped sand dune. In addition, the "finger-like protuberance" (referring to the plane pattern) adhere to a sand ridge is also a kind of interme-

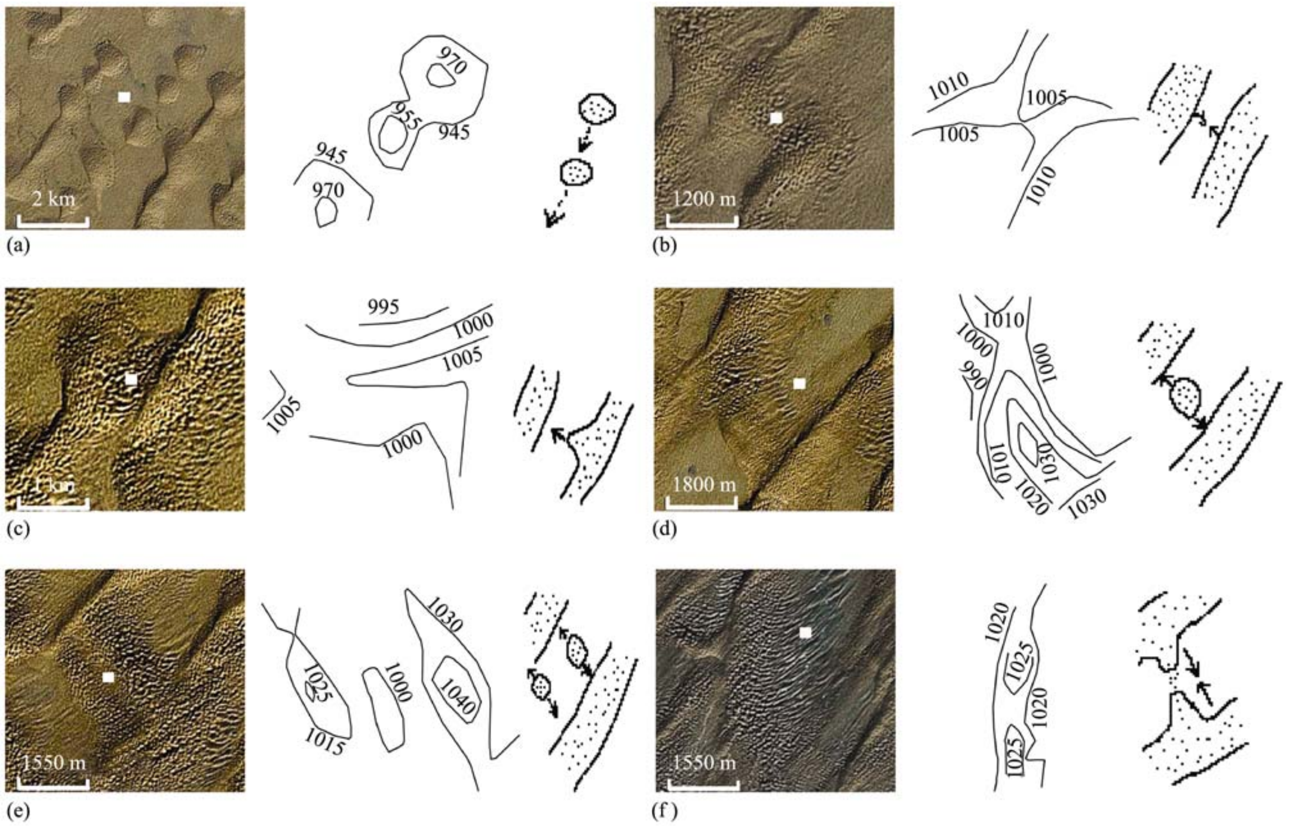

Figure 3 The connection modes of sand ridges in the CLSRZ. Figures drawn in line indicate contour lines; the unit of altitude is meter. The arrows in the sketch maps are the extending or connecting trends of sand ridges.

diary, as shown in Figure 3(c), (f). Figure 3(d), (e) are the examples of connection of sand ridges through dome-shaped dunes, in which it is obvious that the dome-shaped sand dune works as a "kernel" for forming the connection ridge (transverse sand ridge) in the inter-ridge area.

We suppose that, just by these three kinds of connections and through the mutual connections of various plane combination forms, the sand ridges (or sand dunes) finally form the different and unique large-scale geomorphic patterns in the CLSRZ. However, all these three are not always equally important in the formation of the geomorphic patterns. Among them, there are usually only one or two connection modes which are dominant in the formation of each pattern. For example, the connection or convergence after natural elongation should apparently be the most important way of producing a parallel pattern, and '日' character-shaped as well as the '乡' character-shaped patterns are obviously formed mainly by the connection through intermediaries.

Of course, the mentioned above is only the analysis and speculation based on the morphological characteristics from satellite images. More specific geomorphologic processes of wind-drift sand related to those connection modes, will still need to be verified by relevant field observations or laboratory tests.

5 Discussion

This article summarizes six types of large-scale geomorphic patterns in the CLSRZ, but whether the summarizing is reasonable and complete or not, still needs to be further explored. From the previous zoning of the CLSRZ, the differences of the large-scale geomorphic patterns are reflected not only by the ways of spatial layout and combination in the desert area, but also by the heights of sand ridges, the lengths and widths of inter-ridge areas, the shapes of ridges, the regularity of the layout of ridges, and so on. So, even if the patterns of different subzones are the same in this paper, some significant dissimilarities of geomorphic characteristics may be found in these subzones. For instance, the '日' character-shaped and '乡' character-shaped pattern with dense obstructive transverse ridges or with narrow inter-ridge areas may differ apparently from that with sparse obstructive transverse ridges or with wide inter-ridge areas not only in morphology, but also in sand disaster degree. Shall we zone the region more detailedly based on these differences? How to fractionize it and how to define the standards for fractionizing? These problems still need to be discussed right along.

Besides these, how to distinguish and relate the standards of the geomorphic patterns described in the paper and those of the usual aeolian landforms such as barchan and star dune, is a noticeable problem. In current various classification systems of aeolian landforms the types are mostly classified and named by the shapes of sand dunes[27]. What is more, generally, these classification systems do not strictly differentiate the spatial scales of landforms, and conversely, they arbitrarily gather the landforms of different spatial scales — even the aggregate of landforms into the same classification system. The large-scale geomorphic pattern types discussed in this paper actually are just classified by the different presentations of aggregates of large-scale aeolian landforms. So, it is not surprising that there may be some problems on relating the standards of the geomorphic patterns described in the paper with those of the usual aeolian landforms and on distinguishing between them. For example, is the so-called lattice-like dune actually a type of sand dune or a kind of large-scale geomorphic pattern? Or it belongs to both of them? At present, it may be still a controversial issue. We think that to solve these problems it may be necessary for us to reconsider the classification of aeolian landforms by integrating current classification and naming of aeolian landforms with those of large-scale geomorphic patterns and to reconsider how to deal with the problems related to the scales of landforms.

Finally, it is worthwhile to mention that because the number of CLSRs controlled by buried ridged landform is relatively small, which can mainly be found at a few areas of fork-shaped pattern, whereas the strikes, heights and widths of most CLSRs have shown a very clear and consistent regularity (only aeolian landforms has this feature and no other geomorphic types possess this[3]), and additionally, there is not enough autoptical evidence to say that buried ridged landform underlying the dunes exists all over the CLSRZ, therefore, the argument that "the CLSRs in the Taklimakan Desert originate from the Quaternary buried ridged landform"[1], is hardly convincing. Otherwise, at least the existence of fork-shaped pattern will be difficult to get a reasonable explanation. At any rate, from the analysis of satellite images we believe that the CLSRs of the Taklimakan Desert and the large-scale geomorphic patterns in the CLSRZ are mainly formed by wind[26], and only a few of them in partial areas may be formed by other factors such as underlying upheavals or buried ridged landform[29] created by past fluvial process.

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