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Morphological and sedimentary features of oblique zibars in the Kumtagh Desert of Northwestern China

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ABSTRACT

Zibars are coarse-grain-armored, low-relief aeolian bedforms with a large spacing but without slipfaces. Little is known of their morphodynamic processes, even though they are ubiquitous at upwind desert margins. In this paper, we describe the morphological and sedimentary features of oblique zibars in the northeastern Kumtagh Desert of China; analyze the effective wind regime; and discuss the significance of the coarse-grained sediments for zibar morphology and sedimentary structures. Due to a mantle of coarse grains, oblique zibars and nearby linear dunes respond to different effective wind regimes that result in the angle between their geomorphological trends. Topographic surveys showed that the spacing of the oblique zibars ranged between 130.5 and 357.5 m, and that the height ranged between 0.6 and 3.0 m. The oblique zibar surface is almost entirely covered by coarse sand, and includes gravel with a particle diameter of up to −2.34 φ. The poorly sorted, positively to very positively skewed surface sediments, with mean grain size ranging between −0.2 φ and 1.5 φ, were characterized by a bimodal distribution. The spacing between the oblique zibars is closely related to the coarsest 5th percentile of the surface sediments, and can potentially be explained by a combination of the saturation length and minimum dune size theories. In addition, the protectionist theory, combined with the surface creep and vibration of coarse grains (which allows infiltration of finer materials between the grains), may account for the alternating coarse and fine laminae in the oblique zibars.

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1. Introduction

Sand sheets and zibars are the most common type of aeolian depositional surface; they occupy about 38% of the world's dune fields and exceed the total area of barchans and star dunes (Fryberger and Goudie, 1981; Cooke et al., 1993). Many of the dune classification systems regard them as independent bedform types because they are armored by distinctive surfaces of coarse-grained sediments (Pye and Tsoar, 1990; Cooke et al., 1993; Lancaster, 1995; Livingstone and Warren, 1996). Pye and Tsoar (1990) classified simple dunes as aerodynamic and/or obstacle disturbed accumulations, and proposed that they reflect the influence of the bed roughness and surface conditions. Depending on the grain size of the sediments, free dunes can be further divided into shifting dunes composed of fine to medium sands and sand sheets or zibars composed of poorly sorted coarse particles. Most dunes, such as barchans, linear dunes, star dunes, parabolic dunes, and shrub dunes, as well as echo and climbing dunes, are composed of fine-grained sediments, and their morphologic evolution mainly reflects the influence of the wind regime or surface conditions (Lancaster, 1995). However, the processes that act on sand sheets and zibars may differ from those that govern the development of dunes composed of finer sand due to the presence of the less-easily transported coarse grains. Unlike the featureless or subtly undulating sand sheets, zibars offer a good example of the significance of sediment characteristics (in particular, the grain size) on the evolution of aeolian bedforms.

In fact, zibar is an Arabic term that was introduced by Holm (1960) to describe the form of "rolling transverse ridge without slipface" in the central Rub' al Khali Desert. Bagnold (1941) described similar forms in the Egyptian Sand Sea as "whalebacks", and regarded them as large plinths of seif dunes. Bristow et al. (2010) also used the term "whaleback dunes" to describe the similar bedforms rather than zibars in the Victory Valley of Antarctica. Other terms for such aeolian bedforms include "giant ripples", "giant undulations", "low-angle aeolian deposits", "low rolling dunes without a slipface", and "granule-armored dunes" (Fryberger et al., 1979; Lancaster, 1982; Greeley and Iversen, 1985; Breed et al., 1987; Cooke et al., 1993). Nielson and Kocurek (1986) described zibars as coarse-grained, low-relief aeolian features without a slipface. Zibars are ubiquitous in the upwind margins of arid deserts and in the broader corridors between linear or star dunes. In the Namib Sand Sea, zibars occupy about 1.5% of the total area (Lancaster, 1989). In the "zibar belt" of the southern Sahara, they

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cover about 150,000 km^2 of northeastern Niger and more than 60,000 km^2 of northern Sudan (Warren, 2013).

Zibars are characterized by a low relief, large crest-to-crest spacing, and the lack of a slipface. Their surface is typically composed of coarse, poorly sorted grains with a bi- or multi-modal size distribution (Table 1). The existence of such coarse sand is considered to be one of the primary factors responsible for the broad lateral dimensions and gentle slope of zibars. Bagnold (1941) proposed that the curvature of a dune depends on the friction Reynolds number of the particles, and that on this basis zibars should have subdued profiles that contrast with the more pronounced profiles of dunes composed of fine sands. Despite this, depending on the angle between the trends of the zibars and the resultant sand-transport direction, Warren (1971, 1972) and Nielson and Kocurek (1986) found that zibars can be interpreted as transverse and oblique bedforms according to the morphodynamic classification proposed by Hunter et al. (1983).

The morphological features and the dynamic processes that act on fine-grained dunes have been well documented (e.g., Pye and Tsoar, 1990; Lancaster, 1995). However, zibars have received little attention, and the mechanism of zibar formation is still imperfectly understood (Cooke et al., 1993; Livingstone and Warren, 1996; Bristow et al., 2010). Nielson and Kocurek (1986) noted that zibars are migrating features that are oriented transverse to or oblique to the dominant sand-transporting direction. It is noteworthy that the morphological and sedimentary characteristics that have been described for zibars mainly focused on transverse zibars within the interdune corridors between linear dunes, and these bedforms generally have discernible fluctuations in height and distinct windward and leeward deposits (Warren, 1971, 1972; Nielson and Kocurek, 1986; Wang et al., 2009).

In the northeastern Kumtagh Desert of China, transverse zibars occupy the corridors between linear dunes, where they extend nearly perpendicular to the surrounding dunes as well as the resultant sand-transport direction. However, zibars with oblique features have developed within the dune-free regions of desert margins and in some extremely broad interdune corridors (Fig. 1). Compared with the transverse zibars, the morphological features of the oblique ones are less distinct due to the subtle slope variation between the two sides of the zibar. In typical zones with oblique zibars in the northeastern Kumtagh Desert (Fig. 1, Plots 1 and 2), the airflow is less strongly influenced by the linear dunes (i.e., due to the greater distance between them), and the zibars can be viewed as “free” bedforms. The co-existence of oblique zibars and linear dunes under the same wind regime and the angle of intersection between their directional trends suggest that the coarseness of the zibar sediments plays an important role in the relationship between the two dune types. Hence, the study of oblique zibars can provide new insights into the effects of coarse-grained sediments on dune morphology and regional dune patterns. In the present paper, we describe the characteristics of zibar morphology and sediments for oblique zibars, analyze the regional wind regime, and discuss the significance of grain coarseness in dune evolution.

2. Study area and methods

This study was conducted in the hyper-arid Kumtagh Desert of northwestern China. Dong et al. (2011, 2012) have described the physiographic settings and geomorphologic features of this desert region in detail. The oblique zibars are mainly distributed at the northeastern margin of the desert, and linear dunes with heights of about 10 m have formed in the northwest of this zone (Fig. 1). During our field investigation, the morphology of typical oblique zibars (Plots 1 and 2, Fig. 1) was measured using a Topcon GTS-721 total station at a spatial interval of about 10 m. The topographic survey transects were perpendicular to the directional trend lines for the zibars, and at least four zibar crests were crossed in each plot. Note that it is difficult to visually distinguish the directional trends of oblique zibars on the ground because the sediments have similar colors on both sides of the crest and the heights of the zibars above the surrounding land are very small compared to their crest-to-crest spacing. To solve this problem, the trends for the oblique zibars were measured using satellite images in which the dark zibar crests differed significantly from the bright inter-zibar areas. Surface sediments to a depth of 1 cm were collected along two typical zibar transects for grain size analysis. To investigate the internal sedimentary structure of the zibars, a profile was excavated to a depth of 1 m at the zibar crest and the sediments within that profile were sampled at intervals of 5 cm to a depth of 20 cm, and at 10 cm intervals below this depth. The sediments were sieved on a shaker with a series of sieves ranging from $-2\ \varphi$ to $6.64\ \varphi$ in size, at an aperture interval of $1/3\ \varphi$. Four grain-size parameters were graphically derived according to the methods of Folk and Ward (1957): the mean grain size (M_z), sorting (σ_I), skewness (Sk_I), and kurtosis (K_G). In addition to the sieving analysis, we calculated Feret's diameters (the geometric mean of the long and short axes) of the topmost grains using the ImageJ software (Abramoff et al., 2004). Fig. 2 shows typical zibars and the nearby linear dunes, as well as the deposits at the zibar surface.

Three-cup anemometers and vanes mounted on a mast at 2 m above the ground were used to automatically record the wind speeds and directions at intervals of 10 min. The wind data from a whole year (2009) were used in this paper to calculate the drift potential according to Fryberger's (1979) formula and Pearce and Walker's (2005) modified wind speed classes. The resulting sand transport rose (shown in Fig. 1) was derived based on a threshold wind velocity of 6 m s^{-1}, which is strong enough for the entrainment of sands in this desert. Because of their coarse grains, zibar deposits undoubtedly have a higher threshold velocity for sand movement, and we will return to this issue in Section 3.4 of the paper.

3. Results

3.1. Morphology of the oblique zibars

Nielson and Kocurek (1986) suggested that zibars are discernable only based on color changes in aerial photographs. In satellite imagery

Table 1
Characteristics of morphology and grain size of the zibars proposed by previous works.

Location	Morphology		Grain size		Source
	Spacing (m)	Height (m)	Mean grain size (φ)	Distribution characteristic	
Ténére Desert, Niger	150 to 400	3 to 7	/	Modes at 0.0 and 4.06 φ	Warren (1971, 1972, 2013)
Selima Sand Sheet, Egypt	500	Up to 10	/	Modes at −0.26 and 3.0 φ	Haynes (1982), Breed et al. (1987)
Skeleton Coast, Namibia	100	1 to 2	1.5 to 2.0	Modes between 1.0 and 1.5 φ	Lancaster (1982, 1983, 1989)
Northern Sinai Desert, Israel	/	4 to 5	/	/	Tsoar (1983)
Algodones dune field, USA	60	Less than 2	0.0 to 2.8	Modes between 0.62 and 3.32 φ	Nielson and Kocurek (1986), Sweet et al. (1988)
Cuddapah Basin, India	/	/	1.05 to 1.91	/	Biswas (2005)
Kumtagh Desert, China	100 to 250	1 to 2	/	/	Wang et al. (2009)
Victoria Valley, Antarctica	/	2 to 12	0.45 to 1.94	/	Bristow et al. (2010)

/: data not available.

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