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Definition and origin of the dune-field pattern at White Sands, New Mexico

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ABSTRACT

A LiDAR-derived digital elevation model (DEM) of a representative portion of the White Sands Dune Field, New Mexico, allows for characterization of an unprecedented range of dune-field parameters and serves as a basis for pattern analysis. Dune-field parameters were measured and statistically analyzed for populations of dunes selected at random and occurring along transects. Populations sampled by these two different methods are comparable, but highlight the sensitivity of transect placement in a dune field that has pattern heterogeneity. Based upon coefficients of variation, pattern emerges at White Sands primarily because of a strong fabric of crestline orientation, and secondarily because of the regularity of spacing between dunes of similar shape as defined by sinuosity, height and length. Linear regression of dune parameters shows that dune geometric relationships vary primarily with crestline length, but there is little correlation between other parameters, including dune spacing and height. This result highlights the sensitivity of identifying topographic heterogeneity in a LiDAR-derived DEM, given that mean ratios conform to global averages. Stripping off the dunes in Matlab shows a terraced surface, which is interpreted to represent paleo-shorelines formed during relative still stands in the overall retreat of Lake Otero. Elevated bands of higher, more closely spaced dunes occur just leeward of the paleo-shorelines. A revised model for the White Sands Dune Field consists of the basinward progradation of successive dune-field segments. Each segment is associated with a paleo-shoreline, and consists of an upwind dune ridge, represented by the elevated bands, and a leeward dune field.

1. Introduction

Aeolian dune fields show some of the most striking geomorphic patterns on Earth and other planetary bodies including Mars and Titan. These patterns have been interpreted to arise through self-organization of complex systems (e.g., Werner, 1995, 1999; Kocurek and Ewing, 2005; Baas, 2007); specifically through dune-dune interactions in which the pattern evolves within a unique set of boundary conditions such that no two dune fields are ever exactly alike (Werner, 2003; Ewing and Kocurek, 2010a,b; Kocurek et al., 2010). Although patterns may be most simply defined as regularly repeated similar shapes, the parameters that cause dune fields to be perceived as patterns have never been specifically addressed. Dune-field parameters such as dune spacing, crest length and orientation have long been measured and statistically characterized from remote images (e.g., Breed and Grow, 1979; Lancaster, 1995; Ewing et al., 2006), but LiDAR (light detection and ranging) surveys and the resultant digital elevation models (DEM) provide a basis from which both commonly measured and heretofore unaddressed dune parameters can be determined with a high degree of accuracy, and thus serve to identify those parameters that cause dune fields to be perceived as patterns. Moreover, dune-parameter characterization from a DEM can be used to quantify spatial heterogeneity within the dune-field pattern. In turn, this heterogeneity may reflect the boundary conditions within which the dune-field evolved, and thus aid in the interpretation of the geomorphic history of the field.

This paper explores the White Sands Dune Field in New Mexico through a LiDAR-derived DEM of a representative portion of the dune field marked by the occurrence of crescentic and barchans dunes. Objectives are to: (1) measure a wide array of dune

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parameters with a DEM using Geographic Information System (GIS) software, (2) define those parameters that cause the pattern to emerge by virtue of having the least variability within the pattern, (3) explore the relationship between dune parameters, (4) identify spatial heterogeneity within the dune-field pattern, (5) identify those boundary conditions that give rise to the heterogeneity, and (6) evaluate models for the development of the dune field based upon the boundary conditions.

2. Geomorphic and geologic context

The White Sands gypsum dune field is situated within the Tularosa Basin between the San Andres Mountains to the west and the Sacramento Mountains to the east. The dune field, measuring ~500 km^2 and considered to be the largest gypsum dune field globally, consists of a core of crescentic and barchan dunes, which is rimmed to the north, east and south by parabolic dunes (Fig. 1). The western margin of the dune field is abrupt, giving way to Alkali Flat, a deflationary gypsum plain. Yet westward, occupying the lowest elevations of the basin, are active playa lakes, the largest of which is Lake Lucero.

The most pertinent aspects of the dune field from previous work for this study are its origin as a lake-shore feature and interpreted boundary conditions that control sediment sourcing and accumulation of aeolian strata within the dune field. The dune field is thought to have originated ~7 ka with the retreat of Late Pleistocene saline Lake Otero during the onset of regional aridity, with the dune field entirely sourced from lake sediment (Langford, 2003; Kocurek et al., 2007; Allen et al., 2009; Langford et al., 2009). Langford (2003) identified two paleo-shorelines at elevations of 1200 m (L1) and 1191 m (L2) between the current Lake Lucero shoreline at 1185 m and the poorly defined Lake Otero high stand, which is given as 1218 m by Lucas and Hawley (2002), 1210 m by Langford (2003), and 1204 m by Seager et al. (1987) and Allen et al. (2009). Each successive fall of Lake Otero would have allowed for the deflation of newly exposed lacustrine deposits and sediment sourcing for the dune field. The deflation of newly exposed lacustrine deposits plus any shoreline sands would have defined a line-source of sediment for dune-field construction (Ewing and Kocurek, 2010a). The dune-field position on the eastern side of the basin argues that earlier Holocene winds were similar to modern winds in terms of the net resultant, which is given as 060° by Fryberger (2003) and 065° by Jerolmack et al. (2011) and based upon the wind record at Holloman AFB, located ~10 km east of the dune field. The modern net resultant coincides with the mode of dominant winds from the SW, but lesser wind modes occur from the NNW and SSE.

The dune field has generated (and is currently generating) a stratigraphic record as evidenced by the: (1) presence of 7–10 m of gypsiferous aeolian sediments overlying Lake Otero strata in cores taken from the center of the dune field (McKee and Moiola, 1975; Kocurek et al., 2007; D. Bustos, NPS, per. comm.), (2) plan-view exposures of cross-strata in interdune areas and on Alkali Flat, and (3) linking of climbing dune and interdune accumulations in trenches to modern migrating dunes (Kocurek et al., 2007). The boundary conditions that cause the accumulations to occur potentially include: (1) a shallow, perched water table (~0.5 m below the surface) that resides within the gypsiferous aeolian sands and above the much more impermeable accumulations of Lake Otero (Kocurek et al., 2007; Langford et al., 2009; Porter et al., 2009; Jerolmack et al., 2012), (2) surface cementation by gypsum, which raises the critical threshold for grain transport (Schenk and Fryberger, 1988), and (3) a decrease in wind energy in the net transport direction (McKee, 1966; Jerolmack et al., 2012), which Jerolmack et al. (2012) related to an internal boundary layer.

Collectively, the points outlined above give rise to a general model for the origin and development of the dune field at White Sands, but the forcing factors, dynamics and chronology of the retreat of Lake Otero, dune-field construction, and accumulation of aeolian strata are not understood in detail. This fact is evident in variations of the general model given by Langford (2003), Kocurek et al. (2007), Langford et al. (2009), Szynkiewicz et al. (2010) and Jerolmack et al. (2012).

3. Methodology

A 38.8 km^2 (15 mi^2) area of the dune field was selected for the LiDAR survey such that it was (1) representative of the length of the dune field containing crescentic and barchans dunes in the net transport direction, and (2) of sufficient width to include numerous full-length dune crests (Fig. 1). Placement of the area includes the easternmost reaches of Alkali Flat, spans the core crescentic and barchan dune field, the crescentic-parabolic dune transition zone, and the western portion of the area of parabolic dunes (Fig. 2). Neither the parabolic dunes nor dunes in the transition zone are considered in the statistical analysis presented here. The LiDAR survey was flown in June 2007 by the Center for Space Research at the University of Texas at Austin, using an Optech ALTM 1225 LiDAR instrument integrated with an Ashtech Z-12 dual frequency GPS receiver and a Litton LN-200 inertial measurement unit aboard a Cessna 206 Turbo Stationair. Laser pulse rate frequency was 100 kHz, yielding over 16 million points within the survey area, or approximately 5 points per square meter. The DEM was constructed with a 1 m/pixel spatial resolution with ~0.1 m vertical resolution.

The LiDAR-derived DEM provided a static base from which to characterize the parameters of the dune-field pattern and to quantify spatial heterogeneity in these parameters. As shown in Fig. 3, two field-scale sampling methods were used: (1) 109 dunes were selected at random by an automated algorithm in ArcGIS, and (2) 247 dunes were sampled along four regularly spaced (~1 km apart) transects that spanned the study area in a N75E direction, which is perpendicular to the mean crestline orientation for the dune field (Ewing et al., 2006). Dunes were additionally sampled within four areas (Areas 1–4 in Figs. 2 and 3) where visually the pattern is distinct. Dunes in Areas 1, 2 and 4 appear to be taller and more closely spaced than adjacent dunes, whereas in Area 3 the dunes appear to be smaller and much more widely spaced. Dunes in these areas were either all sampled (Area 1, $n = 26$; Area 2, $n = 20$) or randomly selected (Area 3, $n = 44$; Area 4, $n = 42$), and compared to the field-scale population of dunes selected at random. These dunes were also sampled along transects spaced 125 m apart in Areas 1–2 and 500 m apart in Areas 3–4 (Area 1, $n = 45$; Area 2, $n = 40$; Area 3, $n = 44$; Area 4, $n = 42$), and compared to the field-scale population of dunes sampled along the transects.

In order to measure the dune parameters for dunes selected at random, each dune was separated from the substrate over which it is migrating and manually traced using ArcGIS (Fig. 4A). Standard parameters were measured that include: (1) average and maximum dune height, (2) dune spacing (crest-to-crest length) and dune spacing without interdune area (crest-to-crest length with the length of the interdune area subtracted), (3) crestline length, (4) dune width, (5) dune length, (6) crescent length, (7) dune horn length, (8) crestline sinuosity, and (9) orientation (Fig. 4A). In addition, the DEM allowed for the measuring of: (10) dune 2-D (footprint) area, (11) total surface area of the dune, and (12) dune volume. For dunes measured along transects, (1) dune height, (2) dune spacing, and (3) dune length were measured where intersected by the transect lines (Fig. 4B).