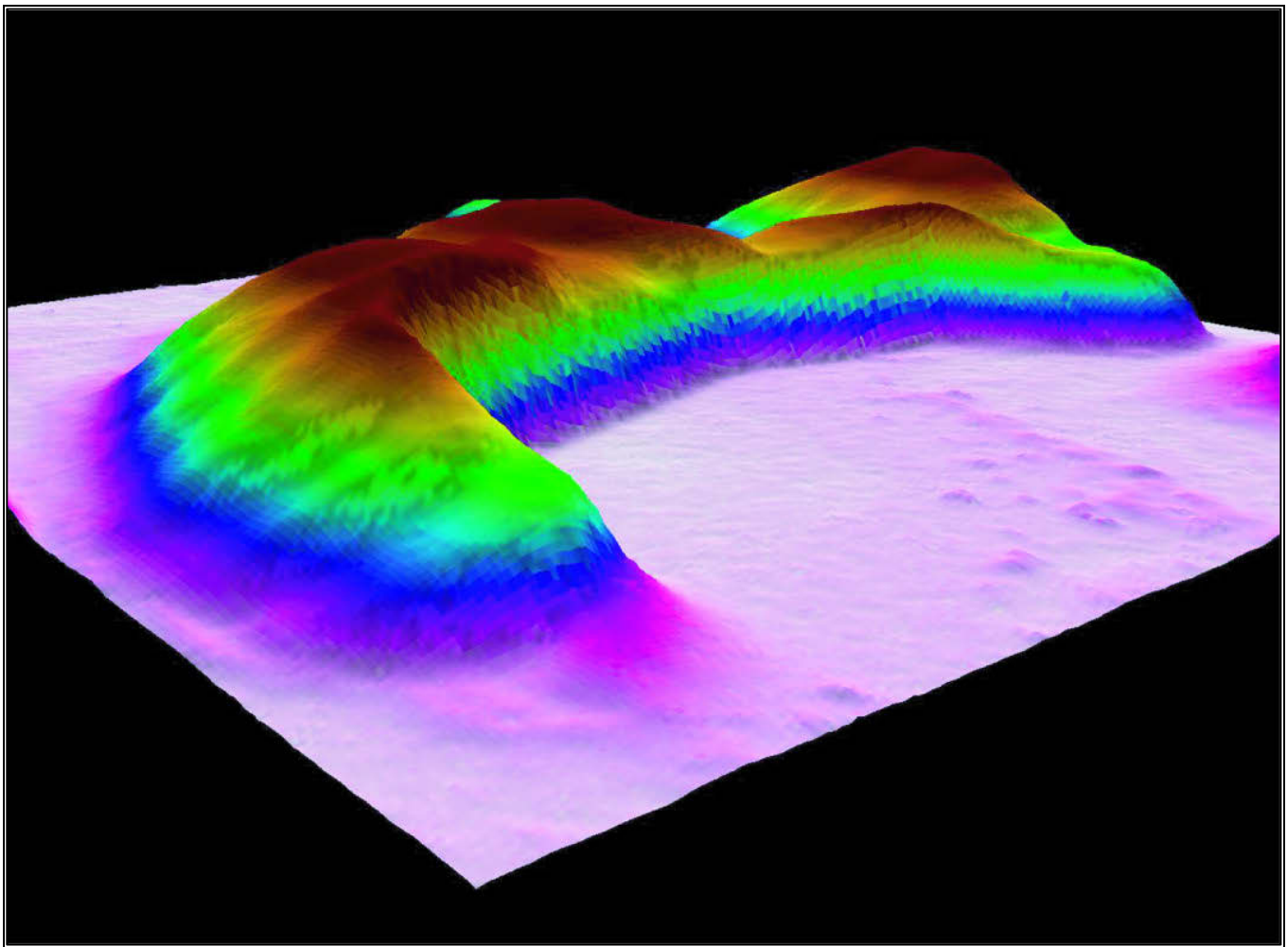




LiDAR Surveys of Gypsum Dune Fields in White Sands National Monument, New Mexico

Natural Resource Technical Report NPS/CHDN/NRTR—2012/558



ON THE COVER

3-D digital elevation model (DEM) of a sand dune at White Sands National Monument,
from LiDAR data

LiDAR Surveys of Gypsum Dune Fields in White Sands National Monument, New Mexico

Natural Resource Technical Report NPS/CHDN/NRTR—2012/558

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Abstract

LiDAR (Light Detection and Ranging) surveys were conducted over a representative 39 km² area of the gypsum dune field at the White Sands National Monument during June 2007 and June 2008. Study objectives were to (1) establish the base physical parameters that characterize the dune field, (2) identify spatial variability in the dune pattern, (3) determine the cause of pattern variability, (4) ascertain dune activity over a year, and (5) gauge the potential for long-term monitoring via LiDAR surveys. Digital elevation models (DEMs) created from LiDAR data using ArcGIS allowed for accurate measuring of an unprecedented range of dune-field parameters from dunes selected (1) at random, (2) along transects in the net transport direction, and (3) within zones where the pattern is visually different. In order to investigate the cause of pattern variability, dunes were computationally removed to reveal the base surface over which they are migrating. Dune activity over the year was determined from a difference map in which the June 2007 topography was subtracted from the June 2008 topography. Results show that the dune field is best characterized by dune height, spacing, dune length, crest sinuosity, and dune orientation, but there is marked variability among most measured parameters and little correlation exists between parameters. Pattern emerges at White Sands because of the strong trend in dune orientation. Dune-field variability is real and is thought to occur because of the young age of the field, ubiquitous dune-dune interactions that rearrange the pattern, and field-scale boundary conditions. However, the nature of LiDAR data forces the recognition of pattern variability, which exists in most dune fields, but that has been deemphasized by traditional measurements. The primary boundary condition that causes pattern heterogeneity at White Sands is antecedent relict topography from paleo-shorelines formed during the episodic retreat of Lake Otero. Disguised beneath the dune field new paleo-shorelines were discovered at elevations of 1203, 1205.5, and 1211 m on the base surface. Dune activity varies significantly over the dune field, from high rates of dune migration and pattern ordering within the first 0.5 km of the field, to low levels of dune activity within the parabolic dunes at the downwind end of the field. Dune growth occurs on sand build-ups lee of the paleo-shorelines, in contrast to dunes in the central portion of the field where the water table is just below the surface. Although the dunes migrate about 3.5 m/yr to the ENE in response to dominate winds from the WSW, streamwise lineations, superimposed stoss bedforms, and both crescentic and parabolic dunes show a component of lateral migration to the south because of winter north winds. The impact of dune migration upon park infrastructure is evident, and LiDAR emerges as a powerful tool for monitoring vital signs within the park and for maintaining park functions.

Acknowledgments

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Introduction

White Sands National Monument, New Mexico, houses the southern portion of the White Sands Dune Field and adjacent portions of Alkali Flat and Lake Lucero. The remainder of the dune field and Alkali Flat are within the White Sands Missile Range. The uniqueness of the White Sands Dune Field is that it is the largest gypsum dune field globally. The challenge to the National Park Service is to maintain the natural environment of the dune field and conduct park operations in what is inherently a dynamic and mobile substrate.

The purpose of this study is to ascertain the effectiveness of LiDAR (Light Detection and Ranging) surveys as a means of (1) establishing the base physical parameters of the dune field, (2) identifying spatial variability in these parameters, (3) determining the controls on the spatial variability, (4) ascertaining dune activity within the survey area over a year, and (5) gauging the potential for long-term monitoring via LiDAR surveys. Toward these goals, the first LiDAR survey was conducted on 9 June 2007, and a second survey was conducted over the same area on 7 June 2008.

Study Area

White Sands Dune Field Overview

The White Sands Dune Field is situated within the Tularosa Basin between the San Andreas Mountains to the west and the Sacramento Mountains to the east (Fig. 1). During the Late Pleistocene, the basin housed Lake Otero (Herrick, 1904; Kottlowski, 1958), and accumulations of this lake underlie the entire dune field. With the onset of regional aridity, Lake Otero retreated in size, and a step-wise deflation of lake deposits sourced the dune field. Mapping and dating of paleo-shorelines that occurred with the Lake Otero retreat (Langford, 2003), and OSL (optically stimulated luminescence) dating of a sediment core (Kocurek et al., 2007) show that the gypsum dune field originated at about 7,000 years ago. Waters in Late Otero were inherently high in salinity because of leaching of gypsum-rich Permian strata in the San Andreas and Sacramento Mountains (Allmendinger, 1972). Concentration of gypsum occurred with lake evaporation and gypsum beds occur within the clays, silts, marls, and limestone accumulations of Lake Otero (Langford, 2003). These gypsum beds are thought to be the primary source of the gypsum dune sand (Fryberger, 2003; Langford, 2003; Szyrkiewicz et al., 2010), although some gypsum continues to be supplied to the dune field through deflation of Alkali Flat and from remaining playas such as Lake Lucero (c.f., McKee and Moiola, 1975).

The dune field consists of a core of crescentic and barchan dunes, which is rimmed to the north, east, and south by fields of parabolic dunes (Fig. 2). The western, upwind margin of the dune field is deflationary and relatively abrupt, giving way westward to Alkali Flat, an extensive gypsum plain. Yet westward, occupying the lowest elevations of the basin, are active playa lakes, the largest of which is Lake Lucero. Measurement of groundwater salinity, with its implied control on vegetation, argues for the rim of parabolic dunes to occur over fresher-water lenses (Langford et al., 2009). However, Reitz et al. (2010) show that sediment flux decreases in the net transport direction, with the parabolic dunes occurring where vegetation can become established because of greater substrate stability. Within most of the dune field the ground-water table is near the surface and, together with surface cementation of gypsum, exerts a significant control on deflation of the substrate (Kocurek et al., 2007).

Long-term monitoring of the wind regime at nearby Holloman Air Force Base yields a 060° wind resultant (Fryberger, 2003), which is borderline transverse (82°) to the mean dune crestal trend of 338°, using the classification of Hunter et al. (1983). Dominant winds are from the WSW and are strongest during the winter-spring, but a second mode of winds from the N-NW occurs during the fall and winter, resulting in an along-slope transport and migration of dune sinuosity to the SSE (Kocurek et al., 2007). A third mode of winds from the S-SE occurs during the spring-summer, and although causing ephemeral dune reversals, it does not appear to be significant in long-term dune morphology and migration.

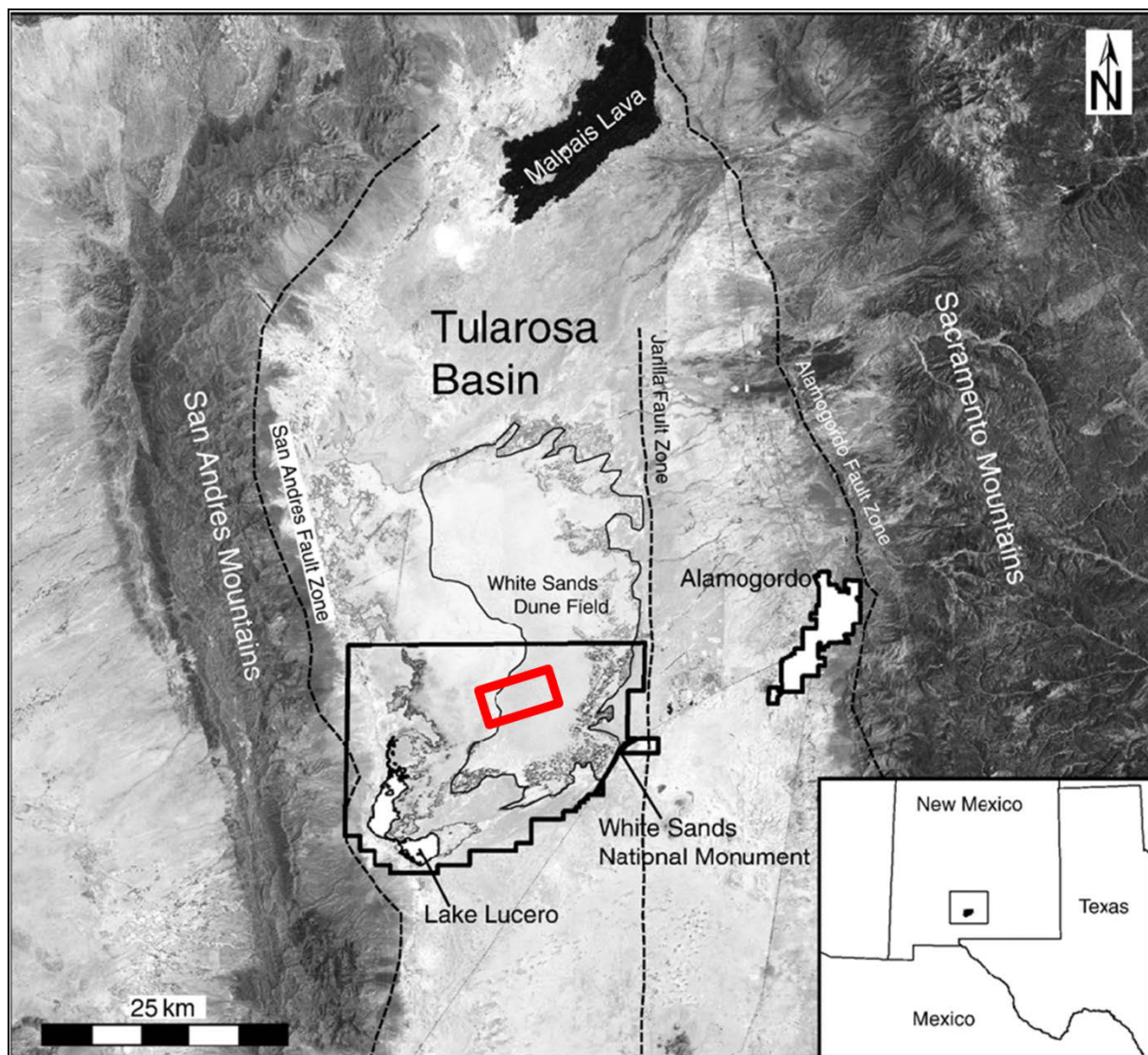


Figure 1. Location of the White Sands Dune Field within the Tularosa Basin. White Sands National Monument and location of the LiDAR survey area (red rectangle) are indicated.



Figure 2. Southern portion of the White Sands Dune Field showing the core of crescentic and barchan dunes, rimmed by parabolic dunes. LiDAR survey area indicated by rectangle. Previously recognized shorelines (L1 at 1,200 m, L2 at 1,191 m, Lake Otero high-stand at 1,215 m) shown, after Langford (2003). West of the dune field is deflationary Alkali Flat and the zone of active playas, including Lake Lucero.

Location of LiDAR Strip

A 15 mi² (38.8 km²) area of the dune field was selected for the LiDAR surveys (Figs. 1, 2).

Criteria for this selection were that the area (1) was representative of the length of the dune field in the net transport direction, (2) was of sufficient width to include numerous full-length dune crests, and (3) contained a portion of the heavily trafficked “Heart of the Dune Loop.” Placement of the area includes the easternmost reaches of Alkali Flat, spans the core crescentic and barchan dune field, and captures the crescentic-parabolic dune transition on the eastern flank of the field.

Methods

LiDAR

LiDAR provides a means of remotely mapping a 3-D surface with a high degree of accuracy. Instrumentation consists of an airplane-mounted laser that directs a laser pulse downward to the surface target, with the total travel time of the reflected beam used to calculate the elevation of the surface. Equally critical to the measured travel time is a precise determination of surface location, which is measured by a GPS (ground positioning system) mounted on the plane. LiDAR surveys for this study were flown 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. The Optech 1225 records the first and last pulse and has been integrated with a full waveform digitizer capable of recording the entire reflected pulse. The instrument was flown in a single-engine Cessna 206 Turbo Stationair. Laser pulse rate frequency was 100 KHz, or approximately 5 points per square meter, yielding over 16 million points within the survey area. Aircraft altitude was approximately 1,000 m above the surface and ground speed was 60 m/s (134 mph). Geo-referencing was done based upon GPS stations at the Alamogordo Regional Airport and at Space Harbor on the White Sands Missile Range. Geo-referenced elevation data were then used to construct a DEM (digital elevation model). Comparison of subsequent DEMs (June 2007 and June 2008) showed an areal accuracy of ~1m, which was adequate for this study, but owing to the limits of the airborne GPS, additional geo-referencing was required vertically. We used 135 stationary objects within the survey area to geo-reference the images to a vertical accuracy in decimeters.

DEM Analysis

Dune-Pattern Parameters and Their Spatial Variability

The single June 2007 DEM was used as a static base from which to characterize the parameters of the dune pattern and to identify spatial variations in these parameters (Fig. 3). Because only a small area of parabolic dunes is included in the survey area, parabolic dunes were omitted from this analysis. First, it was necessary to define dunes from the substrate over which they migrate, essentially isolating dunes as polygons on the DEM. This distinction is trivial where the steep lee face intersects the flat interdune surface, but more judgmental where the low-angle stoss slope merges with the interdune surface. In agreement with field observations and the DEM as a whole, dunes were defined to begin where the slope was $\geq 2.5^\circ$ (Fig. 4). Using this definition, the footprints of the dunes to be sampled were manually traced in ArcGIS. Three sampling methods were used (1) 110 dunes were selected at random by an automated algorithm, (2) 231 dunes were sampled along four regularly spaced transects that spanned the field in the net transport direction, and (3) dunes were sampled within four zones where visually the pattern was distinct (Fig. 5). The number of sampled dunes within these zones was Zone 1: 45 dunes, Zone 2: 41 dunes, Zone 3: 44 dunes, and Zone 4: 42 dunes.

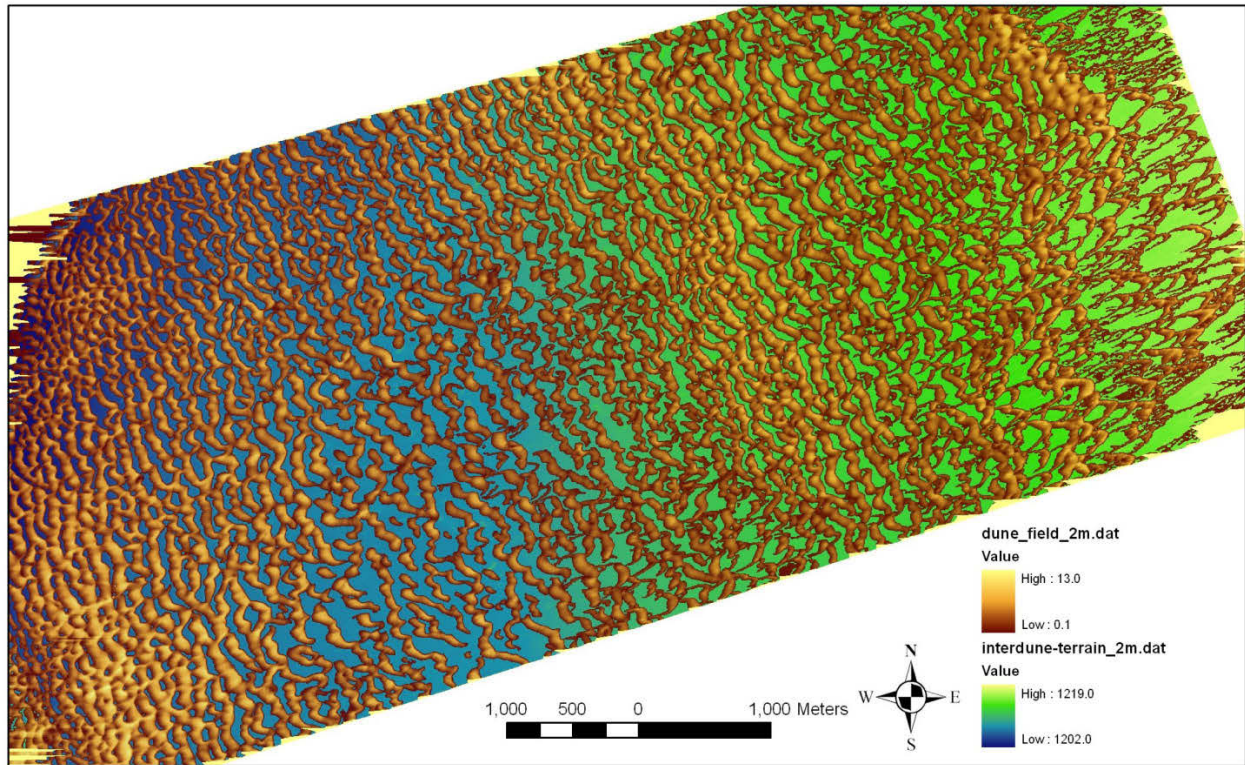


Figure 3. DEM from the June 2007 LiDAR survey, upon which dune parameters and their spatial variability were determined. Upper color bar shows dune elevation in meters above the interdune floor. Lower color bar shows interdune elevation in meters; note gentle slope of the surface to the SW.

LiDAR data allow for an unprecedented measuring of dune parameters at a high level of accuracy and within a 3-D context. Standard parameters were measured that include (1) maximum and average dune height, (2) crest-to-crest spacing with and without interdune areas, (3) crestline length, (4) dune length, (5) crestline orientation, (6) crestline sinuosity, (7) crescent length, and (8) dune horn length. The nature of the LiDAR data also allowed for measuring (9) dune footprint area, (10) total surface area of the dune, and (11) dune volume. Figure 4 is a definition diagram for all parameters as used here for the dunes chosen at random (Fig. 4A), and along field-scale transects and transects within Zones 1-4 (Fig. 4B). In addition, cross-plots of select parameters were made, including (1) spacing with and without interdune areas to average and maximum dune height, (2) crestline length to average and maximum dune height, (3) dune length to average and maximum dune height, (4) dune volume to maximum dune height, crestline length and footprint area, (5) dune footprint area and to dune width, (6) dune width to maximum and average dune height, and (7) total dune surface area to dune width. Standard statistics were derived, including mean, median, standard deviation, coefficient of variation (standard deviation/mean) for populations of single parameters, and mean and goodness-of-fit (r^2) for cross-plot linear regressions.

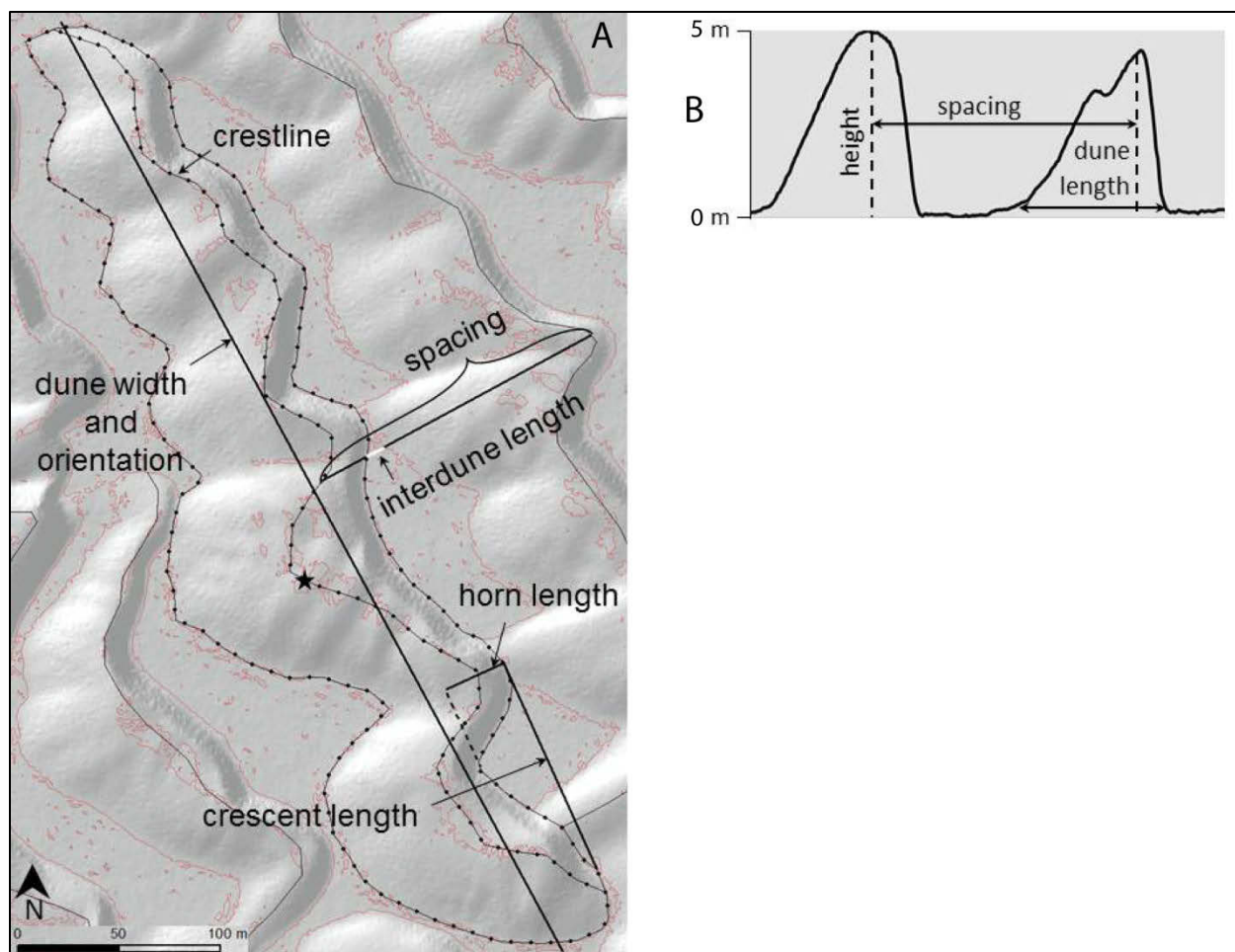


Figure 4. Definition diagram for (A) dunes selected at random, and (B) dunes sampled along transects. Dune polygon defined by slope $\geq 2.5^\circ$. In (A) dune height is the difference in elevation between the mean crestline elevation and the mean dune base elevation, each sampled at 10 m intervals. Maximum dune height noted by star. Dune crestlines taper to zero or truncate against adjacent or downwind dunes. Dune footprint area, total dune surface area, and volume determined from polygons. Sinuosity is crestline length divided by dune width. Dune length, spacing, and interdune length measured perpendicular to dune orientation. Crescent length measured from horn to horn; horn length is perpendicular to crescent length. In (B) dune length, spacing and interdune length as encountered along transects.

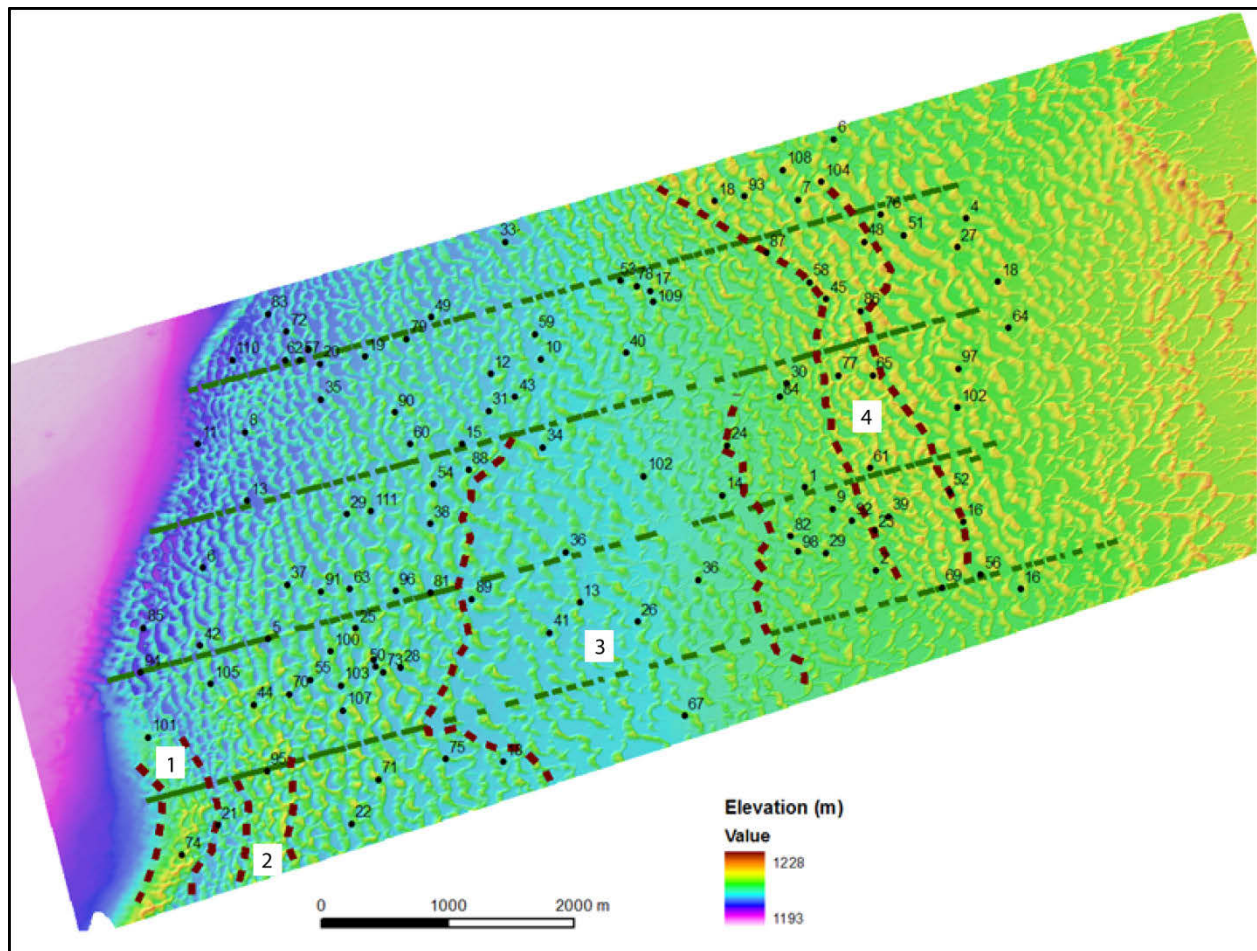


Figure 5. Sampling methods used in this study. In the first method dunes to be sampled were selected at random, as indicated by numbered black dots. In the second method dunes were sampled along four equally spaced transects oriented in the net transport direction, as indicated by green lines. In the third method dunes were sampled within four areas (Zones 1-4) where the dune pattern is visually distinct.

Determining the Controls on Spatial Variability

Given that there is spatial variability in the dune pattern (e.g., Zones 1-4 in Fig. 5) and that paleo-shorelines have been identified on Alkali Flat at elevations lower than the dune field (Langford, 2003), a reasonable hypothesis is that additional paleo-shorelines occur within dune field between paleo-shoreline L1 and the high-stand shoreline of Lake Otero at 1,215 m in elevation (Fig. 2). To test this hypothesis and to determine any spatial relationship between the paleo-shorelines and the dune-pattern variability, the base substrate over which the dunes are migrating was established. A Matlab algorithm was used to identify the local minima along profiles of the dune field oriented in the net transport direction and spaced at the 1-m resolution of the DEM. A filter was used to remove local short-wavelength variations to create a smooth base surface. The base surface was then subtracted from the original DEM using the raster calculator in ArcGIS Spatial Analyst, essentially removing the dunes from the surface. Changes in the slope of the base surface were used to identify paleo-shorelines, and profiles were sampled at 500-m intervals to statistically define the elevations of the paleo-shorelines.

Determining Topographic Change via LiDAR Monitoring

In order to determine the amount of topographic change that occurred between the June 2007 and June 2008 LiDAR surveys and to gauge the potential for LiDAR as a means of long-term monitoring the dune field, a difference map was constructed by subtracting the 2007 DEM from the 2008 DEM in ArcGIS. The difference map can be used to determine dynamic parameters such as dune migration rates, changes in dune morphology, and spatial variations in dune activity over the dune field. In turn, these parameters can be compared to external controls such as the sand-transport winds that occurred over this period.

Results

Dune Pattern Parameters and Their Spatial Variations

Measurements of dune parameters from the population of dunes selected at random are given in Table 1, measurements from the field-scale and Zones 1-4 transects are given in Table 2A-B, and results of cross-plots are given in Table 3A-B. These dune-field statistics serve to: (1) characterize the dune field overall, (2) illustrate that differences are minor between the sampling method, (3) quantify spatial pattern heterogeneity, (4) rank parameters according to their viability in depicting the dune pattern, and (5) highlight the high degree of variability within single parameters and the low degree of correlation between parameters at the dune-field scale.

Basic characterization of the dune field from the population of randomly selected dunes is straightforward (Table 2A). Dunes range in height from 2 to 9 m, with an average height of 4.7 m. Maximum height ranges from 3 to 13 m with a mean of 7.5 m. Including interdune areas, dune spacing averages 134 m with a range of 51 to 302 m; excluding interdune areas, dune spacing averages 97 m with a range of 30 to 188 m. Dune crestline length averages 559 m with a range of 81 to 1,556 m; whereas dune width averages 449 m with a range of 80 to 1,282 m. Dunes average 87 m in length with a range of 25 to 164 m. Crescent length average 93 m with a range of 28 to 238 m. Dune horn length averages 26 m with a range of 2 to 91 m. Crestline sinuosity averages 1.5 with a range of 1.2 to 2.7. Dune footprint area averages 23,755 m², total dune surface area averages 24,344 m², and average dune volume is 87,556 m³. Dunes are oriented at 338° with a range of 33 to 286°.

Only relatively minor differences occur between parameter measurements for populations of randomly selected dunes and dunes sampled along transects. Average dune height encountered along the transects is 4.5 m. Dune spacing measured without interdune areas is 92 m, 121 m with interdune areas included. Dunes average 86 m in length.

Dunes in Zones 1-4 are differentiated from the field-scale population. Dunes in Zone 1 are smaller in height (3.5 m) and length (75 m), and more closely spaced. Comparable spacing with interdune areas included (76 m) and without interdune areas (71 m) shows the near absence of interdune areas within this zone. Dunes in Zone 2 are higher (6.4 m) and have greater length (98 m) than the field average, but as in Zone 1, interdune areas are minor with an average spacing of 106 m with interdune areas included and 102 m with interdune areas excluded. In contrast to Zones 1 and 2, interdune areas are broad in Zone 3 with average spacing of 147 m (above the field average) with interdune areas included, and only 87 m (below the field average) excluding interdune areas. Dunes are also lower (4.0 m) in this zone than the field average. Dunes in Zone 4 are comparable to the field-scale population except that they are greater in length (99 m).

Table 1. Measurements of dune parameters, as defined in Fig. 4A, taken from 110 dunes selected at random and shown in Fig. 5.

Random Dune Population	Range	Mean	Median	Standard Deviation	Coefficient of Variation
Average dune height (m)	2.1 - 9.3	4.7	4.6	1.3	0.28
Maximum dune height (m)	3.1 - 13.1	7.5	7.4	2.0	0.26
Spacing with interdune areas (m)	50.9 - 302.1	134.1	128.3	46.2	0.34
Spacing without interdune areas (m)	29.8 - 187.5	96.6	93.7	30.6	0.32
Crestline length (m)	80.7 - 1555.6	559.0	467.1	335.1	0.60
Dune width (m)	80.0 - 1282.2	448.6	372.6	250.0	0.56
Dune length (m)	24.6 - 164.3	86.7	86.9	23.7	0.27
Crescent length (m)	28.0 – 238.0	93.0	85.0	37.6	0.40
Average horn length (m)	1.5 – 91.0	26.0	25.0	16.6	0.65
Sinuosity	1.2 - 2.7	1.53	1.43	0.41	0.15
Dune footprint area (m ²)	2640 - 107764	36140	28746	24601	0.68
Dune total surface area (m ²)	2713 - 110136	37027	29453	25231	0.68
Orientation (°)	32.6 - 285.7	337.5	340.3	21.9	0.14
Dune volume (m ³)	4900 - 473434	123348	90987	98874	0.80

Table 2A. Measurements of dune parameters, as defined in Fig. 4B, taken from 231 dunes encountered along four transects shown in Fig. 5.

A. Transect Dune Population	Range	Mean	Median	Standard Deviation	Coefficient of Variation
dune height (m)	0.5 - 13.1	4.5	4.2	2.0	0.44
spacing with interdune areas (m)	16.8 - 359.6	121.2	122.5	54.6	0.41
spacing without interdune areas (m)	16.8 - 212.3	91.9	87.5	30.7	0.33
dune length (m)	22.1 - 154.8	86.3	83.2	25.3	0.29

Table 2B. Measurements of dune parameters, as defined in Fig. 4B, taken from dunes encountered along transects in Zones 1-4, as outlined in Fig. 5.

B. Zone Transect Dune Population	Range	Mean	Median	Standard Deviation	Coefficient of Variation
Zone1 (n = 45)					
Dune height (m)	1.1 – 6.5	3.5	3.5	1.5	0.26
Spacing with interdune areas (m)	38.6-115.8	76.0	76.0	19.0	0.26
Spacing without interdune areas (m)	38.6-115.8	71.0	67.6	19.4	0.27
Dune length (m)	28.1-130.8	75.4	69.7	24.3	0.32

Table 2B. (Continued)

Zone 2 (n = 41)					
Dune height (m)	1.8-11.2	6.4	6.6	2.4	0.36
Spacing with interdune areas (m)	37.4-161.0	106.0	106.0	29.0	0.27
Spacing without interdune areas (m)	37.4-161.0	102.2	104.9	26.3	0.26
Dune length (m)	47.8-167.5	97.8	96.3	26.7	0.27
Zone 3 (n = 44)					
Dune height (m)	0.5-9.5	4.0	3.8	1.9	0.47
Spacing with interdune areas (m)	43.6-359.6	156.0	147.0	68.0	0.44
Spacing without interdune areas (m)	41.3-184.9	86.9	87.2	23.7	0.27
Dune length (m)	40.7-133.8	90.5	88.4	24.9	0.27
Zone 4 (n = 42)					
Dune height	1.2-8.6	4.9	5.2	1.9	0.39
Spacing with interdune areas (m)	53.0-204.1	124.0	121.0	41.0	0.33
Spacing without interdune areas (m)	38.6-184.9	95.0	98.9	26.8	0.28
Dune length (m)	45.0-146.1	99.3	99.4	21.8	0.22

A ranking of parameters by their degree of variability within the field indicates which parameters are most consistent and, therefore, most useful in dune-field characterization. For the dunes selected at random (Table 1), coefficients of variation are the highest (0.56-0.76) for complex parameters such as dune volume, dune footprint area, and total dune surface area. High variation (0.56-0.65), however, also occurs for less complex parameters such as crestline length, horn length, and dune width. More consistent parameters (0.26-0.34) are maximum and average dune height, spacing without or with interdune areas included, and dune length. Lowest variation occurs with dune sinuosity (0.15) and orientation (0.14). These values are consistent with Ewing et al. (2006) who used a digital aerial photo of the White Sands Dune Field to measure crest length ($n = 2151$, $\bar{x} = 247$ m, c.v. = 1.03), dune spacing ($n = 217$, $\bar{x} = 136$ m, c.v. = 0.36), and crestline orientation (345° , c.v. = 0.16). Differences in crest length between Ewing et al. (2006) and this study we attribute to the greater resolution of dunes in the LiDAR images. Somewhat greater coefficients of variation occur for all parameters sampled along transects (Table 2A). Parameter variability in Zones 1-4 departs from the field-scale trends in Zone 3 where greater variability occurs with dune height (0.47) and spacing with interdune areas included (0.44).

Apart from dune orientation and crestline sinuosity, there is significant variability in the pattern parameters at White Sands. Although dune fields are commonly cited as examples of patterns in nature, there has been little discussion as to why dune patterns emerge to the human eye. For White Sands, patterns emerge because the dunes show a consistent orientation (c.v. = 0.14). Significantly more variability occurs with most other parameters measured. Crestline orientation, therefore, emerges as the single most important parameter in defining what appears as a pattern visually.

In addition to the relatively high degree of variation in most dune parameters, the goodness-to-fit (r^2) for linear regressions of parameters is striking. Although there is a strong relationship

between dune volume to crest length and total dune surface area, remarkably little correlation exists for other cross plots, even for long-accepted relationships such as dune spacing to dune height. We deduce from these low values of correlation that the statistical variability about the mean value of most dune parameters precludes the existence of well defined trends within the dune field. At face value this conclusion runs counter to other studies where correlations have been reported for a variety of measured parameters. Foremost is the correlation between dune height and spacing within single dune fields for a variety of dune types (e.g., Wasson and Hyde, 1983; Lancaster, 1988, 1989). Indeed, the simultaneous plotting of linear regressions of height and spacing for numerous dune fields still shows a reasonable trend (Lancaster, 1988). Linear regressions of the mean values of dune width and spacing (Breed and Grow, 1979), and crestline length and spacing (Ewing et al., 2006) show correlations where numerous dune fields are considered. Various length scales of individual barchan dunes show correlations (Sauermann et al., 2000).

Table 3A. Linear regressions of parameters for dunes selected at random and field-scale transects and transects within Zones 1-4. Dune height for randomly selected dunes is the average height, whereas it is the height encountered along the transects for field-scale and zonal transects.

A. Cross Plots	Random		Transect		Zone 1		Zone 2		Zone 3		Zone 4	
	Mean	R ²	Mean	R ²	Mean	R ²	Mean	R ²	Mean	R ²	Mean	R ²
Spacing with interdune areas/height	30.5	0.005	32.6	0.092	26.4	0.026	18.6	0.266	50.7	0.186	28.2	0.308
Spacing without interdune areas/height	21.8	0.042	21.7	0.132	25.2	0.001	18.0	0.236	28.4	0.029	22.7	0.225
Dune length/height	19.3	0.135	17.9	0.256	26.6	0.031	16.2	0.181	25.2	0.146	18.3	0.122

Table 3B. Linear regressions of additional parameters for dunes selected at random.

B. Cross Plots	Mean	R ²		Mean	R ²
Crest length/average height	121.6	0.083	Dune width/maximum height	59.2	0.199
Spacing with interdune areas/maximum height	19.0	0.002	Dune volume/ average height	24581	0.391
Spacing without interdune areas/maximum height	13.6	0.027	Dune volume/crest length	203.9	0.767
Crest length/maximum height	74.0	0.149	Dune volume/ surface area	3.1	0.909
Dune length/maximum height	12.0	0.112	Dune footprint area/dune width	75.4	0.498
Dune width/average height	96.7	0.133	Dune surface area/dune width	77.3	0.956

The high degree of variability at White Sands is significant and understandable in three ways. First, the variability is real in that the pattern at White Sands does appear less well ordered than in some other dune fields. The dune field is relatively young and pattern development is thought to improve with development time (Ewing et al., 2006). Reported stronger correlations all occur

in dune field of considerable greater antiquity than White Sands (e.g., Namibia, Lancaster, 1989; Gran Desierto, Lancaster, 1988; Australian dune fields, Wasson and Hyde, 1983). Because of the young age of the field, dune-dune interactions are very common and these impart a high degree of pattern dynamics (Ewing and Kocurek, 2010a). In addition, White Sands has numerous boundary conditions, foremost of which appears to be antecedent topography from paleo-shorelines (addressed below), which cause spatial heterogeneity in the dune pattern (Ewing and Kocurek, 2010b). Second, although the variability at White Sands is real, when compared to markedly different dune fields, this variability will shrink to a single, diffuse datum point. For example, although average dune height and spacing have significant variability around means of 4.7 m and 134 m, respectively, these are distinctly different from dune heights of > 100 m and spacing of 2,000 to 2,500 m measured for linear dunes in Namibia (Lancaster, 1989). The White Sands mean spacing/height ratio of 30 is within the data range given in Lancaster (1988). Third, as approached by Lancaster (1988, 1989) for dune spacing and height, there is significant variability in all dune patterns, but this tends to be lost in emphasizing trends, especially where mean values are only reported and sample size is small. LiDAR provides a means of measuring a much more diverse range of dune-field parameters, and obtaining a much larger and accurate population size for all measured parameters than has traditionally been done. Greater variability emerges with larger populations and greater measurement precision. We strongly suspect that all dune fields will show significantly more variability than is currently assumed once they are subject to LiDAR surveys.

Paleo-Shorelines and Their Control on Dune-Field Pattern

The base surface over which the dunes are migrating is not a smooth slope, but rather it is broadly terraced (Fig. 6). Terracing within a lake basin typically develops as a result of shoreline development during lake stands, with the rollover points in slope approximating beach berms or high points along the paleo-shorelines. These White Sands examples, therefore, are interpreted to represent stands of Lake Otero formed during the episodic drawdown of the lake. This interpretation is in agreement with conclusions reached by Langford (2003), but goes farther in identifying shorelines that previously lay disguised beneath the dune field.

In order to refine the elevations of the broad rollover points evident in Figure 6, profiles were sampled at 500-m intervals (Fig. 7). For each profile, lines were fitted to the local slopes; the lines intersect at points of maximum convexity or slope rollover (Fig. 8). Plotting of frequency and cumulative frequency for elevation of rollover points clearly resolves into three modes, which are at 1,203, 1,205.5, and 1,211 m in elevation when rounded to the nearest 0.5 m (Fig. 9). Combining these newly recognized paleo-shorelines with those previously identified by Langford (2003), yields paleo-shorelines at 1,215 m (Lake Otero high-stand), 1,211 m, 1,205.5 m, 1,203 m, 1,200 m (L1 of Langford (2003) is 1,198 m here), 1,191 m (L2 of Langford, 2003), and the current shoreline on Lake Lucero is at an elevation of 1,185 m.

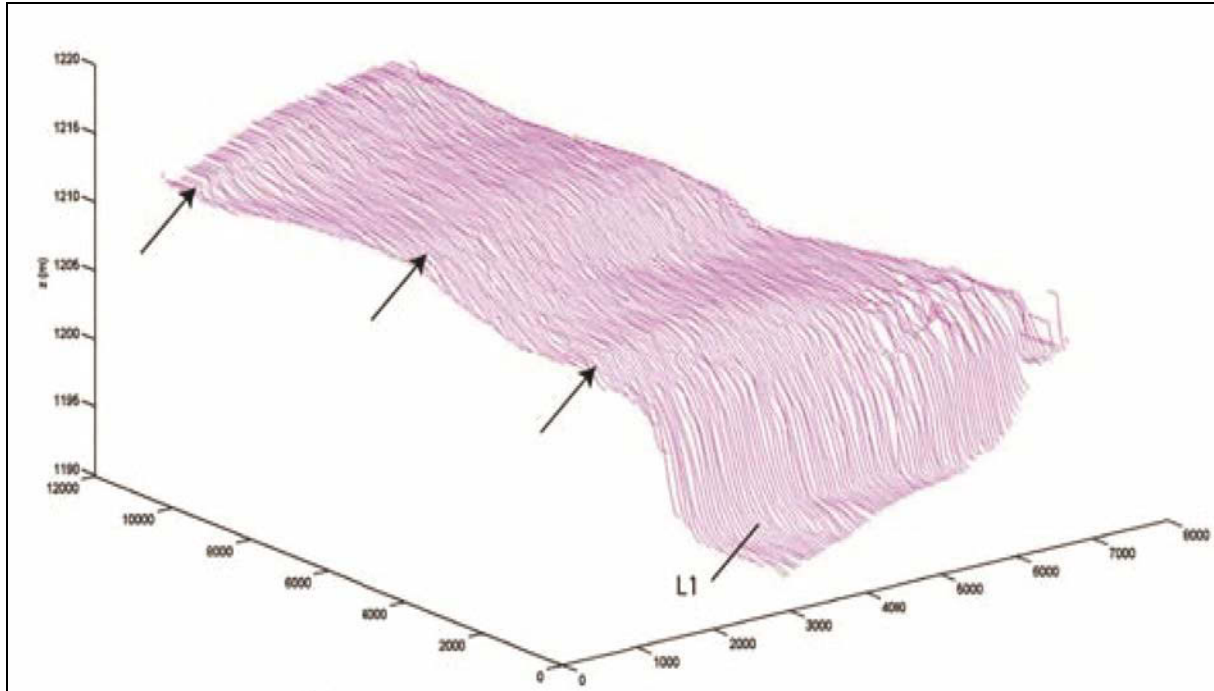


Figure 6. Terraced base surface over which the dune are migrating. Arrows indicate broad zones of slope rollover, which are interpreted to represent paleo-shorelines developed during successively lower stands of Lake Otero. The LiDAR survey captures a small segment of paleo-shoreline L1 identified by Langford (2003). Note that the vertical exaggeration is about 200X; the changes in slope are in reality very subtle features ($< 1^\circ$), similar to previously identified paleo-shorelines L1 and L2 shown in Fig. 2.

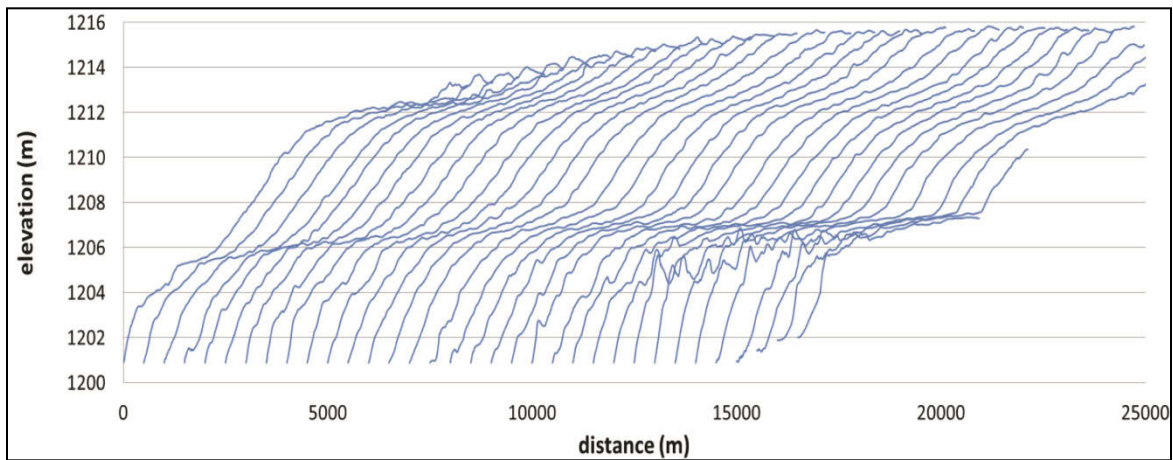


Figure 7. Stacking of 34 sampled profiles, arranged from north to south show the spatial change in the profiles. These profiles were used to define the point of slope rollover (Fig. 8). VE = 500X.

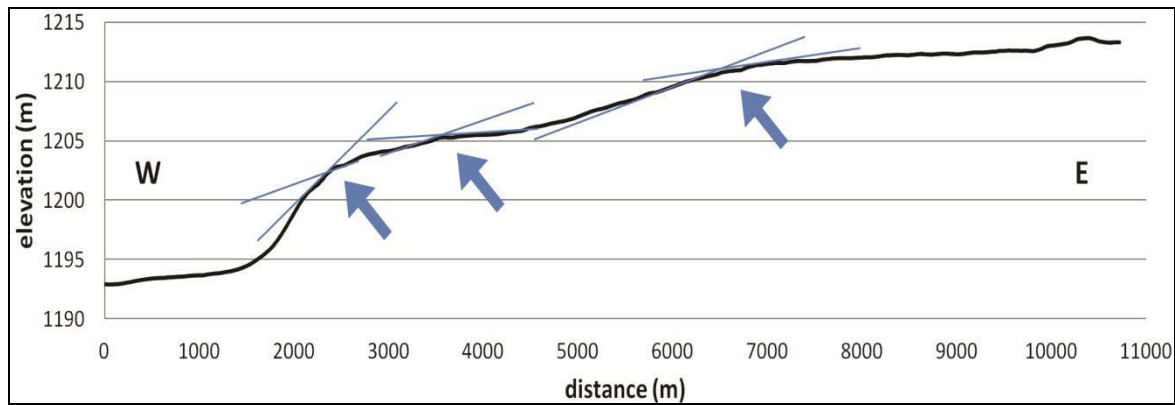


Figure 8. Sample profile in which the point of intersection of lines fitted parallel to the local slopes defines the point of slope rollover. VE = 100X.

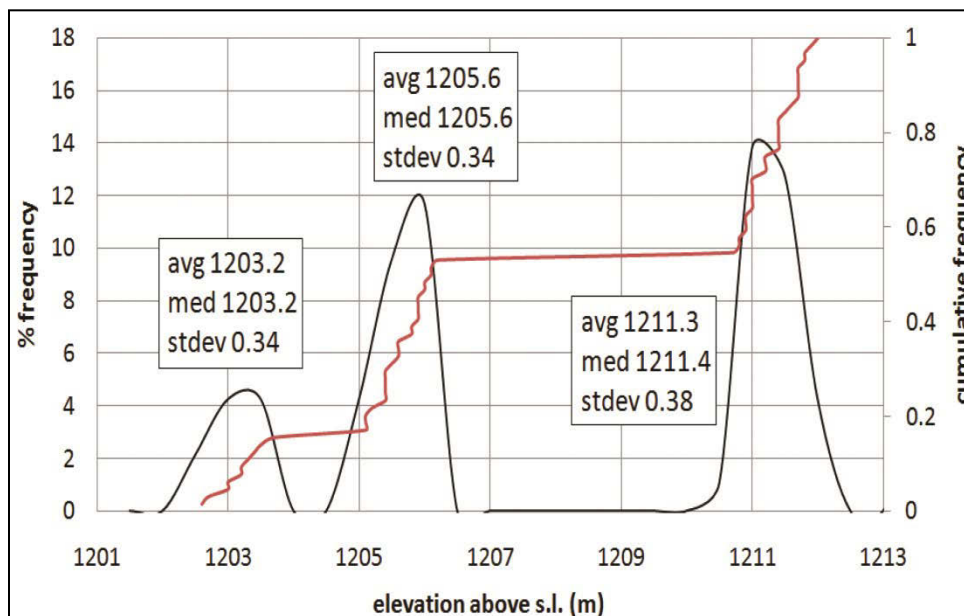


Figure 9. Frequency and cumulative frequency plots of rollover points by elevation show three distinct modes.

Although we follow Langford (2003) in interpreting the subtle terraced topography as representing stands in the episodic retreat of Lake Otero, the complete interpretation of these features is not straightforward. The gypsum dune field was sourced by deflation of lake accumulations with successive, lowered lake stands, each of which exposed new substrate to deflation. In turn, judging by cores taken through the dune field, an accumulation of gypsum sand of about 8.5 m in thickness occurs in the center of the field and tapers to zero into the basin where Lake Otero strata are exposed (see Langford, 2003; Kocurek et al., 2007). The amount of deflation that has occurred along each paleo-shoreline is unknown, as is the thickness of dune sand at these points. Judging by the definition of rollover points in the various profiles sampled, these features clearly are modified or even lost over time, but, as evident in Figure 6, their

overall topographic expression has remained robust. Although upward translation of topography is fairly common in the stratigraphic record, additional work is required to understand the evolution of basin topography at White Sands (e.g., Langford et al., 2009).

Regardless of the evolution of the basin topography or the probable changes in climate that fostered the episodic lake drawdown, the paleo-shoreline appears to continue to exert a significant, if not primary, control on the dune-field pattern. Figure 10 shows the placement of the paleo-shorelines by elevation across the LiDAR area. Zones 1-4, in which we identified changes in the dune pattern, appear to correlate with the paleo-shorelines. Zones 1, 2, and 4 occur lee of paleo-shorelines at 1,203, 1,205.5, and 1,211 m in elevation, respectively. As described above (Table 2B), dunes in this zone are distinct when compared to the rest of the field. In addition, as evident from Figure 10, Zones 1 and 2 occur on distinct sand build-ups, well above the base surface. These zones represent larger, drier build-ups of dune sand. This trend is less evident in Zone 4, which occurs lee of what is probably a significantly older paleo-shoreline. In contrast, Zone 3 occurs within the broad expanse between the 1,205.5 and 1,211 m paleo-shorelines. Zone 3 is characterized by somewhat smaller dunes with markedly larger, wetter interdune areas that coincide with the base surface. Although only limited LiDAR data are available, it should be noted that the sand build-up within the transition zone from crescentic to parabolic dunes largely coincides with the 1,215-m paleo-shoreline. In all cases, the zones are discontinuous—the control by the paleo-shorelines on dune morphology is not everywhere well defined, similar to the spatial variability in the manifestation of the paleo-shorelines themselves. Zone 1 in particular shows an eastward retreat owing to its occurrence at the upwind deflationary edge of the dune field.

In our interpretation, the paleo-shorelines form a boundary condition on the dune-field pattern in which an antecedent topographic feature exerts a control on dune-pattern development (c.f., Ewing and Kocurek, 2010b). The dynamics by which this occurs cannot be demonstrated with the available data. In terms of speculation, however, placement of the dune build-ups lee of the paleo-shorelines is analogous to foredune ridges that would be expected to form lee of beach berms; the placement of Zone 3 is reminiscent of a low-relief lagoonal area, bypassed by successive beach berms. It is not unreasonable to speculate that this paleo-topography has been translated upward through the accumulation of the dune field, similar to the upward translation of the paleo-shorelines themselves. In this hypothesis, the current dune field carries a topographic signature imprinted by the stages of drawdown of Lake Otero.

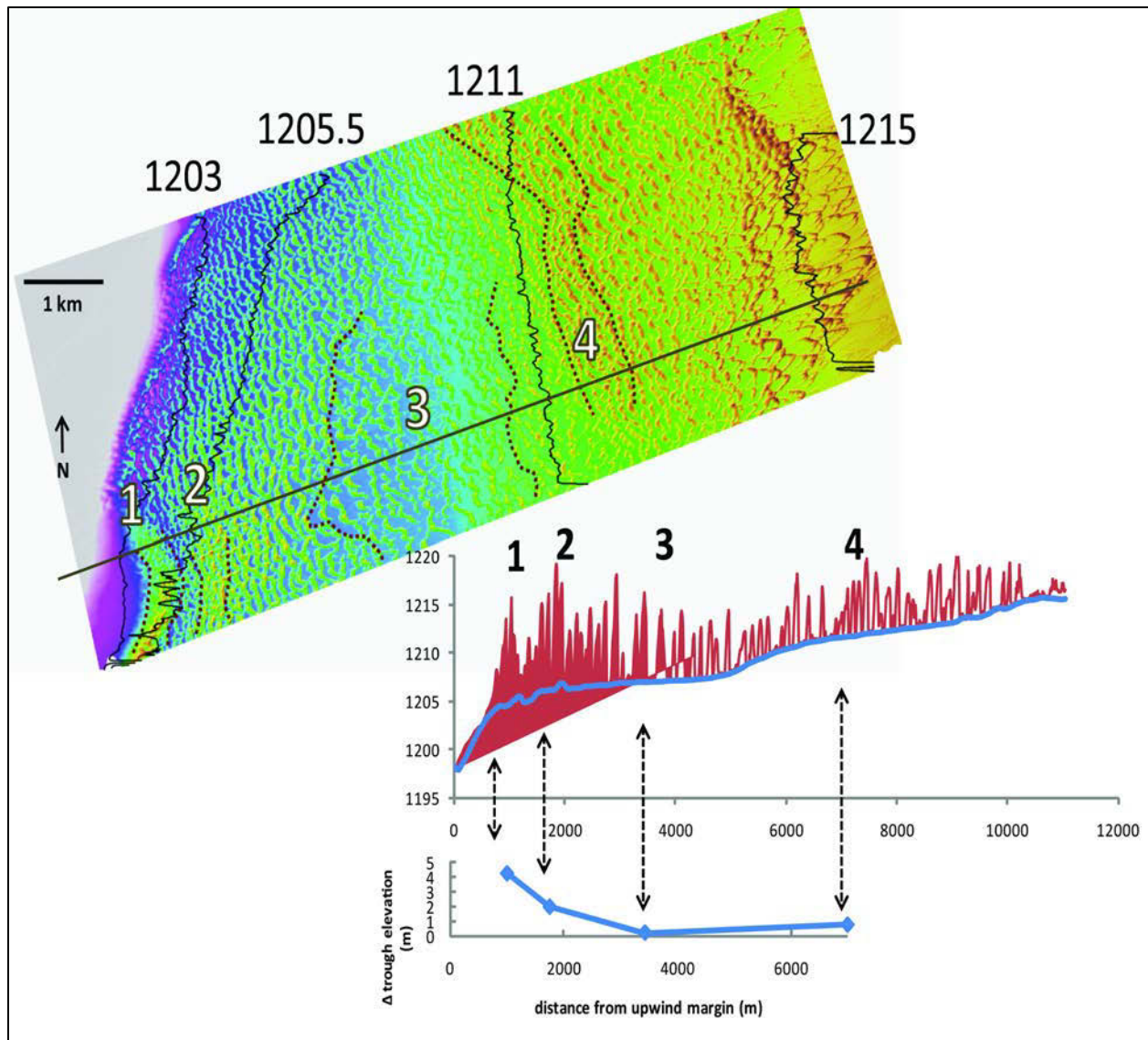


Figure 10. Location of paleo-shorelines and Zones 1-4. Profile shows that Zones 1, 2, and 4 are sand build-ups lee of the paleo-shorelines, whereas Zone 3 is a low, wet area between paleo-shorelines. Note that the sand build-up within the crescentic-to-parabolic dune transition zone also coincides with a paleo-shoreline.

Spatial Differences in Dune Mobility

The topographic change that occurred in the dune field from June 2007 to June 2008 is readily shown by the difference map for this time interval (Fig. 11), with enlargements of specific areas of the dune field in Figures 12-16. Changes in elevation are scaled from dark blue (highest erosion) to dark red (highest deposition) and are a direct reflection of dune mobility. For example, the pervasive pattern of the field is for stoss slope erosion (blue) to lee deposition (red) as the dunes migrate. The difference map can be used to determine dune activity spatially and to gauge its impact upon park infrastructure, and, conversely, park activities upon the dune field.

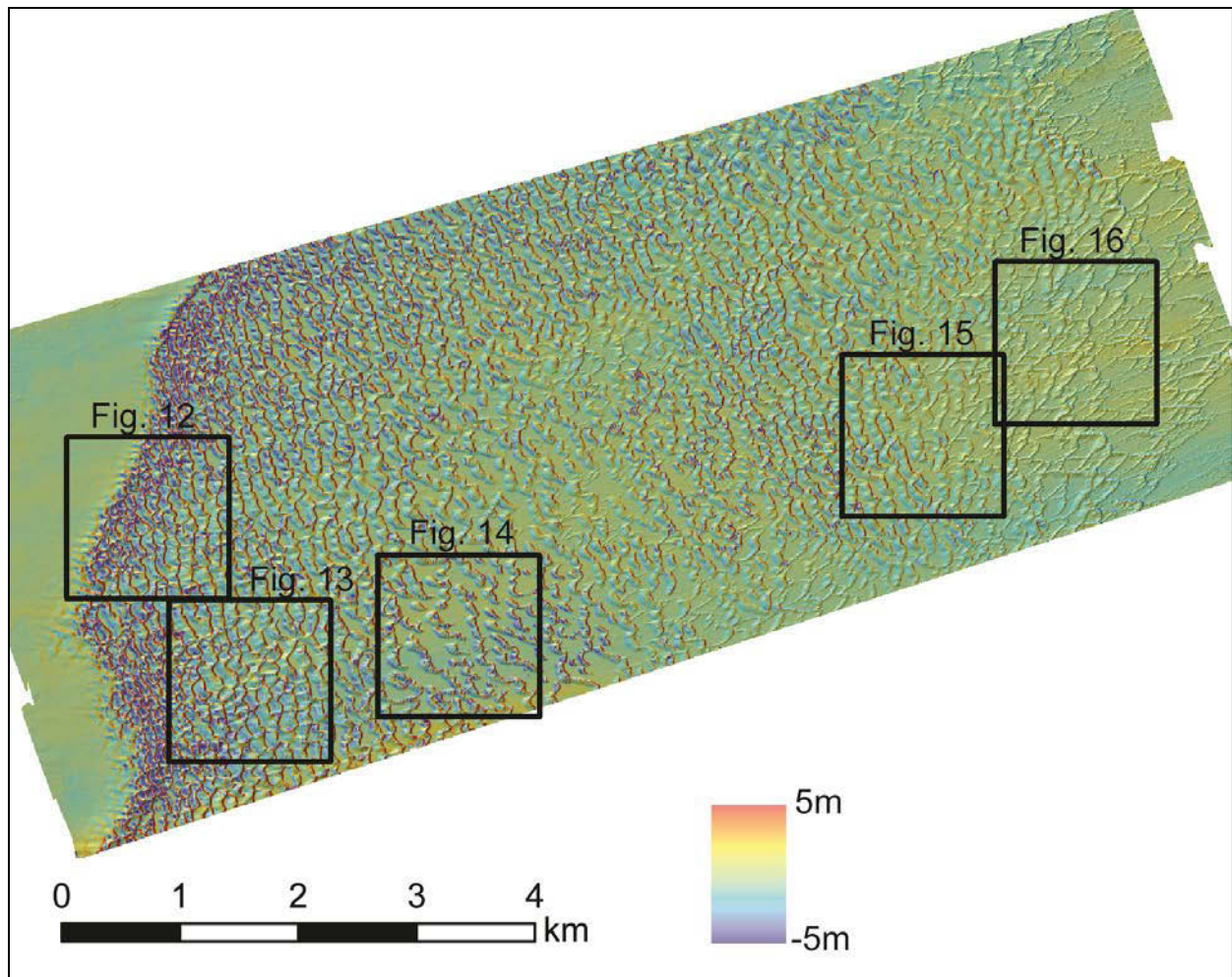


Figure 11. Difference map created by subtraction of June 2007 LiDAR DEM from the June 2008 DEM. Changes in topography scale from erosion (blue) to deposition (red). Note locations of enlargements in Figures 12-16.

Figure 12 highlights the short distance over which the dunes develop at the upwind edge of the dune field. Initial dunes are low diffuse features, but vertical growth is indicated over broad portions of the crestal areas (arrow 1). These initial dunes are replaced within one or two spacing distances by larger, closely spaced dunes with fairly uniform stoss erosion, restricted crestal growth, and lee deposition beyond a well defined brink (arrow 2). These dunes are replaced within a few more dune spacings by yet larger, more continuous dunes with low-relief superimposed stoss bedforms that characterize most of the field (arrow 3). Overall, the first 0.5 km of the dune field represents a “big bang” zone in which dunes form and evolve over short migration distances to assume a size and morphology typical of the whole dune field.

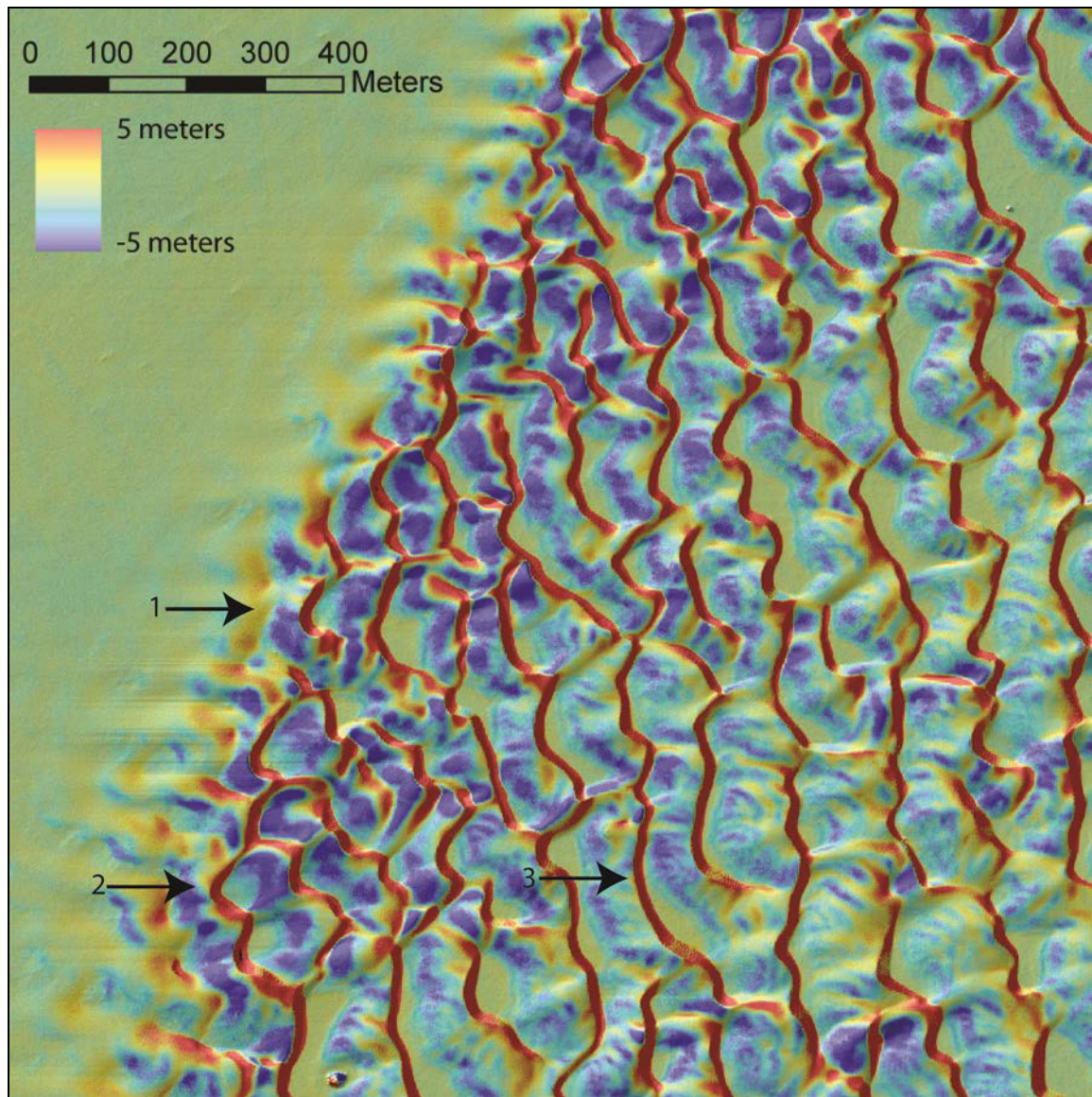


Figure 12. Difference map of the upwind portion of the dune field, showing vertical growth of initial diffuse dunes (arrow 1), their replacement by well-defined dunes with broadly uniform stoss erosion, restricted crestal growth and distinct lee deposition (arrow 2), and larger, more continuous dunes with superimposed lee bedforms (arrow 3).

Figure 13 shows the higher, drier area lee of paleo-shoreline at 1,205.5 m where dunes are larger and interdune areas are minor or restricted to hollows between dunes. The striped appearance of the stoss slopes results from superimposed bedforms. Note that the crestal areas of many dunes in this area are depositional—this is a zone of dune growth. In addition, the streamwise lineations (some indicated by arrows) that characterize this portion of the field are clearly migrating features with erosion of north slopes and deposition on south slopes. These features are interpreted as extensions of dune terminations that largely migrate to the south under winter winds from the north, and that can persist in this portion of the field because the dunes are interconnected lee-to-stoss owing to limited interdune areas.

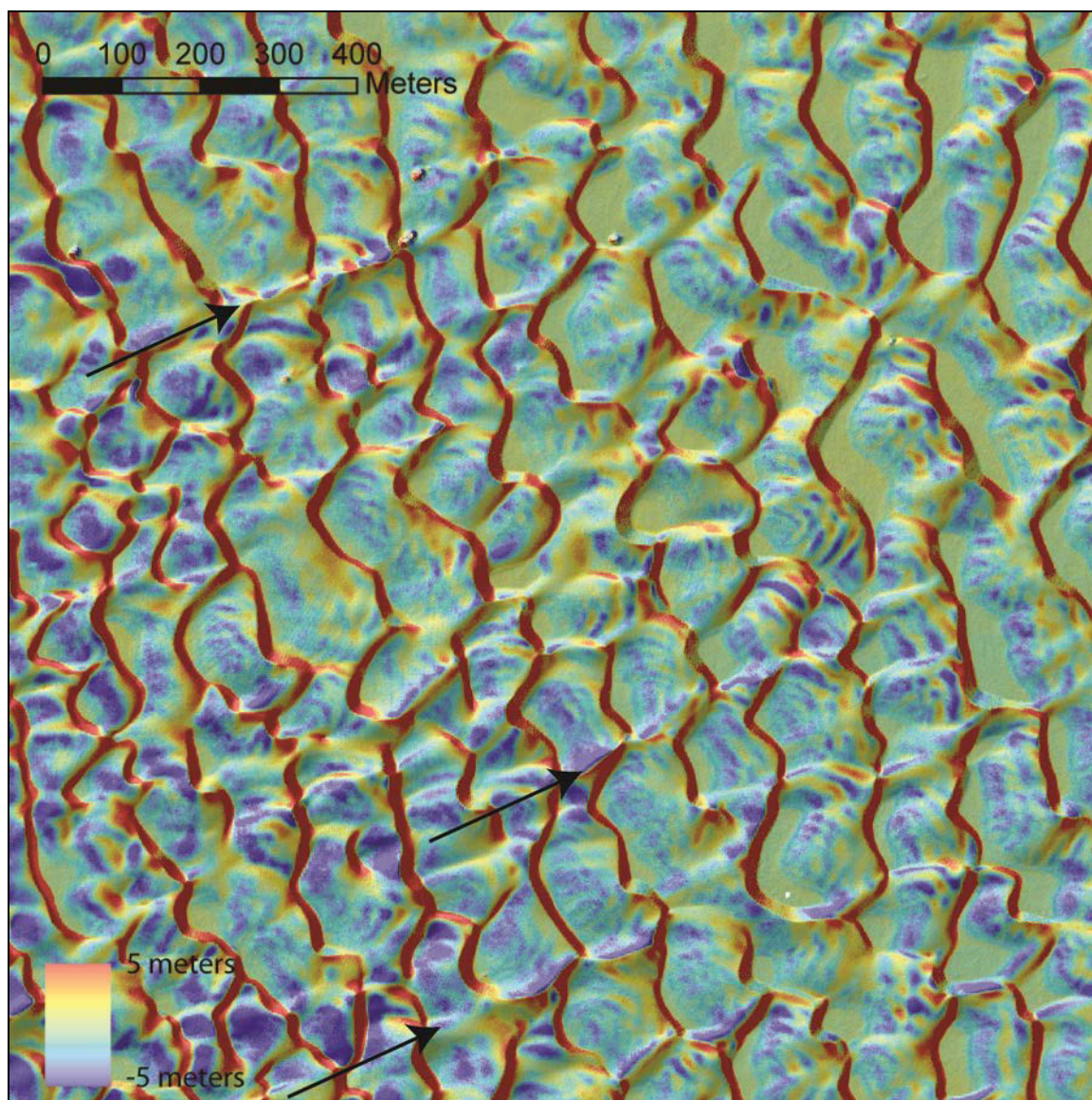


Figure 13. Closely spaced dunes with minimal interdune areas located on the sand build-up lee of paleo-shoreline 1,205.5. Note well defined stoss bedforms, common crestal growth, and streamwise lineations (arrows) that show migration to the south.

In contrast to Figure 13, Figure 14 shows dunes in Zone 3 where interdune areas are broad and the water table is just below the surface. Stoss-slope bedforms are especially well defined and show an alongslope migration to the south, evident by erosion on north slopes and deposition on south slopes. Indeed, stoss bedforms dominate the stoss slopes of the main dunes to their brinks. The main bedforms are not growing in size, again in contrast to those in Figure 13, and some show crest-parallel zones of erosion. Portions of the park road network and picnic shelters are plainly visible.

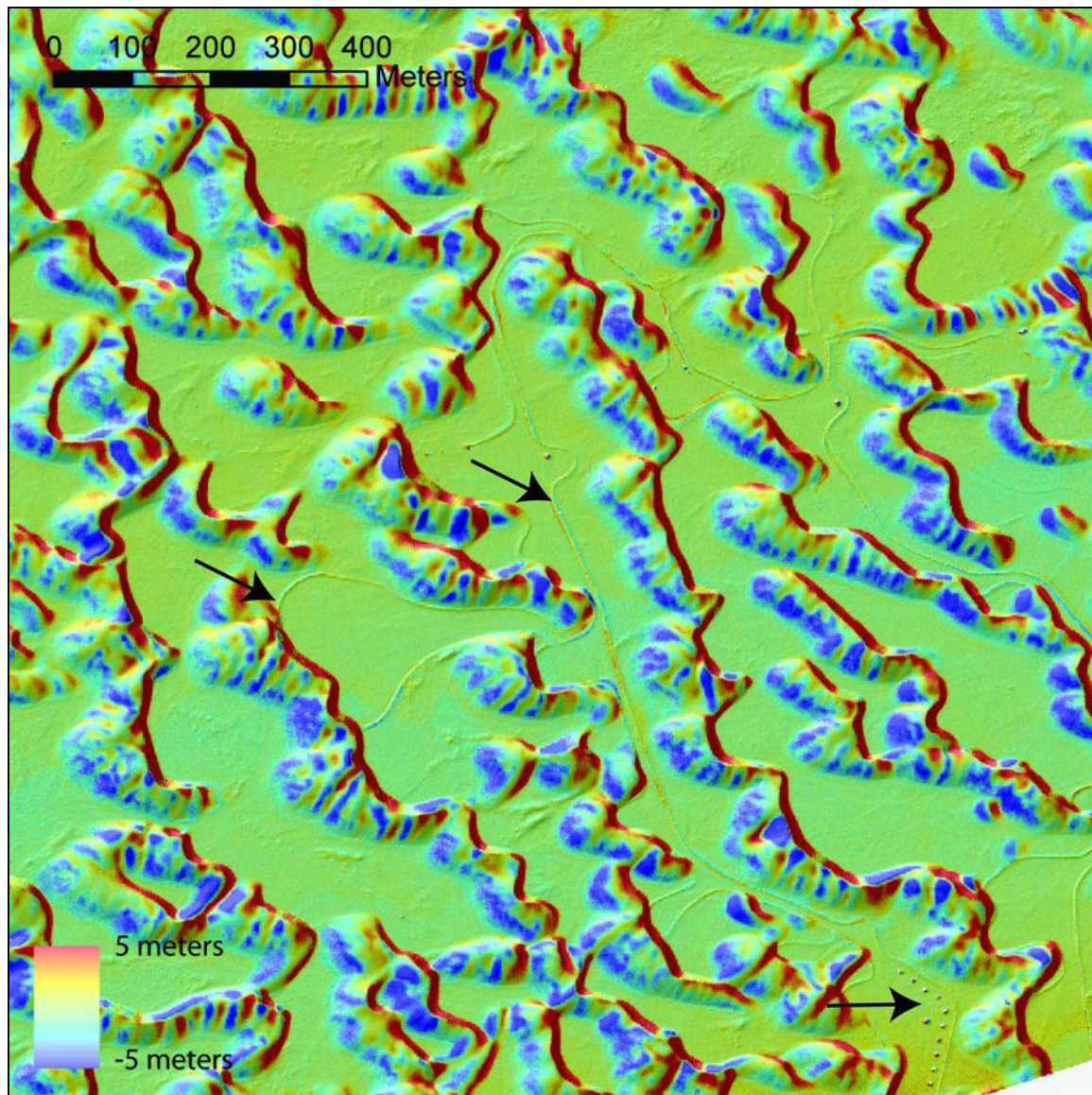


Figure 14. Widely spaced dunes and broad interdune areas of Zone 3. Note well defined stoss bedforms with alongslope migration to the south. Picnic structures and road-scraped gypsum ridges are evident (arrows).

Figure 15 shows the transition from crescentic to parabolic dunes, and Figure 16 is well within the parabolic-dune area. Crescentic dunes in Figure 15 show less activity than crescentic dunes elsewhere in the field, and there is an additional marked decrease in dune activity into the zone of parabolic dunes. Superimposed stoss bedforms are also lost in the transition zone.

Deposition/erosion is spotty on the parabolic dunes, confined to dune arms and nose. For this time interval, erosion characterizes the north arms and dune nose; sporadic deposition occurs largely on the south arms. This asymmetry of dune activity suggests that the parabolic dunes have a component of lateral migration, probably in response to the north winds that cause the alongslope migration of the bedforms superimposed on the stoss slopes of the crescentic dunes. This tendency may account for observations of south arms of dunes that have migrated onto the trailing north arms of adjacent dunes (arrows in Fig. 16).

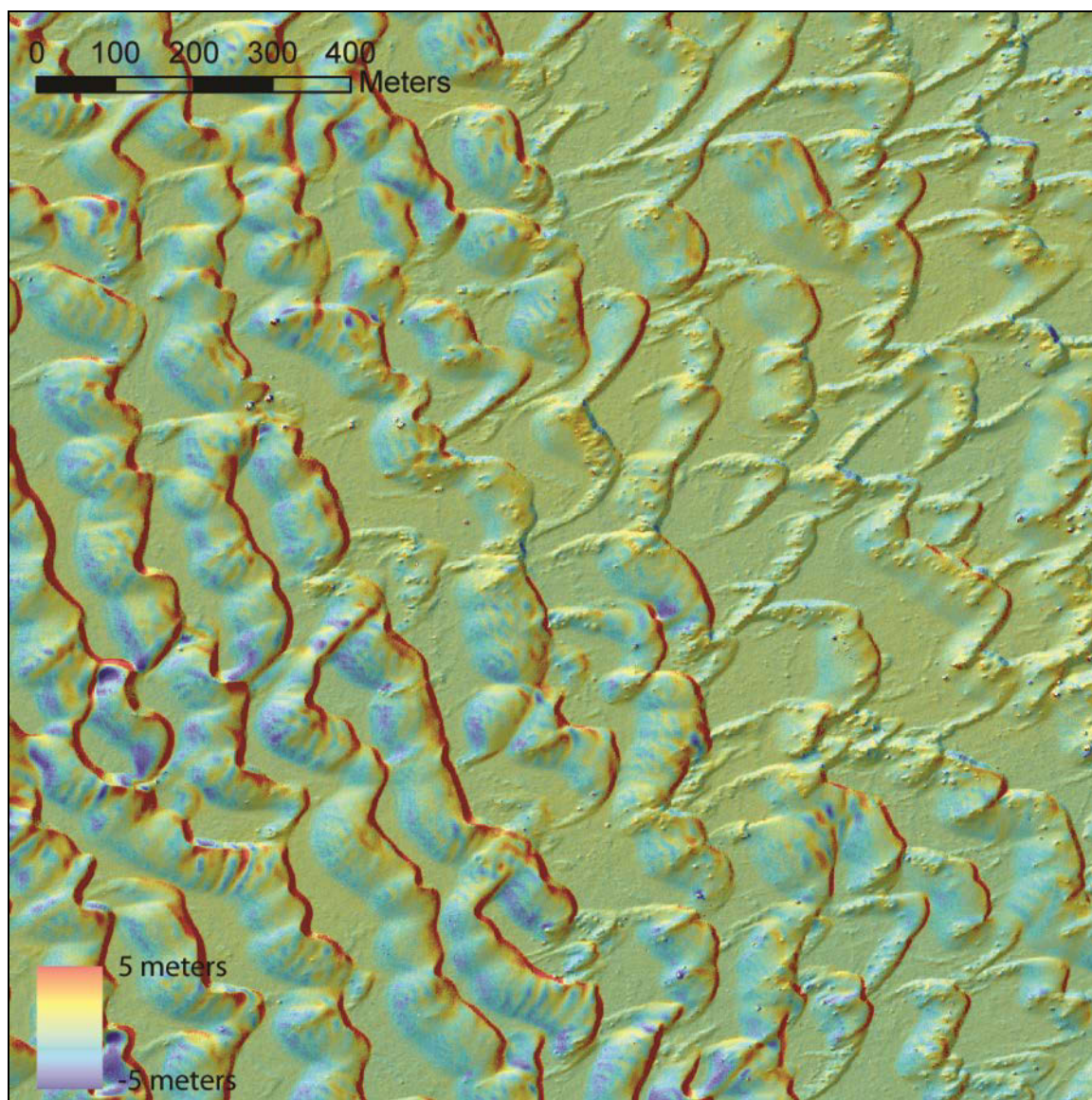


Figure 15. Transition from crescentic dunes to parabolic dunes. Note the decrease in dune activity across this transition and loss of superimposed stoss bedforms.

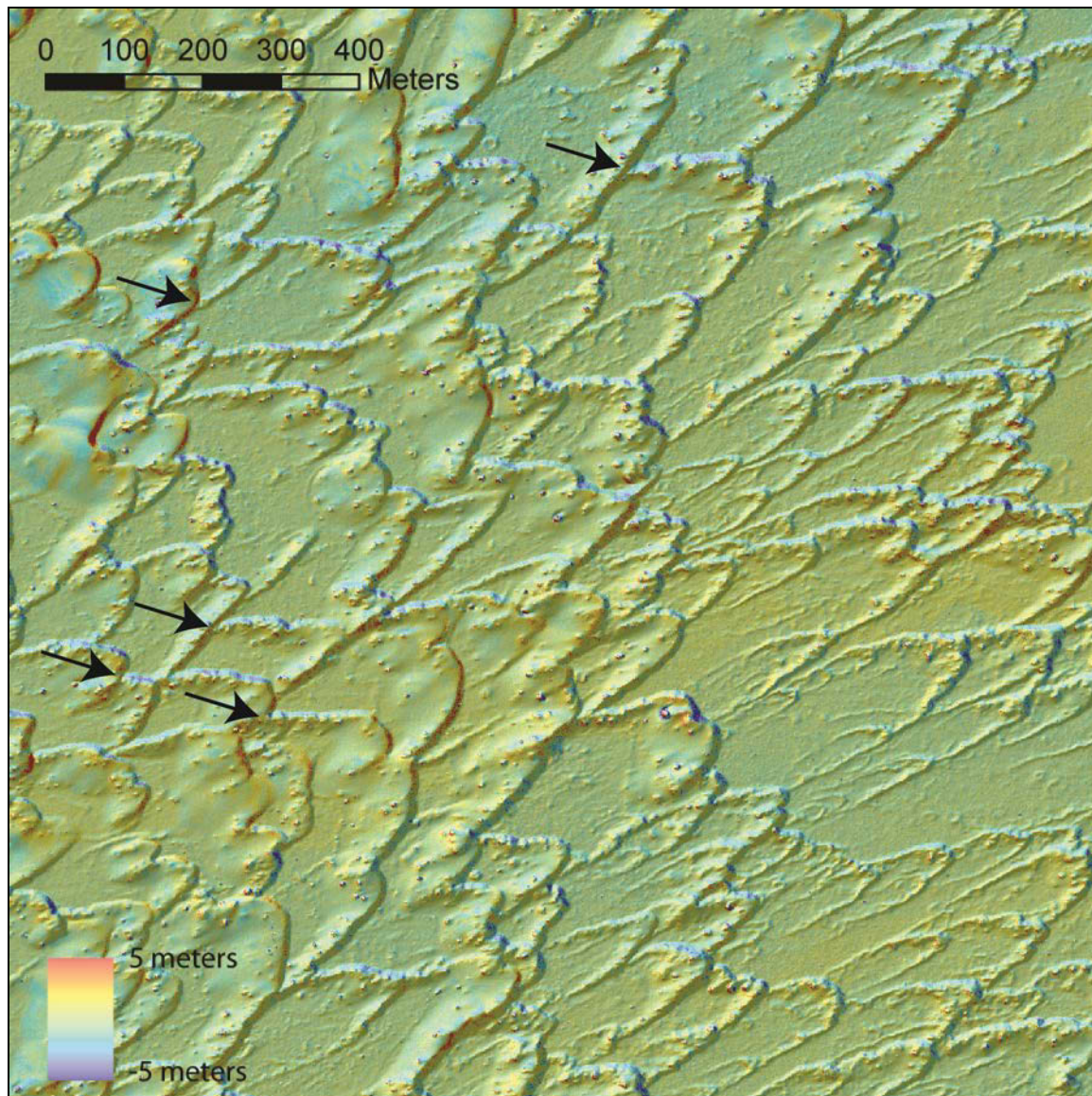


Figure 16. Parabolic dunes at eastern portion of the dune field. Note the general lack of dune activity in comparison to the remainder of the field, and spotty erosion of north dune arms and nose, and deposition on south arms. Arrows indicate a few of many areas where the south dune arm is migrating over the north arm of an adjacent dune.

Figures 12-16 demonstrate that dune activity at White Sands is not uniform, but rather spatially varied and that this needs to be considered in management of the park and its infrastructure. In related work, using this LiDAR data and a series of aerial photos (1985, 1996, 2003, 2005), Ewing and Kocurek (2010b) demonstrated that average annual dune migration rate fell from 6 m/yr near the upwind margin of the field (e.g., Fig. 12) to a near constant of 3.5 m/yr in the field interior (e.g., Figs. 13-14). Moreover, Ewing and Kocurek (2010a) showed that the type and frequency of dune interactions changed over this same area of the field. Reitz et al. (2010) demonstrated a decrease in the sand transport rate from the upwind margin into the zone of parabolic dunes. Spatial heterogeneity in the dune field (previous section) and spatial differences in dune mobility presented here have direct impact upon management. For example, traffic and

human activity is concentrated along the “Heart of the Dunes” Loop. As evident in Figure 14, because of dune mobility maintaining roads in this area will be a constant challenge. Conversely, because the dunes are so mobile, human impact on the dune surfaces is largely erased. Stability of the wet interdune areas of this zone, however, means that vehicle and, to a far lesser extent, human trails are long lasting. Similarly, the stability of the substrate in the zone of parabolic dunes, where natural trails exist, means that human activity is not readily erased by the wind.

Discussion and Conclusions

LiDAR has been demonstrated in this and other studies as a means of both addressing significant scientific questions and characterizing landscape topography. For inherently mobile landscapes such as dune fields, repeated LiDAR surveys represent the most effective means of monitoring topographic change.

In this study, LiDAR data from a representative area of the White Sands Dune Field were used with ArcGIS software to characterize the dune field by precise measurement of far more parameters than has previously been done. In addition to overall characterization of the field, LiDAR data allowed the identification of spatial heterogeneity within the field. Emergent from this enhanced array of parameter measurement is recognition of the variability that exists within single parameters and the lack of strong trends in linear regressions of coupled parameters. For White Sands, these pattern aspects are real owing to the young age of the field, boundary controls that impart spatial heterogeneity, and the ubiquitous dune-dune interactions that cause dynamic redefining of the dune-field pattern. In a broader sense, however, the intensity and precision of LiDAR-based data force the identification of pattern variability that exists in all dune patterns but is deemphasized in traditional approaches. Quantification of the pattern parameters at White Sands argues that “pattern” emerges in this dune field because of the strong orientation of the dunes.

The primary boundary condition that causes spatial heterogeneity in the White Sands Dune Field is antecedent topography that results from paleo-shorelines developed during stages of retreat of Lake Otero. Computational stripping of the dunes from the base survey over which they are migrating shows a terraced surface interpreted as reflecting the paleo-shorelines. Newly discovered shorelines occur at current elevations of 1,211, 1,205.5, and 1,203 m. These occur between previously identified paleo-shorelines at 1,215, 1,200, 1,191, and 1,185 m. Because both deflation and accumulation occurred in development of the current topography, additional work is needed in order to determine the original elevations of the new paleo-shorelines and how this subtle topography has been translated through basin topographic evolution.

The topographic change that has occurred between June 2007 and June 2008 has been shown by a difference map. Consistent with the spatial heterogeneity of the dune-field pattern, dune mobility also varies. Rapid evolution of the dunes occurs within the first 0.5 km from the upwind margin of the field, accompanied by a rapid drop in dune migration rates from 6 m/yr to 3.5 m/yr in the field interior. Streamwise lineations, which extend across closely spaced dunes developed on sand buildups lee of paleo-shorelines, are actively migrating features, as are stoss-superimposed bedforms that occur throughout most of the field. Sand transport decreases in the transport direction, reaching a low in the zone of parabolic dunes, where dune activity is at a minimum. Erosion/deposition patterns for this one year suggest that the parabolic dunes have a component of lateral migration to the south, similar to all other dune elements. Additional LiDAR data, especially as collected at the ends of seasonal winds (June, September, February), afford the best opportunity to more fully understand and monitor dune activity at White Sands National Monument. LiDAR data is arguably the most efficient approach to monitoring dune field “vital signs,” dune activity, and park infrastructure.

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