

Geomorphic and hydrologic controls of dust emissions during drought from Yellow Lake playa, West Texas, USA



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ABSTRACT

Numerous complex geomorphic and hydrologic factors have been identified that control dust emissions from playas, yet there are few measurements of dust emissions from playas during drought, which is assumed to enhance emissions, or during low-emission seasons. We used the PI-SWRL (Portable in situ Wind Erosion Laboratory) to measure dust emission potential at Yellow Lake, a saline playa in West Texas, USA, during the drought of 2011. Direct aeolian entrainment of dust occurred primarily on supply-limited surfaces consisting of mud-cracked surfaces as well as crusts containing halite, thenardite, and gypsum. High-magnitude, low duration peaks in dust emissions occurred over parts of the playa underlain by shallow groundwater (<1 m) where conditions encouraged the crystallization of efflorescent salts. In contrast, surfaces characterized by loose sand-sized aggregates produced sustained dust emissions two to three orders of magnitude higher than the playa surface because aggregates broke apart during saltation. Prolonged drought at Yellow Lake will significantly change the frequency and type of dust emissions. We propose that a similar scenario characterizes dust production at many hydrologically similar playas. More research is needed to assess the impacts of changing groundwater levels on dust emissions in the context of extended drought and anthropogenic climate change.

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1. Introduction

Approximately 30% of global dust emissions are derived from ephemeral bodies of water, including playas (Ginoux et al., 2012). Dust emissions from playas vary widely depending on surface moisture, surface roughness, the strength of surficial sediment or salt crusts, and the availability of saltating grains (Gill, 1996; Gillette et al., 2004; King et al., 2011; Nield et al., 2015; Sweeney et al., 2011; Tollerud and Fantle, 2014). Furthermore, the impact of drought duration, the depletion of groundwater, and other factors influencing water table dynamics exert significant control on the timing of deflation and the composition of the emitted dust (Elmore et al., 2008).

Playas are seasonally or less frequently inundated with surface runoff, some of which infiltrates and some of which evaporates.

Two general types of playas – dry and wet – are recognized (Reynolds et al., 2007; Rosen, 1994). Dry playas are characterized by deep groundwater (>5 m) and mud-cracked surfaces that produce dust composed primarily of silicate minerals with low concentrations of salt. Wet playas are underlain by shallow groundwater (<5 m, and frequently ≤1.5 m) and strong evaporation and capillary processes keep the playa surface moist, facilitating the precipitation of efflorescent salts that are low density with a fluffy structure. Efflorescent salts are easily entrained by the wind (Cahill et al., 1996; Gill, 1996; Gillette et al., 1980; Reynolds et al., 2007), and deflation of salt dust can lead to the contamination of soils and groundwater (Gill, 1996; Wood and Sanford, 1995; Wood et al., 2011). Zlotnik et al. (2012) quantified the mass-balance of salt in closed shallow saline lakes of the Nebraska Sand Hills. Their proposed “salt-dust conveyor” concentrates large volumes of salt from groundwater at the playa surface, which is episodically deflated, initiating a new cycle of salt accumulation by evaporation. The sediments of these lakes contain smaller volumes of salt than would otherwise be generated over long-term fluctuations in groundwater, making it likely that salts are episodically removed by

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the wind (Langbein, 1961; Zlotnik et al., 2012).

Some salt minerals are more susceptible to dust generation than others. Studies have shown that the most emissive salts are hydrous/anhydrous salts and salts with acicular or prismatic mineral habits (Buck et al., 2011; Joeckel and Ang Clement, 2005). Hydrous/anhydrous salts, including mirabilite/thenardite and other Mg-sulfate salts, tend to be unstable, dissolving and reprecipitating with changing temperature and humidity. Salts with acicular or prismatic mineral habits such as glauberite are disruptive as they precipitate and form loose, puffy crusts. Collectively, these salts are the most prone to wind erosion and several studies have documented their contribution to dust emissions (Buck et al., 2011; Gill, 1996; Gillette et al., 1980; Reynolds et al., 2007; Zlotnik et al., 2012). Physical disruption of the surficial sediment by the growth of such salts brings other playa sediments, chiefly detrital grains of silicate minerals, to the surface for aeolian deflation as well (Buck et al., 2011). Dust emissions from playas are further complicated by spatial and temporal changes in salt crust morphology and surface roughness (Nield et al., 2015).

Lunette dunes are deposited on the downwind margins of deflating playas on the Southern High Plains, USA during arid episodes (Holliday, 1997; Holliday et al., 2008; Rich, 2013; Wood and Sanford, 1995). In general, playa sediments deflate to the capillary zone (Wood and Sanford, 1995), yielding quartz-rich sand (low calcareous sand of Holliday, 1997) and aggregates of sand, silt and clay (carbonate sandy loam of Holliday, 1997) to the growing lunettes (Holliday, 1997).

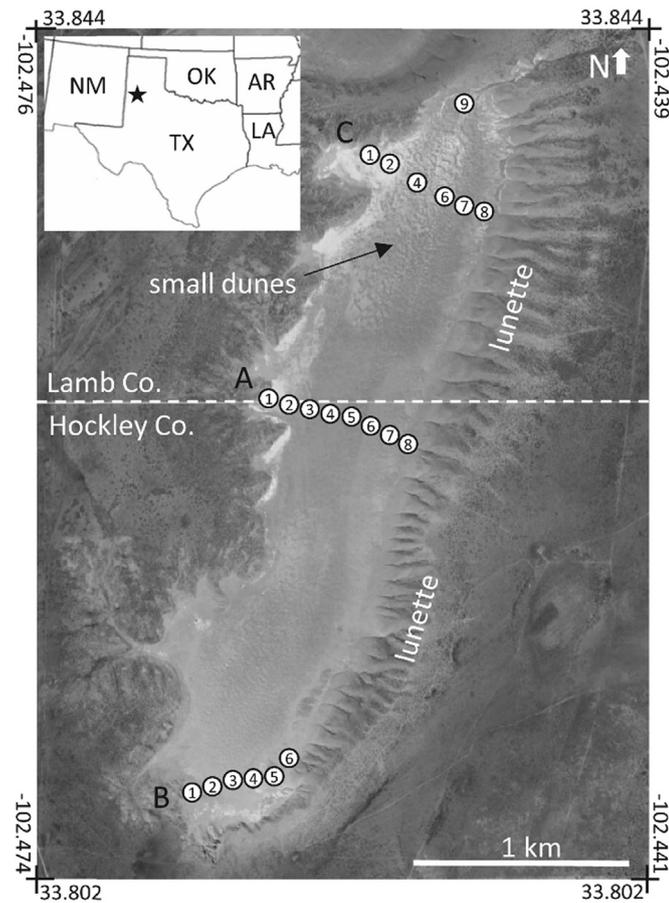


Fig. 1. Location of Yellow Lake playa in Texas. Transects A, B, and C where PI-SWERL tests, surface samples, and groundwater samples were collected are shown. 2012 image from Google Earth. Latitude and longitude are noted on the corners of the image.

Yellow Lake, a 3.5 km² wet saline playa in Lamb and Hockley counties on the Llano Estacado of West Texas (Fig. 1), provides an opportunity to investigate how the interaction of geomorphic, hydrologic, and geochemical processes influence salt dust emissions during drought conditions. There are lunette dunes on the downwind, eastern margin of this playa. Its western boundary is a 5-m escarpment eroded into the Pleistocene Blackwater Draw Formation which is underlain by the Ogallala Formation, the principal aquifer for the region (Wood et al., 1992).

Aeolian activity has been continuously recorded on the floor of Yellow Lake using piezoelectric saltation sensors since 1998 (Stout, 2003, 2007, 2014). Saltation primarily occurs in the winter to early spring months (December–March) when wind speed peaks and humidity and precipitation are low. The spring months (April–May) are windy, but precipitation wets the playa surface, keeping saltation low. Aeolian activity at Yellow Lake usually precedes the timing of regional dust emissions from bare agricultural fields (Stout, 2003) that occur mostly in the spring months from strong west-southwesterly winds (Lee et al., 1994; Stout, 2001). Regional dust storms are low-frequency, intermittent events driven primarily by short-term gusts (Stout, 2001). Despite the relatively small area of playas on the Southern High Plains, playas are some of the largest natural dust sources in the region (Lee et al., 2012).

To assess the role of Yellow Lake as a regional dust source, we considered geomorphic properties of the playa surface and bordering dunes, depth to the water table, geochemistry of the salt crusts and associated groundwater, and measured dust emission potential using the Portable in situ Wind Erosion Laboratory (PI-SWERL). Field testing occurred from June 26 through June 28, 2011 when West Texas was experiencing high temperatures and exceptional drought conditions (Table 1). The drought was described by Nielsen-Gammon (2012) as “unprecedented in intensity” and broke the previous record set in 1956 for the least amount of rainfall over a 12-month period, leading to eight consecutive months with the Palmer Drought Severity Index (PDSI) below -5 (with negative numbers indicating drought), and set record high temperatures. While regional droughts are usually linked to an increased occurrence of dust storms (Hahnenberger and Nicoll, 2014; Reheis, 2006), conditions were not optimal for dust production because aeolian activity and efflorescent salt development is at a minimum during the summer months. This methodology provides a baseline for future studies of dust emissions from playas encompassing wet-dry cycles and will require a denser network of groundwater depth and geochemical data collection at groundwater-controlled playas. These studies have important practical implications, such as for suppression of dust emissions or forecasting dust storms.

2. Methodology

The PI-SWERL was used to measure dust emission potential from the surface of Yellow Lake along three east-west oriented transects (‘A’, central; ‘B’, south; ‘C’, north; Fig. 1). The testing surface was photographed and described at each site. Surface samples consisting of the upper 1 cm or less of crust were collected at each testing location for grain size and mineralogical analysis. A 1-m long, 5-cm in diameter hand auger was used to assess the depth to groundwater along each transect. Water samples were collected if groundwater was intercepted and later tested in the lab for solute composition.

The PI-SWERL measures the potential of a surface to emit dust (Etyemezian et al., 2007) and generates dust emissions data approximately equivalent to large field wind tunnels (Sweeney et al., 2008). The rotation of an annular blade within a closed cylindrical chamber creates shear stress that mobilizes sand and dust.

Table 1
Yellow House Ranch meteorological Data.^a

Date	Avg wind speed (m/s)	Avg wind dir. (deg.)	Max gust (m/s)	Max temp (°C)	Min temp (°C)	Max rel hum (%)	Min rel hum (%)	Rain (mm)
6/26/2011	6.18	214	16.76	44	25	62	6	0
6/27/2011	4.59	216	18.82	42	24	56	10	0
6/28/2011	4.05	142	15.19	40	23	60	13	0

^a Meteorological station located at southeast side of playa: 33.807614, -102.461355.

The annular blade rotates at predefined number of rotations per minute (RPM) and generates pre-specified friction velocities (u^* , m s^{-1}) (Etyemezian et al., 2007). The dust emitted from the surface is measured as particulate matter $<10 \mu\text{m}$ (PM_{10}) using a dust monitor (DustTrak TSI Model 8520) in mg m^{-3} . An emission flux E_i ($\text{mg m}^{-2} \text{s}^{-1}$) at pre-specified i -th friction velocity (RPM step) can be calculated using the equation

$$E_i = \frac{\sum_{begin,i}^{end,i} C_i \times F_i}{(t_{end,i} - t_{begin,i}) \cdot A_{eff}} \quad (1)$$

in which C_i is the dust concentration (mg m^{-3}), F_i is the flow rate of fresh air entering the PI-SWRL chamber ($\text{m}^3 \text{s}^{-1}$), A_{eff} is the effective test area under the annular ring (m^2), and $t_{begin,i}$ and $t_{end,i}$ is the time (s) at the beginning and ending of each i -th RPM step.

Shear velocity under the PI-SWRL was initially determined by testing on a smooth surface at different RPMs (Etyemezian et al., 2007). A succeeding study (Etyemezian et al., 2014) tested the PI-SWRL on different rough surfaces, which are more akin to the majority of natural land surfaces, using a viscometer. They yielded correction factors ($\alpha = 1$ for perfectly smooth surfaces, and $\alpha < 1$ for progressively rougher surfaces) that can be applied to different types of rough surfaces to calculate a more realistic shear velocity. In turn, we used correction factors of $\alpha = 0.98$ for smooth, flat mud cracked surfaces, $\alpha = 0.96$ for loose dune sands, and $\alpha = 0.90$ for botryoidal salt crusts.

Two types of PI-SWRL tests were conducted in the present study. 1) *Ramp tests* gradually increase the RPM, and associated friction velocity, in order to determine the threshold friction velocity at which sand or dust particles are emitted. Optical sensors attached to the inner side of the PI-SWRL chamber count sand grains that pass through the sensor. Saltation is interpreted to begin if sand movement is sustained. The dust emission threshold is determined as the inflection point in the dust curve, where dust concentrations rise above the background concentration. 2) In *step tests*, emissions are measured at a constant friction velocity as RPM is increased to a constant level, and emission fluxes are then calculated.

We conducted two to three step tests at each point along each transect at Yellow Lake in order to assess the heterogeneity of E_i over the crusted playa surface. In addition, one ramp test was conducted at selected sites (Table 2). PI-SWRL tests were also conducted on wind-ripple and dune surfaces with intact crusts and with crusts carefully removed to reveal loose dune sand. PI-SWRL tests on loose sand simulated dust emissions when sand was actively saltating.

Crust and surface samples (upper 5 cm) were sampled separately at each site. Surface samples were weighed, dried for 24 h at 105 °C and weighed again to determine weight percent H_2O . Splits of dried samples were used for particle size analysis. Dry sediment and crust colors were determined using Munsell soil colors.

Three methods of particle size analysis were used: laser diffraction of dispersed sediment, laser diffraction of non-dispersed sediment, and dry sieve. A Malvern Mastersizer 2000™ laser diffraction particle size analyzer (Hydro 2000 mu sample module)

was used to measure detailed particle-size distributions of playa and aeolian sand using two different pretreatments. First, samples were pretreated with HCl to remove carbonates and then 10 mL of 50 g L^{-1} sodium metaphosphate was added to disperse the samples, followed by shaking overnight. Samples were added to the particle size analyzer, circulated in deionized water and sonicated for 60 s prior to analysis. Additional splits of aeolian sand were analyzed without pretreatment or sonication prior to analysis because the aeolian sands were primarily composed of sedimentary aggregates. The aggregates were added to the particle size analyzer and grain size was continuously measured at 30 s, 60 s, 240 s, and 420 s while the sample was continuously circulated through the instrument, in order to document the breakdown of sedimentary aggregates over time, following similar procedures for loess (Mason et al., 2011) and aggregates from lakebeds (Greene et al., 2006). Percentages of sand ($>63 \mu\text{m}$), silt (4–63 μm), and clay ($<4 \mu\text{m}$) are presented for all samples. Dry sieving was applied only to aeolian sands to avoid disaggregation in water and to more accurately determine sand content and the distribution of sand sizes.

Samples of surface crusts (sediment and/or salts) were stored in sealed plastic bags at room temperature. Subsamples were gently powdered using a ceramic mortar, screened to less than 63 μm , (the oversize fraction was rejected), and backloaded into randomly oriented powder mounts. A Rigaku Mini-Flex™ X-ray diffractometer using $\text{CuK}\alpha$ radiation at 30 kV and 15 mA was employed for XRD analysis. Scans were made from 2° to 90° 2 θ at a step time of 1° or 2° 2 θ /minute. Mineral identification was facilitated by the search-match function in JADE™ software from Materials Data, Inc. (Livermore, CA), which uses the Powder Diffraction Files as references. Repeated onscreen qualitative comparisons of diffractograms and match lines were employed in addition to peak-matching software.

3. Results

3.1. Land surface and groundwater conditions

Table 2 summarizes surface crust types, surface moisture, mineralogy, and measured or approximate groundwater depths. The playa floor was mostly dry at the time of our study. Soft, smooth to botryoidal bright white salt crusts (Fig. 2a) were present at its margin and hard, smooth mud-cracked sediment crusts (Fig. 2b) with localized, less extensive salt crusts existed at its center. Salt crusts are representative of exposed playa sediments, whereas mud-cracked surfaces are commonly representative of crusted, wind-blown sand cover on the surface of the playa, identified by wind-ripple morphology. Removal of the surface crust in wind-rippled areas revealed dry, loose sand-sized aggregates. Wind-rippled surfaces were common on the playa floor along transects 'A' and 'C' but absent on southern transect 'B'. Dry playa sediment Munsell soil colors ranged from light gray (2.5Y 7/1), gray (2.5Y 6/1), light brownish gray (2.5Y 6/2), pale yellow (2.5Y 8/2), to very pale brown (10YR 7/3), while crusted wind-blown sand color was gray (2.5Y 6/1). Playa margins adjacent to the western escarpment, and especially along transect 'B' (Fig. 1), commonly contained

Table 2
Site characteristics, crust morphology and mineralogy.

Site	Surface type	Crust type ^a & morphology ^b	XRD crust mineralogy ^c	Surface ^d %H ₂ O	Ground water depth (m)	PI-SWRL ramp tests	PI-SWRL step tests
A1	playa	s; bot	thenardite, calcite, halite	ND	0.35	3	6
A2	aeolian ripples	m; sm	calcite, dolomite	ND	>1.0	1	2
A3	aeolian ripples	m; sm	calcite, dolomite	ND	>1.0	1	3
A4	aeolian ripples	m; sm	calcite, dolomite	ND	>1.0	1	3
A5	playa	s; sm, sbot	halite, calcite	ND	>1.0	0	3
A6	aeolian ripples	m; sm	calcite, dolomite	ND	>1.0	0	3
A7	aeolian ripples	m; sm	calcite, halite, dolomite	ND	>1.0	0	3
A8	playa	s; sm	ND ^e	ND	>1.0	0	3
A9	lunette	m; sm	halite, calcite, dolomite	ND	>1.0	1	4
B1	playa	m; sm, ir	calcite, dolomite	5.2	>1.0	1	3
B2	playa	m; sm, ir	halite, calcite, dolomite	3.5	>1.0	1	3
B3	playa	m; sm, ir	halite, thenardite, calcite	4.2	>1.0	0	3
B4	playa	s; sm, sbot	ND	5.3; 21.4 ^f	0.35	1	3
B5	playa	s; sm, sbot	thenardite	4.7	1.0	1	4
B6	playa	s; sm, sbot	halite, glauberite	17.1	ND	0	3
C1	playa	s; sm, bot	halite, dolomite	8.6	ND	0	3
C2	playa	m; sm, sbot	halite, calcite, dolomite	4.0	>1.0	0	3
C4	aeolian ripples	m; sm	halite, calcite, dolomite	4.0	>1.0	0	3
C6	aeolian ripples	m; sm	halite, calcite, dolomite	3.8	>1.0	1	3
C7	playa	s; bot	halite, gypsum	4.6	0.30	0	2
C8	playa	s; sbot, ir	halite	12.5	0.35	0	3
C9	playa	s; sbot, ir	halite	18.8	ND	0	3

^a m = mudcrack, s = salt.

^b bot = botryoidal, sbot = slightly botryoidal, sm = smooth, ir = irregular.

^c Quartz is a major component of most samples.

^d Surface = upper 5 cm.

^e ND = no data.

^f %H₂O at 1.0 m.

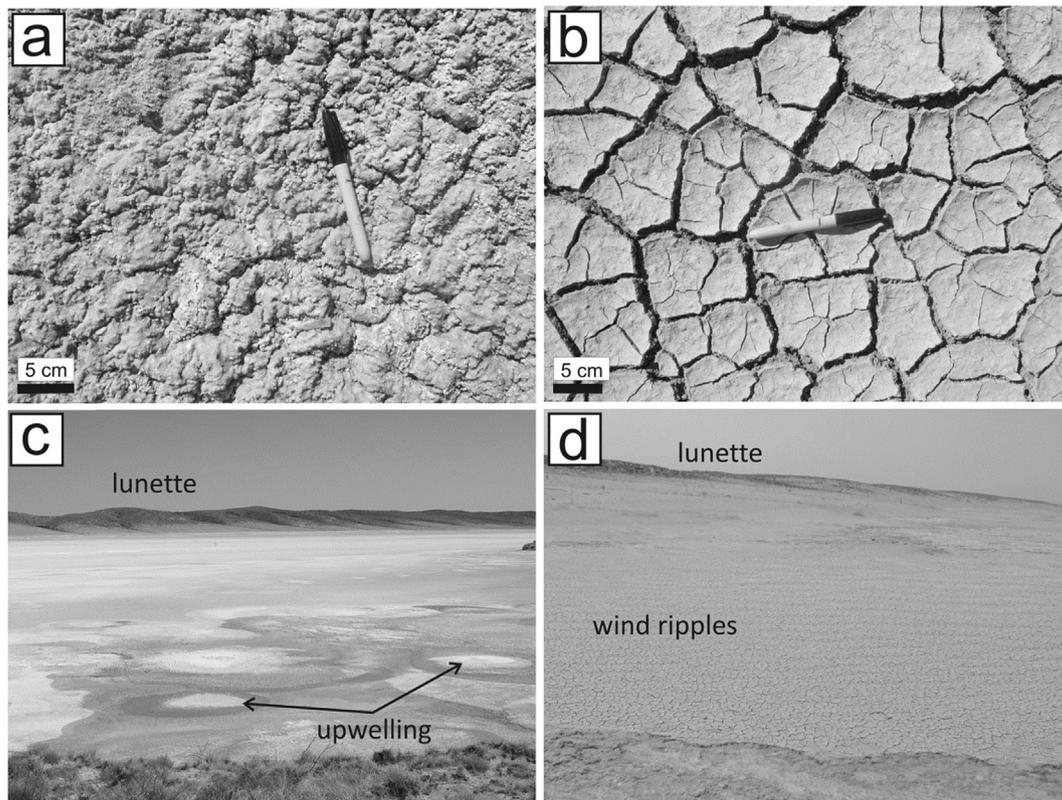


Fig. 2. Surface characteristics of Yellow Lake. a) botryoidal salt crust typical along playa margin, b) mud cracked surface typical in the playa center, c) view of Yellow Lake facing east, with lunettes in the background, and circular areas of groundwater upwelling noted by bright white salt cover in foreground, d) aeolian wind rippled surface stabilized by mud cracked surface crust. Lunette dune is in the background.

yellowish selenite gypsum crystals 2 mm to more than 100 mm in length. The eastern and western margins of the playa exhibited

thin, dry salts over moist playa muds. Sediments underneath the crusts were loose to slightly cohesive mud aggregates or saturated

and unaggregated mud, depending on water content, which was 3–5% in dry areas and >8% in moist to wet areas (Table 2). Zones of groundwater upwelling were characterized by circular areas (Fig. 2c) containing puffy, botryoidal salt crusts underlain by wet (>17% H₂O) mud. Hand augering revealed groundwater within 1 m of the surface along the margins of the playa, but greater than 1 m deep towards the center of the playa (Table 2). Sediments near the playa center were hardened at depth and difficult to sample by hand auger in many places. Previous investigations at Yellow Lake revealed that groundwater was within ~2.5 m of the surface and that brine concentrations in the groundwater were on the order of 140 g L⁻¹; moreover, freshwater springs once flowed near the eastern shore (Meigs et al., 1922).

Groundwater samples collected in this study contain high levels of Na⁺, Cl⁻ and SO₄²⁻ at concentrations of about 140 g L⁻¹ (Table 3), an observation consistent with Meigs et al. (1922). Groundwater samples from the southern and western parts of the playa had higher solute concentrations than those from the northern and eastern parts of the playa.

XRD analysis revealed that the surface crusts are dominated by quartz, which is cemented by halite (NaCl), calcite (CaCO₃), dolomite (CaMg[CO₃]₂) and in some cases by gypsum (CaSO₄·2H₂O) and the efflorescent salts thenardite (Na₂SO₄) and glauberite (Na₂Ca[SO₄]₂) (Table 2). These efflorescent salts were observed closer to the playa margins, where groundwater is typically within 1 m of the playa surface. Mud-cracked crusts on wind-rippled sand contained appreciable quantities of quartz, halite, calcite, and dolomite.

Sediments on the playa surface are primarily silt loam, loam, and sandy loam. Silt predominates in all samples and clay contents are uniformly less than 20% (Fig. 3). Playa-margin sediments are generally sandier, as are the sediments in a small drainage entering the north end of the playa along transect 'C' (C9, Fig. 1). Playa sediments exhibit a bimodal distribution having a mode of fine silt (~7–12 μm) and another of coarse silt to very fine sand (~50–70 μm).

Wind-ripple and lunette sands consist of sub-rounded mud aggregates that are gray (2.5Y 6/1) when dry. Dry-sieving the dune sand revealed that the samples are 97–99% sand-sized particles (Fig. 3) with a fine sand mode, as documented in other lunettes in the region (Holliday, 1997). These sand-sized mud aggregates broke down in water within the laser particle analyzer. Initial grain-size distribution measurements after 30 s circulating in water resulted in 50% or more sand-sized grains, and the mode shifted to coarse silt. Thereafter, the percent of sand declined and the percent silt and clay increased over time as the particles disaggregated in the water (Fig. 3). After the dune sands were fully dispersed, their particle size distribution was similar to the playa sediments with less than 20% sand and a mode of fine silt. These results strongly suggest that the sand-sized aggregates are derived from the playa and are very delicate and easy to disaggregate in the presence of water, indicating that any active dune sand would stabilize quickly underneath a crust following a rain storm.

Lunettes on the eastern margin of the playa were stabilized by low density salt-tolerant vegetation including alkali sacaton

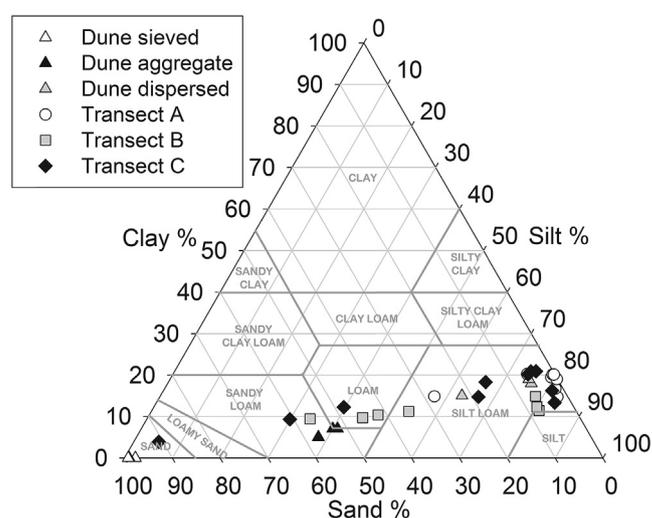


Fig. 3. Textural triangle plotting the percent sand, silt and clay of playa and lunette dune sediments. Dune sands are plotted to show changes in grain size distribution compared with dry sieving and wet, laser diffraction of aggregated (at 30 s) and dispersed samples.

(*Sporobolus airoides*), a native perennial bunchgrass, and mud-cracked soil crusts approximately 0.5 cm in thickness. No loose sand was observed on the surface. Wind-rippled surfaces (Fig. 2d) and slipfaces on smaller dunes were clearly identifiable but immobilized due to crust cover. Loose sand-sized aggregates existed underneath the crusts. The dunes are gullied on the western margin, with gullies draining toward the playa floor.

3.2. Dust and sand entrainment

PI-SWRL tests were conducted on solid surfaces and the areas of groundwater upwelling were avoided. Brief (2–3 s) high magnitude (1–25 mg m⁻³) concentrations of dust were emitted at the beginning of most tests where surfaces contained intact salt crusts or intact mud cracks (Fig. 4a, b). Dust concentrations rapidly declined to background levels (<0.05 mg m⁻³) and remained nearly constant for the duration of the RPM step. Saltation was absent on all crusted playa surfaces except for site B5. These supply-limited surfaces emitted small concentrations of dust by direct entrainment rather than by saltation bombardment (Fig. 4a, b). Dust emissions were an order of magnitude higher along the playa margins (Fig. 4a) compared to the playa center (Fig. 4b).

PM₁₀ dust fluxes from transects 'A', 'B', and 'C' are similar but low, averaging about 0.01 mg m⁻²s⁻¹ at a surface friction velocity of $u^* = 0.6 \text{ m s}^{-1}$ (Fig. 5). Sites along the playa margin containing salt crusts (A1, B6, C1, and C7) have slightly higher fluxes compared to mud-cracked surfaces toward the center of the playa. Site B1 was a soft, mud-cracked surface that had an irregular morphology which may have trapped and stored loose dust-sized particles at the surface, resulting in a slightly higher flux during testing. These

Table 3
Groundwater chemistry – Yellow Lake.

Site	Depth (cm)	Na (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Cl (mg/L)	SO ₄ (mg/L)
A1	35	35,418	1954	2218	7229	49,678	38,662
B4	35	37,040	2094	2317	7531	28,802	19,572
B5	100	34,754	2017	2186	7192	28,776	19,770
B6	NR	37,154	1932	2302	7632	51,888	40,227
C7	30	12,965	1320	686	2537	15,364	18,243
C8	35	19,655	1378	1118	3667	28,718	19,617

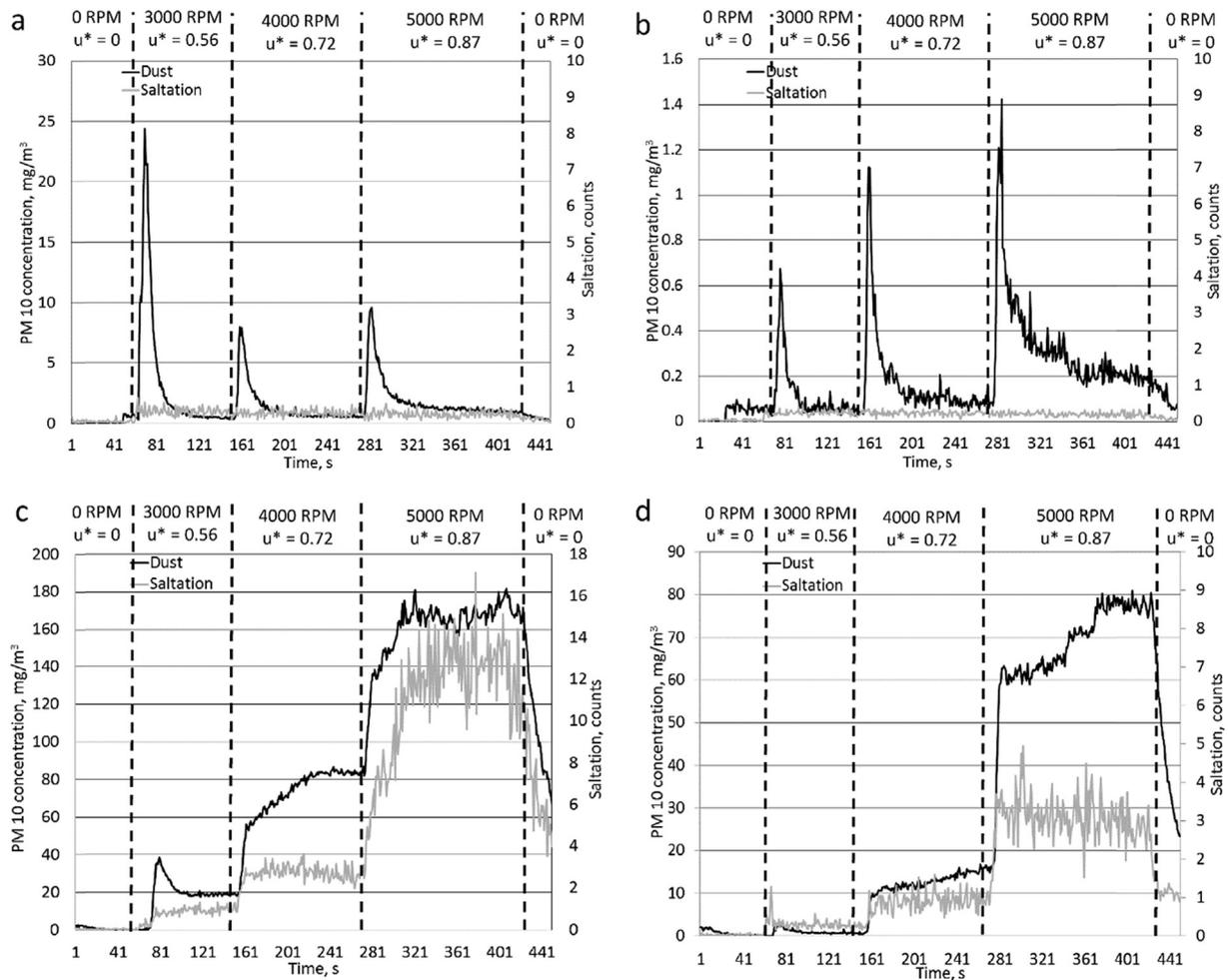


Fig. 4. PI-SWERL step tests showing PM_{10} dust concentrations and sand movement. a) Site C1.1 on intact salt crusts along the playa margin shows high magnitude but short duration pulses of dust at the beginning of each RPM step. Dust concentrations rapidly fall to background levels, typical of a supply-limited surface. No saltation is measured. b) Site A6.3 on intact mud cracks in the playa center shows a similar supply-limited response but with lower concentrations of dust. c) Site A9.4 is lunette dune sand where the surface crust has been removed. Saltation and associated dust emissions are high compared to the playa surface. Sand grains are composed of aggregates and may also contribute to dust emissions as they break apart during transport. d) Site B5.5 was the only site on the playa floor where saltation was recorded on intact crust. Saltation is noted starting in the second RPM step with associated high concentrations of dust, increasing with an increase in friction velocity.

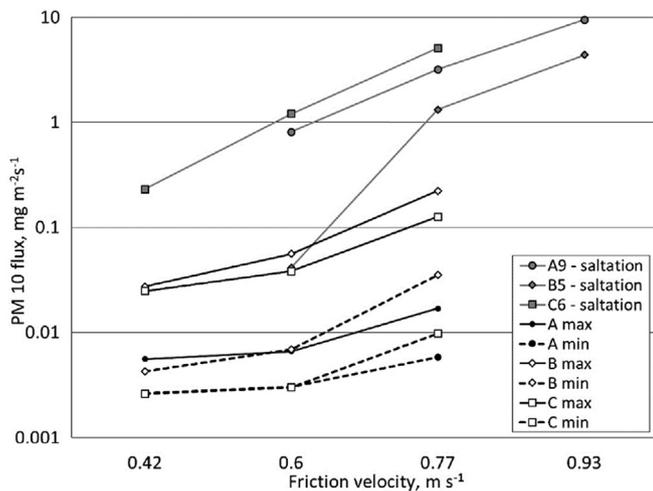


Fig. 5. PI-SWERL maximum and minimum PM_{10} fluxes for each transect as functions of friction velocity u^* ($m s^{-1}$). Sites where saltation occurred are also shown (A9, B5, C6) and reveal the potential for high dust emissions if sand is available for aeolian transport. A9 and C6 have crusts removed for testing.

results are consistent with supply-limited surfaces, typical for silt-clay or salt-crustured playas or alluvial surfaces with a protective gravel lag (Macpherson et al., 2008; Nickling and Gillies, 1989; Sweeney et al., 2011).

Salt-dust emissions were limited by the growth rate of efflorescent salts during the study period, so fluxes calculated over the time of the test mask short-lived, high-magnitude pulses of dust. Therefore, when dust emissions are very low, little to no difference exists in fluxes at the playa margin and those at the playa center. In order to differentiate emissions on different parts of the playa, we looked at the maximum concentration of dust emitted from the playa surface at constant shear velocities ($u^* = 0.6 m s^{-1}$ and $0.9 m s^{-1}$). Paired with depth to water table data, dust emissions peaked (commonly 5–20 $mg m^{-3}$) where the water table was 1.0 m or less below the surface, or if the surface was wet beneath salt crusts (Fig. 6; Sites A1, B5, B6, C1, C7, and C8). Transect A, across the center of the playa, recorded the lowest emissions, whereas transects B and C recorded higher emissions, especially along the playa margins where groundwater was shallow (Fig. 6). Emissive salts (thenardite, glauberite), as identified by XRD, are associated with playa margin or shallow water table sites. It should be noted, however, that these emissive salts are highly susceptible to

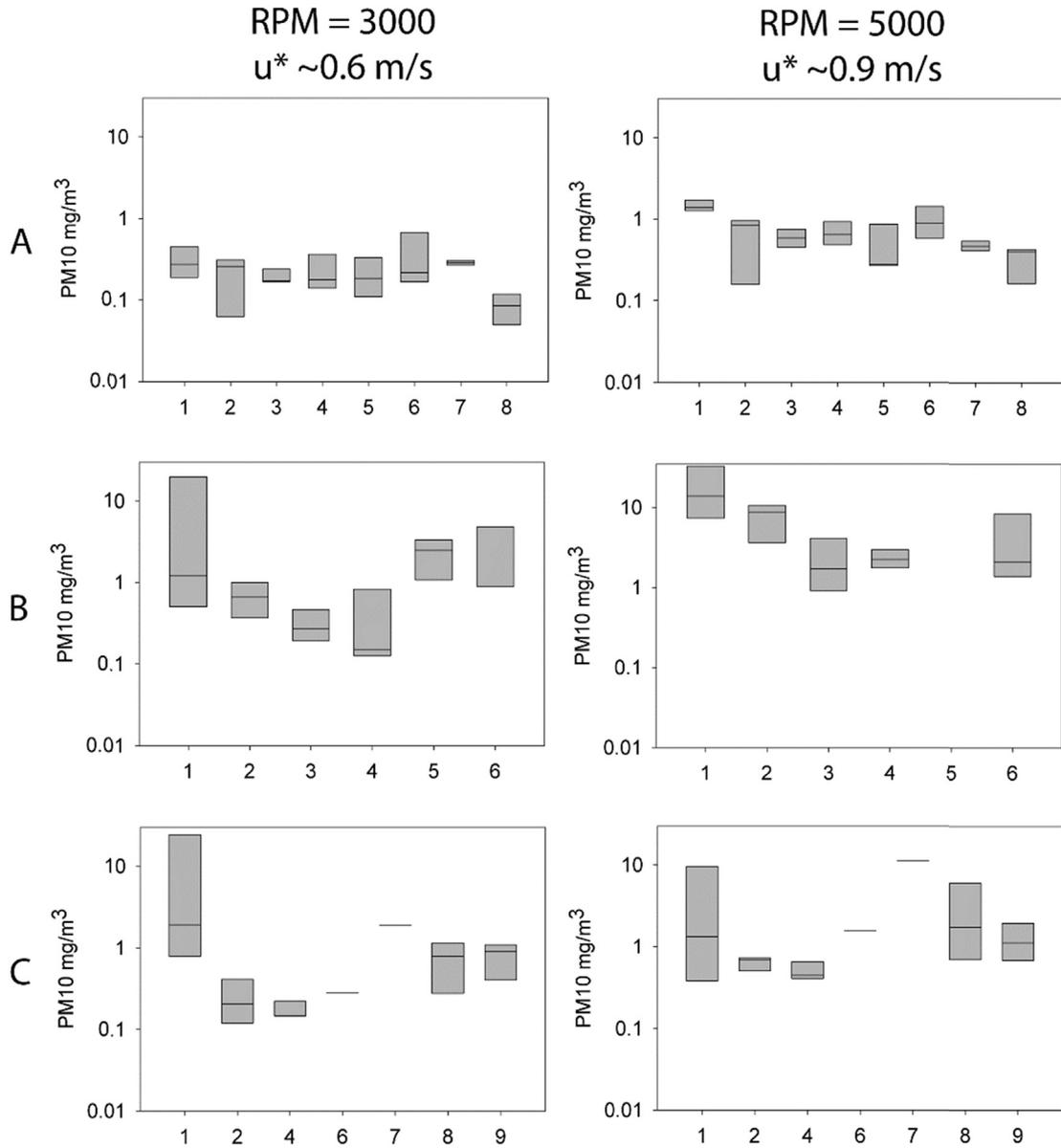


Fig. 6. Maximum dust concentrations measured along each transect compared by friction velocities. Crusts are intact for all sites. Transect A recorded very low dust emissions consistent across the transect, whereas transects B and C both recorded higher emissions on the margins where groundwater was shallow compared to the playa center. Site location on each transect is indicated by a number on horizontal axis.

changing environmental conditions and the suite of efflorescent mineral phases may have changed between the time of collection and analysis by XRD (Buck et al., 2011; Joeckel and Ang Clement, 2005).

To estimate potential of dust emissions when sands were actively saltating, PI-SWERL tests were also conducted on wind-rippled sand located on the playa floor as well as on the large lunettes on the eastern margin of the playa (A9 and C6). With the crust removed, saltation of sand was recorded followed by dust emissions, which were high and sustained ($80\text{--}170\text{ mg m}^{-3}$) until the end of the test (Fig. 4c). One locality on the playa floor, site B5, also recorded saltation (Fig. 4d). This site is in close proximity to field saltation sensors (Stout, 2003). The surface had an intact crust but also contained loose grains of sand-sized gypsum. Dust emissions began following the initiation of saltation. Of the sites that exhibited saltation, areas covered by dune sand emitted more dust compared to the playa sediments themselves (Fig. 5).

The threshold for sand movement, as measured by the PI-SWERL sensors, was at RPMs corresponding to $u^* = 0.42\text{--}0.61\text{ m s}^{-1}$. Stout (2007) determined threshold wind velocities at 2-m height of $6.4\text{--}13.3\text{ m s}^{-1}$ for saltation at Yellow Lake in 2001–2003, using a piezoelectric sensor (Sensit™) to detect saltation. To compare those results with our data, we applied the “law of the wall”:

$$u_z = \frac{u^*}{\kappa} \ln \frac{z}{z_0} \quad (2)$$

in which u_z is the wind speed (m s^{-1}) at height z (0.07 m, height of the PI-SWERL blade), κ is von Karman’s constant (0.4), and z_0 is the aerodynamic roughness height (m). We calculated the value of u_z at 2-m given u^* values corresponding to PI-SWERL-based saltation thresholds and a z_0 of roughly $3 \times 10^{-4}\text{ m}$ estimated from similar types of playa surfaces (Sweeney et al., 2008), yielding threshold 2-

m wind speeds of 9.4–13.8 m s⁻¹, in good agreement with Stout (2007).

4. Discussion

4.1. Controls on salt-dust emissions

Dust emissions from Yellow Lake are comparable to those from similar environments (Fig. 7), including wind tunnel measurements from Owens Lake (Nickling and Brown, 2001, where PM₁₀ emissions are comparable to PI-SWERL, see Sweeney et al., 2008) and PI-SWERL measurements along the margins of the Salton Sea (King et al., 2011), and Mesquite and Soda Lake playas in the Mojave Desert (Sweeney et al., 2011). At Owens Lake playa, most dust emission studies have focused along the eastern part of the playa where saltation is a key process in dust emissions (Cahill et al., 1996; Gillette et al., 2004). Other areas of the Owens Lake playa are almost always covered with hard crusts, limiting dust emission potential, however, direct entrainment of dust occurs seasonally in the late winter and spring in areas influenced by shallow groundwater (Cahill et al., 1996; Gill, 1996; Gillette et al., 2001). Dust emissions measured in this field study are comparatively lower, but otherwise similar, to emissions described at Owens, Mesquite, and Soda lakes, and demonstrates heterogeneity of dust emissions of playa systems is common and in need of additional study (Bryant, 2013; Sweeney et al., 2011). The comparatively low emissions at Yellow Lake appear to be the result of specific conditions at the time of our study: 1) exceptional drought and below normal precipitation (Nielsen-Gammon, 2012), 2) extensive, stabilizing crust cover on the playa surface, 3) a seasonally lower water table, and 4) lack of efflorescent salt growth. Conditions facilitating efflorescent salt growth tend to occur earlier in the year (Stout, 2003). Our PI-SWERL results are consistent with supply-limited conditions that are typical for crusted surfaces. High magnitude, short duration pulses of dust are emitted from playa surfaces containing very few saltating grains or none at all. Surface roughness, potential subsurface moisture on a playa, as well as cohesion by carbonates or salts must be overcome before higher magnitude dust emissions occur in these settings (Gillette et al., 1980). At the nearby Morgenstern Dunes (Stout, 2007), the threshold for saltation is lower and over a narrower range of velocities compared to Yellow Lake, likely due to the lack of crusting and an abundant supply of fine quartz sands at

the Morgenstern Dunes (Stout, 2007).

The maximum concentrations of dust emitted (Fig. 6), rather than dust flux, reveals that the playa margins were potentially more emissive at the time of testing. The playa margins coincide with groundwater less than 1 m below the surface, or notably wet subsurface sediment (Table 2). Even though the entire playa surface was crusted and lacked loose surface particles or aggregates, shallow groundwater along the playa margins facilitated the growth of efflorescent salts. These salts were likely emitted as dust by direct deflation at higher concentrations compared to other parts of the playa. Seasonal wetting and groundwater influx at Yellow Lake result in the formation of efflorescent salt minerals under particular meteorological conditions, and these are subsequently deflated from the basin (e.g., Zlotnik et al., 2012). New salts will continue to precipitate and be subject to deflation, even during persistent droughts, as long as the depth to groundwater remains within the zone of capillary rise (Buck et al., 2011; Reynolds et al., 2007).

If surface crusts can be degraded during high wind events such as noted by Stout (2007), mud aggregates can be transported by the wind via saltation to produce large volumes of dust (Alfaro et al., 2004). Freeze-thaw cycles, typical in the winter months on the Llano Escatado, can also contribute to the dust emissions by disrupting the playa crust, forming aggregates and exposing loose sediment that can be mobilized by the wind (Stout, 2014). PI-SWERL tests of wind ripple and lunette sands at Yellow Lake demonstrate that aggregates break apart during saltation transport, thereby producing dust. As sand grains bombard the surface, dust-sized particles are liberated through sand-blasting. Moreover, when we artificially removed crusts and made sand available for saltation, dust emission fluxes increased by two to three orders of magnitude (Fig. 5), indicating that Yellow Lake is very likely to be a significant dust source when sands are not stabilized by surface crusts, such as what would have been the case during late Pleistocene to Holocene dune building episodes (Holliday, 1997; Rich, 2013).

4.2. Role of aggregates and lunette dunes in dust generation

Efflorescent salts may actually be essential ingredients in the formation of sand-sized mud aggregates, and hence lunettes as well, in Australia and Texas (Bowler, 1973, 1983; Price and Kornicker, 1961). Bowler (1983) provided a comprehensive description of playa-lunette processes and most notably observed that prolonged drying of the playa surface facilitated the breakdown of surface crusts to form aggregates that could be mobilized by the wind. Aggregate formation was closely tied to a shallow water table within 1–1.5 m of the surface and efflorescent salt precipitation at the surface (Bowler, 1983). These observations parallel the conditions at Yellow Lake playa and at other playa-lunette systems on the Southern High Plains. Other researchers have also noted the importance of the disruptive nature of efflorescent minerals to create loose, fluffy playa surfaces that are prone to wind erosion (Buck et al., 2011; Joeckel and Ang Clement, 2005; Reynolds et al., 2007).

Mobile, non-crusted sand was previously observed on the floor of Yellow Lake by Stout (2007), and small dunes existed on the floor of Yellow Lake playa in 2012 (Fig. 1). These small dunes have covered a majority of the Yellow Lake playa floor in the recent past, therefore vastly increasing the potential for dust emissions compared to the prevailing conditions in this study. Dune erosion by gullying and the subsequent remobilization of eroded sand by the wind sets up a feedback loop where times of dune erosion and degradation may provide the primary source of sand for subsequent dust emissions and dune building episodes (eg., Thomas

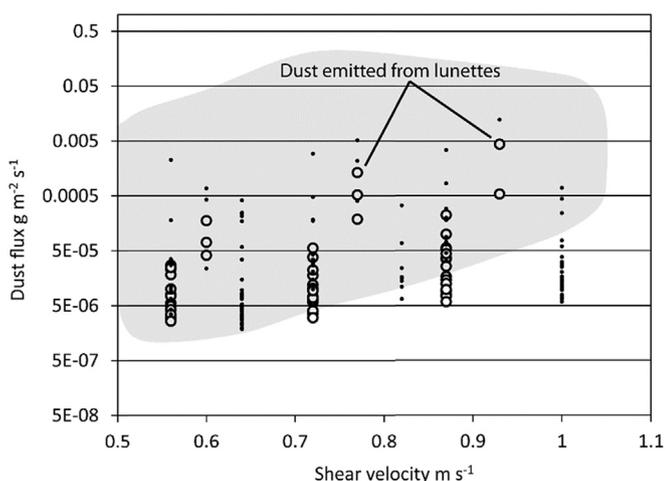


Fig. 7. Yellow Lake dust flux as measured by the PI-SWERL (open circles), compared to fluxes measured from other saline playas, such as in the Mojave Desert (dots; Sweeney et al., 2011) and salt crusted surfaces along the margin of the Salton Sea and Owens Lake (shaded area; King et al., 2011; Nickling and Brown, 2001; respectively).

et al., 1993), rather than most of the sand being derived from the erosion of the playa itself.

4.3. The future of the salt-dust conveyor

Linked playa-lunette processes, likely involving a shallow water table and saline groundwater conditions, have been episodically active on the Southern High Plains since at least ~250 ka (Rich, 2013). Holliday (1997) interpreted the mid-Holocene deposition of sands with low carbonate contents on lunettes as a response to major regional droughts. This interpretation implies that the water table must have declined and that the source of carbonate (calcareous loamy sand) from the playa had been exhausted. The return to wetter conditions and a higher water table in the late Holocene, however, initiated the groundwater salt-dust conveyor once again, and calcareous loamy sands accumulated on the lunettes. The supply of salt for aeolian transport can be replenished indefinitely provided the water table is near the land surface and groundwater has a high concentration of solutes (Buck et al., 2011; Reynolds et al., 2007). Remote sensing data have shown a downward trend in groundwater levels in the Southern High Plains Aquifer in Texas, a trend linked to increased water usage (Famiglietti and Rodell, 2013) and exacerbated by recent drought. A deepening of the water table would likely minimize salt precipitation at the surface (e.g., Buck et al., 2011) as Yellow Lake likely transforms from a wet playa to a dry playa. A significant decline in the water table may result in the excavation of the playa floor by the wind and a new phase of lunette dune accumulation coeval with an increase in dust emission potential.

5. Conclusions

PI-SWRL tests that measured the potential of Yellow Lake to emit dust support the general conclusions of Reynolds et al. (2007) and Zlotnik et al. (2012) that shallow groundwater conditions promote the formation of efflorescent salt minerals that are susceptible to wind erosion, especially along the playa margin. The surface of Yellow Lake was supply-limited during our investigation and most dust was emitted by direct entrainment. Degradation of salt crusts produces sand-size aggregates that contribute to dust emissions as well as lunette dune development. Some aggregates break apart during saltation transport and emit high quantities of dust (2–3 orders of magnitude higher than crusted playa surfaces). Threshold velocities for saltation estimated by PI-SWRL tests agree with threshold velocities for saltation measured using saltation sensors on the playa floor (Stout, 2003, 2007). This study was conducted during extensive drought conditions at the time of year when aeolian activity on saline playas in West Texas is at a minimum. Studies that focus on conditions favoring low dust emission rates are rare, yet are important to help understand the emission dynamics of a system. To learn more about how groundwater influences aeolian activity on Yellow Lake, future study will require PI-SWRL measurements in the winter and spring seasons (when efflorescent salts are abundant), detailed information on water table depths, and high resolution data on physical and chemical properties of salt crusts. Our study, though preliminary, suggests that major changes in climate and land use will impose significant changes on the playa-lunette systems of the Southern High Plains.

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