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Dust Emission from Wet and Dry Playas in the Mojave Desert, USA†

Richard L. Reynolds,[1]* James C. Yount,[1] Marith Reheis,[1] Harland Goldstein,[1] Pat Chavez, Jr.,[2] Robert Fulton,[3] John Whitney,[1] Christopher Fuller[4] and Richard M. Forester[1]

[1] *U.S. Geological Survey, Denver, CO, USA*
[2] *U.S. Geological Survey, Flagstaff, AZ, USA*
[3] *California Desert Studies Consortium, California State University Fullerton, Baker, CA, USA*
[4] *U.S. Geological Survey, Menlo Park, CA, USA*

**Correspondence to: Richard L. Reynolds, U.S. Geological Survey, Box 25046, MS 980, Denver, CO 80225, USA. E-mail: rreynolds@usgs.gov*

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Abstract

The interactions between playa hydrology and playa-surface sediments are important factors that control the type and amount of dust emitted from playas as a result of wind erosion. The production of evaporite minerals during evaporative loss of near-surface ground water results in both the creation and maintenance of several centimeters or more of loose sediment on and near the surfaces of wet playas. Observations that characterize the texture, mineralogic composition and hardness of playa surfaces at Franklin Lake, Soda Lake and West Cronese Lake playas in the Mojave Desert (California), along with imaging of dust emission using automated digital photography, indicate that these kinds of surface sediment are highly susceptible to dust emission. The surfaces of wet playas are dynamic – surface texture and sediment availability to wind erosion change rapidly, primarily in response to fluctuations in water-table depth, rainfall and rates of evaporation. In contrast, dry playas are characterized by ground water at depth. Consequently, dry playas commonly have hard surfaces that produce little or no dust if undisturbed except for transient silt and clay deposited on surfaces by wind and water. Although not the dominant type of global dust, salt-rich dusts from wet playas may be important with respect to radiative properties of dust plumes, atmospheric chemistry, windborne nutrients and human health. Published in 2007 by John Wiley & Sons, Ltd.

Keywords: dust; playa; evaporite minerals; Mojave Desert; wind erosion

Introduction

The growing recognition of the importance of dust for global climate, air quality with respect to visibility and human health, the fertilization of marine and terrestrial ecosystems, transportation and indications of desertification has spawned many recent efforts to locate sources of dust (e.g. Prospero *et al.*, 1981; Goudie and Middleton, 2001; Middleton and Goudie, 2001; Prospero *et al.*, 2002; Ginoux and Torres, 2003; Mahowald *et al.*, 2003; Washington *et al.*, 2003). Continued advances in understanding dust emissions and the ability to forecast locations and amounts of dust emission depend on better understanding of the geologic and hydrologic processes that promote or suppress emission from source areas. As one type of source, playas (also known as dry lakes) have been associated with dust emission (see, e.g., Blackwelder, 1931; Young and Evans, 1986; Pye, 1987; Rosen, 1994; Wood and Sanford, 1995; Gill, 1996; Goudie and Middleton, 2001; Yechieli and Wood, 2002; Prospero *et al.*, 2002; Bryant, 2003; Washington *et al.*, 2006).

The aim of this paper is to show that different processes control fundamentally different amounts and compositions of dust emitted from two distinct types of playa – the wet playa and the dry playa. The Mojave Desert in southern California (USA) offers the opportunity to examine both types of playa under conditions of minimal to extensive human disturbance. Repeated ground-based and satellite observations of wet and dry playas in the Mojave Desert between 2000 and 2005, along with previous hydrologic studies (Czarnecki, 1997), provide the basis for this report. These observations reveal that surface sediments at three wet playas (Franklin Lake, Soda Lake and West Cronese

Lake playas) in the Mojave Desert are dynamic and at times are vulnerable to wind erosion and dust emission when sufficiently soft and (or) loose. Surface sediments at dry playas, on the other hand, are typically stable and hard and thus generally do not emit large amounts of dust when undisturbed by human activities. The emphasis of this report is on the hydrologic and sedimentologic interactions that may sustain dust production from wet playas.

Wet and Dry Playas – Definitions and Characteristics

Playas vary greatly in their geologic and hydrologic settings, leading to several classification schemes that group playas by sedimentologic or hydrologic characteristics (summarized by Smoot and Lowenstein, 1991; Rosen, 1994; Gill, 1996). With respect to dust emission from playas, we find useful the distinction between 'wet' and 'dry' playas (see Rosen, 1994). In a wet playa, ground water is near (typically <5 m) or at the playa surface, through which it is lost by evaporation or fluid outflow (Figure 1(a)). In a dry playa, ground water does not interact with the surface because the water table lies far below the surface (typically >5 m; Figure 1(b)). Both wet and dry playas may receive surface-water runoff.

The different hydrological and hydrochemical processes operating at wet and dry playas produce very different surfaces and surficial sediments (see, e.g., Thompson, 1929; Stone, 1956; Neal, 1965, 1972; Neal and Motts, 1967; Eugster and Jones, 1979; Smoot and Lowenstein, 1991; Rosen, 1994). In wet playas, capillary action in sediments, as controlled largely by sediment texture and structure, allows for continuous evaporation of water from shallow ground water (Figure 1(a)). Evaporation of shallow ground water through playa sediments commonly produces very soft surfaces as well as the formation of evaporite minerals (such as $CaCO_3$, $CaSO_4 \cdot 2H_2O$, NaCl, Na_2SO_4) in the capillary fringe zone and on the surface. As evaporite-mineral crystals form, their mass physically displaces rock-derived clastic minerals, expanding the sediment upward; on hot days, such evaporite minerals can be seen crystallizing within minutes of exposure of wet sediment to air. The evaporative loss of large quantities of water may thus produce 'fluffy' sediment having abundant evaporite minerals and a high volume of pore space (see Smoot and Lowenstein, 1991; Czarnecki, 1997). Fluffy sediment may also form on a playa surface when efflorescent salts grow directly from evaporating water or from the dehydration of hydrated salts. More compact, but still friable, sediment may develop on surfaces of wet playas. Such sediment, termed 'puffy' (Neal, 1972; Czarnecki, 1997), contains a smaller volume of evaporite minerals as a result of lower rates of evaporation and (or) lower salinity of evaporating groundwater. In addition to the production of soft surfaces, evaporation of solute-rich ground water commonly results in durable crusts (Smoot and Lowenstein, 1991). The crusts may consist of evaporite minerals or a mixture of evaporite and clastic sediments. Several studies have investigated the resistance of salt crusts to wind erosion (e.g. Gillette *et al.*, 1980, 1982; Argaman *et al.*, 2006). Surfaces of dry playas are hard when composed of compact and fine-grained clastic sediments, and they generally resist dust emission (see Gillette *et al.*, 1980, 1982).

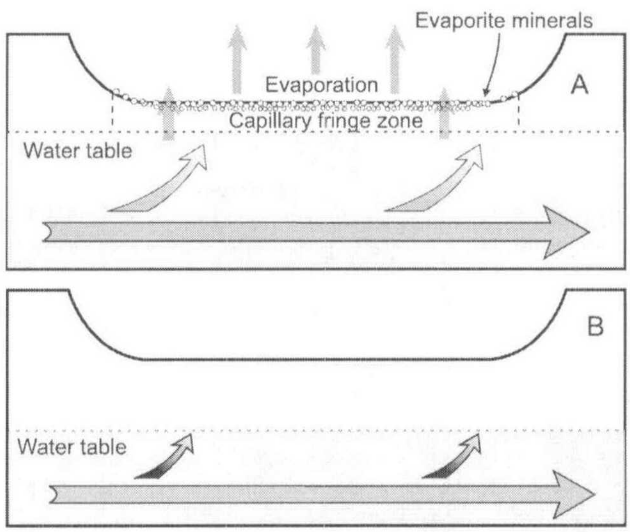

Figure 1. Schematic cross-sections illustrating elements of (a) wet and (b) dry playas, illustrated for a hydrologically closed basin. Modified from Figure 2 of Rosen (1994). The large arrow denotes the regional path of ground-water flow.

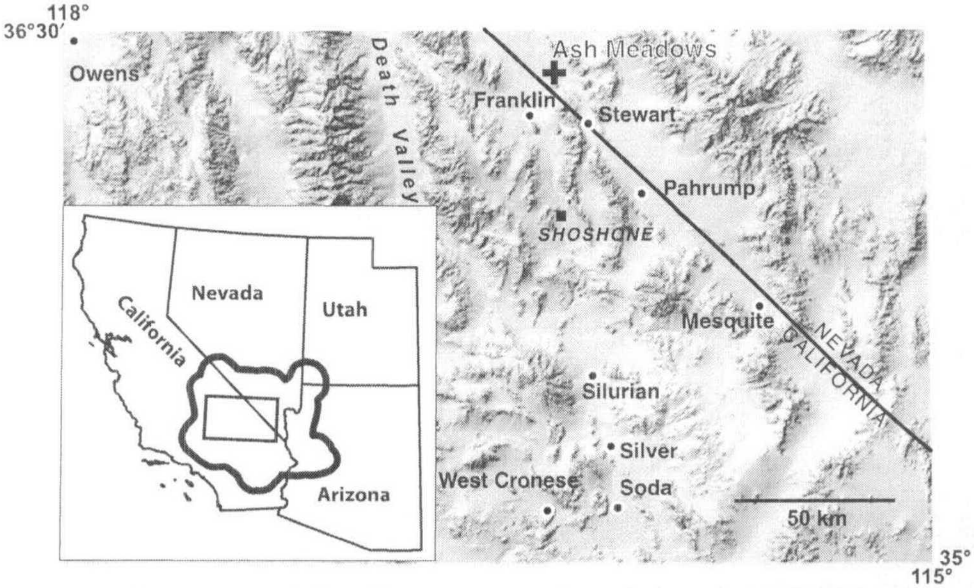

Figure 2. Location map of the study area (indicated by an open rectangle inside the outline of the Mojave Desert shown by the heavy line in the inset map) in California and Nevada. The map shows playas (filled circles), the town (filled square) and other features described in the text.

Setting

The study area is in the Mojave Desert, Nevada and California (Figure 2). The Mojave Desert, most of which lies at 600–1200 m elevation, receives nearly all of its precipitation (50–125 mm annually) during winter frontal storms from the Pacific Ocean (Hastings and Turner, 1965). General aspects of climate, soils and plants are described by MacMahon and Wagner (1985).

Few studies have investigated regional dust issues in the Mojave Desert. Visibility data from widely separated meteorological stations indicates that most dust emission occurs during the late winter and spring (Brazel and Nickling, 1987; Bach *et al.*, 1996). Interannual dust emission has varied greatly over the past few decades and appears to be associated closely with antecedent precipitation (Brazel and Nickling, 1987; Bach *et al.*, 1996). Relations among El Niño-Southern Oscillation (ENSO) events, dust sources and dust composition have been elucidated by Okin and Reheis (2002) and Reheis (2006). The fluxes of silt–clay dust and soluble-salt dust increased during regionally wet El Niño events at sites close to wet playas. The silt–clay flux also increased during periods of drought at sites downwind of alluvial sources and dry playas. These increases are probably related to loss of vegetation on alluvial sediments, and in some cases to local runoff events that deliver fresh sediment to playa margins and distal parts of alluvial fans. Some dust source areas have been discussed by Wilshire (1980), Muhs (1983) and Gill (1996). The most thoroughly studied of these sources is Owens (dry) Lake (Figure 2) that has been the largest single source of particulate-matter emission in the United States since the lake developed into a wet playa after diversion of inflow to the lake basin beginning in 1913 (e.g., Saint-Amand *et al.*, 1986; Gill and Gillette, 1991; Cahill *et al.*, 1996; Gill *et al.*, 2002).

We focus observations and discussion on Franklin Lake playa in the Amargosa Desert of the eastern Mojave (Figure 3) as our primary example of the processes involved in dust emission from a wet playa. For comparison, we include supplementary observations and preliminary results from other wet and dry playas nearby. The other wet playas are Soda Lake and West Cronese Lake, and the dry playas are Stewart, Pahrump and Silurian playas (Figure 2).

Franklin Lake playa receives most surface-water flow from two ephemeral drainage systems, the Amargosa River and Carson Slough (Figure 3). Flow in these streams merges in the southwestern area of Franklin Lake playa and, when sufficient, continues southward towards Shoshone and ultimately into Death Valley, as it did in February and March of 2005. Local runoff also comes from mountains and alluvial fans bounding the playa on its east and west margins. Despite lying in the path of these drainage systems, Franklin Lake playa does not become a lake during times of heavy precipitation and runoff. This condition reflects the capacity of these streams to carry runoff through the playa basin. Using MODIS and Landsat satellite images, we monitored the Mojave Desert between September 2004 and March 2005, which included periods of heavy precipitation (for example, 238 mm near Pahrump Playa; http://www.wrcc.dri.edu/) and found that Franklin Lake playa remained free of standing water whereas several playas in the

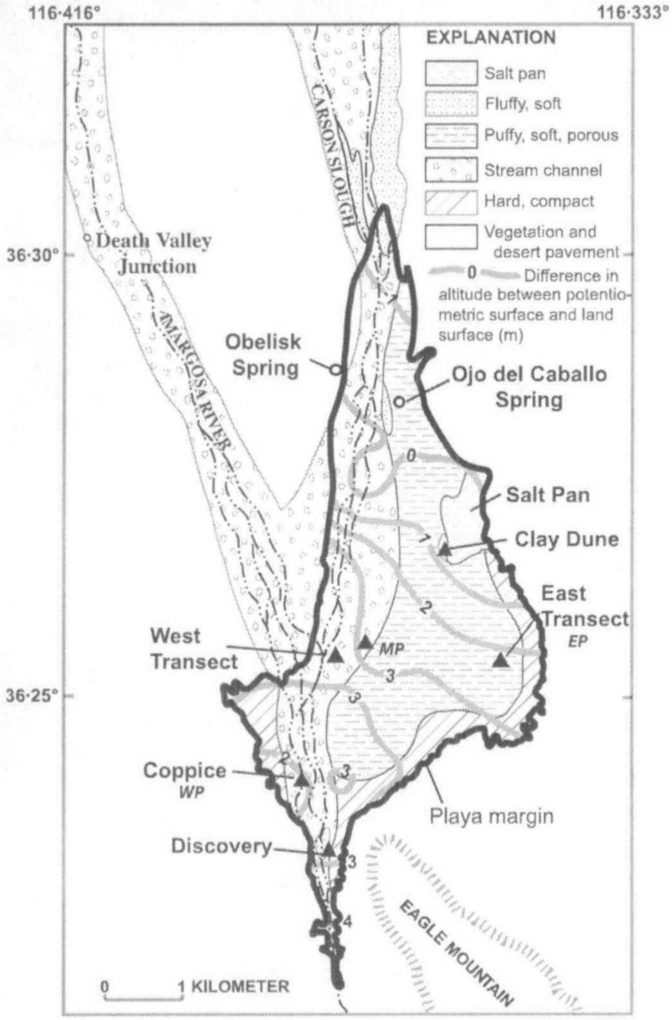

Figure 3. Distribution of surfaces at Franklin Lake playa, locations of repeat sampling sites and difference between potentiometric surface and ground surface. Modified from Figures 3 and 12 in Czarnecki (1997). Triangles denote sampling sites, and open circles denote springs. Collecting sites for cesium-137 analyses (Figure 9): WP, west playa at Coppice site; MP, middle playa; EP, east playa at East Transect site.

region were submerged for many weeks. Eastern parts of Franklin Lake playa receive local runoff and sediment from mountains and fans that bound the eastern side of the playa.

Previous hydrologic studies at Franklin Lake playa (Czarnecki, 1997) and in the region north of the playa in the Amargosa Valley (Winograd and Thordarson, 1975) provide a framework for this investigation. The shallow ground-water potentiometric surface in the valley-fill aquifer describes a north-to-south ground-water flow gradient in the Amargosa Valley to Franklin Lake playa (Plate 1 of in Winograd and Thordarson, 1975). Flow in the valley-fill aquifer is likely focused along the Amargosa River and Carson Slough channels, thereby delivering solutes from throughout the valley to Franklin Lake playa. Chemical analyses of ground water from 11 sampling sites on the playa reveal enormous variations in salinity (McKinley *et al.*, 1991). These data show highest salinities beneath parts of the playa to the east of the channels of the Amargosa River and Carson Slough (Figure 3); dissolved solids (TDS) in ground water from the central and south-central part of the playa reach about 70 000–80 000 mg/L. Ground waters from areas closer to the main surface-drainage paths have TDS levels of typically 6000–20 000 mg/L. These salinities contrast with those in ground water under confined flow in the valley-fill aquifer in the northern part of Franklin Lake playa. Ojo de Caballo Spring has a TDS of about 2500–5000 mg/L, and a flowing well at Obelisk Spring, approximately 1 km to the west, has a TDS of about 1000 mg/L (Walker and Eakin, 1963). Taken together, these results reflect the degree to which evaporation elevates TDS in ground water at Franklin Lake playa, with highest salinities produced in the ground water having relatively long residence times in the central and south-central areas (Czarnecki, personal communication, 2006).

As unconfined ground waters evaporate at Franklin Lake playa, they precipitate minerals such as halite (NaCl), trona ($NaH[CO_3]\cdot Na_2[CO_3]\cdot 2H_2O$), thenardite ($Na_2SO_4$) and burkeite ($2Na_2[SO_4]\cdot Na_2CO_3$). The primary solutes in the ground water are derived from rock–water interactions within sediments in the valley-fill aquifer (Winograd and Thordarson, 1975). A secondary solute source in the valley-fill aquifer is dissolution of evaporite minerals following large storms.

At Franklin Lake playa the depth to ground water, and hence the thickness of the capillary fringe zone, appears to be static in places and dynamic in others. Measurements of water levels in piezometers were made during a 16–24 month period (1983–1985) by Czarnecki (1990) and used to contour the water-table altitude (Figure 3). The hydrographs of water levels show very little variation for wells in highly transmissive sediments and large variation, sometimes gradual and sometimes abrupt, for wells in less permeable sediments.

Methods

Field studies were designed to examine various sediment types with respect to their vulnerability to wind erosion and to their general hydrologic setting. Five sampling sites representing a variety of surface types were selected for repeat characterization of physical and mineralogic properties over a 2 year period (Figure 3). Sediment samples at all sites were typically taken at 0–1 cm, 1–5 cm and 5–10 cm depths. Sediment mineralogy was determined by standard X-ray diffraction techniques. Surface and subsurface penetration resistance measurements were made periodically at selected sites with a spring-piston style pocket penetrometer and a simple soil compaction tester. Surface shear-stress measurements were made *in situ* with a hand-held shear vane tester. These measurements were made to evaluate changes of the playa surface and its sediments at these few sites and were not intended for comprehensive description of playa sediment strength (see Sanglerat, 1972). The relations between sediment strength and eolian erosivity are not straightforward and are not assessed here (see Rice *et al.*, 1997; Gillette *et al.*, 2001; Langston and McKenna Neuman, 2005).

Concentrations of cesium-137 were measured in sediments at Franklin Lake playa to determine whether this radionuclide recorded aggradation and (or) deflation during the past half-century. Cesium-137 is produced by nuclear fission and first appears in the geologic record coincident with the onset of hydrogen-bomb detonation. Ritchie and McHenry (1990) discuss the application of cesium-137 studies to elucidate geomorphic processes and dating of surficial deposits, and Fuller *et al.* (1999) describe the radioanalytical procedures used here.

We began systematic monitoring of dust emission in April 2005 using an array of anemometers at 2 m height above the playa surface and images from a digital camera placed on a telephone pole at 4 m height about 200 m west of the western playa margin; the camera is programmed to obtain images when the wind at the camera site exceeds $6\cdot 7\ m\ s^{-1}$. The time of images can be compared with the time of wind records on the playa.

Results and Observations

Surface sediment characteristics and dust emission – Franklin Lake playa and other wet playas

Observations during the course of this study, building on detailed prior work especially at Franklin Lake playa (Czarnecki, 1997), document that surface characteristics of wet playas are highly variable in space and time. Repeat measurements of sediment strength further show that surfaces may change rapidly. These changes influence the capacity of wet-playa surfaces to emit dust, as well as the timing of dust emission.

Surface sediments of Franklin Lake playa differ spatially at any one time (Figure 3). Sediments residing above a shallow water table are sometimes fluffy and contain abundant efflorescent salt minerals (halite, thenardite, trona, burkeite) and calcite, as well as clastic silt and clay particles. Clay minerals in these samples are illite, smectite, mixed-layer illite–smectite and kaolinite. The fluffy sediments are common in both the southern and northern parts of the playa, where the potentiometric surface is normally one to two meters below the surface (Figure 12 in Czarnecki, 1997), and they are also associated with clay-pellet dunes. In all areas of fluffy sediments, saltgrass (*Distichlis stricta*) is common. The capacity of saltgrass to excrete salt on its plant surfaces (Wiebe and Walter, 1972) raises the possibility that saltgrass contributes salts to the fluffy surfaces. Thenardite is the only evaporite mineral identified at the clay-pellet dune study site ('clay dune' in Figure 3). Puffy sediments characterize the central and southern areas of Franklin Lake playa east of the stream channels, where the unconfined water table varies between 2 and 4 m below the surface (Figure 3: Czarnecki, 1997). Salt minerals in these sediments are mainly thenardite, with lesser amounts of halite. Consistently puffy, very soft sediment occurs in the south-central part of the playa, where it is associated with ground water having the highest salinity, even though ground-water levels are relatively deep (to 5 m) and variable (Czarnecki, 1990; personal communication, 2006). Thinly laminated salts (thenardite, halite, burkeite and trona) commonly occur in a limited area (about 50 hectares) in the east-central part of Franklin Lake playa, where ground water is within 1 m of the playa surface.

Surface sediments of Franklin Lake playa change over time in texture and strength. Areas capable of producing fluffy sediment undergo frequent changes in the amount of efflorescent minerals on the ground surface (Figure 4) and associated measures of sediment strength (Figure 5). These changes can result from wind deflation over periods of days or weeks, from rainfall events over minutes to hours, from seasonal temperature changes (Saint-Amand *et al.*, 1986) or possibly from seasonal or longer-term fluctuations of the near-surface water table. Examples of changes from a rainfall event (February 3 2004) and from wind deflation (April 15 to May 26 2005) are illustrated in Figure 4. The meteorological station at Amargosa Valley, 27 km north of Franklin Lake playa, recorded 1·3 cm of rainfall on February 2 2005, and standing water in small depressions was observed in the vicinity of Discovery site on the following day. Daily maximum wind gusts in excess of 20 m s^{-1} were recorded at the same meteorological station during the dust mobilization events of late April and early May 2005.

Puffy surface sediment also may change with time, as expressed both in horizontal sediment surface strength and vertical surface strength (Figure 5). Measured changes in strength at two sites of consistently puffy sediment, however, show much less variability compared with changes at the Discovery site that are capable of producing fluffy sediments along with evaporite-mineral crust. Puffy sediment at a depth of less than a meter changes in strength (penetrability) over time periods of only a few weeks. Five spear penetrometer measurements at the East Transect site, made between May 2003 and May 2005, revealed an initially stiff subsurface that softened over the summer of 2003, gained stiffness through the winter of 2004 and spring of 2005 and softened again later that spring (Figure 6). Interestingly, the sediment within the top 10 cm at this site appeared to weaken while the subsurface strengthened over the period from May 11 2003 to January 31 2004. Some of the changes at the surface may be related to drying and associated mineralogic change during intense summertime heat.

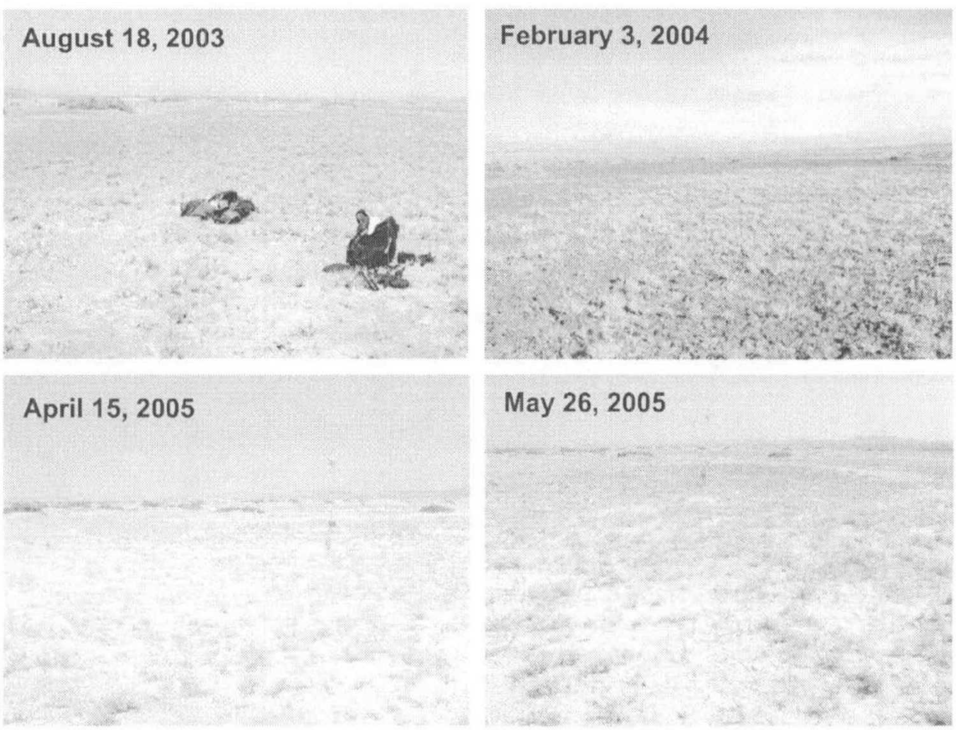

Figure 4. Repeat photographs at Discovery site, Franklin Lake playa. Surface in August 2003 consisted mainly of gray silt with remnants of white fluffy evaporate-rich sediment near clumps of saltgrass. Efflorescent salts were removed by heavy rainfall on February 2 2004 as shown in the photograph taken the next day. On April 15 2005 the surface consisted of extensive fluffy efflorescent salts that were subsequently removed by wind erosion, as shown in the photograph taken on May 26 2005.

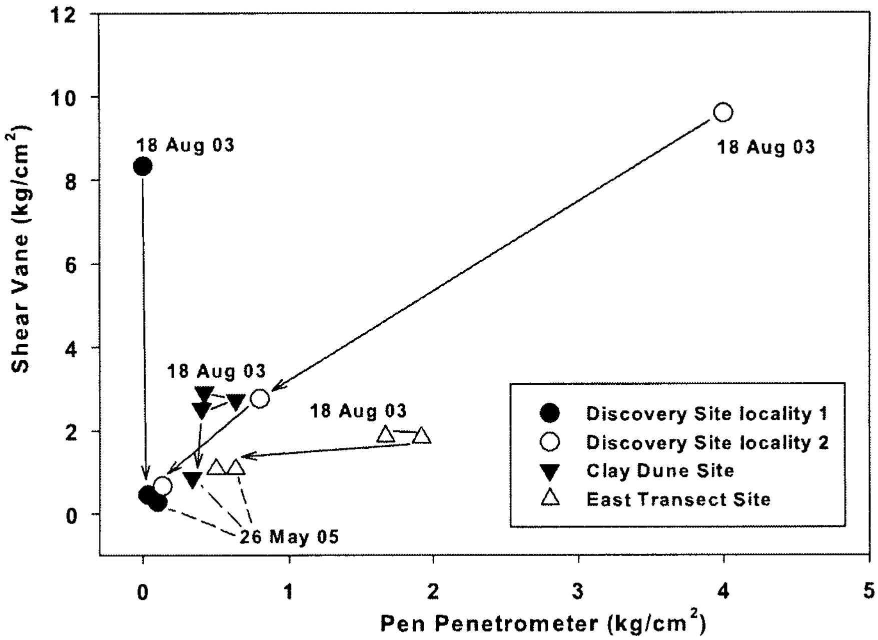

Figure 5. Plots of pen penetrometer versus shear vane tests for repeat-measurement localities in surface sediments at Discovery, Clay Dune and East Transect sites. At each locality, the initial measurements were made on 18 August 2003 and the last on 26 May 2005. The intermediate measurements were made at the Discovery site on 31 January 2004, and on this day as well as 16 April 2005 at the Clay Dune and East Transect sites. Over the period of measurement, locality 1 at Discovery site was mostly characterized by fluffy or puffy sediment, whereas locality 2 on 18 August 2003 had a hard crust. The Clay Dunes and East Transect sites have nearly always had dominant characteristics of puffy sediment. For Discovery site (locality 1, solid circles), the 18 August plot indicated very low vertical strength and high horizontal strength. This condition was caused by a very thin (a few millimeters) layer of weak sediment at the surface atop evaporite-mineral crust.

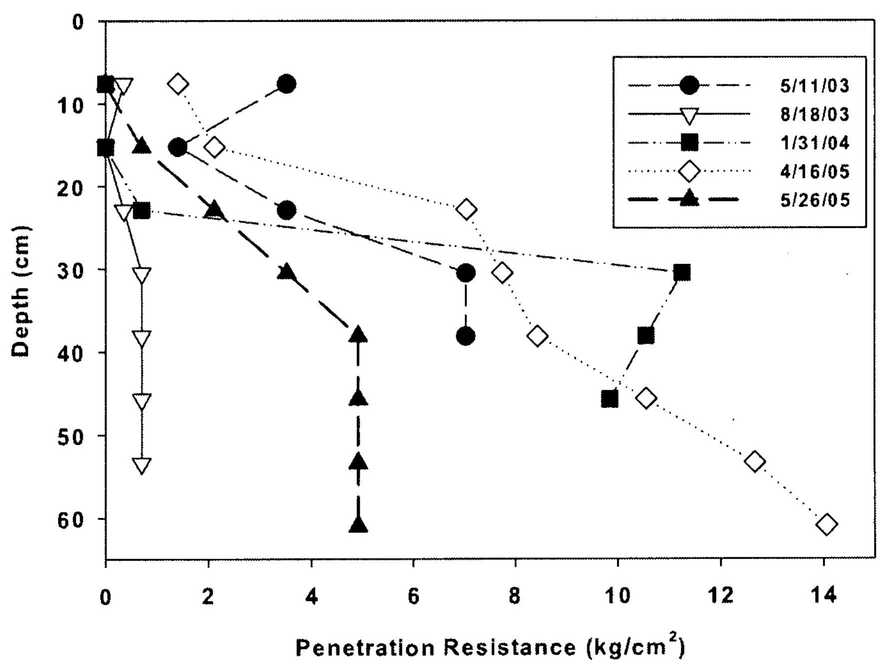

Figure 6. Subsurface spear-penetrometer measurements at East Transect site showing changes in sediment strength at depth from 2003 until mid-2005. Sediment weakens from May 11 2003 to August 18 2003, strengthens to January 31 2004 and then weakens again to May 26 2005.

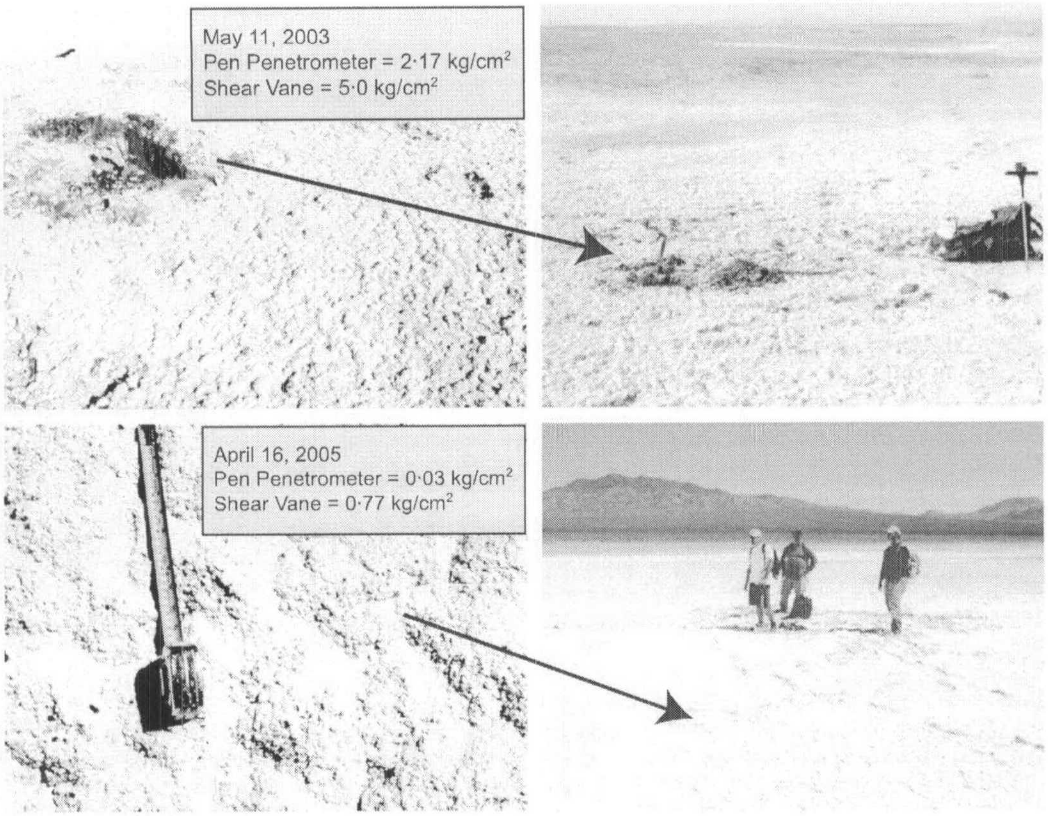

Figure 7. Surface characteristics and strength properties of the salt-pan area on Franklin Lake playa during crusted conditions (May 11 2003) and fluffy conditions on April 16 2005. The dark soil in the upper-left (May 11) photograph was wet. The two locations at the repeat-measurement site were within 3 m of each other.

The area of laminated salt undergoes dramatic and rapid shifts in properties (Figure 7) in response to local hydrologic change. During 2003, a thick stiff salt crust covered wet sediment. In spring of 2005 thin, fluffy, efflorescent-rich sediment covered remnants of older salt crust and wet sediment. The structure of the salt crust can be complex. In February 2004, efflorescent salts filled desiccation cracks in the bedded salts. These cracks implied a drop in the water table that led to the evaporative crystallization of efflorescent salts in a deepening capillary fringe zone. Remarkably, the water table at this site appeared to fall (drying) over the time span when the shallow unconfined aquifer in the northern part of the playa was recharged and flowing.

The character of evaporite-mineral surfaces above valley-fill aquifers also changes over time. In the northeastern part of the study area (in and near the channel of Carson Slough), and north of the playa in Ash Meadows, the potentiometric surface varies from shallow (<1 m) to above ground surface (Czarnecki, 1997). Surface sediments on these areas can be fluffy, puffy or crusty. Regardless of texture, evaporite minerals in these sediments almost always consisted of trona, halite, thenardite and burkeite over the period of our mineralogic observations (2003–2005). Fluffy sediment may also form by evaporation of shallow ground water following large storms and wet years. Such deposits were still common in February 2004 following a large storm event in August 2003 that resulted in substantial surface flow and recharge of the shallow unconfined aquifer.

The parts of Franklin Lake playa with fluffy sediments frequently emit dust under moderate winds. Using images from the remote digital camera, we have documented emission of evaporite-mineral dust in response to winds between about 6·7 and 9·0 m s^{-1} at 2 m height on the playa (Figure 8). Puffy sediments are also susceptible to dust emission as observed, for example, when disturbed by a moving field vehicle. We have not made detailed observations of dust emission from Franklin Lake playa in very high winds exceeding about 25 m s^{-1}. Nevertheless, our observations of GOES satellite images acquired during April 22 2004 revealed high dust emission from Franklin Lake playa in winds that reached a maximum of 13 m s^{-1} that day at Amargosa Valley.

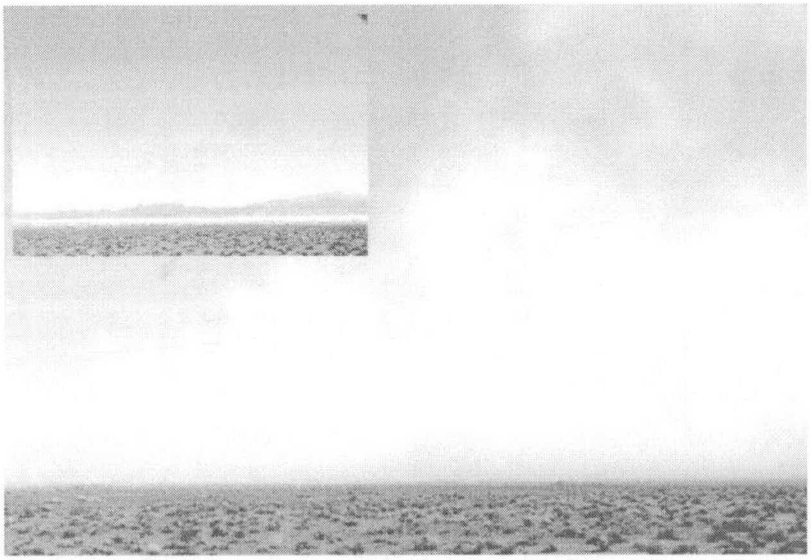

Figure 8. Dust emission from the central parts of Franklin Lake playa, at 0935 on March 14 2005, in about 9 m s^{-1} windspeed based on the anemometer record at Discovery site (Figure 3). The inset shows the playa condition about one hour later in calmer conditions. Images were taken by a remote digital camera mounted at 4 m height that is triggered when winds at the camera station exceed 6·7 m s^{-1}.

White plumes of dust, presumed to be salt rich, from Franklin Lake playa have also been observed from areas underlain by coarse-grained fluvial sediment that are sites of recharge into and discharge from the valley-fill aquifer. For example, dust emission from surfaces along the Amargosa and Carson Slough drainages was seen in January 2004 and in April 2005. These episodes may have been engendered by unusually heavy rainfall in the area during August 2003 and during the winter of 2004–2005, which likely recharged the shallow aquifer in the fluvial sediments.

Dust emission from Franklin Lake playa is also affected by seasonal meteorological variations. The strongest winds are associated with passage of winter frontal storms and cause the greatest dust generation. Dust devils may occur at any time of the year and appear to be the main cause of dust entrainment during the hot summer months that are typically characterized by mild regional winds. In both regional winds and dust devils, dust is transported from the playa onto adjacent alluvial fans and beyond, and dust is sometimes carried from these fans back onto the playa floor (Czarnecki, personal communication, 2006).

The variable time spans of wetting from rainfall and drying of Franklin Lake playa have direct influence on dust emissions. When surfaces are wet, little dust is produced because the evaporite minerals are soluble or bound in damp sediment and thus unavailable for eolian entrainment (see, e.g., McKenna Neuman and Nickling, 1989; Fécan *et al.*, 1999). Moist phases in the study area may be short lived, often lasting only a few days, or of longer duration, such as during the winter of 2004–2005. During the wet late autumn, winter and early spring of 2004–2005, efflorescent salts crystallized locally on the surface within only a few days after heavy rainfall. The arid phase has the potential to produce dust continuously as long as ground-water flow in the valley-fill aquifer maintains near-surface water (within about 5 m) in the playa sediments. Evaporation of near-surface water promotes the production of evaporite minerals in clastic sediment and may thus maintain soft sediment surfaces. The most consistently soft surfaces at Franklin Lake playa are in the central and south central parts above the most saline ground water, even though the depth to the ground-water table there may be as much as 5 m (Czarnecki, personal communication, 2006). This association underscores the important influence of ground-water salinity on sediment type and texture in wet playas. The central and south central parts of the playa are thus highly vulnerable to dust emission under high winds (greater than about 15 m s^{-1}) capable of dismantling very thin salt crusts (see Argaman *et al.*, 2006).

Estimates of the aggradation and deflation of clastic sediment on Franklin Lake playa over the past 55 years are provided by cesium-137 results of samples collected at five sites: from the playa surface at western, middle and eastern sites, and also from places of eolian accumulation in coppice dunes in the western part of the playa and in clay-pellet dunes in the eastern part (Figure 3). Cesium-137 concentrations and distributions vary greatly. Relatively high concentrations are found within the upper 29 cm at the western site (to 0·120 pCi g^{-1}) and within the upper 24 cm at the middle site (to 0·084 pCi g^{-1}). The results indicate net sediment alluvial accumulation of about 5 mm/year since

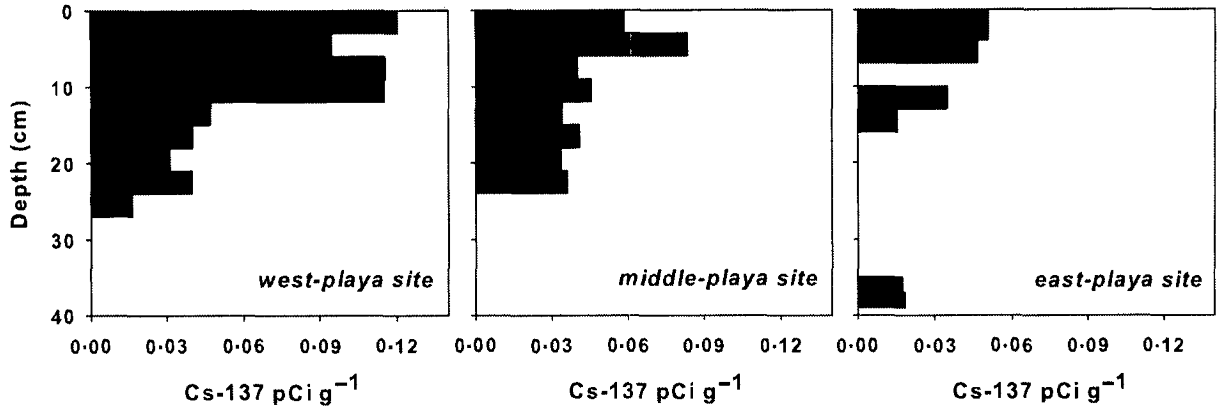

Figure 9. Plots of depth against cesium-137 activities in picoCuries per gram for the west-playa (WP), middle-playa (MP) and east-playa (EP) sites (see Figure 3 for locations). The cesium activities have been decay-corrected to March 1 2005.

~1951 at the west-playa and middle-playa sites (Figure 9) from floods that occur, on average, every 5 years. Lower concentrations (to 0·051 pCi g^{-1}) are measured at the eastern site, nearly all of it within only the upper 15 cm. These depth distributions compare with cesium-137 occurrences limited to 6 cm depths at four isolated reference sites on stable Pleistocene terraces about 70 km north of Franklin Playa, where cesium-137 accumulation is believed to be primarily from airfall (BSC, 2004). Although some downward movement of cesium-bearing particles cannot be discounted at the playa setting, the results strongly imply that the observed differences are related to proximity to floodways and to deflation. The western-playa site, where the greatest cesium-137 concentrations are found, is located closest to the braided and coalesced floodplains of the Amargosa River and Carson Slough. The lowest concentration and mostly shallow distribution of cesium-137 at the eastern site is consistent with lower amounts of flood-borne sediment and active wind deflation. Firm evidence that modern flood and playa sediments are actively being reworked by winds is the presence of cesium-137 in samples of the clay-pellet dune and coppice dunes (maximum values 0·141 and 0·028 pCi g^{-1}, respectively).

Our observations of two other wet playas in the region, Soda and West Cronese lakes (Figure 1), reveal similar characteristics during 2000–2004 to those observed at Franklin Lake playa. At West Cronese playa the presence of bedded and efflorescent salts, along with observations from field augering of sediments, suggest that ground water is frequently near the surface. Evaporite-mineral production on West Cronese appears to vary with antecedent precipitation (over periods of a few months) on the basis of infrequent observations that show conditions ranging from limited to extensive salt cover.

Soda Lake commonly has large areas of bedded salt and efflorescent salts where ground water is at or near the surface of the playa, especially around flowing springs along the western playa margin and near inflowing drainages at the south end of the playa (Thompson, 1929). Ground-water levels deepen toward the east and north (http://nwis.waterdata.usgs.gov/nwis/gw), where the playa sediments tend to be hard packed and lack efflorescent salt. Heavy local or regional precipitation results in periodic episodes of flooding and standing water on Soda Lake. Ground observation and MODIS satellite imagery documented such flooding during late August 2003 and January–February 2005 and also subsequent drying that produced widespread surfaces rich in efflorescent salt. Within nine days after the playa flooded in January 2005, efflorescent salt had crystallized across much of the playa, and soon afterward the entire playa surface was deflated during a windstorm lasting less than a day. Similarly, West Cronese Lake produced large plumes of saline-mineral dust after the formation of soft, salt-rich surficial sediments during the winters of 2004 and 2005. An example of dust emission from Soda Lake is shown in Figure 10.

Surface sediment characteristics and dust emission – dry playas

The surfaces of dry playas in the study area (e.g. Silurian, Stewart, Silver and Pahrump playas; Figure 1) are mostly composed of tan to brown fine silts and clays that mostly form hard-packed surfaces (Figure 11; see also Thompson, 1929; Neal, 1972). These surfaces lack bedded or efflorescent salts. Loose silt and sand on dry-playa surfaces are periodically derived from overland flow down alluvial fans and from transient eolian deposition. Widespread sediment dispersion onto playas probably occurs when storms are large enough to create shallow lakes, as occurred on all the aforementioned playas during the winter and spring of 2005. The water-table depth is typically 10 m or more under

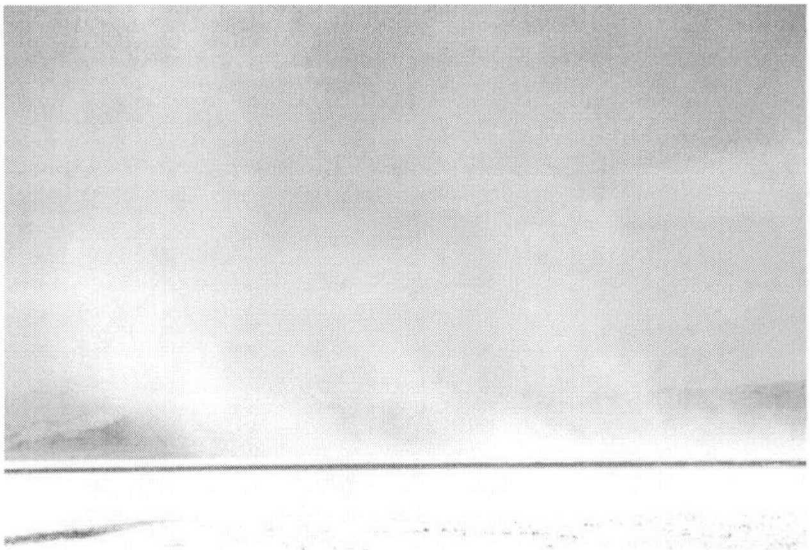

Figure 10. Emission of evaporite-mineral dust from Soda Lake, February 6 2001.

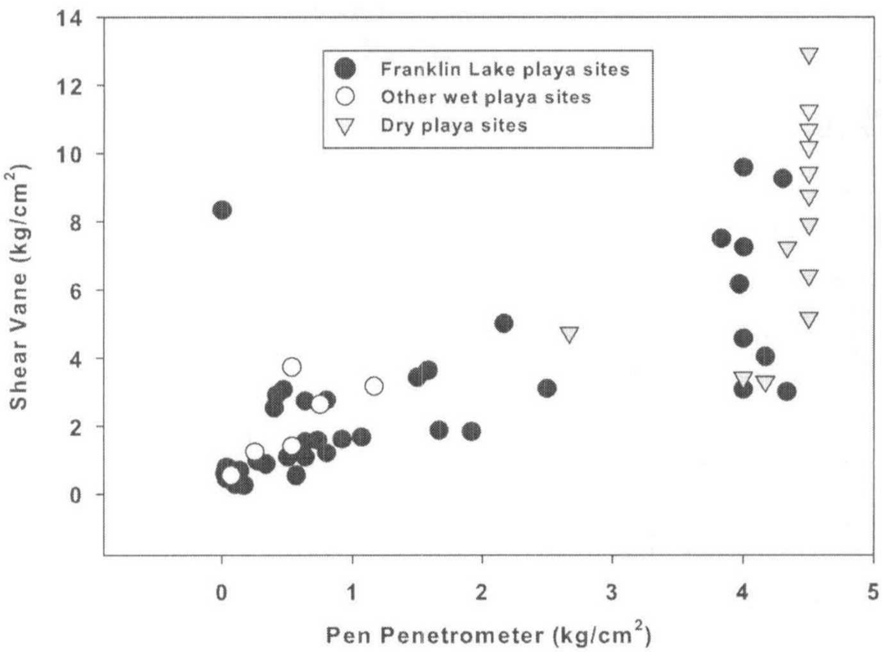

Figure 11. Plot of pen-penetrometer (representing vertical strength) versus shear-vane (representing horizontal strength) results for several playas classified as both wet and dry in the Mojave Desert. The data point from Franklin Lake playa with high horizontal but low vertical strength is discussed in the caption for Figure 5. Crusted surfaces at Franklin Lake playa yielded results showing high vertical strength (pen penetrometer readings >3 kg cm^{-2}).

Stewart Lake and more than 20 m under Pahrump playa (http://nwis.waterdata.usgs.gov/nwis/gw). In the late 1950s and early 1960s the water-table depth at the eastern margin of Silver Lake was 11 m, and before then Thompson (1929) reported depths greater than 15 m beneath the playa. We do not have information about the depth of the water table under Silurian Lake.

The surfaces of dry playas having surfaces of compact clastic sediment (i.e. clay crusts) in the study region are very stable, and they are not usually sources of large dust emissions. Dust may be generated from dry playas when the surface is broken by human activity, or in high wind (1) when turned-up edges of mud cracks are mobilized and involved in impacts and disaggregation and (2) when loose, clastic alluvial sediment is available for saltation and deflation (see Gill, 1996; Houser and Nickling, 2001). For example, after flooding by the August 2003 storms, Silurian Playa subsequently produced local plumes of dust that appeared to be derived largely from the sediments recently deposited on the playa rather than from deeper sediments within the playa fill.

Discussion

Summary of playa types and potential for dust emission

Although many factors combine to control the potential for dust emission from playas, we can develop a general concept of the fundamental factors that influence the susceptibility of playa sediments to wind erosion (Figure 12). The factors considered include relations among hydrologic characteristics, thickness of the capillary-fringe zone and playa-surface characteristics, with respect to wet and dry playas. Surface characteristics illustrated in Figure 12 describe common, but not all possible, conditions for wet and dry playas. The separation between fluffy and puffy surfaces is transitional and is shown schematically. Moreover, areas occupied at times by fluffy and puffy surfaces may change to crusted surfaces sufficiently thick to shut down all dust emission. The presence of fluffy and puffy surfaces is illustrated to correspond to the depth to the potentiometric surface, without influence from other factors, such as rate of vapor discharge, salinity of evaporative vapor, precipitation and runoff, or the presence of hard evaporite-mineral crust. This model also does not account for disturbance to the surface and assumes sufficient wind shear stress on the surface to break up the weak mineral crust on puffy surfaces.

Rapid changes in wet-playa surfaces and sediments

The properties and characteristics of surficial sediment at Franklin Lake playa may change rapidly both as a response to rainfall on the playa surface and as a consequence of changing near-surface depth to ground water. Weather events that affect the ground-water table and thus influence subsequent dust emission include (1) intense storms, which can result in flow in local channels and recharge of the shallow ground water, (2) persistent and elevated winter precipitation, as observed during the 2004–2005 winter, (3) cool to cold winters that lower evaporation, thereby promoting recharge, and (4) intense summer heat that promotes evaporation from shallow ground water. Coupling between weather conditions and shallow ground water results in a very dynamic playa surface. For example, the degree of

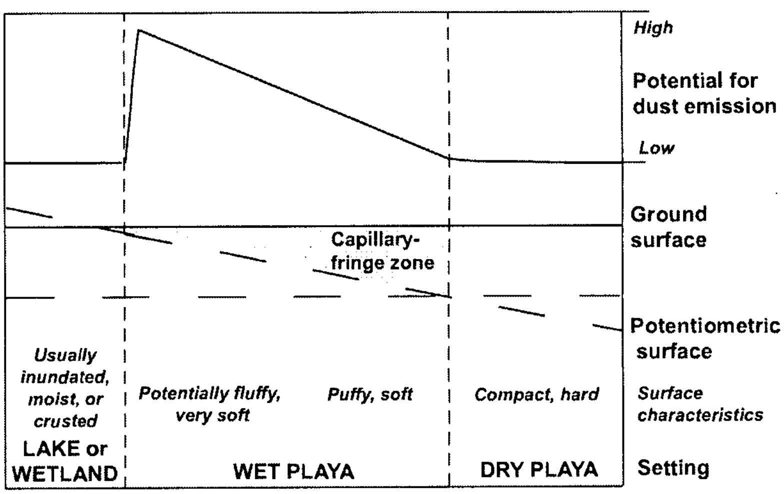

Figure 12. Schematic illustration of relations among potential for dust emission, thickness of the capillary-fringe zone and playa-surface characteristics, with respect to wet and dry playas. The horizontal dashed line represents the maximum depth of the capillary fringe zone. Surface characteristics describe common, but not all possible, conditions for wet and dry playas. The separation between fluffy and puffy surfaces is transitional and is illustrated schematically. The lines showing the potential for dust emission are schematic and are not based on observations or algorithms. The illustration assumes sufficient wind shear stress on the surface to break up the weak mineral crust on puffy surfaces.

sediment strength changed over the time span of our repeat measurements (Figures 5–7). Sediments in the uppermost 1 cm at sites having consistently puffy surfaces show much less change in strength than sediments at the Discovery site, which are seen to change among fluffy, puffy and crust states (Figure 5). This difference in behavior may reflect the higher sensitivity at Discovery site to (1) changes in ground-water salinity, (2) changes in temporal variability of water-table depth (Czarnecki, 1990) or (3) mineralogic change. The area sometimes characterized by laminated salt also changed dramatically between 2002 and 2005, alternating among a uniform surface of halite, a desiccation-cracked surface and a fluffy surface, composed dominantly of halite. These changes are likely related to changes in water-table depth and resulting changes in the thickness of the capillary fringe zone that characterize this site, as documented by Czarnecki (1990) during the 1980s.

Another cause of change in surficial sediment might be related to variations in ground-water salinity. Relatively saline ground water results in higher potential for the development of fluffy sediment and likely affects the strength of puffy sediment as it controls the concentration and sizes of evaporite minerals.

Despite rapid changes in surface properties, we have not observed evidence for major areal shifts in zones of dominantly fluffy or puffy textures, or for interchangeability between these surface types as shown in Figure 3. Over the short period of our study, this result is expected, because the types of dominant surface texture are probably linked to fundamental characteristics of aquifers and confining beds that remain spatially fixed.

Although this study emphasizes the development of soft, wind-erodible surfaces on wet playas, it is important not to lose sight of the hard, evaporite-mineral crusts that suppress dust emission from wet playas and coastal sabkhas. Gillette *et al.* (1980, 1982) have documented the resistance of these kinds of crust to wind erosion using wind-tunnel experiments on natural surfaces. Many other laboratory studies have investigated the effects of salt-mineral content and (or) different kinds of crust on the threshold shear velocity (e.g., Nickling and Ecclestone, 1981; Nickling, 1984; Rice *et al.*, 1996, 1997; Argaman *et al.*, 2006). We have observed that evaporite-mineral crusts commonly form a protective cover for a layer of unconsolidated and dry fine-grained sediment that may be relatively thick (of the order of 10 cm) compared to the crust (commonly <1 cm). When such crusts are broken in strong winds, large volumes of underlying soft sediment are likely to be readily emitted as dust or in sand drift. This condition has been described at Owens (dry) Lake and Mono Lake (see, e.g., Saint-Amand *et al.*, 1986; Cahill *et al.*, 1996; Gillette *et al.*, 2001).

The variations and changes in surface properties observed at Franklin Lake playa appear to be common for wet playas in the western United States. In numerous observations in this region, Neal and Motts (1967) and Neal (1972) noted that playas are dynamic landforms as reflected by their geomorphic changes over daily, seasonal, annual and interannual time frames. At individual playas, Neal (1972) also noted that hard crusts may replace surfaces of soft friable sediment and the other way around. These observations have been extended by detailed studies of spatial variations and changes in properties and mineralogy of playa surfaces by others, most notably in work on Owens (dry) Lake (e.g. Saint-Amand *et al.*, 1986; Cahill *et al.*, 1996; Gillette *et al.*, 2001; Gill *et al.*, 2002).

Mixed and changing types of playa

The differences between wet and dry playas, as described in the foregoing, define end-member conditions with respect to their hydrology, surface textures, sediments and potential for dust emission. Many playas may not be strictly categorized into one or the other type. For example, some parts of Franklin Lake playa and Soda (dry) Lake have stable surfaces where depth to groundwater exceeds about 5 m, and these parts behave as dry playas.

Another type of dry playa lacks hard surfaces of fine-grained clastic sediment and instead is underlain by sediment that contains large proportions of evaporite minerals. These evaporite minerals were chemically precipitated in evaporating surface or ground water of an earlier lake or wet playa that no longer exists; they contrast with modern, ephemeral evaporite minerals, whose formation contributes to the development of soft, hummocky surfaces of contemporary wet playas. One playa in the study area, Mesquite Lake playa (Figure 2), contains thick deposits of gypsum and is capable of emitting large volumes of dust, as recently detected in geostationary satellite images (e.g. April 15 2002). The surface of Mesquite Lake is mostly stable, except after heavy rainfall, and depth to the water table is more than 4 m, on the basis of water-level measurements near the margins of the playa in November 2006. As recently as the 1960s, however, the surface was vastly different; moist soil conditions were widespread and 'fluffy' textures characterized the dry, upper few centimeters of the surface (Glancy, 1968; personal communication, 2006). Depth to ground water was 1–3 m, and ground-water discharge over the playa was estimated at 760 000 m^3 annually. These observations emphasize that some playas may produce dust from evaporite minerals that have formed during the past in wet playa or evaporative lake systems. Understanding the conditions and causes of dust generation at Mesquite Lake playa is complicated by long-term and ongoing disturbance there. The playa surface supports a gypsum-mine pit and many roads, and for decades ground water has been pumped for agriculture near the playa. Although the record of ground-water level in the area and its change with time is spotty, Mesquite Lake playa apparently records a conversion from a wet-playa state to a dry-playa state over a few decades. Unless the surface of low density, soft gypsum particles is covered by a hard blanket fine-grained clastic sediment in the future, Mesquite Lake playa will likely continue to produce dust.

Types of mineral dust and the importance of evaporite-mineral dust

There are many types of naturally emitted dust in the Mojave Desert and elsewhere, including: (1) clastic dusts produced in a variety of geomorphic and land-use settings (e.g. alluvial, dry lake, agricultural and other disturbed), (2) evaporite-mineral dust in dry lake (e.g. wet playa) and marginal marine settings and (3) biogenic dust, such as dust derived from diatomite beds, in former lacustrine settings. Improved assessments of the past, current and future environmental effects of dust depend on better understanding of the locations, conditions and processes involved in emission of different types of dust.

The distinction between clastic and evaporite-mineral dusts is important for many reasons. First, the differing chemical composition, size, shape and color of different types of dust likely control contrasting radiative properties (Sokolik and Toon, 1999) and thus may influence climate in diverse ways. Second, the different compositions of chemical and clastic dusts can be expected to produce differing atmospheric chemistry alone or in combination with other aerosols (Ellis *et al.*, 1993; Arimoto *et al.*, 1990; Li *et al.*, 1996). Third, the different types of dust will likely have different residence times in the atmosphere on the basis of different specific gravities, shapes and solubilities. Fourth, the different types of dust may have variable effects on human health and on marine and terrestrial ecosystems through differing biogeochemical pathways. Finally, associations between changes in playa hydrology and dust emission may combine to produce temporal lags between precipitation and dust emission from some important dust sources (Bryant, 2003; Mahowald *et al.*, 2003; Reheis, 2006; Zender and Kwon, 2005).

Analysis of satellite data strongly suggests that dusts from alluvial and lacustrine sources dominate global dust emission from natural settings (Prospero *et al.*, 2002). Documentation of the roles of playas and dry lakes as sources for a variety of dust types is improving (Bryant, 2003; Engelstaedter *et al.*, 2003); however, the lack of observations at high spatial and temporal resolution along with inconsistent behavior of dust emission in response to inundation (Mahowald *et al.*, 2003) limit our ability to determine the contributions of these settings to regional dust loadings. Recognition of different dust-producing processes at wet and dry playas, as discussed here, will shed light on the roles of dryland basins in the dust cycle. For example, our observations may partly explain the lack of consistent correspondence between playa inundation and dust emission.

The high sensitivity of large playas to regional rainfall patterns is recognized elsewhere (Bryant, 1999). In a study of Chott el Djerid, a large salt playa in southern Tunisia, Bryant documented close correspondence among rainfall events, lake-surface area and evaporation. Using remotely sensed data from advanced very high resolution radiometers (AVHRRs), he found that temporal reflectance profiles could indicate changes in the playa surface in response to large floods. More work is needed to understand when and why dust is emitted from these and similar settings, partly through recognition of the types and timing of emitted dust (clastic or evaporite mineral) after heavy rain.

Effects of human activity on dust emissions from wet playas

Human modification of playas and their hydrology has the potential to change the natural condition of dust activity. Understanding the effects of such human activity will improve forecasts of future dust loading as climate changes and as human pressures on hydrologic systems continue. For example, there are numerous and well known examples of water diversions that have starved lakes of surface water (e.g. Aral Sea, Owens Lake; Gill, 1996), thereby initiating desiccation and the beginning of a wet-playa phase. Similarly, ground-water pumping may desiccate shallow lakes to produce wet playas (Gill, 1996). Conversely, pumping could shut down dust production from wet playas by lowering their water tables to levels at which ground water can no longer interact with the surface by vapor discharge. The time period over which lowered or raised water tables may increase or eventually terminate dust production can vary greatly depending on several factors. Such factors include the rate of ground-water withdrawal or injection and related water-table decline or increase, as well as the stratigraphy, structure and type of sediment at the playa surface.

Broader Implications

Understanding the hydrochemical and sedimentologic processes at wet playas provides the framework to recognize how interacting hydrologic and geomorphic factors exert fundamental control on the size, shape, chemistry and mineralogy of atmospheric dust generated from them. Wet playas do not demonstrate constant behavior. The texture and hardness of their surface sediments change over periods of weeks to seasons to perhaps a few years, and such changes likely control the amount of dust generated over time. Although evaporite-mineral dust appears to make up a subordinate component of global dust load, it can be regionally and locally important in volume and potential chemical effects. Examples of regionally important dust sources from dry lake beds that behave as wet playas include parts of the Aral Sea (Kazakhstan and Uzbekistan), Owens Lake (CA, USA) and probably the Hamoun wetlands (now mostly dry) of Afghanistan and Pakistan. The distinctions between evaporite-mineral and clastic mineral dusts are likely important with respect to radiative properties of dust plumes, atmospheric chemistry, ecosystem dynamics and human health.

In the Mojave Desert, the production of salt-rich dust may be amplified or dampened by climatic factors, such as drying following wet years (e.g. El Niño) or large storms (e.g. related to strong monsoons or tropical depressions), by changes in ground-water salinity, by human activities that change the elevation of water tables or by inundation of playa surfaces over a long-time interval. We expect that similar factors and activities influence dust emission elsewhere.

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