THE ROLE OF WATER IN THE DEVELOPMENT OF
SURFACE ROUGHNESS AND MINERALOGICAL
VARIABILITY ON PLAYA SURFACE SEDIMENTS:
IMPLIEDSATIONS FOR AEOLIAN ERODIBILITY AND DUST
EMISSION

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by
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Abstract

Playas are significant sources for atmospheric mineral dust, but the evolution of their surface erodibility through time is not well established, leading to difficulties in modeling dust emission. Investigation of the spatial and temporal variability of surfaces within dust source regions has the potential to elucidate the processes that control erodibility and to improve model predictions of dust emission. In this dissertation the variability in time and space of surface mineralogical composition, particle size distribution, and surface roughness is measured in a playa (the Black Rock Desert, NV, USA). Water is found to be critical to the development of playa surfaces. Analysis of samples from the Black Rock playa demonstrates that the playa is mainly composed of quartz (∼30 wt%), clay (∼45 wt%), plagioclase (∼10 wt%), calcite (2-15 wt%), and halite (0-40 wt%). Composition varies between the center of the playa (more frequently inundated) and edge, with smaller particles, more clay, less plagioclase, and less calcite in the central areas. The surface roughness of the Black Rock playa is observed through time (2004-2010) using synthetic aperture radar (SAR) remote sensing data. Surface roughness is relatively constant during the dry summer months, but changes significantly from year to year, suggesting that water and inundation have more control on playa surfaces than anthropogenic activity or saltation abrasion. Roughness is low in years with heavy
precipitation, but late drying areas of the playa are rough. Small scale lab experiments on a playa analog surface demonstrate that cycles of wetting/drying increase roughness, particularly for surfaces with added CaCO$_3$; a surface with added CaCO$_3$ produced aggregates of a size appropriate for saltation (<100 µm) through wetting/drying cycles, while a surface with added NaCl remained relatively smooth. These observations suggest a conceptual framework for the development of surfaces in a playa: inundation smooths the playa surface while cycles of wetting/drying roughen it. The surface is particularly susceptible to roughening when it is rich in calcite.
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Chapter 1

Introduction

1.1 Dust: a critical component in the Earth system

Atmospheric mineral dust is an important component of geochemical cycles in the Earth system. In recent years, there has been growing recognition of the crucial role dust plays in many ecosystems, as a source of nutrients. Examples include arid grasslands and shrublands in the Canyonlands, USA (Reynolds et al., 2006), oak forest in the Montseny mountains, Spain (Avila et al., 1998), tree islands in the Okavango Delta, Botswana (Humphries et al., 2013), the tropical Hawaiian islands in the central Pacific (Chadwick et al., 1999), Barbados and the Bahamas in the Caribbean (Muhs et al., 2007), and the lowland and montane rainforests in South America (Koren et al., 2006; Boy and Wilcke, 2008). The Amazon rainforest in South America is perhaps the most striking example, receiving significant nutrient input from Saharan dust that has been transported 10,000 km across the Atlantic Ocean. Nutrients supplied to ecosystems include calcium, phosphorus, iron, magnesium, and potassium.
There has been much discussion of the impact of dust on oceanic productivity by means of iron fertilization (Martin, 1991; Jickells et al., 2005; Mahowald et al., 2009; Crusius et al., 2011; Schulz et al., 2012; Smetacek et al., 2012). The iron in dust is suggested to provide a limited micronutrient to remote areas of the ocean (particularly in the Southern Ocean), increasing productivity and removing carbon from the atmosphere via the biological pump. Since cooler temperatures are associated with increased dust deposition (Petit et al., 1999), there is a potential positive feedback; cooler temperatures lead to increased dust, which fertilizes the ocean, reduces atmospheric CO$_2$, and further cools the planet. This could help to explain how the Earth reached the extremely cold temperatures seen during glacial maximums.

One of the most significant impacts of atmospheric dust is on the Earth’s climate. Dust affects radiative transfer in the atmosphere in multiple ways depending on mineralogical composition and particle size/shape (Andreae and Rosenfeld, 2008; Hoose et al., 2008; Kok, 2011). Dust can scatter radiation, increasing albedo and cooling the climate, or it can absorb radiation and contribute to global warming (Arimoto, 2001; Forster et al., 2007; Mahowald et al., 2011). Dust also has an indirect effect on radiative transfer by affecting cloud formation by nucleating water droplets (as cloud condensation nuclei); here again, the chemical and mineralogical composition of dust is important, as cloud formation can be enhanced or suppressed by dust based on its affinity for water (Koehler et al., 2007). Dust is thought to have produced twice as much radiative forcing (cooling) during the dusty period at Last Glacial Maximum as today, contributing to the colder climate (Takemura et al., 2009). Also, anthropogenic changes in atmospheric dust
may have modified regional patterns of precipitation and affected the rate of increase of
global temperature between \textasciitilde1960 and \textasciitilde1985 (Mahowald et al., 2010).

There is a direct human impact component to atmospheric dust, particularly
near playas. Dust storms have an economic and public safety impact due to visibility
reduction (Ashley and Black, 2008). The fine particles (i.e. particle size \( < 2.5 \mu m; \text{PM}_{2.5} \))
common in dust are a health hazard. In addition, dust is associated with the transport
of pathogens, such as valley fever in the southwestern U.S. (Kolivras et al., 2001). Dust
from dry lakes is of special interest as it can contaminate nearby areas with large amounts
of salts and heavy metals (Gill et al., 2002; Argaman et al., 2006; Wood et al., 2011).

1.2 Dust source locations

To predict the effects of atmospheric dust, it is necessary to locate sources of dust.
Dust cannot be emitted into the atmosphere unless small (\(<\text{order } 100 \mu m\)) particles are
present at the surface and are exposed to ablation by wind. Solid bedrock is unlikely
to produce much dust, and dust emission is also low when small surface particles are
protected by large scale roughness elements (e.g. gravel/cobbles/boulders, or vegetation)
or by inter-particle attractive forces. Soil moisture protects surface particles from wind
in two ways; it promotes inter-particle attraction to such an extent that dust emission
is almost completely inhibited in wet soils (Chepil, 1956), and it supports the growth
of vegetation, which can protect surface particles even during dry periods. Thus dust
source regions are most frequently located in arid areas.

The distribution of warm, arid areas (and dust sources) is uneven and variable
between the continents. Deserts are most common in the bands between approximately
15° and 35° south and north latitude, due to dry sinking air delivered by Hadley Cell circulation. Precipitation is also inhibited in the rain shadow on the lee side of mountains and by the presence of cold oceanic currents offshore.

Here I provide a short summary of the Earth’s warm deserts, and associated dust sources, to highlight the variability seen in arid dust source regions. Recent remote sensing developments have revolutionized dust source identification, producing a large improvement in knowledge of dust source locations.

1.2.1 Dust detection methods

Until recently (∼1990’s), studies of the global distribution of dust were limited to meteorological visibility measurements. Analysis of these measurements provided a broad overview of dust source locations (e.g. Goudie and Middleton, 1992), and still provides the only source of long term atmospheric dust data (Mahowald et al., 2007). The drawback of visibility data is that meteorological sites are concentrated in inhabited areas (coverage is very sparse near desert dust sources), sites can be strongly influenced by local effects (as small scale as a neighboring road), and measurements do not unambiguously detect dust (as opposed to fog or pollution).

Given the drawbacks of visibility data, remote sensing of dust provided a great improvement in knowledge of dust source locations. Remote sensing allows an enormous improvement in the coverage of atmospheric dust measurements. The landmark paper is Prospero et al. (2002). They were able to highlight source areas in a way that had not previously been possible; for example, while it had been known that the Sahara as
A whole is an important source of dust, they were among the first to suggest that the Bodélé Depression is the most productive source in the world.

Ultraviolet (UV) data is commonly used to detect atmospheric dust. Small atmospheric aerosols interact more strongly with shorter UV wavelengths, so a comparison between two different wavelengths can be used to compute an aerosol index (AI; Herman et al., 1997),

\[
AI = -100 \times [\log \left( \frac{I_{340}}{I_{380}} \right)_{\text{measured}} - \log \left( \frac{I_{340}}{I_{380}} \right)_{\text{calculated}}]
\]  

where \( I_{340} \) is the radiance of the 340 nm band, the “measured” values are measured by the instrument, and the “calculated” values are determined from theory. Aerosols that absorb more strongly at shorter UV wavelengths (i.e., dust and smoke) will have a positive AI. This algorithm has the advantage of not detecting clouds, unlike some algorithms in the infrared (IR). Additionally, the algorithm distinguishes absorbing aerosols from scattering aerosols (i.e., sulfate and sea salt particles), which have a negative AI.

A similar calculation can be applied to data from other UV instruments. The Ozone Monitoring Instrument (OMI) on the Aura satellite, in service since 2004, has been employed in more recent studies (e.g., Knippertz and Todd, 2010; Schepanski et al., 2012). A TOMS instrument was present on three satellites (Nimbus-7, Meteor-3, and Earth Probe), extending the AI UV record back to \( \sim 1980 \). Recently (2011), the Ozone Mapping and Profiler Suite (OMPS) instrument was launched on the Suomi National Polar-orbiting Partnership spacecraft.

In the last few years, the Deep Blue algorithm has come into common use for detection of atmospheric dust (e.g., Ginoux et al., 2012). Deep Blue utilizes the blue
channels (412-470 nm) of the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. These wavelengths are more difficult to use than UV bands, as it is necessary (in some areas, but particularly in high-albedo deserts) to account for light that is reflected from the Earth surface. This has been accomplished by creating a global database of surface reflectance (Hsu et al., 2004). The Deep Blue algorithm is less sensitive to aerosol height than the UV AI calculation (Schepanski et al., 2012), and it can be computed with data from a wider array of instruments, in particular MODIS and Sea-viewing Wide Field-of-view Sensor (SeaWiFS).

Other instruments that have been used to detect dust include the Multi-angle Imaging SpectroRadiometer (MISR), the Polarization and Anisotropy of Reflectances for Atmospheric science coupled with Observations from a Lidar (POLDER), and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO satellite). Ground based sun photometer observations, often used to validate satellite data, are produced by the Aerosol Robotic Network (AERONET). Intercomparison of data from multiple satellites and multiple detection methods can be particularly beneficial; for example, MODIS Deep Blue has daily coverage, whereas CALIPSO provides less frequent but more detailed information, including aerosol height profiles.

When identifying dust source regions, the initial source of atmospheric dust is more relevant than its position in the atmosphere during a satellite overpass, but remote sensing measures current position of dust rather than the source location. Prospero et al. (2002) approached this problem by mapping the frequency of occurrence (FOO) of AI above a cutoff value. This method assumes that dust is transported in different directions after emission depending on conditions, but that the source location will have
dust above it during most if not all emission events. Mapping of FOO provides a useful first approximation to locating dust sources, but there are several problems: FOO cannot find the source of a single event, dust emission at a preferential time of day combined with satellite overpasses at the same time every day can produce a bias, and smoke aerosols are difficult to distinguish from mineral dust and can contaminate data. Ginoux et al. (2010) address the last problem with particle size data derived from MODIS Deep Blue; they assume that larger particles are only present in mineral dust near the source region. An alternative to FOO for defined events is to estimate the back-trajectory of a dust-carrying air parcel using meteorological data and models. An example code is the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT; e.g., Escudero et al., 2006).

Using satellite observations, combined with climatology, it is possible to highlight dust source regions around the Earth, to elucidate the conditions under which dust can be emitted.

1.2.2 Africa

The northern part of Africa is dominated by the Sahara desert, by far the largest dust source in the world (>50% of total mass emitted; Ginoux et al., 2012). The hyper-arid (defined as <100 mm of annual precipitation) core of the Sahara is the largest such area on Earth. Several subregions of the Sahara are particularly important for dust production. Multiple factors combine to make the Bodélé Depression in northern Chad the largest Saharan dust source (Bristow et al., 2009). It is in a sub-basin of paleolake Mega-Chad, which dessicated soon after 4000 years ago (Drake and Bristow, 2006), and
much of its surface is now covered in loosely consolidated, highly ablatable diatomite (Bristow et al., 2009). Also, the Bodélé is in a hyper-arid region, with no wet season (17 mm annual precipitation Goudie and Middleton, 2006), and wind is high year round due to the Bodélé Low Level Jet (Washington et al., 2006). Another dust source is the zone of Chotts in Algeria and Tunisia, a salt lake/playa region in north Africa. Other major dust sources in the Sahara include eastern Libya/western Egypt (a significant source of Mediterranean dust), Sudan, and a chain of important sources much of the way across the Sahara to the west of the Bodélé Depression, from Niger, through Mali (with a break at the Air Mountains) and Mauritania to the Atlantic (Prospero et al., 2002).

Immediately south of the Sahara, the Sahel is a prominent source of dust in its own right (Ginoux et al., 2012). The significance of anthropogenic activities to land degradation (and thus dust mobilization) in the Sahel has long been a topic of discussion (e.g. Mulitza et al., 2010). In any case, drought in the 1970’s and 1980’s was associated with an increase in atmospheric dust in the Sahel zone (Middleton, 1985).

Although not as large as the Sahara, there are also significant desert dust sources in southern Africa. The Namib Desert stretches along the Atlantic coast from approximately 14°S-32°S. It is hyper-arid, but rivers from the interior carry some water a few days a year. These river beds, and salt pans, are the main dust sources in the Namib (Eckardt and Kuring, 2005). The Kalahari and Karoo deserts extend inland from the Namib, in Namibia, Botswana, and South Africa. There are many pans (or playas) in southern Africa; the Etosha Pan and Makgadikgadi Pan are the largest, and are significant dust sources (Prospero et al., 2002).
1.2.3 Asia

As the largest continent, with the Earth’s tallest mountains, Asia is host to a large and diverse set of deserts. The main arid regions stretch in a band from the Arabian peninsula eastward, through interior deserts dominated by a continental climate. Dust from Asia is globally important, and is transported across the Pacific to North America and occasionally eastward back to Asia and beyond, more than a full circuit of the Earth (Uno et al., 2009).

Much of the Middle East is occupied by deserts, but not all desert areas are significant dust sources. Dust emission is most common in Oman, northeastern Saudi Arabia, and Mesopotamia. Several sabkha in eastern Saudi Arabia are prominent sources, as is much of the Tigris-Euphrates basin, but dust source activity is limited in the Zagros Mountains, as well as the Rub’/hlapostrophe al Khali in Saudi Arabia, and western Iraq (Prospero et al., 2002). In Iran, dust sources are located near the coast, and in association with large salty lakes (Ginoux et al., 2012). Recent increases in dust emission near lakes in the Sistan region in southern Iran have been associated with the desiccation of lakes (Rashki et al., 2012).

In India and Pakistan, dust emission mainly occurs in a band from the Pakistan coast, through the Indus valley and Thar Desert, and across the upper Ganges basin. The monsoon inhibits dust emission after July, and produces numerous ephemeral lakes in dust emission regions. In particular, the Rann of Kutch, a dust source during the spring, is almost entirely flooded during the monsoon (Goudie, 2002).
Dust is visible between the Caspian and Aral Seas in TOMS, with the most activity over the Garabogazköl playa on the east side of the Caspian (Prospero et al., 2002). The Aral Sea has lost significant area over the past decades, due to anthropogenic utilization of its input rivers, and the newly exposed surfaces are dust sources. Salts are common on dust producing surfaces in the dessicated Aral Sea, potentially leading to salinization of dust deposition sites downwind (Mees and Singer, 2006).

Further east, the Taklimakan is the most prominent central Asian dust source in satellite-based dust source maps. The Taklimakan is located within a significant depression (the Tarim), and is hyperarid, with annual precipitation as low as 10 mm (Goudie, 2002). Other depressions (in particular, the Qaidam and Turpan) are also important central Asian dust sources (Ginoux et al., 2012). Lake Ebinur (in the Junggar Basin) is another example of a lake that has been dessicated due to anthropogenic activity; it is a source of saline dust (Abuduwaili et al., 2008). The Gobi has long been recognized as a region with significant dust emission, but is not as prominent in the satellite dust maps, perhaps because dust storms often occur during winter storms (when clouds block detection; Prospero et al., 2002).

1.2.4 Australia

Australia is dominated by desert environments, and has a long history of aridity. Currently, approximately 70% of Australia is semi-arid or arid, and dust from arid regions is an issue for even the wetter and more populated areas (Goudie, 2002). While Australia does not produce as much dust as major sources in Africa and Asia, it is the largest dust source in the southern hemisphere (Tanaka and Chiba, 2005), and thus it is important as
a source of dust to the Southern Ocean. The basin containing Lake Eyre, an ephemeral lake in south central Australia, is the most active dust source in Australia (Prospero et al., 2002). Other sources include agricultural lands in southeast Australia and rangeland in the northeast (Ginoux et al., 2012).

1.2.5 South America

Although much of South America is humid, there are regions of notable aridity. The Atacama Desert, along the Pacific coast, is one of the driest places on Earth; some meteorological stations receive less than 2 mm/yr of precipitation (Goudie, 2002). Its extreme aridity has made Atacama chemistry an interesting target for study, for example of deposits of highly soluble nitrate salts, and as an analog for Mars (e.g. Davis et al., 2010). The Atacama is also the most significant dust source in South America (Ginoux et al., 2012). Further inland, there are a number of salars, or playas. The largest is the Salar de Uyuni, which is a salt flat with <1 m of relief over nearly $10^4$ km$^2$ (Bills et al., 2007). Many of the salars are associated with dust emission in the austral spring (Prospero et al., 2002). Yet further to the southeast, the Patagonian Desert is currently a dust source (Ginoux et al., 2012), and extensive loess deposits suggest more extensive dust transport in the past (Goudie, 2002).

1.2.6 North America

North America is not a major global dust source at the present time. Arid regions with dust emission are concentrated in the southwestern section of the continent. Playas
are common sources (Ginoux et al., 2012). During the 1930’s Dust Bowl, the southern Plains were a highly significant source, producing dust storms that reached the east coast of North America. The Dust Bowl of the 1930’s was an important impetus for dust emission research. The economic and human impacts of the large dust storms spurred research on practical methods of dust control in drought prone areas, particularly in agricultural fields. William S. Chepil published a series of papers in the 1950’s that summarized some of this research (Chepil, 1953a,b, 1954, 1955a,b, 1956). Chepil discussed the effect of moisture on dust emission, as well as particle size distribution, organics, and chemistry. Further work produced the wind erosion equation (WEQ Woodruff and Siddoway, 1965), an estimate of the erosion potential of fields in the Great Plains. In more recent years, sources in the southern Plains have produced intermittent regional dust storms (e.g., Yin et al., 2007).

1.3 Surface erodibility and mechanisms of dust emission

One of the main difficulties in dust research is a mismatch in scales. Many of the most interesting questions about dust are on a large scale; for example, global transport of nutrients and geochemical cycling, or the interaction between dust, climate, and glacial advances. However, small scale variability in erodibility is critical to dust emission, and so it is necessary to understand small scale dust emission processes in order to estimate global dust emissions.

Temporal variability in dust emission can contribute to difficulty in studying dust sources. Significant dust emission can occur on short timescales; dust storms often are present for only a few hours (p. 68, Goudie and Middleton, 2006), and a few individual
dust events can dominate the annual total of dust emission (Duce, 1995). Thus a long, continuous study period is necessary to observe all the variability in the system. With only occasional large events, it is challenging to identify the cause of a short term increase in dust emission, as a few large events might be due to random chance. Thus it is problematic to attribute changes in dust emission to shifts in climate or land use.

In many ways, spatial scale mismatch presents even more difficulties than temporal variability. Dust emission varies on spatial scales ranging from thousands of km (i.e., the Sahara) to meters (i.e., an animal wallow). Dust emission can to be localized to such an extent that a relatively small area within a dust source region can dominate total dust transport (Koren et al., 2006). Out of the $\sim 5.2 \times 10^7 \text{ km}^2$ of the world’s drylands (Jickells et al., 2005), the $\sim 1.3 \times 10^5 \text{ km}^2$ Bodélé Depression is the globe’s most active source of dust (Bristow et al., 2009). On a smaller spatial scale, precipitation (and its effect on dust emission) can be very uneven in deserts (p. 62 Laity, 2009), and gaps in vegetation cover can influence dust emission from a vegetated region (Okin et al., 2006). If poorly understood small scale processes exert a major control on total dust emission potential, then it becomes very difficult to predict dust emission, and to model dust in the past or future.

### 1.3.1 Wind erosion conceptual framework

Dust is entrained from the ground surface into the atmosphere by wind. Wind produces a transfer of momentum from the atmosphere to the surface, and when enough
momen tum is transferred to an erodible surface, particles can be ablated. The momentum flux from the air to the surface is usually referenced using the friction velocity, \( u_* = \sqrt{\tau/\rho} \), where \( \tau \) is the drag (or momentum flux, or shear stress; units mass*length\(^{-1}\)*time\(^{-2}\)) and \( \rho \) is the air density (Bagnold, 1941, p. 99). Thus friction velocity is a measure of the force from wind shear exerted on the surface and available to entrain dust particles. Particles cannot be entrained from the surface unless \( u_* \) attains a minimum value, the threshold friction velocity (\( u_{*t} \)). Below this threshold (which varies depending on the erodibility of the surface), there is not enough momentum to lift particles into the air.

Roughness elements on the surface of the Earth affect the atmosphere by producing a drag on the flow of wind. Thus roughness elements generally increase the amount of momentum that can be absorbed by the surface. For the purposes of atmospheric flow, the morphology of the surface is described by the aerodynamic roughness length, \( z_0 \). The aerodynamic roughness length is defined based on the wind velocity profile in the surface layer of the atmosphere (i.e., the lower \( \sim 100 \) m). The wind profile is derived from the assumption that vertical transport of turbulent momentum is proportional to the gradient of mean momentum (known as K-theory; \( K \) is the eddy diffusivity, a constant analogous to the diffusion coefficient in molecular diffusion). This leads to the equation

\[
\frac{\partial U}{\partial z} = \frac{u_*}{\kappa z},
\]  

(1.2)
where $U$ is wind velocity, $z$ is height, and $\kappa$ is the von Karman constant (Shao, 2008, p. 71). Integration of (1.2) produces a logarithmic wind profile (e.g., Tegen et al., 2006)

$$U(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0},$$

where $z_0$ is a constant of integration. $z_0$ is the height where the wind profile in the surface layer would go to zero if extrapolated to the surface (Figure 1.1). However, the wind profile is modified as it approaches the surface by roughness elements or a viscous surface layer, so $z_0$ is not necessarily the point of zero net wind. In effect, $z_0$ is a measure of the amount of momentum that can be absorbed by the surface and so it is a measure of the surface roughness that absorbs momentum.

The main forces acting on particles in the atmosphere are gravity and aerodynamic drag. Electric force and other aerodynamic forces also affect particle motion, but are not as well understood and are likely to be smaller in magnitude (Shao, 2008, p. 151). The force of gravity is $F_g = mg$, where $m$ is the particle mass and $g$ is the acceleration due to gravity, so $F_{gravity} \propto d^3$ (where $d$ is the particle diameter). The magnitude of the drag force is approximately proportional to the particle area exposed to the wind, so $F_{drag} \propto d^2$. Thus gravity is most important for larger particles (sand sized; $\sim 63\mu m - 2mm$), but for smaller particles (silt and clay sized; $<63 \mu m$) gravity is less important, and so the smaller particles can be more easily transported by atmospheric drag forces. Long distance transport occurs for the smallest ($<20 \mu m$) particles (p. 132 Shao, 2008).

Entrained particles are transported through the atmosphere by three different types of motion (creep, saltation, and suspension), determined primarily by particle size.
Creep occurs when particles are not lofted at all, but roll or slide due to aerodynamic drag. In saltation, sand sized particles move in jumps that are roughly ballistic, but are also affected by wind. Suspension is the mode of long distance dust transport; small particles (silt and clay sized) are transported on paths that can be roughly approximated as atmospheric tracers. Under Earth surface conditions, the 63 \mu m boundary between silt and sand is a rough approximation for the boundary between suspension and saltation. However, the particle size boundary between the modes is not a hard limit; with increased $u_*$, larger particles can transition from saltation to suspension.
Although the smallest (<20 µm) particles are most effectively transported in the atmosphere, they are not the most easily entrained from the surface. During entrainment, forces of inter-particle attraction are important, in addition to gravity and aerodynamic drag. The magnitude of inter-particle force is more difficult to estimate than gravity and drag, but the Van der Waals force and electrostatic attraction can each be approximated as proportional to $d$, and so it is plausible to argue that inter-particle forces are roughly proportional to $d$ (p. 144 Shao, 2008). Thus with small particles (clay and silt sized), inter-particle forces outcompete drag, and with large particles (gravel sized) gravity outcompetes drag, so that between gravel and silt, there is an optimal particle size ($\sim 75 – 100\mu$m) for entrainment (p. 137 Shao, 2008). Another way to phrase this observation is that $u_{*t}$ attains a minimum for particles $\sim 75 – 100\mu$m diameter, while smaller and larger particles require more momentum flux at the surface to be entrained into the atmosphere.

So if direct entrainment is a relatively inefficient mechanism for the emission of atmospheric dust, how is dust being emitted? Some field observations suggest that direct entrainment can be important under some conditions (Macpherson et al., 2008). However, saltation bombardment (i.e., sand blasting) is the main entrainment mechanism. In saltation bombardment, dust emission is initiated when $u_*$ is high enough to begin directly entraining sand particles near the optimal size. These sand particles saltate, as they are too large for suspension. Every time the saltators impact against the surface, they potentially eject smaller dust particles into the air, which then are able to go into suspension (Figure 1.2). This mechanism has been observed directly in the laboratory under controlled conditions (Shao et al., 1993).
Figure 1.2: (a) Diagram of dust emission due to saltation. On impact with the surface, a sand-sized saltating particle ejects particles small enough (silt- or clay-sized) to be transported in the atmosphere. (b) In direct entrainment, wind lofts dust directly, without an intermediary.

Real surfaces in the Earth system are a complex mix of particles including various sizes, degrees of aggregation, and coatings, with a wide range in erodibility. This mix can add more complexity to saltation bombardment dust emission. Sand sized aggregates of small particles are potential saltators; saltators which might break down into dust-sized particle on impact with the surface. Coatings on saltators or the surface are also potential sources of dust-sized particles in a saltation impact.

The approach to modeling dust emission is thus to use $u_*$ to calculate the saltation flux, and then to estimate the dust flux based on the saltation flux. The second step in particular is difficult to model given current understanding; the binding energy between particles can vary widely, even given similar macroscopic conditions (p. 226 Shao, 2008), so it is difficult to estimate the amount of dust released in a particle collision, even in the lab. Thus it is useful to investigate larger-scale factors that might influence erodibility in dust source regions.
1.4 Variability in dust source erodibility

Dust has a large impact on a variety of topics of current interest, and thus it is crucial to establish the processes that control the amount and timing of dust emission to the atmosphere. The erodibility of surfaces in dust source regions is central to models of dust emission, but an understanding of spatio-temporal variation in surface erodibility is not well established (Webb and Strong, 2011). Global-scale dust models are relatively similar in how they simulate transport and deposition of dust, but differ in their treatment of emission and erodibility. Erodibility factors in global dust models have been based on topography (higher erodibility at the bottom of basins; Ginoux et al., 2001), catchment area (higher erodibility in locations with more upstream area from which sediments might accumulate; Zender et al., 2003), surface reflectance (higher erodibility from light desert surfaces; Grini et al., 2005), and surface roughness (higher erodibility in areas with more meter-scale topographic roughness; Koven and Fung, 2008). Current erodibility factors are based on large-scale empirical correlations, which are not effective at modeling small-scale heterogeneity in dust emissions, do not account for changes over time, and cannot be accurately projected into the past or future.

The response of dust emission to changes in rainfall provides an example of the difficulties inherent in applying a single conceptual framework to all dust sources. Studies have found a link between dryness/drought and increased dust emission (e.g. Chepil, 1956; Woodruff and Siddoway, 1965; Middleton, 1985; Potter, 1990; Hagen, 1991; Zobeck, 1991; Cahill et al., 1996; Blank et al., 1999; Prospero et al., 2002; Prospero and Lamb, 2003; Offer and Goossens, 2004; Engelstaedter et al., 2006; Goudie and Middleton, 2006;
Greene et al., 2006; Laity, 2009; Shao, 2008; Bristow et al., 2009; Mulitza et al., 2010; Crusius et al., 2011; Liu et al., 2011). However, other studies have found the opposite effect: increased dust emission after particularly wet periods (e.g. Mahowald et al., 2003; Zender and Kwon, 2005; Reheis, 2006; Bryant et al., 2007; Reynolds et al., 2009). Hypotheses to explain this relationship include increased supply of erodible particles supplied by flooding (Zender et al., 2003; Bryant et al., 2007), a rise in groundwater that disrupts the surface (Reynolds et al., 2007), and destruction of strong surface crusts by wetting (Saint-Amand et al., 1987; Gillette et al., 2001; Reynolds et al., 2009). These hypotheses are only applicable to specify geomorphic types of surfaces, demonstrating the danger of applying empirical relationships too broadly.

Dust emission is highly variable at scales ranging from meters (i.e., an animal wallow) to thousands of km (i.e., the Sahara), with emission dominated by hotspots (Figure 1.3; Prospero et al., 2002; Okin et al., 2006; Bryant, 2013). Distinct geomorphic categories of dust sources (e.g., playas, alluvial fans, sand dunes, etc.) emit different amounts of dust. For example, Lee et al. (2012) found that playas produce almost twice as many dust plumes per unit area compared to any other dust source type; Reheis (2006) found that playas produced more dust after El Niño events, while alluvial sources produced less. To model this behavior, Bullard et al. (2011) propose mapping dust sources according to a classification system, and then applying a separate model for erodibility to each category independently. This approach requires research on the erodibility of each type of geomorphic environment that is known to emit dust.
Figure 1.3: A large degree of variability is seen in dust emission, with the importance of source locations changing over time. (a) A dust cloud at the Black Rock Desert, NV, USA. Credit: Matt Fantle. (b) A satellite image (WeaWiFS) displaying dust emission from localized sources in the Namib desert, Namibia; Etosha Pan in the bottom right corner is ∼100 km long. Credit: SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE. (c) A dust event in the Bodélé Depression, Chad, with plumes of light-colored dust sourced from the upper right; bar at bottom left corner is 20 km. Credit: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC. (d) A comparison of measured (black plusses) and modeled (red lines) atmospheric dust at several stations in the Sahara, from Tegen et al. (2013).
1.5 Playa surface characteristics: importance for erodibility

Thus, the erodibility of playas is an important topic for the modeling of dust emission. Despite a uniform appearance, playas are dynamic environments with variable surface compositions. Playas (dry lake beds) are ephemeral water bodies in arid areas. They are noteworthy for flat topography (an extreme example is the Salar de Uyuni, with $<1\ \text{m}$ relief over $10^4\ \text{km}^2$; Bills et al., 2007). Inundation differs from year to year, depending on rainfall (Lichvar et al., 2004). Playas have variable chemical and mineralogical compositions, and can form a range of evaporite minerals (Saint-Amand et al., 1987). Human interactions with playas include mining of evaporite minerals (Mason and Kipp, 2002), vehicle testing (Henley, 1987; Gillies et al., 2010), and use as catchment areas for collection of water (Nepesov et al., 1999). Playas are particularly useful study areas due to their lack of vegetation and topography; studies can focus on erodibility characteristics of the soil surface, rather than complex dynamics involving vegetation (e.g., Okin et al., 2006; Vest et al., 2013). Playa studies are needed to understand playa erodibility dynamics, and also might be useful as a starting point for characterizing erodibility in other areas.

The erodibility of playas is dependent on surface characteristics, but the processes that control variation of playa surfaces in space and time are not well established. Field studies have observed a wide diversity of surface states on playas, including hard-packed clay, completely loose particles, strong crusts, weak crusts, salt crusts, and “self-rising” or “puffy” surfaces (Neal, 1965; Langer and Kerr, 1966; Gill et al., 2002; Mees and Singer, 2006). When the surface of a playa is completely covered in a strong clay crust, it is
resistant to wind erosion (Reynolds et al., 2007). However, surfaces composed entirely of loose particles have a high erodibility (Gillette et al., 2001). Playa surfaces have been observed to change between states after rainfall or wind (i.e., sandblasting) events (Saint-Amand et al., 1987; Cahill et al., 1996; Gillette et al., 2001), but the process responsible for the changes is not always clear when observations are restricted to a small study site. Thus, a large scale study of the distribution of a variety of surface characteristics in a playa is needed to correlate changes in the surface with processes (e.g., inundation locations).

1.6 Playa nomenclature

When comparing dust sources in many parts of the world, it can be useful to have a basic understanding of playa nomenclature. Arid depressions are often described using the term playa in geologic literature, but there are a wide variety of names for these types of features, many of which are specific to a certain region. Additionally, the definition of “playa” and related terms varies between authors, creating ambiguity within the literature (Rosen, 1994; Briere, 2000). The term “playa” is commonly used in the arid southwest and southern High Plains of the United States and northern Mexico, but other North American terms include “dry lake” and “salt flat.” Other regional terms include “salar” (South America; e.g. Salar de Uyuni), “pan” (South Africa; e.g. Makgadikgadi Pan), “chott” (North Africa; e.g. Chott el Djerid), and “takyr” (Central Asia). Briere (2000) provides an extensive chart of terms used to describe playas and similar systems.

The term “sabkha” should be mentioned in a discussion of playa nomenclature, although they are not a major topic within this thesis. Sabkha (salt marsh in Arabic), is
defined by Briere (2000) as a “marginal marine mudflat where displacive and replacive evaporite minerals form in the capillary zone above a saline water table.” This is distinct from playas, which are continental, and not influenced by marine brines. While sabkha has often been restricted to marine settings in geological contexts (Rosen, 1994), “inland sabkha” is sometimes used to describe inland saline depressions (Barth, 2001).

Ambiguity in, and disagreement over, the definition of playa and similar terms adds further confusion to playa nomenclature. Neal (1965) defined playa broadly, as a term to describe “the flat and generally barren lower portions of arid basins of internal drainage that periodically flood and accumulate sediment.” More recently, others have proposed narrower definitions; in particular, Briere (2000) defined playa as “an intra-continental arid zone basin with a negative water balance for over half of each year, dry for over 75% of the time, with a capillary fringe close enough to the surface such that evaporation will cause water to discharge, usually resulting in evaporites.” This excludes areas with a deep water table, even though such regions have been described as “dry playas” (e.g. Reynolds et al., 2007) or “recharge playas” (Rosen, 1994). It also excludes the playas of the southern Great Plains. In this dissertation, the term playa is used in the broader sense.

1.7 The distinction between wet and dry playas

The distinction between “dry” and “wet” playas is important for interpreting surface characteristics and erodibility because the two types are dominated by different processes (Reynolds et al., 2007). A wet playa has shallow groundwater and is affected by evaporation through the surface, whereas a dry playa is dominated by surface water
wet playas tend to have more evaporite minerals, while dry playas have clay-rich surfaces (Rosen, 1994; Reynolds et al., 2007). A similar distinction is made in central Asia, between hard, clay-rich “takyrs” and salt-rich “solonchaks” (Mees and Singer, 2006; Maman et al., 2011). The differing water regimes of the two types of playas have implications for their response to changes in climate.

![Figure 1.4: Comparison of the characteristics of playas that are dominated by interaction with groundwater with those that are mainly affected by surface water. Playas with a less permeable subsurface are less affected by groundwater, but are more likely to pond surface water, as they have little drainage. When dry, the more permeable playas can bring water and solutes to the surface via capillary action, producing efflorescence and friable surfaces.](image)

In the southwestern U.S., the surface characteristics and erodibility of wet playas has been more extensively studied than that of dry playas. Owens Lake (with properties like that of a wet playa, since it has been dried due to anthropogenic activity; Gill et al., 2002) has been a target. After a wet period, when the water table is high and there is
more evaporation bringing solutes up from the subsurface via capillary forces, wet playas form more precipitates and have a friable surface (Reynolds et al., 2009). They have a hard surface during the summer, which reduces erodibility (Gillette et al., 2001). High wind events have been observed to degrade surface crusts in wet playas, producing a surface of loose particles (Cahill et al., 1996). Wet playa surfaces containing only NaCl or nonhydrated minerals tend to be less soft and friable, but damp (Saint-Amand et al., 1987).

The dynamics of dry playa surface crusting has been less thoroughly studied. Reynolds et al. (2007) suggested that dry playas are not significant dust sources, except when disturbed or shortly after inundation. However, Reheis (2006) identified dust from dry playas, and found that dry playas were more emissive in years with less precipitation. Thus, a study is needed to determine the degree of surface variability seen in dry playas.

### 1.8 Remote sensing synergy with ground measurements

Remote sensing can be an extremely powerful tool given its advantages in spatial and temporal coverage, but it is best paired with ground measurements to help with interpretation. Remote sensing allows for the observation of large areas at frequent time intervals and at relatively low cost. Also, inaccessible sites can be monitored with satellite remote sensing. However, without previous knowledge of the ground environment, remote sensing data can be difficult to interpret; important features can be unresolved in satellite imagery, and data can be underconstrained in the sense that multiple different types of surfaces can produce the same signal (e.g., an area that is bright in visible imagery could be clouds, or snow, or evaporites, or even white paint). To maximize the
benefit of remote sensing, it is helpful to utilize measurements at multiple wavelengths, and also to incorporate any other observations available, in particular reports on, or visits to, field sites. For example, additional observations in shortwave IR can remove the above degeneracy between snow and clouds, climate knowledge might in some circumstances rule out snow as a possibility, and a field site visit could easily distinguish between the four categories above.

In the current study, satellite-based remote sensing instruments at a variety of wavelength are utilized (Table 1.1). These observations are combined with ground samples and climate data to investigate the development of erodibility.

Table 1.1: Summary of satellite remote sensing data utilized in this dissertation.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite</th>
<th>Wavelength</th>
<th>Spectral bands</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>Terra/Aqua, NASA</td>
<td>Visible/IR</td>
<td>36</td>
<td>250/500/1000 m</td>
</tr>
<tr>
<td>TM/ETM+</td>
<td>Landsat 5/7, NASA</td>
<td>Visible/IR</td>
<td>7</td>
<td>30 m</td>
</tr>
<tr>
<td>Hyperion</td>
<td>Earth Observing-1, NASA</td>
<td>Visible/IR</td>
<td>220</td>
<td>30 m</td>
</tr>
<tr>
<td>ASAR</td>
<td>Envisat, ESA</td>
<td>Microwave</td>
<td>N/A</td>
<td>30 m</td>
</tr>
<tr>
<td>OMI</td>
<td>Aura, NASA/NIVR/FMI</td>
<td>UV/Visible</td>
<td>740</td>
<td>13 km</td>
</tr>
</tbody>
</table>

1.9 Dissertation goal

In this dissertation, the focus is on the processes that control the formation and variability of surface characteristics in dry playas. A conceptual framework is developed, stressing the importance of water and surface composition to the temporal evolution of surface characteristics in a playa. Remote sensing data, field samples, and lab experiments are utilized to develop this framework, including what is, to my knowledge, the first large scale (10’s of kilometers) study of temporal variation in surface roughness within a playa and the first study of micro scale (10’s of µm) structural variability in
evaporite mineral rich surfaces undergoing wetting/drying cycles. Ultimately, the goal is to elucidate surface characteristics in dry playas in order to quantify playa erodibility and improve process-based models of dust emission in the past and future.

In dust research, there are major questions about the development and distribution of the erodibility of dust source surfaces. These are the major questions addressed in this dissertation.

- How does water affect the surface of a playa dust source?
- Are there identifiable processes that affect the development of surface crusting in a playa?
- How does surface erodibility vary over time?
- How dynamic and heterogenous are playas?
- How can models of dust emission from playa surfaces be improved?

Such questions are significant, as they have the potential to improve estimates of dust transport, and thus improve our knowledge of climate and ecosystems in the past and future.

1.10 Dissertation outline

In this dissertation, playa surfaces are investigated using multiple methods, including field observations, surface sample analysis, remote sensing, and lab experiments. A conceptual framework ties together the playa surface observations.
Chapter 2 discusses the spatial distribution of mineralogy and particle size across the Black Rock Desert, NV. Evidence for playa surface heterogeneity is seen in the mineralogy and particle size data. The central, frequently inundated, part of the playa surface is high in clay, while the surface sediments on the edges are high in calcite and plagioclase. As the presence of calcite increases the erodibility of surfaces, the playa edges have the potential to produce more dust, with a higher calcium content. This chapter is to be submitted for publication in the future, with co-authors Andrew Elmore and Matthew S. Fantle. Andrew Elmore assisted in the 2007 field visit, particularly by supplying the field spectrometer and collecting hyperspectral field data. Matthew S. Fantle collected field samples and Hyperion satellite data, and provided guidance and advice. I went on the 2010 field visit, performed much of the sample analyses (Katherine Lindeberg ran X-ray diffraction, and Khadouja Harouaka did the acid digestions), and completed the satellite data processing and data analysis.

Chapter 3 is a synthetic aperture radar (SAR) study of the surface of the Black Rock playa over multiple years (2004-2010). Surface roughness varies significantly from year to year, but is relatively constant during the summer, and the years with the most rainfall have the smoothest surface. This suggests that water is critical for surface roughness, and highlights the importance of the process of inundation. This chapter has been submitted to the journal Remote Sensing of Environment, with co-author Matthew S. Fantle. Matthew S. Fantle provided guidance and advice. I processed the satellite data and analyzed the data.

Chapter 4 presents a set of laboratory experiments focused on the effect of cycles of wetting and drying on a playa analog surface. The experimental surfaces roughened
through the course of multiple wetting/drying cycles. The experiments demonstrate that wetting/drying cycles have the potential to increase the roughness of playa surfaces, and suggests that the increased erodibility of calcite-rich surfaces could be due to the breakdown of surface crusts into smaller aggregates. This chapter is to be submitted for publication in the future, with co-author Matthew S. Fantle. Matthew S. Fantle provided guidance and advice. I ran the lab experiments, made the surface measurements, and processed and analyzed the data.

Chapter 5 is a conceptual framework for the processes that control dust emission from dry playas. This chapter brings together information from the other chapters to emphasize the importance of water to the erodibility of playas, in particular inundation and cycles of wetting and drying. The importance of evaporite mineralogy to erodibility is also addressed.
Chapter 2

Surface mineralogical and particle size variability across spatial scales in a dry playa

2.1 Abstract

The composition of atmospheric mineral dust is critical for geochemical cycling (as dust can transport sediments long distances) and climate (by affecting atmospheric radiative transfer). Improved knowledge of surface composition in dust source regions aids in modeling the composition of atmospheric dust, and in determining the erodibility of the surface through time. Playas (dry lakebeds) are frequently dust sources; thus it is useful to determine their composition, and establish how much composition can vary at different scales within a single playa. Mineralogy and particle size are measured for samples from a playa (the Black Rock playa, NV, USA) and compared to inundation and calcite composition measured by remote sensing. Semi-quantitative X-ray diffraction
analysis of surface sediments shows that evaporite content is variable; halite content varies from 0-40 wt%, and calcite from 2-15 wt%, with average sediment compositions of 30% quartz, 45% clay, and 10% plagioclase. The central region of the playa is more frequently inundated and has higher clay concentrations (57% center vs. 40% edge), while samples from the edges of the playa have a larger average particle size (2.3 µm edge vs. 1.1 µm center) and more plagioclase (13% vs. 7%). Remote sensing demonstrates that playa edges also have up to 15% calcite (compared to ~7% near the playa center). If the probability of dust emission differs between the playa center and edge, the amount of calcium in dust from the playa could differ by a factor of two.

2.2 Introduction

Atmospheric dust is important for geochemical cycling of elements, including transport of vital biological nutrients to terrestrial ecosystems (Avila et al., 1998; Chadwick et al., 1999; Okin et al., 2004; Reynolds et al., 2006; Muhs et al., 2007; Boy and Wilcke, 2008; Lawrence and Neff, 2009; Humphries et al., 2013) and to the ocean (Martin, 1990; Jickells et al., 2005; Mahowald et al., 2010; Crusius et al., 2011; Schulz et al., 2012). Knowledge of dust mineralogical composition is also needed for atmospheric radiative transfer calculations and climate models (Claquin et al., 1999; Sokolik and Toon, 1999; Forster et al., 2007; Maher et al., 2010). To predict the mineralogical and elemental composition of atmospheric dust, an understanding of the surface composition of dust source regions is necessary. Thus, as playas can be significant dust sources (Prospero et al., 2002; Washington et al., 2003), the measurement of playa surface composition is relevant for the study of dust and also of climate.
At first glance, playas tend to appear relatively similar to each other (and featureless) given their lack of topography and vegetation, and their high reflectivity. However, playas display significant differences in evaporite composition, inundation regime, depth to groundwater, and propensity for surface crust formation (Neal, 1965; Langer and Kerr, 1966; Lichvar et al., 2006; Reynolds et al., 2007; Scuderi et al., 2010). Such differences may impact dust emission; for example, both shallow depth to ground water (Reynolds et al., 2007) and absence of surface crusting (Gillette et al., 2001) have been associated with increased dust emission.

More specifically, variability in the mineral composition of playa surfaces has the potential to affect aeolian erodibility. Due to their small size, clay mineral particles are relatively easily transported as dust (Shao, 2008). Calcite increases erodibility when added to agricultural fields (Chepil, 1956), and a correlation has been seen between CaCO$_3$ content and erodibility in playa sediments (Amante-Orozco and Zobeck, 2002; Argaman et al., 2006). Qualitative field observations suggest that NaCl might reduce erodibility in playas via cementation (Bullard et al., 2011).

Variation within individual playas is an important, but less frequently investigated aspect of playa variability (Crowley and Hook, 1996; Mees and Singer, 2006; Buck et al., 2011). If there is significant mineralogical variation within a playa, it might help to explain variability in dust emission from that playa. Since weather and other larger scale influences are broadly similar across one playa, elucidation of the effect of evaporite mineralogy on surface processes is simplified by studying variations within a single playa rather than investigating multiple variables simultaneously among multiple playas.
Remote sensing is a powerful tool for investigating surface variability in a playa. In some cases, the mineralogical composition of a playa surface can be estimated from spectral reflectance data in the visible and near-IR (Crowley and Hook, 1996; Katra and Lancaster, 2008). Compositions can be calculated from a spectrum either from an empirical fit utilizing a training dataset appropriate for the study area, or from a known spectral line(s) of the mineral of interest (Lagacherie et al., 2008). The known feature approach utilizes only a fraction of the spectral data, and so might miss relevant information. However, the full spectrum approach uses empirical correlations, which are potentially not valid across multiple scales or regions. Gomez et al. (2008) evaluate calcite mapping using partial least squares regression (PLSR) to fit the entire spectrum available, and find that it is more powerful than feature-based calcite mapping, but is not necessarily applicable to regions beyond the one used to create the PLSR fit. To map calcite concentrations, it is advantageous to evaluate which of these two approaches is most successful.

In the current study, variability is investigated in playa surface sediments in the Black Rock Desert, NV, USA. Laboratory analysis of field samples (including mineralogy, chemistry, and particle size) is combined with remote sensing data (including images, inundation, and surface calcite composition) to determine the degree of surface variation across the playa. Inundation maps are then compared to mineralogy, particle size, and elemental composition to elucidate the impact of water on the playa surface. Development of the relationship between playa surface composition and playa processes (particularly inundation) can improve understanding of the conditions controlling dust emission.
2.3 Methods

2.3.1 Field site description

The field site is the Black Rock Desert playa (dry lakebed), in northwestern Nevada, USA. The $\sim 350 \text{ km}^2$ Black Rock playa is located in a hydrological basin, with mountains to the west and east (Sinclair, 1963). Alluvial slopes surround the mountains, grading into the playa proper. The playa surface is extremely flat (elevation variation on order of a meter), and sits at an elevation of 1,190 m above sea level (Gesch et al., 2002). The playa proper has little vegetation; its surface is dominated by silt- and clay-sized sediments, and fill extends to depths of as much as 2400 m (Welch and Preissler, 1990).

The Black Rock playa is in an arid climate, with hot summers and cold winters. Annual precipitation in the town of Gerlach (on the south end of the playa) averaged $\sim 200 \text{ mm/year}$ for the periods 1963 to 1971 and 1986 to 2010, and most precipitation fell during the non-summer months (Section 3.3.2). Precipitation varies significantly between years. In the wetter years ($\gtrsim 200 \text{ mm precipitation}$), an ephemeral, shallow ($\sim 1 \text{ m deep}$) lake forms on the playa between January and May, and evaporates through the spring and summer (for 2004-2010, never observed to last past the end of July; Section 3.4.2).

Hydrologically, the Black Rock playa is the sink of the ephemeral Quinn River (which enters the playa from the northeast) as well as for water sourced in the surrounding mountains. Groundwater flow is from north to south; the playa sediments have a low hydraulic gradient, but with an upward component (Welch and Preissler, 1990). Horizontal permeability in the playa is generally greater than vertical permeability (Sinclair,
1963). This suggests that water-related processes on the Black Rock playa surface are
dominated by surface water rather than groundwater, as enough surface water reaches
the playa to produce inundation, but only limited amounts of groundwater are able to
seep out through the low permeability playa sediments.

Twenty three sites were sampled in the vicinity of Black Rock Desert in August
2007. Twenty of the sampling sites were located on the playa itself (Figure 2.1). Three
non-typical playa sites were sampled for comparison with the playa sites: DPAVEN (a
desert pavement site near the edge of the playa), ROAD1 (on a gypsum gravel road), and
VLTN1 (a playa edge site with significant evaporite formation). At each site three to
four samples were collected. In total, 73 samples were taken. Playa crusts were collected
by scraping up approximately 1 cm of 10 cm\(^2\) of the surface layer with a clean plastic
trowel. Samples were air dried in breathable cotton bags, then double bagged in plastic
to prevent cross contamination during transport.

Before sampling of surface sediments, spectra of all samples were measured at each
site in the field using a portable spectrometer (spectral range: 350-2500 nm). Each sam-
ple was measured at least four times with an integration time of 17 seconds. The sample
spectra were then averaged to produce an average spectrum for each sample. A larger
scale averaged spectrum was also produced for each of the sites by measuring spectra of
the ground in a grid pattern, with ~50 measurements. Grid points were separated by
approximately ten step intervals. For all samples, a white reference was measured at the
beginning of data acquisition and subsequently every 20-30 minutes in order to calculate
reflectance in the ambient lighting conditions. Data was collected within approximately
three hours of solar noon, under cloud-free conditions (as determined by eye).
Figure 2.1: MODIS Geocover (www.landcover.org; Band 2, 858 nm) of the Black Rock Desert study site in northwest Nevada, USA. The Black Rock Desert playa is more reflective than in the mountainous areas that surround it. Sampling sites are marked with circles.
2.3.2 Sample analysis

Particle size was measured on 55 samples using a Malvern Mastersizer “S” at the Materials Characterization Laboratory (MCL) at Pennsylvania State University. We suspended samples in deionized water and sonicated them for at least 3 minutes prior to measurement. Samples were then pipetted into the sample dispersion unit of the Mastersizer. Residuals for the fit of the particle size distribution were at or below 1% for all samples. Particle size fractions are reported as volume %. Replicate measurements were made for 7 samples. For particle sizes below 10 µm, the location of peaks in the particle size distribution was reproducible in replicate measurements. However, at particle sizes above ∼50 µm, small peaks in the particle size distribution were not reproducible, so the interpretation of particle size data focuses on particle sizes below ∼50 µm.

Bulk elemental chemistry of 31 samples (at least one from each field site) was measured after lithium metaborate fusion and acid digestion, by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Samples were disaggregated, homogenized, ground in an agate mortar, and sieved to 0.15 mm. Next, 100 mg of sample was mixed with 1000 mg lithium metaborate salt, fused at 1000°C in graphite crucibles, and dissolved in 5% nitric acid. Concentration measurements were performed on a Perkin-Elmer Optima 5300DV ICP-AES at the MCL; calibration standards were made from high-purity Specpure single element solution standards. Elements measured included Al, Ca, Fe, Mg, Na, and Si. Uncertainties are estimated to be ∼5% of the measured value. Long term reproducibility values are all within 5%.
Calcium isotope measurements are reported in detail in Fantle et al. (2012). Calcium isotopic composition was measured for 22 samples. Calcium was separated into three fractions: the calcium removed in an initial deionized water leach, that removed in a subsequent acid leach in 0.5 M HCl, and the residual silicate fraction.

To determine the mineralogy of bulk sediment samples, X-ray diffraction (XRD) was utilized. Samples were ground in ethanol (to inhibit dissolution of soluble minerals) with a McCrone Micronizing mill (zirconium beads) until < 2µm. Samples were then dried and homogenized in a Spex MixerMill 5100. Samples were prepared as back-loaded dry powder mounts. Then, XRD spectra were collected on a PANalytical X’Pert Pro MPD θ/θ goniometer at MCL using Cu-κα radiation and variable slit incidence (Figure 2.2). Mineralogical components in the samples were identified by characterizing peaks with the Jade+9 software by MDI of Livermore, CA, based on reference spectra from the International Centre for Diffraction Data. Characteristic XRD peaks used for mineral identification are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Peak (°2-θ)</th>
<th>Integration range (°2-θ)</th>
<th>MIFa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>26.7</td>
<td>26.0-27.0</td>
<td>0.41</td>
</tr>
<tr>
<td>Calcite</td>
<td>29.5</td>
<td>29.0-30.0</td>
<td>1.07</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>27.8</td>
<td>27.2-28.2</td>
<td>0.71</td>
</tr>
<tr>
<td>Halite</td>
<td>31.7</td>
<td>31.0-32.0</td>
<td>1.11</td>
</tr>
<tr>
<td>Clays</td>
<td>61.0-61.9</td>
<td>60.2-62.4</td>
<td>0.11</td>
</tr>
</tbody>
</table>

a Mineral intensity factor, from Srodon et al. (2001).
Figure 2.2: Examples of X-ray diffraction spectra, after background subtraction. (a) DKN1 000-004; (b) GRPUR1 000-004; (c) LTN4 000-004.
Semi-quantitative mineralogical compositions were calculated based on the method of Chung (1974). This method assumes that the intensity of XRD peaks corresponds to the amount present in the sample, and that all components are measured and sum to one. To prepare the data, the Jade+9 software was used to remove the background from the XRD spectra. Peak intensities were measured by integrating across each characteristic peak. The quartz, calcite, halite, and plagioclase peaks utilized were well separated, with little interference from other minerals present in the samples. The range used for the clay peak (60.2-62.4 degrees 2-θ) includes three small calcite peaks, so 0.086 * \( I_{\text{calcite}} \) was subtracted from the clay peak (Srodon et al., 2001). Quantitative composition was estimated with the sum to one assumption:

\[
W_\alpha = \frac{I_\alpha / MIF_\alpha}{\sum_n I_n / MIF_n}
\] (2.1)

where \( W_\alpha \) is the weight fraction of component \( \alpha \), \( I_\alpha \) is the intensity of the selected peak of component \( \alpha \), and \( MIF_\alpha \) is the mineral intensity factor (MIF) for component \( \alpha \) with respect to corundum (Kahle et al., 2002). The MIF values are from Srodon et al. (2001) for calcite, halite, quartz, plagioclase, and clays, where MIF values are cited in reference to corundum (Table 2.1). Sixteen samples were measured in duplicate; the standard deviation of the duplicates was 1% of the total for plagioclase and calcite, 2% for quartz and halite, and 4% for clays. The XRD spectra of samples from the VLTN1 site contained additional peaks (identified as thenardite); since the sum to one constraint assumes all constituents are included in the calculation, the VLTN1 samples are excluded from quantitative XRD analysis.
Statistical analyses reported in this work were performed using R (http://www.r-project.org/). To calculate the variability seen within sites, the pooled standard deviation was used.

2.3.3 Calcite spectral detection

We evaluated several methods of calculating the weight percent of calcite from reflectance spectra. Methods were evaluated by comparison of the field spectra of the samples with calcite weight percent derived from XRD analysis. The calcite absorption feature near 2330 nm (Figure 2.3; Clark et al., 2007) was utilized for band differencing, band ratioing, and to calculate average band depth. Average band depth was selected for use since this method was better able to reproduce the calcite XRD weight percent. Average band depth ($D$) was calculated by first averaging bands on each edge of the 2330 nm calcite feature to estimate the background spectrum, and then subtracting measured reflectance from the line interpolated between the edge points using

$$D = \frac{1}{N} \sum_{n} \frac{R_1(\lambda_2 - \lambda_n) - R_2(\lambda_n - \lambda_1)}{\lambda_2 - \lambda_1} - R_n,$$

where $R_n$ is the reflectance of the nth band, $\lambda_n$ is the wavelength of the nth band, band 1 is the shortwave end of the feature, band 2 is the longwave end of the feature, and $N$ is the number of points utilized (Figure 2.3). The spectral size of the calcite feature was selected empirically. A feature between 2270 and 2340 nm was used, with endpoints averaged over 20 nm and centered at 2240 nm and 2360 nm. This is similar to Lagacherie et al. (2008), who used a feature range of 2275 nm to 2375 nm.
Band depth can be directly used to predict composition in the case of an areal mixture, where patches composed of one component are relatively large. Then each photon will only sample particles of one composition, and the final spectrum of the region will be a linear combination of the component spectra (Hapke, 1993). In the case of an intimate mixture (particles intermixed on a scale small relative to the wavelength), the final spectrum is generally a nonlinear combination of its components. Our plot of composition vs. band depth appears linear, indicating that calcite in the Black Rock Desert occurs as an areal mixture.

The continuum removal (CR) method for approximating nonlinear mixtures was also tested (Lagacherie et al., 2008). In this procedure, the measured reflectance is divided by the estimated background spectrum (rather than subtraction, as in the band depth method)

$$CR = \frac{1}{N} \sum_{n} \frac{R_n(\lambda_2 - \lambda_1)}{R_1(\lambda_2 - \lambda_n) - R_2(\lambda_n - \lambda_1)}.$$  

The continuum removal method will introduce non-linearity if the target surface is an areal mixture.

### 2.3.4 Satellite data analysis

Hyperspectral remote sensing data from the Hyperion instrument on NASA’s Earth Observing-1 satellite were analyzed. This pushbroom instrument contains 242 spectral bands and 256 spatial lines. After removing low-signal and overlapping spectral
bands, there are 158 usable bands in the wavelength range 420-2400 nm. Two observations of the Black Rock Desert were collected on September 15, 2007 (BRD1) and November 5, 2007 (BRD2).

The Hyperion instrument has a spectral “smile” (i.e., a bias in the wavelength center) and noticeable pixel noise leading to striping across the image, especially in pixels with low signal to noise ratios (Datt et al., 2003). A correction was applied for the spectral “smile” by recentering the wavelengths. Striping was corrected using a line correction scheme, such that \( R_{\text{corrected}} = R_{\text{measured}} + R_{\text{band}} - R_{\text{line}} \), where \( R_{\text{band}} \) is the average radiance of the playa in each band and \( R_{\text{line}} \) is the average radiance of each line.

Figure 2.3: Library reflectance spectrum of calcite, from The International Geoscience Programme (IGCP). Points \( a_1 \) and \( a_2 \) are average endpoint values, and the vertical lines represent individual bands. The band depths are averaged to produce average band depth.
within the band. Only data from on the playa was used in the destriping algorithm, in
order to avoid artificial striping from non-uniform surface features off the playa.

The Flaash atmospheric correction program (Felde et al., 2003) in ENVI was used
to correct for atmospheric absorption and to convert radiance to reflectance. This code
corrects for water vapor absorption based on the water absorption feature at 1135 nm,
and for lighting conditions. The data were smoothed with a low pass Gaussian filter 65
pixels across to increase the signal to noise ratio at each point, particularly important
as the feature of interest for this study is on the long wavelength end of the Hyperion
spectral range, where the signal to noise ratio is lower. Each dataset was georeferenced
by choosing tie points between the image and a geolocated Landsat Geocover image (28.5
m resolution, Global Land Cover Facility, www.landcover.org).

The above procedure produces a corrected, georeferenced reflectance image for
each Hyperion scene. The satellite reflectance was used to create calcite abundance
maps by calculating the average band depth of the calcite feature as described in Section
2.3.3. The Hyperion images have lower spectral resolution than the field spectra, so the
average band depth was calculated with fewer spectral bands but the same spectral range
as the field spectra. The Hyperion calcite abundances were validated by comparison
with calcite abundances calculated from the field site spectra. Hyperion band depth was
converted to weight percent calcite using a linear conversion produced by combining the
regression fit of XRD calcite weight percent against sample field band depth with the
regression fit of site field band depth against Hyperion band depth.

For comparison, calcite abundances were also calculated with an empirical fit
of the reflectance spectra (using PLSR). We averaged the ground data to the same
wavelength bin sizes as Hyperion data, and performed PLSR on the averaged sample spectra and their calcite XRD values (Wehrens and Mevik, 2007). The PLSR method can be used on the whole spectrum or on a subset, so both the whole range and a subset including the calcite feature were tested. The number of components that minimized the root mean square error was used to compute coefficients.

2.4 Results

2.4.1 Classification of inundation regions

To invgeate the effect of inundation on mineralogy and particle size, sites were categorized by the frequency of inundation at the site (based on inundation maps from the winter of 2005-2006, the most recent significant playa inundation event before sampling). The inundation mapping method is described in more detail in Section 3.3.4. Briefly, inundated pixels on the playa were identified in MODIS (Band 6, 1628-1652 nm) and Landsat (Band 5, 1550-1750 nm) data by using a threshold cutoff value. In the north central area of the playa, near the Quinn River sink, five sites were categorized as “center”. Sites DKN1, DKN2, DKN3, and LTN1 were inundated from January 2006 until the beginning of July 2006, and site DKN4 was covered with water for most of the January to May period, with the exception of intervals of subaerial exposure at the end of March and April (not inundated in Landsat imagery on 2/17/06, 2/25/06, and 4/30/06). Further south, two sites in a more narrow zone of inundation were categorized as “south center”. Sites LTS1 and GRNS2 were inundated from January to the end of June, with intermittent exposure of site GRNS2 during May and June (subaerial on
5/24/06 and 6/9/06, but inundated on 6/1/06; Landsat). Inundation was either highly sporadic or not observed at other sites, which were categorized as “edge” (GREEN1, GREENS, GRPUR1, GRPUR2, LTN2, LTN3, LTN4, LTNRD3, LTSRD, PURSOU, and PURSRD).

### 2.4.2 Particle size distributions across the playa

Black Rock Desert surface samples have particle sizes between $\sim 0.1$ and 300 $\mu$m. Particle size distributions have two peaks, at approximately 1 and 20 $\mu$m (Figure 2.4). The 1 $\mu$m peak ranges from 0.1 $\mu$m to 10 $\mu$m, while the 20 $\mu$m peak ranges from 10 $\mu$m to 300 $\mu$m, but the peaks are not fully separated.

When the particle size data are sorted by inundation category, clear patterns emerge. The central sites have a smaller median particle size (1.1 $\mu$m) than the edge sites (2.3 $\mu$m), and the 1 $\mu$m peak is shifted to smaller sizes and is larger in the center sites compared to the edge sites. The south center sites combine characteristics of the center and edge sites; the median particle size is intermediate (1.7 $\mu$m), and the 1 $\mu$m peak is shifted to larger sizes (similar to edge sites), while the 20 $\mu$m peak is smaller (as in center sites).

### 2.4.3 Sample mineralogy

The XRD-derived mineralogy demonstrates that Black Rock playa sediments contain mainly quartz, plagioclase, clays, and evaporites (calcite and halite). Additional peaks (matching thenardite) were present in samples from the VLTN1 site; other sites had no additional peaks. Gypsum peaks were not seen in any of the samples, suggesting
Figure 2.4: Particle size distribution for samples from the Black Rock playa. The thick solid line is the average of all samples from the playa center sites, the thick dashed line is the south center site average, and the thin solid line is the edge site average. Particle size is reported as volume% of the solid.
that gypsum is, at most, a minor constituent (<1% by weight) in the Black Rock playa surface sediments.

Comparison of independent measurement methods is useful for validation of quantitative XRD mineralogy. The clay mineral wt% measured by XRD can be compared to the clay size (<2 µm) fraction from the particle size distribution. Since the particle size measurements were in deionized water, with much of the halite and calcite dissolved, the non-evaporite clay mineral fraction is computed as \( \frac{\text{clay}}{\text{clay} + \text{quartz} + \text{plagioclase}} \) for comparison with particle size. Considering that the clay size fraction and the clay mineral fraction are not necessarily identical, the two measurements are well correlated (p <10\(^{-14}\), \( R^2 = 0.69 \); Figure 2.5a).

Additionally, XRD mineralogy is validated by comparison to the elemental composition of our samples measured by ICP-AES. Of the elements measured by ICP-AES, Fe and Mg are present mainly in clays, and are not important constituents of quartz, plagioclase, calcite or halite. Both Fe and Mg are well-correlated with clay abundance (Figure 2.5b; \( R^2 = 0.83 \) and 0.87 for Mg and Fe, respectively). Previously, calcite XRD was found to correlate with ICP-AES calcium measurements, suggesting that most (>90%) of the Ca in the samples is in the form of calcite (Fantle et al., 2012). Silicon is present in all three of the non-evaporite minerals (quartz, plagioclase, and clay), so Si from ICP-AES serves as an upper bound for quartz measured by XRD. All samples except one (GRPUR2 005-009) have at least 5 wt% more SiO\(_2\) (calculated from ICP-AES) than quartz (from XRD); since the GRPUR2 005-009 sample has less SiO\(_2\) than it does quartz, and since its quartz wt% is 10% higher than any other sample, the GRPUR2 005-009 XRD measurements are excluded from analysis.
Figure 2.5: Intercomparison of XRD, ICP-AES, and particle size measurements for clays. (a) Mineralogical clay wt% of non-evaporites from XRD is plotted against the volume % of particles < 2µm. (b) XRD clay wt% vs. Fe and Mg wt% from ICP-AES. Fit lines are shown; equations are (0.038±0.003)∗XRD+(0.4±0.2) and (0.070±0.005)∗XRD+(0.8±0.2) for Mg and Fe, respectively. Error bars are 5% for particle size, 5% of measured for ICP-AES, and 4% for XRD.

2.4.3.1 Regional patterns of mineralogical variability

Regional patterns are seen when mineralogy data are organized by inundation category. The edge sites have higher calcite and plagioclase concentrations, while the center sites have more clay (edge vs. center: calcite 9.4±2.1% vs. 6.8±0.9%, plagioclase 13.1±3.2% vs. 7.2±0.9%, clay 39.4±10.4% vs. 57.2±3.5%; Table 2.2). Higher concentrations of clay minerals in the center sites is consistent with the smaller particle sizes seen there. The quartz concentration is slightly lower in the center (26.1±2.5%) than the edges (31.1±3.9%). South center sites are similar to edges sites for calcite (9.3±1.7%), quartz (32.9±5.4%), and clay (40.2±9.5%), but have intermediate (9.8±1.7%) plagioclase concentrations. Edge sites have more halite (7.0±10.6%) than center sites (2.6±1.4%) in this subset of samples, but this is not a robust observation for the playa as a whole.
Table 2.2: Black Rock playa surface mineralogy and particle size by region.

<table>
<thead>
<tr>
<th>XRD (wt%)</th>
<th>Center</th>
<th>South center</th>
<th>Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Calcite</td>
<td>15</td>
<td>6.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Halite</td>
<td>15</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Quartz</td>
<td>15</td>
<td>26.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>15</td>
<td>7.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Clay</td>
<td>15</td>
<td>57.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Non-evaporite mineral fraction (wt%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>15</td>
<td>28.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>15</td>
<td>8.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Clay</td>
<td>15</td>
<td>63.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Quartz/Plagioclase</td>
<td>15</td>
<td>3.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Particle size (volume%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 2µm</td>
<td>15</td>
<td>68.9</td>
<td>10.4</td>
</tr>
<tr>
<td>&gt; 50µm</td>
<td>15</td>
<td>1.9</td>
<td>3.1</td>
</tr>
</tbody>
</table>

given the limited number of samples with significant halite (14 samples with >5% halite), especially since the sampling method was not completely randomized.

Samples from the three Black Rock playa regions show distinct patterns in a plot of quartz vs. plagioclase (non-evaporite fraction; Figure 2.6). Samples from the center sites plot along a line, such that linear regression of the center samples produces a fit of Plagioclase = 0.28 * Quartz (intercept is not significant, p=0.9). South center samples have more of both plagioclase and quartz compared to center sites, but are close to the fit line. Samples from edge sites do not plot on a well defined line; most have a lower quartz:plagioclase ratio (average 2.5 ± 0.6) than center site samples (average 3.6 ± 0.3).

2.4.3.2 Mineralogy variability within sites

Even after accounting for variation between regions, there is a significant amount of variability between samples (Figure 2.7). For the most part, this variability is from samples taken within the same site. Intra-site variability is higher than measurement
Figure 2.6: Sample non-evaporite quartz concentration vs. non-evaporite plagioclase concentration from XRD. Samples are identified by region. Line is the regression fit for the center region samples (Plagioclase = 0.28 * Quartz). Error bars are the XRD measurement error.
error (Table 2.3). This variability is potentially due to non-random sampling; however we suggest that non-random sampling is not a sufficient explanation. Some of the sites were sampled in a more random manner, so if the variability within sites is due to non-random sampling, a difference in variance between sites would be expected. When equality of variance in the XRD measurements is tested for using Levene’s test, there is no difference in variance between the sites (p >0.7 for all), supporting the argument that there is significant small scale (cm- to m-scale) compositional variability between locations on the playa.

Figure 2.7: Calcite wt% from XRD in Black Rock Desert samples. All samples for each site are plotted at the same x-value, grouped by region of the playa.
Table 2.3: Standard deviation of XRD measurements.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Intra-site (wt%)$^a$</th>
<th>Repeated measurement (wt%)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Halite</td>
<td>6.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Quartz</td>
<td>3.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Clay</td>
<td>5.3</td>
<td>3.7</td>
</tr>
</tbody>
</table>

$^a$ Standard deviation of all samples from the same site.

$^b$ Standard deviation of all repeated XRD measurements of the same sample.

2.4.4 Elemental data

The elemental data are consistent with the XRD data. Aluminum ranges from 3.8-7.5 wt% (mean 6.6 wt%), Ba ranges from 0.05-0.07 wt% (mean 0.07 wt%), Ca ranges from 3.1-6.0 wt% (mean 4.2 wt%), Fe ranges from 1.4-4.7 wt% (mean 3.9 wt%), K ranges from 1.1-2.9 wt% (mean 2.5 wt%), Mg ranges from 0.7-2.5 wt% (mean 2.0 wt%), Mn ranges from 0.03-0.08 wt% (mean 0.07 wt%), Na ranges from 1.8-22.7 wt% (mean 4.8 wt%), P ranges from 0.06-0.13 wt% (mean 0.09 wt%), Si ranges from 12.9-24.2 wt% (mean 21.6 wt%), Sr ranges from 0.03-0.05 wt% (mean 0.04 wt%), and Ti ranges from 0.17-0.35 wt% (mean 0.32 wt%).

The elemental data demonstrate that Al, Fe, K, Mg, Si, and Ti are correlated with each other, whereas the important evaporite constituents Ca and Na behave differently (Figure 2.8). In addition, Ca is correlated with Ba and Sr (Table A.1). The elements Al, Fe, K, Mg, Si, and Ti all correlate with the clay mineral concentration as measured by
Table 2.4: Calcium isotope data by region.

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th></th>
<th>South center</th>
<th></th>
<th>Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean</td>
<td>Standard deviation</td>
<td>n</td>
<td>Mean</td>
</tr>
<tr>
<td>Water δ⁴⁴Ca (‰)</td>
<td>2</td>
<td>1.32</td>
<td>0.03</td>
<td>4</td>
<td>1.04</td>
</tr>
<tr>
<td>Acid δ⁴⁴Ca (‰)</td>
<td>2</td>
<td>0.75</td>
<td>0.02</td>
<td>4</td>
<td>0.73</td>
</tr>
<tr>
<td>Resid δ⁴⁴Ca (‰)</td>
<td>3</td>
<td>0.76</td>
<td>0.05</td>
<td>3</td>
<td>0.78</td>
</tr>
<tr>
<td>∆water–acid (‰)</td>
<td>2</td>
<td>0.58</td>
<td>0.05</td>
<td>4</td>
<td>0.31</td>
</tr>
</tbody>
</table>

XRD (p-values for a linear regression fit are: Al: p=4e-8, Fe: p=2e-12, K: p=2e8, Mg: p=7e-11, Si: p=4e-6, Ti: p=7e-5). Calcium correlates with calcite (p<2e-16), as do Ba (p=4e-13) and Sr (p=3e-13).

2.4.5 Calcium isotopes

There is a difference in δ⁴⁴Ca between the center and edge sites in the calcium fraction sampled by the water leach, with higher values in the center of the playa (Table 2.4). This difference is small, and is within the external reproducibility of the measurements (0.18‰); however, if we assume the samples are independent, the difference between center and edge sites is significant (t-test; p=2e-4). The south center sites are more similar to the edge sites (t-test for south center vs. south, p=0.04; for edge vs. south, p=0.8). Water leach calcium has higher δ⁴⁴Ca than acid leach calcium in all samples.
Figure 2.8: Elemental compositions of playa surface sediments. Each panel is a plot of one element against another (on the x- and y-axes); elements are labeled in the panels along the center diagonal. Axes are weight\% of the bulk sample.
2.4.6 Hyperion processing algorithm

The Hyperion data were compared to the ground site spectra to validate the satellite correction algorithm (Figure 2.9). The spectral features match well, although at some sites, there is an offset in the reflectance.

![Figure 2.9: Comparison of reflectance spectra taken at three ground sites with the portable spectrometer (solid) and of Hyperion satellite spectra of those sites (dotted; includes ground truthing correction). The ground spectra are the average of ∼50 spectra taken across an area of order 10^4 m^2 in August 2007. The satellite spectra are from BRD1 observation (9/15/2007).](image)

Beyond the procedure described in the methods section, a systematic range of alternate processing methods for the Hyperion images were implemented, including not performing every step, using a different water retrieval method, smoothing the spectrum based on our ground spectra, and alternate destriping methods. Most of these procedures produced very similar calcite maps, with root mean square error (RMSE) less than 1 wt.% between each pair of maps. However, the calcite map is very noisy without a smoothing step, and there is visible striping and higher RMSEs (1-2%) when no destriping is applied or when the destriping correction is based on nearby lines.
2.4.7 Calcite concentration measurement by spectral analysis

We find that all three of the spectral methods for determining calcite concentrations (average band depth, continuum removal, and PLSR) can predict the calcite wt% of a surface sample (Figure 2.10). Sample DPAVEN1 is not included in these fits since that site was not on the playa proper. In particular, for the preferred method of average band depth, the fit of band depth vs. calcite wt% (from XRD) is highly significant $(p < 10^{-12})$.

The continuum removal method produced results similar to band depth. However, with continuum removal, the DKN samples were outliers below the fit line. This non-linear response is a problem, as we are assuming a linear fit between the spectral-derived calcite wt% and the concentration of calcite on the surface. In addition, a non-linear response would be expected from the continuum removal method if the surface is an areal mixture, since continuum removal introduces a non-linear procedure (division) into the calculation. Thus the band depth method is preferred to continuum removal.

The band depth and PLSR methods were compared based on their ability to predict calcite concentrations at each ground site using the Hyperion satellite data. Average calcite concentrations for the sites were calculated in two ways for this comparison: from an average of the XRD calcite wt% for all samples from that site, and from the ground-measured site spectrum (band depth method). A PLSR fit of the Hyperion data was tested for just the spectral range around the calcite feature (2220-2380 nm), for a larger spectral range including clay features (2070-2380 nm), and for all bands not strongly influenced by water vapor. Smaller spectral ranges in the region of the calcite feature
Figure 2.10: Fit of XRD calcite wt% and calcite concentration measurements derived from the field sample spectra. (a) Average band depth method. The fit is calcite = 
\[(0.00075 \pm 0.00009)D - (0.0128 \pm 0.0009)\] with \(p < 10^{-10}\). (b) The continuum removal method. The fit is calcite = 
\[(0.0029 \pm 0.0003) \times CR - (0.044 \pm 0.003)\] with \(p < 10^{-12}\). (c) is the “leave one out” validation of the PLSR method, where a fit is performed without each point successively.
were more successful in reproducing the band depth map and the known surface concentrations (Table 2.5) in all fits other than ground band depth in BRD1. The PLSR(all) fit of BRD2 is particularly poor, perhaps due to changes in factors other than calcite which affect the reflectance of the playa.

Table 2.5: R-squared values for fits of ground calcite measurements vs. Hyperion calcite measurements.

<table>
<thead>
<tr>
<th></th>
<th>Ground band depth</th>
<th>XRD calcite wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BRD1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band Depth</td>
<td>0.74</td>
<td>0.47</td>
</tr>
<tr>
<td>PLSR(2220-2380 nm)</td>
<td>0.56</td>
<td>0.36</td>
</tr>
<tr>
<td>PLSR(2070-2380 nm)</td>
<td>0.42</td>
<td>0.29</td>
</tr>
<tr>
<td>PLSR(all)</td>
<td>0.62</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>BRD2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band Depth</td>
<td>0.78</td>
<td>0.48</td>
</tr>
<tr>
<td>PLSR(2220-2380 nm)</td>
<td>0.53</td>
<td>0.49</td>
</tr>
<tr>
<td>PLSR(2070-2380 nm)</td>
<td>0.43</td>
<td>0.31</td>
</tr>
<tr>
<td>PLSR(all)</td>
<td>0.08</td>
<td>0.16</td>
</tr>
</tbody>
</table>

* Calcite feature band depth calculated from the field site spectrum.

Band depths calculated from the Hyperion spectral data are well correlated with band depths calculated from the field site spectra (Figure 2.11), suggesting that the Hyperion band depth is a good predictor of the band depth calculated from the ground spectra. The slope of the Hyperion versus field site fit line is very close to one for BRD1 (0.99 ± 0.07). The DKVEGS1 outlier fits poorly in BRD2; without it, the fit line slope is 1.01 ± 0.09.
Figure 2.11: Average calcite band depth of the field sites versus the average band depth of Hyperion at that location. Hyperion observation is BRD1, fit equation is $D_{\text{Hyperion}} = 0.99 \times D_{\text{site}} + 0.0042$ with $p < 10^{-8}$.

The negative band depths of low calcite samples (Figure 2.10) are a potential complication of the band depth method, in that they suggest that the calcite feature is not the only factor in this spectral region. Clay minerals also have spectral features in this wavelength range. To investigate the possibility that fit of calcite band depth vs. calcite wt% is due to clay minerals, or to a statistical coincidence, we calculated average band depth for hypothetical features centered at other wavelengths. The feature used for the hypothetical fits is 70 nm across with 20 nm edge points offset 20 nm on the short wavelength end and 10 nm on the long wavelength end. Since the calcite feature is asymmetric, the feature is centered at a wavelength 25 nm higher than the midpoint. The fit of calcite wt% vs. a feature is most significant at the wavelength of the calcite feature (2330 nm; Figure 2.12).
Figure 2.12: Significance of linear regression between sample calcite wt% and the average band depth of a feature centered at the wavelength plotted on the x-axis. The solid line is the F-statistic for each fit, and the dotted line is the R-squared value for each fit. The calcite feature is located at 2330 nm.

Since the most significant feature fit is at the wavelength of the largest calcite feature in the wavelength range, and since a clay mineral feature at 1400 nm (IGCP spectral library in ENVI) does not have a particularly significant fit, we argue that band depth at 2330 nm is directly measuring the amount of calcite present on the surface. However, since the clay mineral wt% of the samples is inversely correlated with calcite wt%, the possibility that the feature fit is measuring clay rather than calcite cannot be excluded. The Hyperion calcite maps in this study would still be valid, since they have been validated by the measurement of surface samples, but the band depth feature fit would be an empirical relationship that is less likely to be applicable to other locations.
In addition, the Hyperion-derived calcite concentration measurements are high in areas outside the playa. Since the Hyperion calcite measurement was validated based solely on samples from the playa, it is plausible that a different mixture of minerals could modify the shape of the background spectrum, or of the calcite feature. Thus the Hyperion-derived calcite measurement is only valid on the playa.

2.4.8 Calcite mapping

The average calcite concentration in the satellite swath of the playa is approximately 9%. This is equivalent to 3.6% calcium, the same as the average global Ca concentration in dust (Lawrence and Neff, 2009). Calcite concentrations are higher along the edges of the playa (as high as 20%; Figure 2.13); average calcite concentrations in the central area are closer to 7% or 8%. This is consistent with the pattern seen in the XRD measurements, providing a sanity check for the satellite calcite maps.

Calcite maps based on BRD1 and BRD2 are similar, but there are some differences. A prominent difference between the two calcite maps demonstrates the importance of water to the distribution of calcite in the playa. In BRD1, there is an area of high calcite concentration on the southwest side of the central part of the playa. This area was inundated during February 2007 (Figure 2.14). In BRD2, this patch is much less distinct. Gerlach, on the edge of the Black Rock Desert, received 0.8 cm of rain during October (National Climatic Data Center, www.ncdc.noaa.gov). This is consistent with the idea that calcite precipitated during evaporation in 2007, but was redissolved during the October rains and not reconcentrated by evaporation in this area. The average calcite concentration across the playa does not measurably change between BRD1
Figure 2.13: Map of calcite distribution in the Black Rock Desert, on 9/15/2007 and 11/5/2007. Base image is Landsat Geocover. Colored plusses are site calcite values. Higher calcite values tend to occur near the edge of the playa and in the north.
and BRD2, so either other areas had little calcite dissolution during October, or calcite reprecipitated after the rain.

Figure 2.14: MODIS data (February 2007) of the Black Rock Desert with calcite contours from BRD1. Modis band 6 (1640 nm) highlights surface water. A water area from winter 2007 is closely associated with calcite in September 2007.

2.5 Discussion

2.5.1 Geochemical heterogeneity in playa surface sediments

There are significant differences in mineralogy and particle size between surface samples from the center or the edges of the Black Rock playa. Since several independent measurements all display a similar pattern, the observation that there is a difference between the frequently inundated playa center and intermittently inundated playa edge
is relatively robust. Differences between the edges and center of the playa in mineralogy and particle size follow the pattern of inundation, suggesting that inundation is the main controller of this variability in playa surface composition.

An addition piece of evidence for the importance of inundation is that the frequently inundated playa center is well mixed, suggesting that inundation plays a role in the mixing of playa surface sediments. Playa center samples have much less variation in the ratio of plagioclase to quartz than edge samples, indicating that areas in the center of the playa are better mixed with respect to plagioclase and quartz (Figure 2.6). In addition, the particle size distribution is more similar between central playa samples than between edge samples.

There is also significant intra-site variability in mineralogical composition. Previous playa studies have not been able to correlate differences in composition with differences in surface crusting/erodibility (Gill et al., 2002; Sweeney et al., 2011). Meter scale variability is a potential cause for this difficulty. If centimeter to meter scale compositional variability is as high as the variability across an entire playa, then the exact location of sampling needs to be considered carefully, perhaps by sampling in multiple locations separated by centimeters to meters and homogenizing carefully before analysis.

Meter scale differences in composition suggest that there could be meter scale differences in erodibility. Centimeter scale differences in crust strength have been observed to affect dust emission (Brown, 2007), so small scale variability is known to matter for erodibility. Small scale compositional differences might help explain small scale crust strength variability; large inter-particle attraction between clay particles, or cementation by evaporites, might help to form a strong surface. Changes in surface erodibility
on the order of meters suggest that it is important to consider variability on the smallest scales in dust emission models.

If the Black Rock playa were sampled in only one location, not only would the small-scale variability be a potential bias, the variability between edges and center would be missed. It is problematic to assume that one sample from a playa is representative, and even multiple samples would not necessarily display the full variability within the playa if they were preferentially chosen from near the playa edge (due to ease of accessibility). The difficulty of finding a representative subset is exacerbated by small scale areas with even larger variations; for example, we excluded sample VLTN1 from some of the regional analysis due to its high evaporite content. If only a few samples could be taken to characterize the entire playa, samples from the center would not display the full range of composition within the entire playa, but could establish the dominant composition of the playa center. Thus, when sampling playas, it might be advisable to select samples from near the playa center.

2.5.2 Controls on the distribution of mineralogy and particle size across the Black Rock playa

Identification of the mechanism that produces the differences seen between the playa center and edge in mineralogy and particle size might help in predicting mineralogy and particle size in other playas. Since these differences are associated with the pattern of inundation, it is plausible that water is involved. Possible mechanisms include size sorting, different source rocks, and varying degrees of weathering.
The preferred hypothesis to explain the difference between the playa center and edges is particle size sorting by water. The large particles are located near the edges of the playa, where water carrying sediments would first arrive, lose energy, and deposit the bigger particles. The smaller particles are concentrated near the playa center, where there is a longer period of inundation, allowing clays (with a lower settling velocity) to be deposited. As the smallest particles are clays (Figure 2.5a) and the largest are plagioclase, size sorting explains the mineralogy distribution.

One alternative hypothesis is that playa particles are sourced from different parent rocks, i.e., the playa center material is sourced from sediments carried into the playa by the Quinn River, while the edges are sourced from the mountains surrounding the playa. However, in this case it might be expected that the Fe and Mg concentrations of the clays would be different, but there is no significant distinction between the center and edges in the fit of clays to Fe or Mg (Figure 2.5b).

A third possible hypothesis is that the distinction between regions is due to increased weathering processes on the playa during inundation. In this case, it would be expected that in the playa center Mg (easily lost during weathering) would be reduced relative to Ti (relatively immobile), but the Mg/Ti ratio has no consistent pattern between center and edge (center: 7.0 ± 0.2, south center: 6.0 ± 0.6, edge: 6.3 ± 0.7).

If the mineralogical and particle size differences seen in the Black Rock playa are caused by particle size sorting in water, the pattern seen in the Black Rock playa might occur in other playas. This has implications for surface erodibility and dust emission since both surface evaporite mineralogy and particle size can affect surface erodibility. In the Black Rock playa, these factors favor dust emission from the high-calcite playa.
edges, where there are more particles in the saltation size range. If the edges of many playas are conducive for dust emission, this could help to explain the correlation between playas and dust.

2.5.3 Comparison of calcite mapping methods

Calcite abundance can be predicted from \textit{in situ} spectra, and it is possible to extend this analysis to large areas with hyperspectral satellite images. Destriping is an important processing step since the calcite feature is at the lower signal to noise, long wavelength end of the Hyperion spectrum. Striping produces errors that vary spatially. In the relatively uniform playa environment, the destriping routine is less likely to introduce new artifacts, so it is quite effective. Systematic errors that apply to all pixels (for example a poor water correction in one band) have less of an effect on the calcite map. Systematic errors change the relationship between band depth and calcite weight percent, and thus should have more impact on the slope of the fit line than on the calcite concentrations derived from the fit. Some form of spatial averaging is necessary to improve the signal to noise ratio for each pixel.

The band depth method is preferred for calculating calcite concentrations from Hyperion spectral data. While both the band depth method and the empirical PLSR method were able to predict the surface calcite composition from spectra taken at the ground site, the band depth method was more successful at predicting surface calcite composition from the Hyperion spectral data. This demonstrates the difficulty of using the empirical PLSR method, since it is less effective when extended beyond the regime that it was “trained” on. In addition, the empirical PLSR method was most successful
when restricted to the wavelength range of the known calcite feature, consistent with the presence of a real spectral feature there.

2.5.4 Implications of calcite distribution for geochemical cycling

To understand the cycling of calcium in the Earth system, it is necessary to establish the variability in the amount of calcium transported by various mechanisms, including atmospheric dust. Measuring the variability of calcium concentrations within a playa dust source can help to better represent the variability seen in dust by distinguishing between variability within a source and variability between sources.

The highest calcite concentrations on the playa are near the edges, especially in the north. These edge areas are not as frequently part of the ephemeral Black Rock Desert Lake, but there are springs in many locations around the edges of the playa, and runoff from the mountains will flow onto the edges of the playa. Alternately, clays are more concentrated in the central areas of the playa, and so the edges have a greater hydraulic conductivity (Sinclair, 1963), and could contain more calcite due to faster evaporation from below.

Higher calcite concentrations in surface sediments has been associated with increased dust emission (Chepil, 1954; Argaman et al., 2006). Thus dust emission from the Black Rock playa could be concentrated along the edges, where the calcite content is higher. Since the edges are higher in calcite and plagioclase, which have more easily accessible micronutrients, this could suggest that dust transported from the playa is more useful for neighboring ecosystems than might be expected based on samples taken from the center of the playa. In addition, while the average playa calcium composition is
similar to global average dust (Lawrence and Neff, 2009), the playa would be a relatively significant source of calcium-rich dust if emission is concentrated along the edges, where calcium concentrations in the surface sediments are \(~50\%\) higher than the global average in dust.

2.6 Conclusions

There is significant geochemical heterogeneity in playa surface sediments. In the Black Rock playa, average sample composition is 30\% quartz, 43\% clay, 12\% plagioclase, 9\% calcite, and 6\% halite, with substantial variability between samples. Much of the variation in composition between sites can be accounted for by considering playa inundation, although there remains a significant amount of variability within samples from the same site. The playa center has more clay minerals (57\% center vs. 40\% edge) and a smaller median particle size (1.1 \(\mu m\) vs. 2.3 \(\mu m\)), while the edges have more plagioclase (13\% edge vs. 7\% center) and calcite (9\% vs. 7\%), and a larger, more variable particle size distribution. Playa center sites are better mixed with respect to quartz and plagioclase.

The distribution of calcite at the surface of the Black Rock Desert playa in northwestern Nevada was mapped. The band depth method for estimating calcite concentration was more robust with changing conditions than the PLSR method. Calcite was more concentrated near the edges of the playa and in a patch that contained water during the previous winter. More activity around the edges of the playa could lead to a higher concentration of Ca in dust.
Acknowledgments

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Chapter 3

The temporal variability of surface roughness in a playa dust source: Synthetic aperture radar investigation of active playa surface dynamics

3.1 Abstract

Emission of mineral dust aerosols is highly dynamic, in part due to variability in surface erodibility. Investigation of the variations of surfaces within dust source regions has the potential to elucidate the processes that control erodibility and to improve model representation of dust emission. In this study, we investigate changes over time on the surface of the Black Rock Desert playa (Nevada, USA) using synthetic aperture radar (SAR) satellite data, and compare the SAR backscatter ($\sigma_0$) measurements of the playa surface to weather and inundation data. These data show that the playa varies more than the neighboring mountains; that the playa surface changes from year to year, but
stays nearly constant during the summer; that the SAR backscatter ($\sigma_0$) on the playa is low in years with heavy precipitation; but that areas that dry late in the season have high $\sigma_0$. The timing of $\sigma_0$ variability suggests that water is the critical factor controlling playa surface structure, and that in the Black Rock Desert, wide scale erodibility changes occur on an annual time scale.

3.2 Introduction

Atmospheric mineral dust is important to the Earth system in a variety of ways. In the atmosphere, dust is a significant component of atmospheric radiative transfer, and thus influences climate (e.g., Arimoto, 2001; Forster et al., 2007; Mahowald et al., 2010). Additionally, dust particles indirectly affect climate by acting as nuclei for ice and cloud formation (Sassen et al., 2003) and by potentially enhancing the marine biological pump via iron fertilization (Martin et al., 1994; Jickells et al., 2005). Dust is an important component of soils, and can influence pedogenesis (Reheis et al., 1995; Lawrence and Neff, 2009) and the biogeochemistry and nutrient supplies of ecosystems both regionally and globally (e.g., Okin et al., 2004; Reynolds et al., 2006; Muhs et al., 2007).

Overall, dust is an important flux to the global ocean for a variety of elements and is therefore critical to the evolution of the surface Earth (e.g., Martin, 1991; Fung et al., 2000; Mahowald et al., 2005). The mass flux of dust emitted to the atmosphere is significant ($\sim$ 1000-3000 Tg/a [Huneeus et al., 2011]) relative to the global dissolved riverine flux ($\sim$ 3500 Tg/a [Drever, 1988]), and may have been two to three times higher in the past (Mahowald et al., 2009). Given the importance of dust to the Earth’s surface
evolution, it is vital that we understand where and how dust is mobilized, and which factors control the evolution of dust sources over time.

The ultimate goal of identifying dust source regions and understanding the controls on dust emission is to predict dust fluxes in the past and future. Since dust is relevant to climate and to the chemical evolution of the Earth’s surface, it is important to model dust in a non-empirical manner. To accomplish this, a solid understanding of the susceptibility of dust sources to wind erosion is needed. Dust is not well mixed in the atmosphere; given its short residence time (<two weeks), accurate predictions of dust loading and deposition require constraints on source locations (Engelstaedter and Washington, 2007). A significant problem for parameterizing dust fluxes is that sources are variable in space and time, even in source regions that appear to be uniform (Okin et al., 2006).

An important, but poorly constrained, factor in the variability of dust sources is variability in the susceptibility of the soil surface to wind erosion, or erodibility (Zender et al., 2004; Webb and Strong, 2011). Shifts over time in erodibility can affect dust emission, but the time scales of changes in surface erodibility of dust sources are not well established (Chappell et al., 2007). An improved understanding of the time scale of variability in erodibility would be of use in dust emission models, and also would help assess which processes are most important for controlling erodibility, by focusing attention on processes that occur on a similar time scale to changes in erodibility.

The current study focuses on observing surface roughness in playa systems over time, with the ultimate goal of elucidating the evolution of erodibility. By measuring
surface roughness via remote sensing, we can observe the meteorological and climatological circumstances under which a dust source changes. Surface roughness is often defined as the standard deviation of surface height measurements (Bertuzzi et al., 1990). Surface roughness is a component of dust emission models; roughness affects the friction velocity, and shelters portions of the soil surface from wind erosion (Raupach and Lu, 2004; Shao, 2008). Roughness is influenced by the cohesive forces that resist ablation, particularly in crusts or aggregates (Zobeck and Onstad, 1987; Macpherson et al., 2008), thus changes in roughness suggest changes in erodibility. As the surface morphology of a dust source changes, surface roughness can be altered (though morphology and roughness are not necessarily directly proportional). Understanding the time scale of variability in roughness will improve model predictions of dust emission by improving friction velocity estimates and by elucidating the processes controlling soil erodibility.

One of the difficulties in studying surface roughness and erodibility in dust source regions is the mismatch in scale between the dust source regions (km scale) and measurements of surface properties (meter scale) (Webb and Strong, 2011). This limitation has been overcome to some extent by remotely sensed multispectral and hyperspectral data, which have been used to investigate the relationship between erodibility and surface properties such as crusting (Katra and Lancaster, 2008; de Jong et al., 2011). We utilize synthetic aperture radar (SAR) to study the evolution of surface roughness over time in a playa system. Radar is sensitive to surface roughness on the order of its wavelength (cm) and the satellite-based platform allows for observations of surface properties over large areas and multiple years. Previous studies documented a relationship between radar backscatter coefficient($\sigma_0$) and the aerodynamic roughness length (Greeley et al., 1997;
Wadge and Archer, 2002; Marticorena et al., 2006), and radar roughness measurements have been used to improve dust emission models (Prigent et al., 2005). More specifically, $\sigma_0$ has been found to correlate with surface roughness in a playa environment (Wadge and Archer, 2002).

Arid playas are recognized to be significant dust producers, but the controls on dust emission in such environments are not entirely clear (e.g. Cahill et al., 1996; Tegen et al., 2002; Prospero et al., 2002; Bryant et al., 2007; Reynolds et al., 2009; Buck et al., 2011; Liu et al., 2011). Playas are particularly interesting targets for a study of dust emission since their limited vegetation cover and lack of topography shifts the focus to the erodibility of the playa surface sediments. A number of controlling mechanisms have been proposed for playa surfaces. Playas undergo ephemeral inundation, with substantial variation between years in the areal extent of inundation (Briere, 2000; Lichvar et al., 2008; Scuderi et al., 2010); this variation is one potential factor influencing erodibility. Previous work has suggested that dust emission is affected by previous playa inundation events due to the delivery of fresh, unconsolidated sediment and/or disruption of stable surface crusts (Mahowald et al., 2003; Bryant et al., 2007). Others have proposed that cycles of wetting and drying roughen soil surfaces, and that surface water washing smooths playa surfaces (Figueira, 1984; Valentin and Bresson, 1992). Groundwater is also potentially important to the development of playa surfaces, as evaporating groundwater precipitates evaporites, disrupting the playa surface crust (Reynolds et al., 2007). Disruption of crusts by sandblasting, producing a loose surface, is another possible mechanism (Gillette et al., 2001). Anthropogenic disturbances also have the potential to
disturb the playa surface, as do freeze/thaw processes (Adams and Sada, 2010). Distinguishing the importance of different mechanisms in a playa is helpful for understanding dust emission from these important dust sources.

In this contribution, the temporal evolution of surface roughness in the Black Rock Desert playa is constrained using SAR data. To our knowledge, the temporal evolution of surface roughness in playa systems has not been previously studied on a large scale. We compare SAR data to the time and location of inundation, as well as the timing of precipitation and summer drying of the playa, in order to ascertain which of these processes are important in controlling playa surface variability. Establishing the time scales and processes that regulate the surface structure of the playa will help in understanding and modeling dust emission changes over time.

3.3 Data and Methods

3.3.1 Study Site

The field location for the current study is the Black Rock Desert, in northwestern Nevada (USA) (Figure 3.1). The Black Rock Desert is a hydrologically closed basin located in a north-south trending normal fault bounded graben in the Basin and Range. The Black Rock playa is a flat (relief < few meters) area in the center of the Black Rock Desert (Sinclair, 1963), on which vegetation is essentially absent. The playa lies at an elevation of 1190 meters above sea level (Gesch et al., 2002). In this study, we define the playa proper to be all surfaces below 1192 meters, which encompasses 350 km$^2$. The playa is comprised of silt- and clay-sized lake deposits, which can be as thick as 2400 meters
Satellite observations show the Black Rock Desert to be a dust source (Lewis et al., 2011; Fantle et al., 2012). Anthropogenic activity is significant on the Black Rock playa, with vehicle traffic allowed anywhere, and particularly common on the south end of the playa (Adams and Sada, 2010).

The Black Rock playa is fed from the northeast by the ephemeral Quinn River. Streamflow data from the Quinn River at 41°46′30″N 117°48′15″W (site 10353500, waterdata.usgs.gov) demonstrates that the Quinn River is generally dry (<1 m³/s) from July to January but flows many years during February to June. Peak flow is typically in April or May. During water years with at least (roughly) 200 mm of precipitation, the basin is inundated (>200 km²) during the spring, but the playa surface dries from May to July.

3.3.1.1 Field observations

During field campaigns in 2007 and 2010, we observed a variety of playa surfaces characterized by qualitative differences in roughness. Typical surfaces contained mud cracks, and either were smooth or had features a few millimeters to tens of centimeters in size (Figure 3.2). Smooth mud-cracked surfaces (i.e., Figure 3.2d) were generally strong (when dry), based on their resistance to deformation by vehicles. Rougher surfaces (i.e., Figure 3.2c) varied in the amount of force required to break the surface; they generally were disrupted by vehicle traffic, and often but not always by foot traffic. Rough surface crusts, on the order of cm in thickness, were often underlain by unconsolidated, uncemented sediments. Regions with similar surface types were as much as order of kilometers across. Transitions between surface types at times occurred abruptly, on the
Figure 3.1: MODIS Geocover (www.landcover.org; Band 2, 858 nm) of the Black Rock Desert study site in northwest Nevada, USA. The Black Rock Desert playa is more reflective than the mountainous areas that surround it. The black outline is the 1192 m contour used to delineate the extent of the playa for this study.
scale of meters. The processes controlling transitions between surface types were not immediately obvious on the ground.

3.3.2 Meteorological data

In this study, meteorological data from the National Climatic Data Centers Gerlach, NV station were utilized (www.ncdc.noaa.gov). The average annual temperature during the study period was 11.6°C (average July temperature: 26.3°C), while average annual precipitation over the period of record (1963-1971, 1986-2010) was ~200 mm/year. For days that were missing precipitation data (2 full months, and 16 other days during the 2004-2010 period), we estimated precipitation by averaging precipitation at the nearby Lovelock, Lovelock Derby Field, Inlay, Rye Patch Dam, Winnemucca Airport, and Winnemucca meteorological stations; a linear regression of Gerlach monthly precipitation as a function of this average produced the equation \( m_{\text{Gerlach}} = (0.95 \pm 0.04) \times m_{\text{other station average}} \), where \( m \) is the monthly precipitation (\( p < 2e-16 \)). The two missing months were January 2004 (15 ± 17 mm estimated) and April 2010 (47 ± 17 mm estimated).

3.3.3 Synthetic aperture radar methods

Radar data reported in this study were obtained from the Advanced Synthetic Aperture Radar (ASAR) instrument on the European Space Agency’s ENVISAT satellite, a C-band instrument (\( \lambda = 5.6 \) cm). Incidence angles for the ASAR instrument range between 15° and 45° (Barstow, 2007). Data utilized in this study had one of four observation geometries, two ascending (incidence ranges 18-22° and 22-26.5°) and
Figure 3.2: Examples of surface morphologies observed in the Black Rock Desert: (a) a view of the Black Rock playa, with different appearing surfaces in the near foreground; (b) a rough, crusted surface with evaporite staining; (c) a relatively weak surface, which is visibly disturbed by a footprint; (d) an example of a relatively strong surface that is resistant to disturbance; (e) a surface with loose material available for ablation; (f) a highly cracked surface.
two descending (incidence ranges 17.5-22.5° and 22-26.5°), all in VV polarization. We analyzed 36 Image Mode Ellipsoid Geocoded (IMG_1P) datasets collected by the ASAR instrument between 2004 and 2010 (Table 3.1). IMG_1P images have 30 meter pixel sizes, and are geolocated by ESA prior to delivery.

Raw data were converted to backscatter by applying the calibration constant supplied by ESA, and elevation corrected to a constant height of 1190 m above sea level (the approximate elevation of the playa) using the IDL/ENVI software package (Exelis, Boulder, CO). We did not implement a terrain correction, since the playa is flat within a few meters (Gesch et al., 2002). In off-playa areas, we performed comparisons only between data with similar observation geometries. Geolocation accuracy was assessed using railroad tracks at the southwest edge of the playa; the tracks were aligned in all ASAR data with <3 pixels offset, validating the geolocation of and the elevation correction.

Field studies have found that backscatter ($\sigma_0$) derived from airborne and space-based radar instruments correlates with surface roughness in arid regions. Several studies have found a correlation between $\sigma_0$ and aerodynamic roughness length (an important surface characteristic for wind erosion studies, measured from vertical wind velocity and temperature profiles) in arid areas (Greeley et al., 1988, 1997; Marticorena et al., 2006). However, the use of radar data to study surface roughness is complicated by the influence of soil moisture on backscatter ($\sigma_0$; Tansey and Millington, 2001). In a playa system with <1 meter depth to groundwater (Chott el Djerid, Tunisia), Archer and Wadge (2001) found that RMS surface roughness was more important than soil moisture in determining $\sigma_0$ from a C-band SAR instrument (ERS-1). In order to reduce
Table 3.1: Summary of ASAR observations utilized in this study.

<table>
<thead>
<tr>
<th>Date</th>
<th>Incidence range</th>
<th>Pass</th>
<th>Median $\sigma_0$(dB)</th>
<th>Date</th>
<th>Incidence range</th>
<th>Pass</th>
<th>Median $\sigma_0$(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/1/2004</td>
<td>17.6°-22.2°</td>
<td>Descending</td>
<td>-11.07</td>
<td>7/3/2009</td>
<td>22.7°-26.3°</td>
<td>Descending</td>
<td>-12.80</td>
</tr>
<tr>
<td>7/13/2005</td>
<td>17.7°-22.3°</td>
<td>Descending</td>
<td>-12.09</td>
<td>7/22/2009</td>
<td>18.6°-22.2°</td>
<td>Descending</td>
<td>-12.65</td>
</tr>
<tr>
<td>8/2/2006</td>
<td>17.6°-22.2°</td>
<td>Descending</td>
<td>-13.30</td>
<td>8/14/2009</td>
<td>18.5°-21.7°</td>
<td>Ascending</td>
<td>-12.10</td>
</tr>
<tr>
<td>9/6/2006</td>
<td>17.6°-22.2°</td>
<td>Descending</td>
<td>-13.03</td>
<td>8/26/2009</td>
<td>18.5°-22.2°</td>
<td>Descending</td>
<td>-12.64</td>
</tr>
<tr>
<td>7/2/2008</td>
<td>18.4°-22.0°</td>
<td>Descending</td>
<td>-10.40</td>
<td>7/7/2010</td>
<td>18.4°-22.0°</td>
<td>Descending</td>
<td>-12.89</td>
</tr>
<tr>
<td>7/9/2008</td>
<td>22.3°-26.4°</td>
<td>Ascending</td>
<td>-13.22</td>
<td>7/14/2010</td>
<td>22.5°-26.5°</td>
<td>Ascending</td>
<td>-14.33</td>
</tr>
<tr>
<td>7/18/2008</td>
<td>22.4°-25.8°</td>
<td>Descending</td>
<td>-12.72</td>
<td>7/23/2010</td>
<td>22.2°-26.5°</td>
<td>Descending</td>
<td>-13.80</td>
</tr>
<tr>
<td>8/6/2008</td>
<td>18.4°-22.0°</td>
<td>Descending</td>
<td>-10.77</td>
<td>8/11/2010</td>
<td>18.4°-22.0°</td>
<td>Descending</td>
<td>-12.20</td>
</tr>
<tr>
<td>8/13/2008</td>
<td>22.5°-26.4°</td>
<td>Ascending</td>
<td>-13.11</td>
<td>8/18/2010</td>
<td>22.5°-26.5°</td>
<td>Ascending</td>
<td>-14.29</td>
</tr>
<tr>
<td>8/22/2008</td>
<td>22.4°-25.8°</td>
<td>Ascending</td>
<td>-11.54</td>
<td>8/27/2010</td>
<td>22.2°-26.5°</td>
<td>Descending</td>
<td>-13.56</td>
</tr>
<tr>
<td>9/10/2008</td>
<td>18.4°-22.0°</td>
<td>Descending</td>
<td>-11.26</td>
<td>9/15/2010</td>
<td>18.4°-22.0°</td>
<td>Descending</td>
<td>-11.09</td>
</tr>
</tbody>
</table>

The impact of soil moisture, we restrict analysis to times when the playa surface is dry (the summer months of July-September), and exclude data from <two weeks after the playa inundation is last observed in MODIS. A qualitative comparison of photographs from sample sites on the playa and ASAR $\sigma_0$ from those sites supports the argument that surface roughness is a control on $\sigma_0$.

In this study, ASAR data are reported as $\sigma_0$, and are interpreted as surface roughness. In previous studies, $\sigma_0$ has been converted to quantitative roughness measurements. Prigent et al. (2005) and Marticorena et al. (2006) determined linear relationships between $\sigma_0$ from the ESA’s European Remote Sensing (ERS) satellites and the log of aerodynamic roughness length ($Z_0$). Prigent et al. (2005) used $Z_0$ measurements from arid regions in North America and Africa to derive a relationship between $\sigma_0$ and $Z_0$:

$$\sigma_0 = 3.13 \ln Z_0 + 8.52.$$ Marticorena et al. (2006) utilized measurements from Tunisia to
find a similar relationship: \( \sigma_0 = 2.73 \ln Z_0 + 2.05 \) (\( Z_0 \) in units of meters). Wadge and Archer (2002) determined a fit equation between \( \sigma_0 \) from ERS and the root mean square variation of surface height profiles measured using a pin profilometer in a Tunisian playa \( (\sigma_0 = 7.82 \ln (RMS) + 35.69) \). The difference between the Wadge and Archer (2002) equation and the previous two is attributable to using different measures of roughness. Since the ASAR C-band, VV polarization \( \sim 23^\circ \) incidence configuration is similar to that of ERS, we assume that the linear equations can be applied to the ASAR instrument. Radiometric offsets between ASAR and ERS are <1 dB (Baghdadi et al., 2008).

### 3.3.4 Playa inundation mapping

The extent of playa inundation over time was mapped using MODIS data. MODIS was selected for its daily return rate and acceptable spatial resolution (500 m), which is adequate for mapping a large playa like the Black Rock Desert (Bryant and Rainey, 2002). Although the spatial resolution of MODIS is less than that of other available datasets, such as Landsat, the return rate of Landsat (16 days) is not sufficient. Infrared bands are used for mapping surface water, as energy at IR wavelengths is strongly absorbed by water, but reflected by soils. MODIS Band 6 (1628-1652 nm) was therefore used to detect surface water. We did not find a good separation between land and water pixels using MODIS Band 2 (841-876 nm). The absorption path length of water at Band 2 is \( \sim 20 \) cm (Bills et al., 2007), and so shallow water (\( < 20 \) cm) is not clearly distinguished in Band 2 data. The absorption path length of Band 5 (1230-1250 nm) is \( \sim 1 \) cm, and Band 6 is \( \sim 1 \) mm (Hale and Querry, 1973). Water area detection was consistent between Band 5 and Band 6 in many images, however water areas were less dark in Band 5 than
Band 6, such that a separation was not clear in some images, even with >100 km$^2$ of inundation, where water depth must be more than 1 cm. We hypothesize that this is due to water turbidity; the suspended sediments reflect light, which reduces the path length traveled through the water (French et al., 2006).

All MODIS data were acquired from NASA’s REVERB server (reverb.echo.nasa.gov). We retrieved 2884 level 1B, 500 m resolution MODIS for the period 2004 to 2011. Images were geolocated using the Georeference MODIS ENVI routine, and a reflectance correction was applied for sun angle. False color images of Bands 6 (red), 3 (green, 469 nm), and 1 (blue, 645 nm) were produced to highlight clouds and snow. Images with clouds, snow, or processing artifacts over the playa were excluded based on visual inspection, after which 638 MODIS observations remained.

We used density thresholding to identify inundated pixels; histograms are created from regions of interest comprised of roughly half water and half land (Birkett, 2000; Bryant and Rainey, 2002), and the resulting histogram contains two peaks: a low reflectance peak containing water pixels and a high reflectance peak containing land pixels. The midpoint between the water peak and the land peak is used as a cutoff between the two pixel types. A constant reflectance threshold of 0.15 was used for all MODIS data based on inspection of histograms from multiple datasets. This approach was validated with higher resolution Landsat data (Band 5, 1550-1750 nm). A 50-50 water-land histogram was created for each Landsat image, and an individual histogram threshold was set for each Landsat image. Inundation areas determined using MODIS data are well-correlated with those established using Landsat data, though MODIS areas are systematically lower by $\sim$5 km$^2$ (Figure 3.3).
Figure 3.3: Comparison of Landsat (Band 5, 1650 nm) and MODIS (Band 6, 1640 nm) derived inundation extents in the Black Rock playa (1:1 line shown for reference). Area of inundation was calculated based on a threshold cutoff, as described in text.

### 3.3.5 Statistical analysis

To measure the degree of change in ASAR $\sigma_0$ on the playa over time, we calculated a correlation coefficient for every pair of observations included in the study. Only pixels on the playa (defined as the region below 1192 m elevation) were included in the correlation. To produce a correlation for an entire summer, all pairwise correlations from that summer were averaged. Similarly, in comparisons between two years, all appropriate pairwise correlations were averaged.

Statistical analyses were performed with the R software package. For generalized linear models, we used an identity link and tested significance with a type II ANOVA.
3.4 Results

3.4.1 Synthetic aperture radar

Over the seven-year record examined, backscatter ($\sigma_0$) is significantly lower (range $\sim$-9 dB to -18 dB) in the Black Rock playa relative to the mountainous areas that neighbor it ($\sigma_0$ range $\sim$-7 dB to -13 dB) (Figure 3.4). Low $\sigma_0$ is expected on the playa due to the absence of large scale roughness elements such as rocks or vegetation. Applying the $\sigma_0$-$Z_0$ relationships of Prigent et al. (2005) and Marticorena et al. (2006), the playa backscatter range corresponds to an aerodynamic roughness length ($Z_0$) of $\sim$1 mm, while the off-playa measurements correspond to $Z_0$ of $\sim$1 cm. Active dust sources are associated with $Z_0$ on the order of a millimeter or less (Prigent et al., 2005).

The Black Rock Desert playa has significant temporal variability in $\sigma_0$ compared to non-playa, non-agricultural locations encompassed within the ASAR images. The temporal variability in $\sigma_0$ is evident in pixel-by-pixel standard deviations calculated over the study period (Figure 3.5). The standard deviation is low (90% range $\sim$0-1.5 dB) in off-playa areas, relative to locations on the playa (90% range $\sim$0.7-2.5 dB). The small standard deviations in off-playa areas demonstrate that large on-playa standard deviations are not caused by systematic instrument drift; similarities between different observation geometries suggest that this observation is not an artifact. Agricultural fields are visible to the west of the Black Rock playa as rectangles of high $\sigma_0$ variability; unlike the playa areas, these fields undergo disturbance by plant growth and sudden increases in soil moisture due to irrigation.
Figure 3.4: Backscatter ($\sigma_0$) from ASAR in the Black Rock Desert on (a) 8/2/2006, after a winter with a maximum observed playa inundation extent of 211 km$^2$ and (b) 8/13/2008, after a winter with a maximum observed inundation extent of 2 km$^2$. The surrounding mountains cause increased signal return from slopes facing toward the satellite, and appear in slightly different locations due to the differing observation geometries of the two datasets.

Further, $\sigma_0$ changes in the playa occur at consistent times during the year within the seven-year period analyzed. Qualitatively, the basic observation is that the spatial distribution of $\sigma_0$ on the playa varies significantly from year to year, but is relatively stable through the summer months (July to September) in any given year. Quantitatively, this is illustrated by comparing the extent to which intra-annual and inter-annual ASAR observations are correlated with each other. Observations that are compared intra-annually (i.e., during the same summer) are more significantly correlated (average $r=0.74$) than observations compared inter-annually (average $r=0.13$; Table 3.2).
Figure 3.5: Images of the standard deviation of all ASAR data at each pixel. Data are from the summers of 2004-2010. Each of the four different observation geometries is shown separately, as a terrain correction would be necessary to compare points above the playa in images from different geometries; (a) ascending, low incidence; (b) ascending, high incidence; (c) descending, low incidence; (d) descending, high incidence. (d) excludes the 8/7/2009 dataset, due to variations in $\sigma_0$ across the north end of the swath.
Table 3.2: Pearson correlation coefficients ($r$) for intra- and inter-year comparisons of ASAR observations (2004–2010) $^{ab}$.

<table>
<thead>
<tr>
<th>Year</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td># of images</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>2004</td>
<td>0.56± N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>0.02±0.02</td>
<td>0.73±0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>0.01±0.01</td>
<td>0.18±0.03</td>
<td>0.84± N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>0.02±0.01</td>
<td>0.08±0.01</td>
<td>0.16±0.03</td>
<td>0.90± N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>0.05±0.02</td>
<td>0.10±0.02</td>
<td>0.10±0.03</td>
<td>0.15±0.03</td>
<td>0.56±0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>0.03±0.02</td>
<td>0.15±0.03</td>
<td>0.12±0.03</td>
<td>0.17±0.03</td>
<td>0.23±0.05</td>
<td>0.73±0.09</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>0.10±0.02</td>
<td>0.11±0.02</td>
<td>0.11±0.03</td>
<td>0.36±0.03</td>
<td>0.17±0.04</td>
<td>0.21±0.06</td>
<td>0.82±0.06</td>
</tr>
</tbody>
</table>

$^a$ Each $r$ value is an average of the Pearson correlation coefficients for all pairwise radar observation comparisons between the two years indicated. Errors are the standard deviation of all pairwise comparisons. Correlations greater than 0.5 are indicated in bold face.

$^b$ Correlation coefficients include only on-playa, and not off-playa, pixels.

The timing of changes in $\sigma_0$ on the playa surface is consistent with surface water being a major influence on playa surface structure. The Black Rock Desert has a winter precipitation regime; during our study period, the July-September period had, on average, 4% of the total water year precipitation. Since we found that $\sigma_0$ is relatively constant in the Black Rock playa during July-September, and most changes occur outside this period, the timing of surface variation is suggestive that a mechanism involving surface water produces significant changes in the playa surface. Also, playa median $\sigma_0$ values were low ($\sim$ -13 dB) in years with >150 mm of precipitation (“wet” years) and significantly higher ($\sim$ -12 dB) when winter precipitation was <150 mm (“dry” years; Figure 3.6; p=0.02 for linear fit of precipitation vs. $\sigma_0$). The difference between wet and dry years is not attributable to high soil moisture during wet years, as high soil moisture would be expected to produce higher (and not lower) $\sigma_0$. A relationship between $\sigma_0$ and precipitation supports the argument that $\sigma_0$ is affected by surface water.
Figure 3.6: The median of $\sigma_0$ on the Black Rock playa as a function of annual precipitation for the previous water year in Gerlach, NV. Playa median $\sigma_0$ is calculated by determining the median of all playa pixels in each ASAR dataset. All datasets from a given year are combined to compute an average and a standard error, in order to produce the annual median $\sigma_0$ and the error bars.

In addition, $\sigma_0$ was more spatially uniform across the playa in years with <150 mm of total winter precipitation, suggesting that more active processes are occurring in years with more surface water. The playa-wide standard deviation of $\sigma_0$ observations averaged 2.5 dB in years with <150 mm of winter precipitation, and 1.9 dB in years with >150 mm of winter precipitation. This relationship is clearly visible in ASAR observations in, e.g., 2006 compared to 2008 (Figure 3.4). The preceding observations suggest that more active processes are occurring during wet years, as some areas are being driven both to higher and lower $\sigma_0$ values during wet years, while during dry years, the entire playa is behaving in a more uniform way. This also supports the importance of surface water, as changes are more common in years when there is more surface water.
The median value of $\sigma_0$ in the playa does not change in a consistent manner through all the summers in the study period. To test for a trend in the playa median $\sigma_0$ through the course of the summer, we used a generalized linear model with two fixed effect explanatory variables for the observation geometry (incidence angle, low or high; pass, ascending or descending) and one fixed variable for the year, plus a random variable for the day of the year (DOY; Table 3.3). The factors for observation geometry and year are significant, but the DOY variable is not. The DOY variable is testing for a trend in median $\sigma_0$ that is consistent over the course of every summer (e.g. if the playa surface increased in roughness between July and September every summer, we would expect the DOY variable to be significant). There are three years during the study period (2008-2010) with enough observations (nine apiece) to investigate independently (Figure 3.7). There is one summer with a significant positive coefficient (2010), one summer with a negative coefficient (2009), and one summer with a near-zero coefficient (2008).
Table 3.3: Coefficients for fit of playa median $\sigma_0$ in each ASAR observation$^{ab}$.

<table>
<thead>
<tr>
<th>Year</th>
<th>Year Day of year</th>
<th>Incidence angle Pass significance (dB/day) (Low) (descending)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All years</td>
<td>*** -0.002</td>
<td>1.3*** 0.7***</td>
</tr>
<tr>
<td>2008</td>
<td>N/A -0.002</td>
<td>1.3*** 1.1***</td>
</tr>
<tr>
<td>2009</td>
<td>N/A -0.013</td>
<td>1.0* 0.4</td>
</tr>
<tr>
<td>2010</td>
<td>N/A 0.018***</td>
<td>1.5*** 0.6**</td>
</tr>
</tbody>
</table>

$^a$ Coefficients for observation geometry denote the difference between low (vs. high) incidence angle observations and the descending (vs. ascending) orbital pass observations.

$^b$ Stars denote the significance of the variable in the fit. * $p<0.1$, ** $p<0.01$, *** $p<0.001$

### 3.4.2 Playa inundation and precipitation

From 2004 to 2010, the areal extent of inundation on the Black Rock playa varied (Table 3.4); the maximum areal extent of inundation was 240 km$^2$ (2005), while the minimum areal extent was 2 km$^2$ (2008). The number of days that the playa was inundated, defined by the presence of a playa lake $>5$ km$^2$ in areal extent, ranged between 0 and 207 days (average: 70 days). In 2006, the playa experienced the most extended period of inundation (207 days), while both 2007 and 2008 saw little to no substantial inundation.

Variability in playa lake extent is generally correlated with precipitation amount, as measured at the nearby Gerlach meteorological station. During the study period, precipitation over the water year (defined as October 1 to September 30) ranged from
Figure 3.7: The progression of playa median $\sigma_0$ during the summers of 2008 (triangles), 2009 (circles), and 2010 (squares). Playa median $\sigma_0$ for each observation is adjusted based on observation geometry; 1.3 dB is subtracted from low incidence angle observations, and 0.7 dB from descending pass observations (see Table 3.3).

59 mm in 2007 to 295 mm in 2005. All summers other than 2010 had <10 mm of precipitation between July 1 and September 30, indicating summers did not greatly affect annual precipitation totals. In 2007 and 2008, when there was effectively no inundation, there was <100 mm of precipitation measured at Gerlach. In 2005 and 2006, when 240 and 211 km$^2$ were inundated, respectively, Gerlach experienced >250 mm of precipitation.

The playa lake dried from the outside inward during the study period (Figure 3.8). The largest extents occurred late in the winter after storm events (February-March). In 2006, only two regions of the playa, on the north and southeast, were not observed to be inundated. Winters with >250 mm of precipitation (2005 and 2006) produced later
Table 3.4: Summary of meteorological and inundation data during the study period (2004–2011).

<table>
<thead>
<tr>
<th>Year</th>
<th>Water year precipitation (mm)</th>
<th>Summer precipitation (mm)</th>
<th>Maximum inundation (km²)</th>
<th>Date of maximum inundation</th>
<th>Inundation days (&gt;5 km²)</th>
<th>Median $\sigma_0$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>122</td>
<td>8</td>
<td>18</td>
<td>38053</td>
<td>29</td>
<td>-11.84</td>
</tr>
<tr>
<td>2005</td>
<td>295</td>
<td>7</td>
<td>240</td>
<td>38407</td>
<td>159</td>
<td>-13.08</td>
</tr>
<tr>
<td>2006</td>
<td>251</td>
<td>3</td>
<td>211</td>
<td>38777</td>
<td>207</td>
<td>-13.16</td>
</tr>
<tr>
<td>2007</td>
<td>59</td>
<td>0</td>
<td>5</td>
<td>39127</td>
<td>0</td>
<td>-12.06</td>
</tr>
<tr>
<td>2008</td>
<td>78</td>
<td>7</td>
<td>2</td>
<td>39598</td>
<td>0</td>
<td>-12.00</td>
</tr>
<tr>
<td>2009</td>
<td>146</td>
<td>0</td>
<td>10</td>
<td>39845</td>
<td>58</td>
<td>-13.04</td>
</tr>
<tr>
<td>2010</td>
<td>202</td>
<td>20</td>
<td>31</td>
<td>40222</td>
<td>37</td>
<td>-13.07</td>
</tr>
</tbody>
</table>

complete drying (July rather than by June). Water remains longest in the center of the playa, where the Quinn River terminates.

On a playa-wide scale, surface smoothing is associated with high amounts of winter precipitation. However, if the playa is examined at smaller spatial scales, there is evidence that inundation time scales affect $\sigma_0$ as well. Regions of the playa that were inundated in February though April had relatively low $\sigma_0$ values (-15 dB to -12 dB) if dry by the end of May, while late drying regions (June/July) had significantly higher $\sigma_0$ (-13 dB to -7 dB; Fig. 3.9). As the bulk of the playa dries by May (largest June inundation extent: $\sim$90 km², 6/5/2006), the late-drying regions do not significantly affect the playa average $\sigma_0$.

Late drying locations might be expected to have higher soil moisture than other areas, so high soil moisture cannot be excluded as a cause of high $\sigma_0$ in late drying locations. However, areas of high $\sigma_0$ in late drying locations are maintained until September, when the playa surface has been dry for at least a month; since playa locations that dry in April-May already have low $\sigma_0$ values in July, this suggests that high $\sigma_0$ values in
Figure 3.8: Map indicating the last day of the year that inundation was observed in the Black Rock playa in 2004-2007, based on MODIS Band 6 data. Inundation is indicated in areas below 1192 m elevation, and the background is a Geocover image. Scale bar indicates the Julian date.
Figure 3.9: Date of last visible water in MODIS data as a function of summer average $\sigma_0$ in the Black Rock playa. Points are plotted separately for each year (2004-2010). X-values are the last day of the year when inundation is visible in MODIS Band 6, while Y-values are computed by averaging $\sigma_0$ for all pixels that were last inundated on that day of the year. X error bars represent the time interval between MODIS datasets; y error bars are the standard error of the pixels averaged. Time bins containing fewer than ten pixels are omitted.
late drying locations can be attributed to high surface roughness rather than high soil moisture.

3.5 Discussion

We find that SAR mapping is an effective method for assessing the relative importance of processes that affect playa surfaces as it provides a measurement of surface characteristics over large areas and times. Field observations demonstrate the diversity of surface morphologies possible in a playa, but are not amenable for quantitative comparisons between years; changes in $\sigma_0$ can, however, be compared to annual precipitation and inundation patterns.

We argue that $\sigma_0$ in this study is mainly representative of roughness rather than soil moisture. If water was dominating the $\sigma_0$ signal, the wettest years in the study should have higher playa median $\sigma_0$, but instead $\sigma_0$ is low in the wetter years of the study. In addition, the playa median $\sigma_0$ does not display a significant trend to lower values through every summer, as might be expected if $\sigma_0$ is dominated by soil moisture and the playa is drying over the course of the summer. Indeed, out of the three years with more than three ASAR datasets, $\sigma_0$ increases during the wettest year (2010; slope=0.018 dB/day; $p<0.05$). Thus, while soil moisture could have a second-order effect on the $\sigma_0$ signal, roughness appears to be the main control on $\sigma_0$ in this study.

3.5.1 Implications for aeolian modeling of playas

Surface roughness is an important variable in dust emission modeling, including in the Black Rock playa. For example, since $\sigma_0$ commonly ranges from -7 to -13 in the
Black Rock playa ASAR observations, we use the equation for wind profile (Shao, 2008),

\[ U(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \]  \hspace{1cm} (3.1)

where \( U \) is wind velocity, \( u_* \) is friction velocity, \( \kappa \) is the von Karmen constant, \( z \) is the height, and \( z_0 \) is the aerodynamic roughness length. Combining with the equation for \( z_0(\sigma_0) \) from Marticorena et al. (2006) in section 3.3.3, assuming dust emission potential is proportional to \( u_*^3 \), and assuming a constant \( U \) at a height of 100 m, a surface with \( \sigma_0 \) of -7 has double the emission potential of a surface with \( \sigma_0 = -13 \).

The annual pattern of variability observed is pertinent for dust emission modeling. Significant variability from year to year demonstrates that if surface structure information is to be utilized by dust models, it is not likely to significantly improve results unless data can be collected for every year. On the other hand, the playa surface can be well characterized by one observation per year, so multiple collections per year will provide diminishing returns. Thus annual characterization of playa surface erodibility is optimal.

The difference between variability in \( \sigma_0 \) on the Black Rock playa and in the desert areas that neighbor it demonstrates the importance of distinguishing between dust source types in dust modeling. For example, while dust sources on some other types of surfaces (e.g. alluvial fans) might potentially be successfully modeled using surface erodibility values that are constant from year to year, annual variability in playa surface erodibility is likely non-negligible. The results of this study are not necessarily applicable to other dust source types, but could be applied to playas in a model that classifies dust sources by type, such as that of Bullard et al. (2011).
When modeling playas specifically, it is important to consider the surface water regime. Not only does precipitation govern the amount of inundation and times of complete dust suppression in playas, it also can be a primary driver of surface structure development. As surface morphology is related to surface crusting, strength, and erodibility, and thus potential for dust emission, the relationship between precipitation and dust emission in playas could be a fruitful target for study. Here again, it is important to distinguish between playas and other source types, as other sources will not have the same relationship with water.

3.5.2 Attribution of changes on the playa surface to processes

The observation that the Black Rock playa is relatively smooth after years with higher precipitation totals (>140 mm) suggests that water is involved in the process that smooths the playa surface, as does the observation that changes in the playa surface occur during the wetter part of the year (October-May). We argue that the playa surface is smoothed during the process of inundation. First of all, wetting of the playa surface leads to slaking and some disaggregation of the playa surface crusts. Inundation then introduces energy, as water flows across the playa surface; there must be some flow of water during the initial inundation, but water movement also occurs throughout the inundation period, as wind agitates the surface of the shallow (order centimeters to meters depth) playa lake (ephemeral lakes on playas have been observed to move significantly during wind events, as water is pushed to the far side of the basin; Stone, 1956). Sediments on the playa surface then become suspended, producing a highly turbid
playa lake (we see this turbidity in the MODIS Band 5 data). When this water dries in the spring, the sediments are re-deposited as a smooth depositional crust.

Alternately, playa surface smoothing in high precipitation years could be related to physical processes during raindrop impact (Valentin and Bresson, 1992). Smoothing of the playa surface during raindrop impact could explain the smoothing seen in intermediate years (precipitation \( \sim 150-200 \) mm), when inundation is relatively localized. Raindrop impact does not, however, explain why variability in \( \sigma_0 \) is localized on the playa, and few changes are seen in other areas. If short term (order hours) inundation smooths the playa surface, similar to the longer duration inundation smoothing process described above, then in intermediate precipitation years the playa could be smoothed by events too short to be observed by MODIS (especially since MODIS does not observe the surface on cloudy days).

Since the playa has higher values of \( \sigma_0 \) during years with less precipitation, there must also be a process that increases playa roughness. This process also occurs during the October-May period, suggesting that it also is related to water. We argue that this process is multiple cycles of wetting (not, however, complete inundation) and drying. Wetting disrupts the playa surface due to slaking and the expansion of clays. If inundation does not redistribute the surface sediments, the disrupted sediments remain unevenly distributed across the surface; on drying, they are further disrupted due to contraction. Further cycles of wetting and drying further disturb the surface, increasing its roughness.

This process might also explain the presence of patches of large \( \sigma_0 \) in late-drying areas of the playa. During the winter, the non-inundated playa surfaces are wet, and so
shifts in the location of the playa lake (due to wind) effectively act as further inundation. However during the heat of summer, the playa surface dries much more quickly, potentially to the very edge of the inundated area, such that the playa could undergo multiple wet-dry cycles as the playa lake level fluctuates (Figure 3.10).

Figure 3.10: Schematic demonstrating the proposed process producing the relationship seen in Figure 3.9. (a) Early in the season, the playa surface is wet, and shifts in the extent of inundation occur on wet surfaces. (b) During the summer (July), the playa surface is dry, and shifts in the extent of the lake wet the edges over short timescales, producing cycles of wetting and drying. The background images are MODIS Band 6 on (a) 3/22/2006 and (b) 7/3/2006.

Other processes that have been suggested to affect playa surface erodibility are not as well correlated with the timescale of variation seen in the ASAR data. Evaporation of groundwater through the playa surface is more effective during the summer months, suggesting that the changes we see in $\sigma_0$ are not caused by groundwater evaporation disrupting playa surface crusts. Potential evaporation in the Black Rock Desert is highest during the summer. For example, at Rye Patch Dam, NV (~70 km east), pan evaporation is above 150 mm per month from May to September, peaking in July and August at ~250
mm/month (www.ncdc.noaa.gov, average of all data available 1966-2001). If capillary evaporation of groundwater is roughening the playa surface, we might expect to see an increase in $\sigma_0$ over the course of each summer, which we were unable to detect. This does not rule out the possibility that groundwater is affecting the playa surface, but it does suggest that it is not the most important process. In addition, spring (April-June) is outside the period that is relatively constant; if water evaporation during this period is important to playa surface development, it could involve both surface and ground water.

Aeolian and anthropogenic processes are also particularly active during the summer months in the Black Rock Desert. Both are, at least in part, inhibited by high levels of moisture on the playa during the winter. In years with more than $\sim 150$ mm of precipitation, much of the playa is inundated, and even in relatively dry years, the surface of the playa is wet during the winter (Adams and Sada, 2010). Dust emission is low from surfaces with high levels of soil moisture (Chepil, 1956). Saltation is suppressed, preventing destruction of surface crusts during periods with high soil moisture. Recreation use of the Black Rock Desert is highest during the late summer and early fall (Adams and Sada, 2010). The lack of change in most of the playa surface during the period of peak visits supports the argument that anthropogenic activity is not the main process affecting surface structures in the playa. However, changes in $\sigma_0$ are visible in a restricted area on the southern end of the playa in late August/early September, a known location for anthropogenic activity; an area of particularly low $\sigma_0$ ($<-16$ dB) appears in late August/early September, but is no longer apparent in the succeeding year.
Significant changes between years in the Black Rock playa demonstrate that variations in $\sigma_0$ are not caused by factors that are persistent between years, such as bulk mineralogy or hydrological flow paths. While some particles are undoubtedly transported across the playa every year, by water or wind, a wholesale change of bulk mineralogy would require a large fraction of the surface to be transported every year. Variability across the playa also argues against subsurface groundwater flow paths governing surface structure, as subsurface composition should be yet more resistant to quick change.

It is more difficult to argue that frost heaving is not a primary mechanism for determining playa surface structure, as frost heaving does occur during the winter, and could produce changes on annual time-scales. However, average winter temperature, average winter low, and number of days below freezing do not show a relationship with summer $\sigma_0$ ($p > .1$), unlike precipitation. Also, while frost heaving might serve to roughen the surface, it is less clear how the surface of the playa could be smoothed, so another primary mechanism is necessary to explain the extent of variation observed in the playa.

### 3.6 Summary and conclusion

In order to understand soil erodibility, it is necessary to identify the processes most important in controlling the texture of the soil surface, and to establish the time scale over which they act. Without this understanding, it is difficult to correctly model dust emission from source areas. However, the difference between the spatial scales of soil measurements and of dust models is difficult to bridge. We find that SAR is a technique that can be used to make a small scale measurement across a large region, and to study soil roughness over time. We make four main observations:
1. In the Black Rock Desert, $\sigma_0$ varies more on the playa than in the neighboring mountainous and desert areas. This variability signals that the playa surface is more dynamic than the other areas, and undergoes more changes on annual time scales.

2. The pattern of $\sigma_0$ is relatively constant during the summer, and changes occur between summers; the time scale of $\sigma_0$ variability on the Black Rock playa is annual. This suggests that water is an important factor in determining playa $\sigma_0$, as precipitation and inundation are the most prominent processes occurring during the non-summer months.

3. The median value of $\sigma_0$ on the playa is lower in years with more precipitation during the preceding winter. This suggests that some combination of rain splash impacts and inundation are acting to smooth the playa.

4. Areas of the Black Rock playa that dry late (June and July) have relatively high $\sigma_0$. If this observation is not due to soil moisture, it could be a suggestion that the conditions under which drying occurs affect the eventual surface structure.

Given the large changes in surface structure that we observe using SAR, it is important to consider the effect of changes in macroscopic surface structures on surface erodibility on relatively short (annual) time scales. This might be a significant factor in the variability of observed dust emission, and it is important to consider how dust producing surfaces change over time in order to understand dust emission in the present, or especially in the past or future.
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Chapter 4

The effect of wetting/drying cycles and evaporite minerals on the evolution of surface roughness: An experimental investigation of playa analog surfaces

4.1 Abstract

Playas are important sources of atmospheric mineral dust, which is a critical component in geochemical cycling and climate. In playa dust sources, knowledge of the type and degree of surface crusting is vital for predicting dust emissions. The surfaces of playas are highly variable in space and time, so an understanding of the processes that control surface crusting in playas is necessary in order to have an estimate of the likelihood of a playa to emit dust. Here we perform laboratory experiments to elucidate the effect of cycles of wetting/drying and differences in evaporite concentrations on a playa analog surface. Multiple cycles of wetting and drying increase the roughness of the
playa analog surfaces, and produce small aggregates of a size appropriate for saltation (tens of $\mu$m). The addition of NaCl reduces the roughness of the experimental surface, particularly after multiple wetting/drying cycles, and inhibits the formation of small aggregates. In contrast, the addition of CaCO$_3$ increases roughness. These results highlight the importance of the history of rainfall and the chemistry of playa surfaces to the potential of playas to emit dust.

4.2 Introduction

Sources of atmospheric mineral dust are an important target of study due to the effects of dust on climate, geochemical cycling, nutrient transport, and human health (Martin, 1991; Koren et al., 2006; Mahowald et al., 2010). Many major dust sources are affected by the presence of ephemeral water (Prospero et al., 2002; Ginoux et al., 2012). In particular, playas (dry lakes) are commonly dust sources; they have particles available to be ablated and little vegetation to reduce the force of the wind against the surface and to trap particles. Playas dust sources are particularly important because they occur in some regions that are relatively wet and thus relatively densely inhabited. Additionally, dust from playas is frequently high in evaporite minerals and heavy metals, and so is especially influential because it can salinize nearby fields and transport toxic metals (Gill et al., 2002; Mees and Singer, 2006; Wood et al., 2011).

In order to model and predict dust fluxes from playas, it is necessary to estimate their surface erodibility. Erodibility describes the susceptibility of a surface to erosion (Webb and Strong, 2011). Playa surfaces vary greatly in their response to wind, depending on the presence and type of surface crust and the availability of loose particles.
For example, Gillette et al. (2001) found that ∼30% of sand drift at Owens dry lake occurred on un-crusted surfaces that were only present ∼6% of the time. Playa surfaces that have strong structural crusts and polygonal mudcracks are observed to have very low erodibility, whereas loose or “puffy” surfaces are more erodible (Reynolds et al., 2009).

Despite the primary importance of surface crusts, spatial and temporal variation of surface crusting in playas are poorly constrained, contributing to uncertainties in erodibility estimates and dust prediction. A number of workers have noted the existence of large qualitative variations in playa surface crusts (Neal, 1965; Langer and Kerr, 1966; Gill et al., 2002; Lichvar et al., 2006). Previous studies of playa surfaces have focused on “wet” playas in the Mojave (USA) defined by Reynolds et al. (2007) as playas with a shallow depth to groundwater. Wet playas in the Mojave tend to have softer, more erodible surfaces during the spring, and then to develop stronger and more resistant crusts during the summer (Reynolds et al., 2009). The evolution of surface crusting in dry playas is less well established, but most of the surface variability in the Black Rock playa, NV, USA occurs on an annual timescale, as does precipitation, and the playa surface is generally smoother after significant inundation (Chapter 3).

To improve estimates of erodibility, it is valuable to elucidate the processes controlling surface crusting in playas. Surface erodibility can be estimated on the field scale by direct measurement of a number of surface properties, including particle size, cropping history, and carbonate content (Woodruff and Siddoway, 1965). However, these models are largely based on empirical correlations in studies from agricultural fields within a
particular regions, so cannot necessarily be generalized to other regions or new conditions. In addition, this approach requires detailed data on surface properties that would be difficult or impossible to collect on a large scale (Chappell et al., 2006). Improvement in the understanding of the processes that control surface crusting is needed for the ongoing development of process-based dust models (Webb and McGowan, 2009), and a mechanistic understanding of surface crusting is essential in order to generalize into the past or future.

As playas are locations with ephemeral water, one potentially important process for the surface crusting of playas is repeated cycles of wetting and drying. Wetting and drying cycles affect soil structure in agricultural fields (e.g. Pillai and McGarry, 1999), and create vesicular structure in arid soils (Figueira, 1984), so it is plausible that cycles of wetting and drying could modify surface crusts in playas. Wetting and drying has been proposed as an important process for playa surfaces (Wondzell et al., 1990; Gillette et al., 1997; Argaman et al., 2006), but has not to our knowledge been tested under controlled conditions.

The presence of and chemistry of evaporite minerals also has the potential to be crucial to the development of playa surface crusting. The addition of calcite to agricultural fields has been observed to increase erodibility (Chepil, 1954), and higher calcite contents in soils are correlated with higher erodibility (Amante-Orozco and Zobeck, 2002). Closer examination of the surface crusting state of calcite-rich surfaces could help illuminate the processes leading to this empirical observation. Halite has long been known to affect cracking patterns in dried mud surfaces (Kindle, 1917), and has been suggested to reduce erodibility (Bullard et al., 2011). Halite-rich surfaces are a topic of
interest, as highly saline lake beds are currently important dust sources in several areas where anthropogenic diversion of water has occurred (Tyler et al., 1997; Mees and Singer, 2006; Liu et al., 2011). Evaporite-rich dust can be of particular importance for transport of soluble elements (Gill et al., 2002), and it can have different radiative properties than dust dominated by darker-colored minerals (Baddock et al., 2009), so it is of particular importance to understand the processes controlling surface erodibility in evaporite-rich surfaces.

Here we investigate the response of surfaces in the laboratory to cycles of wetting and drying and the presence of evaporite minerals. The goal is to elucidate the processes that control the structure of a playa analog surface. The experiments are analyzed at a scale relevant to dust emission and saltation (µm to mm). Also, we present a conceptual model of the development of surface structure in a playa.

4.3 Methods

4.3.1 Experimental setup

Experiments were prepared with the objective of simulating a playa surface formed by inundation. The clay used in these experiments was 96% kaolinite, 3% anatase, 1% other (KGa-2 from the Clay Mineral Society, clays.org Chipera and Bish, 2001). Other components were from Alfa Aesar (SiO$_2$, CaCO$_3$, and NaCl). The sediment mixture used for the experimental substrate was 56% clay and 44% SiO$_2$ (by weight), based on the average composition of surface samples from the Black Rock Desert playa in Nevada, USA (Chapter 2). Evaporites were mixed with deionized water (enough to suspend the
entire clay mixture, ∼20 mL), left overnight, and then the dry clay mixture was added. The final slurry was homogenized with a vortex mixer and an orbital shaker. The slurry was poured into a wet clay saucer (edges wrapped with parafilm to prevent spilling), and the saucer was rotated on the orbital shaker for several minutes to remove air bubbles. We utilized clay saucers as experimental platforms since they provide friction on the bottom of the experimental layer (needed to produce cracking patterns; Peron et al., 2006), and because they absorb water (reducing the possibility that water and dissolved solutes will pond at the bottom of the experimental layer). The total mass of the (dry) clay/evaporite mixture was ∼6.80 g, and the corresponding thickness of the dried layer on order of 1 mm. Mud crack polygons are approximately an order of magnitude larger than the thickness of the layer in which they form (Groisman and Kaplan, 1994), so a 1 mm layer forms polygons of a size appropriate for analysis in the clay saucers used (∼45 mm radius). Polygons in playas in the field tend to be several centimeters across (Neal, 1965), so these experiments produce polygons within the same order of magnitude as are seen in the field.

After preparation, samples were dried in a temperature controlled box (Figure 4.1) at 36°C for at least 2 days, until weight was approximately constant (indicating that evaporation was complete). We implemented at least 10 cycles of wetting and drying for each experimental run. Subsequent wetting was effected by spraying the sample with DI water. Water was added at a rate of ∼0.25 g every half minute (i.e. ∼4.5 mm/hour), for ∼20 minutes, totaling 10.6±1.5 g (i.e. ∼1.5 mm). For additional rounds, samples were dried at 35°C for at least 18 hours, until sample weight returned to approximately the same value as after the initial drying cycle (within ±0.02 g). Visible pictures were taken.
of surfaces when dry and also after wetting. Temperature and humidity were monitored
during drying with an EXTECH datalogger (RHT10). Relative humidity ranged from
10% to 45%, with the highest values at the initiation of drying.

We compared three different treatments over the course of multiple cycles of
wetting and drying. The first experiment was a control with a mixture of clay and SiO$_2$.
The other two experiments each had an evaporite added to the clay mixture: CaCO$_3$
and NaCl. The amount of evaporite included in the experiments was set by the average
composition of samples from the Black Rock playa in Nevada, USA: 10% CaCO$_3$ (by
weight) in the CaCO$_3$ experiment, and 5% NaCl in the NaCl experiment.

Figure 4.1: Schematic diagram of the experimental setup. Experimental surfaces are
dried under temperature controlled conditions.
4.3.2 Surface height measurements

We measured the surface topography of our experimental samples using a Zygo 7300 Optical Profilometer in Penn State’s Materials Research Institute. The profilometer produces 2D images of surface height by using interferometry; white light reflected from the experimental surface is combined with light traveling a known length to produce an interference pattern, which is fit to produce a measurement of the height of points on the experimental surface (this procedure is performed by software from Zygo). Vertical resolution for this instrument is <0.3 nm. All measurements utilized the 10x objective, with 0.5x magnification (field of view: 1.41 x 1.06 mm). Pitch and roll were set to 0° and 0°, respectively. A 3x scan speed was used, which detected approximately half the points in the field of view. In order to measure areas larger than the field of view, we stitched together individual measurements using the Zygo software, typically areas of 18x10 (totaling 180 individual measurements).

All surface height measurements were made on dry samples. Surface height measurements were made both after the initial drying and after 10 cycles of wetting/drying. To compare the same experimental surface at different times, we scored two “x” marks on the edge of each saucer for use as control points. For each observation, we placed the sample on the profilometer stage and, without moving the sample with respect to the stage, we made stitches of both control points and then of regions of interest.

Data from the profilometer were analyzed using IDL (Excelis Visual Information Solutions). The initial horizontal resolution of the data was 2.18 µm/pixel. To reduce the number of pixels with no data (as not every pixel was measured by the profilometer)
and to reduce computation times, we reduced the size by a factor of 3 in each dimension by neighborhood averaging (horizontal resolution $6.54\ \mu m/pixel$). We determined the coordinates of the center of the control points manually, and utilized the coordinates of the control points and the coordinates of the corners of the profilometer observations to rotate measurements from after wetting/drying cycles into the same orientation as the initial measurement.

Additionally, we photographed dry experimental surfaces with a digital camera in order to produce a larger scale topographic model. From this data, orthoscopic images were produced for the surfaces at cycles 1, 2, 3, 4, 5, 7, and 10 using a software package named Apero-MicMac (Bretar et al., 2013). The images and procedure are described in more detail in Appendix B. We estimated the fraction of the experimental surfaces that was covered by cracks using orthoscopic images. In the orthoscopic images, the cracks are shadowed; we estimated the area of the image covered by cracks by converting the images to greyscale, and then categorizing all pixels less bright than a cutoff value as cracks. The cutoff value was set by finding the median brightness value for each image, and subtracting a set value of 40.

4.3.3 Roughness characterization

To characterize roughness, profilometer data were used to calculate tortuosity, defined here as the surface area ($A_S$) divided by the horizontal planar area ($A_0$); $A_S/A_0$ (Taconet and Ciarletti, 2007). It is one of a number of possible roughness measurements; we use it here because it provides a local measure of roughness (as opposed to, for example, the standard deviation of height measurements, which is dependent on the
average and thus is sensitive to large scale jumps and slopes; Figure 4.2). Another advantage of tortuosity is its ease of calculation (Bertuzzi et al., 1990).

4.4 Results

4.4.1 Surface topography measurements

After the first drying cycle, the experimental surfaces form polygons separated by cracks (Figure 4.3). The cracks extend all the way to the bottom of the clay substrate. Qualitatively, the surfaces are similar to playa surfaces seen in the field (Figure 3.2), suggesting that some of the same processes occur both in the small scale experiments and in the field. In some cases (particularly the outer edges) the surface does not fully separate into individual polygons, leaving cracks that end in the middle of a polygon. The presence of cracks is a feature of a relatively shallow cracking layer (Groisman and Kaplan, 1994). The edges of some of the polygons in the 5% NaCl experiment curl upwards.

Qualitatively, the experimental surfaces display a more rough and degraded appearance after 10 cycles of wetting and drying than they do initially (Figure 4.4, Figure 4.5). Cracks and bubbles generally maintain the same position throughout the wetting/drying cycles, but they are progressively filled such that the width of the crack itself is greatly reduced. In the initial observations, these features form the majority of the topography; the polygons between the cracks are relatively flat, with the highest heights on the edges of the polygons. Later, the crack region is still visible as an area of lower height (order 100 µm lower); the low elevation region around the crack is wider in
Figure 4.2: Example roughness calculations in 1D on a surface profile with randomly selected heights. (a) The calculation of tortuosity as surface length over the length of the profile. (b) The equivalent standard deviation calculation. (c) The effect of adding a slope to the random profile; the tortuosity is robust, while the standard deviation is sensitive to the slope.
Figure 4.3: Images of experimental playa analog surfaces after the initial preparation and drying and after ten cycles of wetting and drying. (a) and (b) are the control experiment (initial and 10 cycles of wetting/drying, respectively), (c) and (d) are the CaCO$_3$ experiment, (e) and (f) are the NaCl experiment. Saucers are $\sim$45 mm in radius.
the cross-crack direction than the original crack (initial cracks \( \sim 100-200 \mu m \) wide, low regions in cycle 10 observations \( >300 \mu m \) wide). Small imperfections on the order of 10 \( \mu m \) are visible in the initial observations, but with smaller vertical height (\( \sim 10-20 \mu m \) initially compared to \( \sim 10-80 \mu m \) after 10 cycles). The cycle 10 observations have more height variability on a larger scale, also, with areas of order 1 mm horizontally having topography on order of 100 \( \mu m \) in cycle 10 observations. These mounds in the cycle 10 observations have no obvious precursors in the initial observations.

Aggregates of order 10 to 100 \( \mu m \) in diameter that have partially fragmented away from the rest of the surface are visible on the cycle 10 control and CaCO\(_3\) surfaces (Figure 4.6). Despite their appearance, these aggregates are attached to the surface. The locations of initial imperfections do not appear to affect the location of later aggregates. The CaCO\(_3\) experiment has aggregates that are larger than in the control (up to 300 \( \mu m \) in diameter; control aggregates rarely more than 100 \( \mu m \)).

There is a qualitative difference between the evaporite treatments; the 5\% NaCl experiment has a more smooth appearance after 10 cycles of wetting and drying, while the control and 10\% CaCO\(_3\) experiments have more jagged edges. In both the NaCl and CaCO\(_3\) experiments, cracks are still relatively well defined at cycle 10, although there is some appearance of filling in the CaCO\(_3\) experiment. The NaCl experimental surface has fractures in the cycle 10 observation that are not seen initially, but the surface has a smoother appearance, with few aggregates but some imperfections similar to those seen in all the initial observations (although there is no obvious correspondence between the initial and cycle 10 imperfections in the NaCl experiment).
Figure 4.4: Profilometer measurements of the experimental surfaces after the initial preparation and drying and after ten cycles of wetting and drying. (a) and (b) are the control experiment (initial and 10 cycles of wetting/drying, respectively), (c) and (d) are the CaCO$_3$ experiment, (e) and (f) are the NaCl experiment. Color indicates the height of the surface. All images have the same vertical color range; repeat images of the same surface additionally have the same zero height. Images are 6.54 mm by 4.90 mm.
Figure 4.5: Orthoscopic images of experimental surfaces after 10 cycles of wetting/drying. (a) CaCO$_3$ experimental surface. (b) NaCl experimental surface.

### 4.4.2 Quantitative observations

Comparing the absolute height of the experimental surfaces after the first drying and after 10 cycles of wetting and drying demonstrates that the surface height is quite variable over time. The surface height of individual points on the experimental surfaces is not well correlated between the two different observation times (Figure 4.7). For example, points that are low in the initial observation have a wide range of heights in the cycle 10 observation, demonstrating that the playa analog surface can change significantly during wetting/drying cycles, and so wetting/drying is an important playa process.

In addition, the median height of the experimental surfaces increases over time (Table 4.1). The median height calculation is performed over the subset for which there are data both initially and after 10 cycles. The median height is greater at 10 cycles for all surfaces (control: 4 µm; CaCO$_3$: 16 µm; NaCl: 41 µm). These height differences
Figure 4.6: Profilometer image of an aggregate formed on the control surface after 10 cycles of wetting/drying. This image is a subset of Figure 4.4b. Image dimensions are 1.3 mm by 0.8 mm.

are notable compared to the approximate range of heights for these surfaces (order 100 \( \mu m \)); however, only surfaces with added NaCl have a difference significantly higher than the height variability of the control points (0-20 \( \mu m \)). The height increase suggests that later surfaces are less dense or otherwise have more void space incorporated underneath.

The fraction of the experimental surface covered by cracks decreases from \( \sim 4\% \) to a relatively constant value of \( \sim 1\% \) by cycle 5 for the control experiment (Figure 4.8). For the NaCl and CaCO\(_3\) experiments, the fraction is relatively consistent at \( \sim 4\% \) throughout the cycles of wetting/drying. At cycle 10, the control experiment has a lower fraction of cracks; this is consistent with the qualitative observation that the cracks fill over time.
Figure 4.7: Comparison of the surface height of points in the control experiment during the initial and 10th cycle of wetting and drying. For visual clarity, each point in the figure is an average of 25 neighboring points from the original data set.

Table 4.1: Summary of surface experiment results.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cycle</th>
<th>Median height (mm)</th>
<th>Median tortuosity</th>
<th>Points measured</th>
</tr>
</thead>
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<td>X1</td>
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<td>1.006</td>
<td>1.98*10^7</td>
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<tr>
<td></td>
<td>10</td>
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<td>1.016</td>
<td>2.30*10^7</td>
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<tr>
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<td>1.010</td>
<td>1.64*10^7</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>54.636</td>
<td>1.018</td>
<td>1.89*10^7</td>
</tr>
<tr>
<td>N1</td>
<td>0</td>
<td>55.039</td>
<td>1.006</td>
<td>6.36*10^6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>55.080</td>
<td>1.009</td>
<td>2.11*10^7</td>
</tr>
</tbody>
</table>
Figure 4.8: Fraction of experimental surfaces covered by cracks after a given number of cycles of wetting and drying. The fractions are computed based on the orthoscopic images of the control experiment (open circles), CaCO$_3$ experiment (grey squares), and NaCl experiment (filled circles).

To demonstrate that profilometer observations from different times are aligned correctly, we show aligned images of a control point (Figure 4.9). The relative heights compare well between the two profilometer observations, but the average difference in height between the two observations is 18 $\mu$m. For other control points, the average difference in height between observations at different times ranges from 0 to 20 $\mu$m. The difference in absolute height could be due to a slight offset of the profilometer between visits, or to small particles adhered to the bottom of the saucer.

The experimental surfaces generally increased in tortuosity between the initial drying and cycle 10 (Figure 4.10). Comparing the different evaporite treatments, the
NaCl treated surface has the lowest tortuosity throughout the experiment, but is particularly low (median 1.009) relative to the control (median 1.016) and CaCO$_3$ (median 1.018) at cycle 10. The CaCO$_3$ treated surface has the highest tortuosity throughout. These numerical measurements are consistent with the qualitative observation that roughness increases over time, the NaCl surface is relatively smooth, and the CaCO$_3$ surface is the most rough and degraded.

4.5 Discussion

4.5.1 Implications for temporal variability in playas

The experimental surfaces underwent considerable variability in surface topography on small scales in the course of the cycles of wetting and drying. The variation seen during cycles of wetting/drying is not just enhancement of pre-existing features, but
Figure 4.10: Range of tortuosity of experimental surfaces after an initial period of drying and after ten cycles of wetting and drying. Bars are offset in the x-direction to assist visibility. Solid bars are the median tortuosity of profilometer observations for a cycle and experimental treatment. The range indicates the first and third quartiles of the tortuosity distribution.

formation of new features and disruption of old features. This variability with wetting and drying demonstrates playa surfaces are highly dynamic. Even relatively frequent and typical events can modify the surface of a playa. This is particularly important for models of dust emission, as it highlights one of the major issues facing dust models; quantifying the surface erodibility, and its evolution through multiple temporal scales (Webb and Strong, 2011).

The increased roughness after cycles of wetting/drying provides an explanation for the correlation observed between low precipitation (i.e. inundation) and high radar-derived roughness in the Black Rock playa (Chapter 3). The years without inundation
did have some rain (>50 mm), so the surface of the playa underwent cycles of wetting and drying. However, during years with inundation, there was little rain after the drying of the playa lake, so there were few cycles of wetting/drying to increase the playa roughness after the initial drying. This demonstrates the importance of rainfall for surface roughness, and suggests that the timescale over which rainfall occurs is important for the development of surface roughness in playas.

Cycles of wetting/drying could also explain the high $\sigma_0$ (high roughness) values seen in late (June/July) drying areas of the Black Rock playa (Chapter 3). Temperatures are high during the summer, which can dry the playa surface quickly (within a day). If the playa lake moves due to a shift in direction of the wind it would re-wet areas that had already dried completely, and perhaps act as a cycle of wetting/drying. However, earlier in the spring, when the temperature is lower, shifts in the playa lake would cover areas that were still wet, so would not serve as a wetting/drying cycle.

4.5.2 The effect of wetting/drying cycles on surface aggregates

Dust emission generally occurs by means of saltation, since the clay-sized particles small enough for suspension in the atmosphere are not easily ablated directly by wind, and instead are emitted during the saltation of larger (sand-sized) particles (Shao et al., 1993). Collisions between saltators and the surface produce clay- and silt-sized particles with the kinetic energy necessary to go into suspension and become dust (Neuman et al., 2005). Even if there are few sand-sized particles, it is possible for aggregates of smaller particles to saltate; if they break down on collision with the surface, the smaller particles can become suspended (Shao, 2008). A mechanistic understanding of the small-scale
processes that control surface crusting and aggregation in playas is desirable in order to improve estimates of surface erodibility.

The aggregates that we observed on the control surface after several cycles of wetting and drying were on the order of 10’s to 100’s of µm, a particle size range appropriate for saltation. The majority of the aggregates were attached to the surface, not loose, and so would not be immediately available for saltation. However, if the surface were disturbed by saltators or other mechanical means, we suggest that these aggregates could be preferentially loosened and saltate themselves. Thus, after several cycles of wetting/drying, the surfaces potentially have a higher erodibility, and are more likely to be dust sources.

4.5.3 Influence of evaporite minerals on clay surfaces

Both of the evaporite-treated surfaces had less filling of cracks through cycles of wetting and drying than did the control experiment, but while the NaCl experiment was smoother than the control, the CaCO$_3$ experiment was rougher. Qualitatively, edges of cracks in the evaporite experiments both appear relatively well-defined at later cycles of wetting and drying. The CaCO$_3$ and control experiment both have aggregated regions at later cycles, while the NaCl experiment appears relatively cohesive, with a higher roughness at later cycles but few aggregates that can be distinguished from the rest of the surface.

We suggest that the difference in behavior between the NaCl and CaCO$_3$ surfaces is related to the difference in flocculation behavior of clays in solution with Na$^+$ and Ca$^{2+}$ cations. Clay flocculation is governed by the balance between van der Waals attraction
and electrical double layer repulsion (Sumner, 1992). Cations in solution screen the negative surface charge that prevents clays from flocculating, but produce their own measure of electrostatic repulsion. Divalent cations, with a higher charge to volume ratio, thus tend to promote flocculation; they can be equally effective at screening the negative surface charge of the clays while forming a thinner positively charged layer than monovalent cations. This allows the clay particles to get close enough to each other that attractive forces become dominant. We argue that slower flocculation in the NaCl experiment allows the clay particles to more easily slide past each other after wetting, such that the NaCl surface undergoes more ductile deformation during the expansion and contraction of wetting and drying, whereas the CaCO$_3$ experiment has more brittle fracturing.

An alternate explanation of the differences between the NaCl and CaCO$_3$ experiments is related to solubility and evaporite cementation. As NaCl is more soluble than CaCO$_3$, the NaCl surface might be expected to have less cementation while wet, and thus have more ductile deformation. However, this mechanism does not explain why the control surface is intermediate between the NaCl and CaCO$_3$ in roughness but has no evaporite to serve as cement, whereas for the flocculation mechanism, the control surface is intermediate in flocculation behavior. In any case, our subsequent observations based on the macroscopic behavior of the surfaces remain robust even if the controlling mechanism is not firmly established.

Calcium is known to be an important element for the stability of clay surfaces. For example, lime is used to stabilize expansive soils for engineering or agriculture (e.g. Bell, 1996). In the experiments here, the CaCO$_3$ surface maintains its crack structure
more effectively during the cycles of wetting and drying than the control experiment, but also has higher tortuosity values throughout. This observation is consistent with the importance of calcium to the structure of clay soils, and also with increases in stability in calcium-treated clay substrates under some circumstances.

Conversely, agricultural fields treated with CaCO$_3$ become more susceptible to wind ablation (Chepil, 1954). Increased erodibility has been observed in calcite-rich soils, including in playa environments (Amante-Orozco and Zobeck, 2002; Argaman et al., 2006). The CaCO$_3$ experiment provides an explanation for the erodibility of calcite rich soils; if the increased number of aggregates seen in the CaCO$_3$ experiment predisposes CaCO$_3$-rich surfaces to produce saltators, dust emission from calcite-rich soils would have more potential for dust emission.

The effect of halite on the erodibility of clay playas fed by surface water is not fully established. Dust rich in salts, including halite, is a problem downwind of lakes undergoing dessication (e.g., Owens Lake (Tyler et al., 1997); the Aral Sea (Mees and Singer, 2006); Lake Ebinur (Liu et al., 2011). This suggests that halite-rich surfaces are eroding, but it does not establish whether halite is increasing the erodibility of the exposed lake sediments. Reynolds et al. (2007) argue that the increased erodibility of “wet” groundwater fed playas is due to disruption of surface crusts by evaporite minerals (including halite). Bullard et al. (2011) suggest that halite strengthens playa surfaces via cementation and reduces erodibility. The experiments presented here suggest the presence of small amounts (∼5%) of halite smooth the surface, potentially reducing the erodibility of the surface. However, the surface of the NaCl experiment changed significantly between the initial cycle and the tenth cycle of wetting/drying; it underwent
a degree of deformation rather than staying entirely cemented together, but still remained relatively smooth. Thus, we argue that NaCl has a smoothing/stabilization effect beyond cementation. This suggests a way to harmonize the observations of Reynolds et al. (2007) and Bullard et al. (2011); when incorporated into the surface, NaCl smooths the surface during wetting and thus reduces erodibility, but in the case of evaporating groundwater, the surface never becomes saturated with water, so NaCl cannot smooth the surface, and instead disruptions during evaporation dominate.

The difference in erodibility between calcite and halite could, at least in a minor sense, help to maintain the flatness of playas. In a playa with a bull’s eye pattern of evaporite minerals, with calcite on the outside and halite on the inside (Handford, 1982), or at least with calcite on the outside (Chapter 2), the edges of the playa are more likely to lose mass to dust than the center (all else being equal).

4.5.4 Conceptual model of playa surface crusting

These ideas lead to a conceptual model of playa surface crusting that might be incorporated into a larger model of geomorphological erodibility (e.g., Bullard et al., 2011). This model applies to dry playas with limited groundwater infiltration or evaporation (Figure 4.11). When there is enough precipitation to produce runoff and inundation of the playa, previous surface features are disrupted. Surface crusts become weaker when wet, and mechanical disturbance by wind and water suspends some of the surface particles in the playa lake. Then, in the process of drying, a strong depositional crust is formed from the particles in suspension. This post-inundation crust is quite smooth and resistant to disturbance, and has polygonal mud cracks. Rain events that are not
heavy enough to produce inundation roughen the surface, by serving as one cycle of wetting/drying. Areas of the playa that are high in calcite are more strongly affected by the wetting/drying cycles, forming a very rough surface.

Figure 4.11: Conceptual diagram of the development of surface crusting in a dry playa. Wetting/drying cycles increase the roughness of surface crusts, while NaCl smooths the playa surface.

4.6 Conclusion

In experiments on a playa-analog surface, we found that cycles of wetting/drying increased the surface roughness. We also found that a surface with added CaCO$_3$ was rougher than a surface with added NaCl; a control with no added evaporite was intermediate in roughness. The difference between the evaporite treatments was enhanced after cycles of wetting/drying. These results suggest that when rainfall on a playa is part of a wetting/drying cycle, it disturbs the playa surface and increases roughness, with
surfaces high in CaCO₃ most strongly affected. On a small scale, the wetting/drying cycles produced aggregates of a size appropriate for saltation. An understanding of the processes responsible for surface crusting in dust source regions is necessary to predict aeolian dust emissions in the past or future.
Chapter 5

A conceptual synthesis of surface crust development in dry playas

In this dissertation, a conceptual synthesis is suggested for the development and evolution of surface crusts in dry playas, based on observations of the Black Rock playa in the southwestern US as well as on observations in the literature. The objective of this synthesis is to improve models of the erodibility of dry playas. This synthesis is focused on water, which is seen to be important throughout this dissertation.

Four main hypotheses are proposed to be of major importance to dry playa surface dynamics.

1. Inundation destroys old crusts and creates new, hard-packed depositional crusts that have low erodibility and are highly resistant to disturbance.

2. Cycles of wetting and drying disrupt the surface crust, increasing roughness, erodibility, and susceptibility to disturbance; wetting/drying might also produce aggregates of a proper size for saltation.
3. Disturbance (i.e., mechanical destruction of the surface crusts) produces loose, ablatable particles with very high erodibility. Re-crusting occurs when the playa surface is wetted.

4. Halite smooths the surface and reduces erodibility, while CaCO$_3$ contributes to the formation of loose particles.

5.1 Inundation

Inundation in a playa reduces erodibility by destroying surface structure that is more sensitive to wind erosion and creating a depositional crust that is strong and smooth. In playas, inundation can persist for months (Chapter 3), allowing aggregated particles on the playa surface time to disperse into the water. In the shallow water of a playa, much of the wind energy that is applied to the water surface is transferred to the sediment, producing mechanical disturbance that encourages suspension of the playa sediments. The high reflectance of the Black Rock playa lake in MODIS band 5 (1230-1250 nm) suggests that it is highly turbid (Section 3.4.2), supporting the argument that sediment from the lake bottom has been mobilized into the water column. This process disrupts previous surface structure and effectively resets the surface to a smooth mudflat once the water has evaporated and the sediment has been re-deposited. Drying of the mudflat produces a strong, smooth surface of clay polygons separated by cracks, as commonly seen in the field (Neal, 1965; Langer and Kerr, 1966; Reynolds et al., 2007). This hypothesis is supported by the correlation seen between higher rainfall and smoother surfaces in the Black Rock playa (Chapter 3).
This is not the first time it has been suggested that inundation reduces erodibility in playas by creating a depositional crust that is strong and has low erodibility. Inundation has been observed to produce hard, strong crusts in a number of environments, including playas (Zobeck, 1991; Reynolds et al., 2007). Previous studies have been limited in areal coverage, so this study is a systematic investigation of this process over an entire playa, demonstrating that inundation has a broad scale and long lasting importance to surface structure (Chapter 3).

5.2 Cycles of wetting and drying

Here the process of wetting and drying is suggested to disrupt playa surfaces, increasing their roughness, erodibility, and sensitivity to disturbance. Wetting disorders the surface through expansion of clay minerals, breakdown of aggregates cemented by evaporite minerals, and/or the mechanical disruption of raindrop impact (Valentin and Bresson, 1992; Le Bissonnais, 1996; Assouline, 2004; Langston and McKenna Neuman, 2005). Then, drying is accompanied by stress due to shrinking.

The increased roughness of lab experiments after cycles of wetting and drying is evidence that wetting/drying affects surfaces (Chapter 4). Other evidence of the effect of wetting/drying is in wet playas; surfaces that have groundwater actively evaporating through them (i.e., continuous wetting/drying) are observed to be more erodible (Reynolds et al., 2007). In the subsurface, it is known that wetting/drying cycles affect the structure and hydraulic conductivity of soils (e.g. Figueira, 1984; Minhas et al., 1999; Pillai and McGarry, 1999; Rao et al., 2001), demonstrating that cycles of wetting/drying is likely to affect soils.
Assuming that inundation smooths the Black Rock playa in wet years, the process that makes it more rough in dry years (i.e., years with no inundation) needs to be identified (Chapter 3). Here it is argued that wetting/drying is the most plausible process to roughen the playa surface. Even the “dry” years in the Black Rock playa study have more than 50 mm of precipitation, from multiple storms. Roughness increases occur during the wet part of the year (winter), suggesting that increased roughness is related to precipitation.

5.3 Disturbance

The disturbance and destruction of surface crusts (by anthropogenic activity, animals, or abrasion by saltating particles) has been observed to lead to increased dust emission in wet playas (Cahill et al., 1996; Houser and Nickling, 2001; Gillette et al., 2001; Argaman et al., 2006; Reynolds et al., 2009), as well as in other environments (e.g. Belnap and Gillette, 1998; Macpherson et al., 2008; Baddock et al., 2011; Buck et al., 2011). Surface crusts protect surfaces from ablation (by means of attraction between particles), but when a crust is destroyed and clay- to sand-sized particles are produced, wind can move the particles, leading to dust emission. Even if a crust is not destroyed, the presence of loose particles on the surface increases dust emission (Macpherson et al., 2008), so a disturbance that produces any loose aggregates could contribute to dust emission. If aggregated sections seen in lab experiments (Chapter 4) were broken from the surface, they could promote saltation and dust emission.

Certainly it is possible to disturb any type of surface crust (with heavy machinery, if nothing else), but some types of crust are more sensitive than others (Langston
and McKenna Neuman, 2005). Hard-packed depositional crusts are difficult to disturb (Baddock et al., 2011), whereas other crusts can be more easily modified (Section 3.3.1.1, Gillette et al., 2001). Thus the effect of disturbance is dependent on the magnitude of the disruption, but also the pre-existing state of the surface crust. I argue that sensitivity to disturbance is related to surface roughness, since rougher surfaces have more projecting area to be disturbed (for example, Romkens et al. (2002) find rougher surfaces lose more particles in water erosion). In addition, “puffy” (and rough) surfaces have been observed to be more sensitive to disturbance (Neal, 1965), and in the Black Rock playa, rougher surfaces generally were more sensitive to disturbance by vehicle and foot traffic.

5.4 Surface evaporite mineral composition

This synthesis suggests that evaporite mineralogy of dry playas plays a crucial role in the development of surface crusts, and that playa surfaces including several percent of NaCl have a lower erodibility, but that playa surfaces with CaCO$_3$ have a higher erodibility. Clays are more likely to disperse into suspension in water high in NaCl (Mason et al., 2011). When playa surfaces rich in NaCl are wetted, they deform plastically and are able to maintain a smooth, strong crust instead of fracturing during the process of wetting and drying. Laboratory experiments demonstrate that adding NaCl reduces the roughness of a playa analog surface, whereas CaCO$_3$ increases the roughness, especially after cycles of wetting/drying (Chapter 4). In addition, the CaCO$_3$ surface has more surface aggregates of an appropriate size for saltation.
Calcite increases erodibility when added to agricultural fields (Chepil, 1956), supporting the hypothesis that it could increase erodibility in playas also. Indeed, a correlation has been seen between CaCO$_3$ content and erodibility in playa sediments (Amante-Orozco and Zobeck, 2002; Argaman et al., 2006). Qualitative field observations suggest that NaCl might have the effect of reducing erodibility in playas (Bullard et al., 2011). Here, I argue that the evaporite mineralogy is one of the more important influences on erodibility, and that knowledge of evaporite mineralogy is necessary in order to estimate erodibility in dry playas.

5.5 Discussion

To summarize, this synthesis suggests that in a dry playa environment rainfall increases the erodibility of a crusted surface due to cycles of wetting/drying. However, once inundation is initiated, water serves to strongly decrease erodibility. Disturbance increases erodibility to the extent that small (clay- to sand-sized) particles or aggregates are released from a crusted surface. Disturbance is much less likely to produce these loose particles when a surface has been recently inundated. If loose particles are present, precipitation can reduce erodibility by re-integrating them into a surface crust.

This synthesis explains both increased and decreased aeolian emission after precipitation. Precipitation (when followed by drying) serves to increase emission by enhancing erodibility through disruption of surface crusts. Conversely, inundation suppresses erodibility within areas that were inundated (or that, perhaps, were affected by significant overland flow) via formation of strong, resistant depositional crusts. This conceptual
model suggests that precipitation increases erodibility until the initiation of runoff, and after that, reduces erodibility (most notably in areas that have periods of inundation).

This synthesis is not consistent with the hypothesis that inundation increases playa dust emission by delivering new sediments to the playa surface (Zender et al., 2003; Bryant et al., 2007), although inundation might have that effect in another environment. An argument against the importance of new sediment supply is that playas are generally well supplied with unconsolidated particles, as befits their position in a depositional environment; for example, fill below the Black Rock playa extends to >2 km depth (Welch and Preissler, 1990). A study like that of Reynolds et al. (2009) could help to distinguish the relationship between inundation and dust emission. Reynolds et al. (2009) placed an automatic camera in a wet playa in order to photograph dust events over the course of several years. A similar study in one or more dry playas could detect when dust is being emitted from the playa, which could be combined with data on inundation, precipitation, and wind to determine if inundation increases or decreases the likelihood of dust events.

No evidence is seen in this study that anthropogenic activity has a large scale effect on surface erodibility in the Black Rock playa. In the Black Rock playa, anthropogenic vehicle traffic is concentrated during the summer and fall (Adams and Sada, 2010), the same season that there is little change in the surface roughness of the playa (Chapter 3). If anthropogenic activity were producing a large-scale disruption of playa surface crusts, some effect on surface roughness over the course of the summer would be expected; this suggests that anthropogenic activity is not a dominant control on playa surface crusts and hence erodibility.

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Saltation abrasion, and other disturbance due to wind, is also likely to be active during the summer, when the playa surface is dry. The constancy of surface roughness during the summer again suggests that saltation abrasion is not greatly modifying the playa surface.

That disturbance (anthropogenic or abrasion) is not a dominant influence on the surface of the Black Rock playa is consistent with the observation that the playa is not a continuously active dust source. The playa could be expected to be extremely active if the surface were highly disturbed to the extent of being covered in loose ablatable material. If playa erodibility is framed as a competition between disturbance and stability (induced by inundation), then in the Black Rock playa stability is more important. In the hyperarid Bodélé Depression, Chad (a dry lake and the largest dust source on Earth; Koren et al., 2006; Washington et al., 2006), disturbance is more important, with abrasion of friable diatomite sediments leading to active dust emission through most of the year (Prospero et al., 2002; Bristow et al., 2009).

It has been argued both that evaporite minerals stabilize playa surfaces and reduce erodibility by cementing particles together (Langston and McKenna Neuman, 2005), and that evaporite minerals disrupt playa surfaces by disturbing/roughening crusts as they precipitate out of solution (Tyler et al., 1997; Reynolds et al., 2007). A refinement of these conflicting conceptions is that salts such as NaCl and KCl stabilize playa surfaces while sulfate, carbonate, and/or hydrous/anhydrous minerals disturb surfaces (Saint-Amand et al., 1987; Bullard et al., 2011; Sweeney et al., 2011). I find that addition of NaCl produces smoother playa analog surfaces than CaCO$_3$ (Chapter 4), consistent with the idea that NaCl and CaCO$_3$ differ in their effects on erodibility.
In the Black Rock playa, calcite is more common around the playa edges (Chapter 2), suggesting that the playa edges might be more erodible. The playa edges are less commonly inundated, which perhaps also increases erodibility. This would suggest that dust from the Black Rock playa is relatively high in calcium. In addition, high erodibility of the playa edges could (in a minor way) help maintain the flatness of the playa.

Under this synthesis, a change in climate would affect the amount of dust emission. Even if precipitation totals remain constant, an increase in the intensity of both wet and dry periods (as is likely to occur with climate change; IPCC, 2013) could both increase the frequency of inundation (during wetter periods) and decrease the amount of precipitation (i.e., wetting/drying cycles), reducing erodibility. A switch from a winter-precipitation regime to a monsoonal regime could be expected to have the opposite effect, with precipitation more evenly distributed throughout the year and more precipitation during the summer, when the drying half of wetting/drying can occur more quickly.

A decrease in precipitation might be expected to increase dust emission, as less frequent inundation of playa surfaces leads to higher erodibility. An interesting complication here is the effect on vegetation. Takyrs in central Asia frequently become covered in vegetation if they are not inundated for \(\sim\)30 years (Maman et al., 2011). On these timescales, a decrease in precipitation might increase vegetation cover and decrease erodibility.

To model dust emission of playas using this synthesis is relatively straightforward. Precipitation and wind reanalysis data are already required in dust emission models, to estimate wet deposition of dust and soil moisture (Zender et al., 2003). Inundation could be estimated based on precipitation. Wind must be a part of any dust model, so
the intensity of saltation abrasion can be estimated. Disturbance due to anthropogenic or animal traffic would need to be estimated independently. Playa surface evaporite mineral composition is perhaps the most difficult to estimate, but sampling of playa surfaces could help establish the distribution of evaporite minerals across the playa.
Appendix A

Composition data from Black Rock playa samples

Mineralogy, particle size, and elemental composition of the individual samples from the Black Rock playa are recorded in Table A.1, as well as site location information.
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<td>&gt;10µm</td>
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Appendix B

Surface height measurements from photographs

In addition to profilometer measurements of the surface height of our experimental surfaces, we determined their topography using the software package Apero-MicMac (website logiciels.ign.fr/?Telechargement,20). This package has been used to measure the surface roughness of volcanic terrains with aerial photography (Bretar et al., 2013). While surface characterization has greatly improved in recent years due to laser topography instruments, it is always desirable to improve the speed and ease of data acquisition. In this case, it was possible to image the experimental surfaces in situ with a commercially available DSLR camera, while it was necessary to transport them in order to produce profilometer data. While we were able to produce orthoscopic images of the experimental surfaces, some of the input images did not have the quality necessary to produce usable roughness data on the scale required.

The Apero-MicMac package uses a set of photographs taken from different viewing angles to compute the height of points that it is able to detect in more than one photo.
Apero-MicMac is an open-source software package developed by the Institut national de l’information géographique et forestière (IGN). The software first compares all pairs of images for tie points. It then computes the orientation of the camera for each of the images. Then it uses these orientations to compute a dense point cloud of points on the surface of the imaged object. Finally, an orthoscopic image can be produced based on the point cloud.

We captured a set of $\sim 15$-20 photographs of each experimental surface with a DSLR camera (Canon Digital Rebel XS). A light source was placed approximately 20 cm above the surface to allow for a high f-value and fast shutter speed. We zoomed in to the limit of the camera in order to capture as much detail as possible. All camera settings were left constant within a set of photographs. We then processed the photos with Apero-MicMac. To set the scale of the output topographic model, we hand-picked the coordinates of the control points in two different photos for each set, and to set the horizontal plane, we created a mask of the flat section of the saucer edge in four different photos for each set.

We produced topographic models of the surfaces for several of the later cycles (Figure B.1). Image sets were also taken for all of the surfaces after initial drying, but none were successfully processed. Processing of image sets of the CaCO$_3$ surface from the first two and the fifth wetting/drying cycles was also unsuccessful.

Orthoscopic images of the experimental surfaces are consistent with other qualitative observations (Figure B.2). The surfaces of all experiments degrade over the course of wetting/drying cycles. New features with no visible precursors appear after a cycle of wetting/drying, while features from previous cycles are often still visible, with a more
eroded appearance. The CaCO$_3$ surface has more fragmented areas, especially after multiple wetting/drying cycles, while the NaCl surface has a more smooth appearance.

Figure B.1: Example of a topographic model of an experimental surface (Control, cycle 10).

B.1 Automatic detection of surface cracking

We utilized the orthoscopic images from Apero-MicMac to estimate the fraction of the experimental surfaces covered by cracks. The cracks are darker in the orthoscopic images due to shadowing. We found that setting a cutoff value produced a good qualitative distinction between the crack network and the rest of the surface (Figure 4.8). The level of illumination varied between the images, so we based the cutoff value for each
image on its median brightness. The procedure we followed was; convert the orthoscopic image to a monochrome PNG; calculate a cutoff value as median minus 40; categorize all pixels below the cutoff as part of a crack; divide by the total number of valid pixels.

This procedure has several sources of error, and thus is only an estimate. The illumination of the images was roughly similar, but not identical; a steeper angle of illumination would decrease the number of shadowed pixels. If the reflectance of the surfaces changes through the course of the experiments, there could be a systematic error if the cutoff value is more appropriate for one type of surface than another. An additional source of systematic error is that the more fragmented surfaces had enough relief to produce some degree of shadowing in areas that were not cracks. We attempted to set the cutoff value such that these areas were rarely included, but it was not possible to exclude them entirely. However, setting an automatic cutoff value applied identically across the entire set of images eliminates the risk of subjective judgment that would exist if we set a cutoff value for each image by eye.
Figure B.2: continued next page
Figure B.2: continued next page
Figure B.2: Orthoscopic images of the experimental surfaces. Produced by Apero-MicMac.
Figure B.3: Example image of surface network of cracks. (a) image of network of cracks (white) detected based on a cutoff brightness value in (b) the orthoscopic image.
Appendix C

Additional experimental surface data

C.1 Full size profilometer images

We subset images of the profilometer measurements in the main figure so that small-scale features would be visible. Here we display the remainder of the profilometer images (Figure C.1). Black regions along the edge of the images are beyond the extent of the measurement. Black regions within the margins are areas where no points were measured; the instrument scans across a vertical range, and any points that are either above or below its vertical range are not measured.

C.2 Intermediate wetting/drying cycle images

We photographed the experimental surfaces at cycles other than after the initial drying and the tenth cycle of wetting/drying (Figure C.2). The surface underwent the most obvious changes in the first five cycles of wetting/drying, but changes also occurred in the later cycles.
C.3 Dry weight of experiments over time

The playa-analog experiments maintained dry weights within a range of 0.04 g throughout the wetting/drying experiments, demonstrating that little mass was lost or gained through experimental error (Table C.1). The dry weight of the experiments showed no consistent pattern through time (Figure C.3).

Weights do, however, correlate with the relative humidity within the experimental box (Figure C.4); a linear regression of dry weight vs. humidity is significant for all experiments ($p < 0.002$). We monitored humidity, but did not control it, so humidity varied within the temperature controlled box due both to the evaporation of the water added to the samples and to environmental variability. The correlation between humidity and weight indicates that the experiments hold a certain amount of moisture even after drying. This observations does not affect the results of the experiment, as we use the dry weight only to demonstrate that the experiments have reached equilibrium with ambient conditions.
Table C.1: Dry weights of experiments minus saucer.

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<td>6.119</td>
<td>6.462</td>
<td></td>
</tr>
<tr>
<td>Evaporite</td>
<td>0.000</td>
<td>0.680</td>
<td>0.340</td>
<td></td>
</tr>
<tr>
<td>Clay+evaporite</td>
<td>6.800</td>
<td>6.799</td>
<td>6.802</td>
<td></td>
</tr>
<tr>
<td>Saucer only</td>
<td>87.012</td>
<td>86.875</td>
<td>86.815</td>
<td></td>
</tr>
</tbody>
</table>

ᵃ Not measured.
(a) Control, initial

(b) Control, 10 cycles wetting/drying

Figure C.1: continued next page
Figure C.1: continued next page

(c) CaCO₃, initial

(d) CaCO₃, 10 cycles wetting/drying

Figure C.1: continued next page
Figure C.1: Profilometer measurements of the experimental surfaces. Color indicates the height of the surface. All images have the same vertical color range; repeat images of the same surface additionally have the same zero height. Images are 20.74 mm by 9.57 mm.
Figure C.2: continued next page
(g) Control, cycle 7
(h) Control, cycle 10

(i) CaCO$_3$, initial
(j) CaCO$_3$, cycle 1

(k) CaCO$_3$, cycle 2
(l) CaCO$_3$, cycle 3

Figure C.2: continued next page
(m) CaCO$_3$, cycle 4  (n) CaCO$_3$, cycle 5
(o) CaCO$_3$, cycle 7  (p) CaCO$_3$, cycle 10
(q) NaCl, initial  (r) NaCl, cycle 1

Figure C.2: continued next page
Figure C.2: Photographs of the experimental surfaces at various cycles of wetting/drying.
Figure C.3: Dry weight of experiments after each cycle of wetting/drying. Weights are computed as weight of experiment minus initial dry weight of saucer.
Figure C.4: Dry weight of the control experiment compared to ambient relative humidity. The fit of weight vs. humidity is significant (p=0.0001).
Bibliography


provides most of the mineral dust to the Amazon forest. *Environmental Research Letters*, 1:014005.


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Research Interests:
Atmospheric mineral dust (specifically, the surface conditions under which it can be emitted to the atmosphere), remote sensing, and playas.

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