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The Pluvial Lake Palomas - Samalayuca Dunes System

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THE PLUVIAL LAKE PALOMAS – SAMALAYUCA DUNES SYSTEM

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THE PLUVIAL LAKE PALOMAS – SAMALAYUCA DUNES SYSTEM

by

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DISSERTATION

Presented to the Faculty of the Graduate School of
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I’ll like to thank all the people that in one way or another helped me along my time at UTEP, throughout all these years. Especially to my wife Maria Elena and my parents Maria Esther and Alberto. To all my geology professors since bachelors thru masters and finally at the Ph.D level, especially to those who participated as advisors mentors and friends. With great respect and appreciation to Dr. Thomas E. Gill and Dr. Richard P. Langford.

“The knowledge of science is the path to follow for a great future as humans”
ABSTRACT

A lacustro-aeolian system formed by the Pluvial Lake Palomas (PLP), the Samalayuca Dunes (SMD) and a connecting aeolian corridor is found in the central Chihuahuan Desert of North America approximately 50 km upwind (SW) of the binational Paso del Norte metroplex. The system is described by its three individual components. They comprise one of the largest paleo-lacustrine (Pleistocene) environments in the Chihuahuan Desert (PLP), one of the largest and least-studied sand seas of North America (SMD), and a newly described and geomorphically heterogeneous aeolian corridor connecting the two.

The Chihuahuan Desert has been a major and underappreciated dust production region of North America. The PLP – SMD system includes many of the prime dust “hotspots” of the Chihuahuan Desert. The individual parts of the system are analyzed separately and specific emphasis is given to previously undescribed or unidentified sedimentological, geomorphological and geochemical characteristics.

An assessment of the dust emission potential based on a reconnaissance of the sedimentological and surface textural conditions and dynamics of each of the PLP sub-basins and other specific areas is presented. These conditions support placing the lacustrine sub-system and its related alluvial and fluvial areas as a major mineral aerosol “hot spot” in North America. Sedimentological and geochemical properties of dust-producing sediments in eight PLP sub-basins (Bolson de los Muertos, central PLP, Laguna Santa Maria, Laguna El Fresnal, Laguna Guzman, Rio Casas Grandes Valley, Laguna Palomas, and Laguna de Patos) and one adjacent basin (Laguna Ascension) are also comprehensively described for the first time.
The presented research identifies and describes the geomorphology, sedimentology and elemental concentrations of a newly described aeolian corridor connecting the PLP and SMD, adding to the scant scientific literature regarding these aeolian corridors.

A revised geomorphic description and identification of dune types in the SMD (including two previously unidentified and undescribed dune forms) is also presented, as well as documentation of the complex interactions among the different types of dunes of the sand sea.

Overall, this study elucidates the intricate linkage between the three areas as one geomorphic system and its combined effects on downwind populations as a mineral aerosol source.
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CHAPTER 1

Introduction

The Pluvial Lake Palomas – Samalayuca Dunes system in the northern Chihuahuan Desert of North America is composed of three individual sub-systems that interact as one lacusto-aolian system. This system comprises the Pluvial Lake Palomas Basin and the marginal fluvial and alluvial deposits delimiting the basin. Sediments eroded from the flat playas at the center of the basins and shoreline areas of the Pluvial Lake Palomas are transported and accumulated downwind from the east-central margin of the playa system on a ∼45 km easterly oriented aeolian corridor to the Samalayuca Dunes. Aeolian sediments accumulating atop this corridor are underlain by low angle westerly dipping alluvial deposits forming the base of the presented aeolian corridor sub-system. Beyond the corridor sub-system, aeolian sediments mostly composed of sand size grains are deposited at the base of the Sierra de Samalayuca and Sierra del Presidio, which form topographical barriers impeding the aeolian transport of these sand size sediments. The sand size sediments accumulate in a large sand sea represented by the Samalayuca Dunes, which form the downwind sub-system of the Pluvial Lake Palomas – Samalayuca Dunes system.

The three sub-systems are described individually in the following chapters of this dissertation as a means to cover detailed sedimentological, geomorphological and geochemical information acquired from field observations and laboratory work performed on collected samples. Each of the sub-systems are described with specific emphasis on key aspects of the individual sub-systems that have not been considered previously, or where new technologies allow for revision and augmentation of the scientific knowledge.
Regardless of this approach, the Pluvial Lake Palomas – Samalayuca Dunes system is one individual geosystem where each of the parts is intimately connected to each other and the mechanisms or disruptions acting on one part of the system would have an effect on the rest of the parts.

The complete system is located in the northern Chihuahuan Desert of North America, with the aeolian corridor, the Samalayuca Dunes and the majority of Pluvial Lake Palomas located in the state of Chihuahua, Mexico. The northernmost extent of the Pluvial Lake Palomas is located in the state of New Mexico, USA. Three major urban areas both in Mexico and the USA are located downwind of the system. Ciudad Juarez (Chihuahua, Mexico) and El Paso (Texas, USA) (collectively forming the binational Paso del Norte metroplex) and Las Cruces (New Mexico, USA) are located approximately 50 km away from the eastern (downwind) margin of the system. The location of these population centers with respect to the Pluvial Lake Palomas - Samalayuca Dunes system can pose both advantages and disadvantages for these communities.

The Samalayuca Dunes are one of the largest and least described (and visited) dune fields of North America. Only recently (after 2006) the Mexican government proposed the designation of the Samalayuca Dunes as a natural protected area, where touristic visits to the dunes would be promoted (DOF, 2009). With the proper research and understanding of the dunes’ dynamics, the Samalayuca Dunes could be transformed into a national park where the international community could benefit from this marvelous natural landmark. On the other hand the lack of serious and comprehensive research and an uninformed designation of the Samalayuca Dunes as an open touristic area could cause adverse consequences to this fragile ecosystem.
The expanse and complexity of these dunes are only comparable to a few other dune fields world wide. The very large dune forms (megastar dunes) rising over 120 m from their surroundings and complex dune interactions are comparable to the forms found in other major sand seas around the world, such as the Namib Desert (Lancaster, 1983) in Namibia, El Gran Desierto (Beveridge, et. al., 2006; Lancaster, 1995) in Sonora, Mexico, The Rub’ al Khali (Ewing, et. al., 2006; Lancaster, 1995) in Yemen, Oman and Saudi Arabia, The Great Sand Dunes (Lancaster, 1995) in USA, the Grand Erg Oriental (Ewing, et. al., 2006; Lancaster, 1995) in Algeria and the Ala Shan Desert (Lancaster, 1995) in China, among others.

Aeolian corridors are not new to the scientific literature, but they seldom are the principal topic of scientific investigation. Only a few of these corridors are partially described in research involving them only with secondary emphasis. Some of the largest corridors in the world are the Sahel – Saharan corridor (Moreno, et. al., 2006; Bristow, 2005) in northern Africa and the Hexi corridor (Xunming, et. al., 2007) in China. In North America’s Mojave Desert smaller versions have been mentioned in the Kelso dunes field (Ramsey, et. al., 1999; Zimbelman, et. al., 1995; Paisley, et. al., 1991) and a developing corridor in the lower Mojave River drainage (Laity, 2003). The majority of the research conducted involving aeolian corridors focuses on geoforms of the sand transport pathways and in the atmospheric emplacement of very fine sediments (< 20 µm) in the clay and fine silt fractions- as is done in this work for the Pluvial Lake Palomas- Samalyuca Dunes corridor. For this matter the Sahel and the Hexi aeolian corridors are amongst Earth’s largest mineral aerosol emitters into the atmosphere (Xunming, et. al., 2007; Bristow, 2005). Aerosols emitted from these areas are transported intercontinentally high in the
atmosphere (Gill, et. al., 2006; Prospero, et. al., 2002) and play important roles in ecosystem development and nutrient cycling both at sea and land (Doney, et. al., 2009; Okin, et. al., 2008). Health hazards to the deep respiratory tract of vulnerable populations are also an effect of concern related to the long-range transport of these mineral aerosols (Gill, et. al., 2007). The presence of a previously unidentified aeolian corridor in the Chihuahuan Desert and the potential of the individual corridor components for mineral aerosol emplacement along with the possible human health impacts of these aerosols constitute a new and imperative research opportunity in the region. A series of diverse geoforms and their granulometric, geomorphic and geochemical relations in this Chihuahuan Desert aeolian corridor are newly observed and described, along with an assessment of mineral aerosol emission potential for each of the geoforms found in the aeolian corridor. The research and descriptions of the Pluvial Lake Palomas – Samalayuca Dunes aeolian corridor serves to increase the scant scientific knowledge about these systems and its relationship to other analogous systems worldwide, as well as the potential health hazards to the Paso del Norte metroplex population located directly downwind from this corridor.

Pleistocene Pluvial Lake Palomas could have inundated a basin covering as much as approximately 7700 km² by the end of the last glacial maximum during Wisconsinian time (Hawley, 1993; Reeves, 1969). Sediments accumulated in this basin form flat, barren playa surfaces, which along with the lacustrine related fluvial and alluvial margins are major contributors to dust storms affecting the Paso del Norte metroplex and far beyond (Lee, et. al., 2009). Pleistocene lacustrine systems along with modern anthropogenically dried lakes have been previously identified as major contributors of atmospheric mineral aerosols
worldwide (Gill, 1996; Prospero et al., 2002) and their effects on climate, ecosystems, infrastructure and health hazards investigated (Gill, 1996).

Only recently has the Paso del Norte region been recognized as one of the major dust producing engines in the Chihuahuan Desert and North America (Prospero, et. al., 2002; Lee, et. al., 2009; Rivera Rivera, et. al., 2009). The dust storms generated from the different basins and areas of the Pluvial Lake Palomas Basin during the windy season are major contributors to air quality violations in the Paso del Norte metroplex. PM-10 and PM-2.5 (particles with spherical diameter less than 10 and 2.5 µm respectively) particles generated from these areas constantly reach unhealthy levels for vulnerable populations in the region (Lee, et al., 2009; Gill, et. al., 2007). These particles can be transported for tens to hundreds of kilometers regionally and even thousands of kilometers downwind high in the atmosphere reaching the locations in the Northeast USA and Southeast Canada (Gill, et. al., 2006).

Prior studies locating these mineral aerosols sources in the Chihuahuan Desert have been conducted by remote sensing (Prospero, et. al., 2002; Lee, at. al., 2009; Janugani, et. al., 2009) and modeling (Rivera Rivera, et. al., 2009), and lack specific and detailed ground truth of the sedimentological, geochemical and geomorphic conditions that cause these areas act as dust sources. This dissertation puts emphasis on the aspects, areas and forms that have not been previously described or identified from this system.

The Pluvial Lake Palomas has been previously described historically, structurally and paleostratigraphically by Reeves, in 1969. Hawley (1993) and Kennedy and Hawley (2003) described the hydrogeological and historical aspects of the Pluvial Lake Palomas. Paleoclimatic descriptions and sediment dating of individual basins was conducted by
Castiglia and Fawcett (2006). One of the system’s sub-basins, the Laguna El Fresnal has been described structurally (Bandy, et. al., 2002), ecologically and geophysically (Ortega-Ramirez, et. al., 2004), and paleoclimatically and tectonically (Campos-Enriquez, et. al., 1999). No detailed ground based sedimentological, geomorphic and geochemical investigations of the system and its sub-basins surface sediments has been conducted previously, nor has any prior assessment been made of the dust emission mechanisms and potential of the individual areas.

The Pluvial Lake Palomas – Samalayuca Dunes Aeolian Corridor is identified and described for the first time in this research. A detailed granulometric, geomorphologic and preliminary geochemical analysis of the different geoforms constituting this system is presented, as well as the dust emission potential of each of the geoforms.

The Samalayuca Dunes were first described by Webb (1969) as “non-descript pile of sands”. Later, a more detailed study was done by Schmidt and Marston (1981) describing the overall conditions of the field and identifying two main types of dunes in the field, akle and echo dunes. The use of new technologies, data, information and extensive field research has yielded a more detailed geomorphologic description of the compound and complex dune patterns and physical parameters of the different dunes forming the Samalayuca Dunes. It is shown that the akle pattern is indeed an interference pattern formed by two (NS and EW) straight crested dune sets. A more detailed description of the megastar dunes (echo dunes) and their morphology is presented, and two new dune forms are identified and described in the field, simple star dunes and relict transverse dunes. The relict dunes are identified as forming the base skeleton of the field.
Overall, the research presented here offers the first holistic geomorphologic, sedimentologic and elemental description of the Pluvial Lake Palomas - Samalayuca Dunes System as an integral lacustro-aeolian system whose components are intricately related. The research detailed within this dissertation also offers an assessment of the potential of the system's different geoforms for mineral aerosol emplacement into the atmosphere.
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CHAPTER 2

Sedimentological and geochemical assessment of potential dust sources in the Pluvial Lake Palomas sub-basins, Chihuahuan Desert, NW Mexico and SW USA

Abstract

The Chihuahuan Desert has been a major and underappreciated dust production region in North America. Mineral aerosol production in the Chihuahuan Desert may be increasing as a result of varied causes, including native ecosystem (grassland) degradation due to a drying climate tendency and anthropogenic effects including cattle overgrazing and rapid human habitat expansion. The Pluvial Lake Palomas Basin (PLPB) includes many of the prime dust “hotspots” in this desert. Sedimentological and geochemical properties of dust-producing sediments in eight PLPB sub-basins (Bolson de los Muertos, central PLPB, Laguna Santa Maria, Laguna El Fresnal, Laguna Guzman, Rio Casas Grandes Valley, Laguna Palomas, and Laguna de Patos) and one adjacent basin (Laguna Ascension) have been investigated. These basins are characterized by flat, barren playa surfaces located in the basin center (except Laguna Santa Maria). Flat playa surfaces and lack of roughness elements provide increased dust emission potential along with the perfect sediment textural distribution for a dust emission “hot spot” formed by abundant surface clays and silts along with sands and fine gravels, potentializing dust production via sandblasting and bombardment of surface crusts. Playa edges are dominated by a heterogeneous Gobi-type texture, while some playa shorelines contain soft efflorescent crusts and abundant coarse sediments serving as abrading elements for the fines covering most playa surfaces. Playa-surface ped tops display very fine (to submicron grain size) thinly-crusted clays forming
easily-deflated upcurled flakes: ped undersides are also rich in fines which may be liberated by disturbance. Geochemically, some PLPB playa sediments (especially Laguna Ascension) show enrichment in potentially hazardous elements such as As, Br and Mo, along with evaporite-related elements such as S and Cl, which may contribute to salinization of downwind agricultural areas. These results complement ongoing regional dust sampling and analysis for assessment of environmental hazards posed by PLPB’s dust emissions, and source comparison and identification of aerosols collected downwind.

Introduction

Mineral aerosol source

The Pluvial Lake Palomas (PLP) Basin (PLPB) in the northern Chihuahuan Desert of North America, near the borders of Texas (USA), New Mexico (USA) and Chihuahua (Mexico), has only recently been described as “the dust engine of the Chihuahuan Desert”, and is now starting to be considered one of the most intense and regular dust emitting regions in the western hemisphere (Gill et al., 2008). The portion of the Chihuahuan desert area where the PLP system is located was previously suggested as a possible source for mineral aerosol production in a global scale study (Prospero et al., 2002) that identified major source areas by analysis and interpretation of TOMS satellite imagery. No ground reconnaissance was conducted in the Prospero et al.,(2002) study, and at the time it was suggested that the Samalayuca Dunes were the possible dust source. New studies reveal that the dunes of Samalayuca cannot act as sources of mineral aerosols due to their lack of fine (clay and silt) sediments (<20 µm) available for atmospheric entrainment (Bullard et al., 2007; Dominguez Acosta et al., 2006). More recent studies have suggested and
identified that the PLPB region is in fact a major key area in the production of mineral aerosols of long transport range (Janugani et al., 2009; Lee et al., 2009; Gill et al., 2006; Rivera Rivera et al., 2006). Some of these studies (Lee et al., 2009) have described broad land use/land cover categories associated with point sources of emplacement of mineral aerosols into the atmosphere. Through the use of remote sensing and field corroboration it was found by Lee et al., (2009) that the dust producing areas in the region were far more heterogeneous than had previously been considered, identifying rangeland, playas and their margins along with fluvial deposits and alluvial fans as some of the point sources for one major dust event (December 15, 2003).

A missing factor in these remote sensing oriented studies, however, has been “ground truth.” Field studies on the ground in the actual source regions are necessary to more comprehensively categorize and understand the geomorphic conditions that allow these areas to act as dust sources. The on-the-ground conditions that cause areas, especially playa basins, to act as dust emitters and or “hot spots” have been described for similar and other types of environments in different regions (Reynolds et al., 2007; Warren et al., 2007; Gillette, 1999; Cahill et al., 1996). The specific sedimentary and geomorphic conditions leading to the generation of mineral aerosols will differ from area to area depending on the local system settings, having a pronounced effect on the generation (or not) of mineral aerosols. This study is aimed to identify and classify some of the specific geomorphic, sedimentary and chemical interactions in the Pluvial Lake Palomas Basin that cause this system to act as a major mineral aerosol emitter.

Mineral aerosols are regularly emplaced into the atmosphere from the central playas and alluvial margins of the Pluvial Lake Palomas (figure 2.1). The frequent
windstorms occurring primarily during the dry season transport very large dust plumes across the area, often covering in their path the Paso del Norte Metroplex, formed by the Ciudad Juarez, (Mexico) – El Paso, (USA) international border communities (Rivera Rivera et al., 2009; Novlan et al., 2007). Clay and fine-silt-sized aeolian particles (PM10, particulate matter less than 10 microns in diameter) derived from the PLP and its sub-basins are entrained to the atmosphere as mineral aerosols and transported from a few kilometers locally to thousands of kilometers at a larger scale, reaching as far as Canada (Lee et al., 2009; Gill et al., 2006; Prospero et al., 2002). These PM10 aerosols contribute to air quality violations in the Paso del Norte metropolitan area reaching unhealthy levels especially for vulnerable populations, with the potential to cause health (respiratory) illnesses (Garcia et al., 2004). These dust storms can also cause major infrastructure and transportation hazards (Rivera Rivera et al., 2009; Gill et al., 2007; Novlan, et al., 2007).

**Physiographic setting**

The Pluvial Lake Palomas (PLP) system is located in the Chihuahuan Desert of North America approximately 40 kilometers upwind (SW) from the international Paso del Norte Metroplex (figure 2.1). This Pleistocene (post-Kansan) system could have inundated a closed basin surface of up to 7700 square kilometers during Wisconsinian time (Kennedy and Hawley, 2003; Hawley, 1993; Reeves, 1969). The lacustrine PLP sediments were deposited in a structural basin of the Basin and Range physiographic province during large pluvial and fluvial events dating back to past glacial maximums (Kennedy and Hawley, 2003; Hawley, 1993; Reeves, 1969). The PLP is confined by northwest trending faults that formed a northwest elongated lake, extending over ~200 kilometers (~130 miles) from the
vicinity of Villa Ahumada in Mexico to just east of Deming, NM in the USA, if the Mimbres River basin is included. At the widest point, the PLP stretches for almost 55 kilometers (~35 miles) between the Rio Casas Grandes Valley (at Guadalupe Victoria) and the east-central area of the PLP (figure 2.1).

The fluvial and alluvial sediments forming the fill of the PLP were deposited by antecedent systems including the inflow of the ancestral Rio Grande during the late and middle Quaternary and the rivers draining the highland watersheds bordering the northern Sierra Madre Occidental (the Rio Casas Grandes, Rio Santa Maria and Rio Del Carmen), along with the southern ranges of the Datil-Mogollon transition zone province drained by the Mimbres River (Kennedy and Hawley, 2003; Hawley, 1993). At the present time only the ephemeral Rio Casas Grandes (west), Rio Santa Maria (SW) and Rio Del Carmen (SE) regularly inundate individual basins during the North American Monsoon of the late summer (Adams and Comrie, 1997), the rainy season of the region.

Pluvial Lake Palomas (PLP) is no longer a homogeneous hydrological system, instead it is an ephemeral lacustrine system with only portions of its sub-basins inundating during the rainy season. The PLP is composed of several open and closed hydrologic basins, partially covered with playas in their central areas. In the Mexican side these basins include (figure 2.1):

- The Laguna de Patos, forming one of the smallest playas located in the far southeast extent of the system.

- The Bolson de Los Muertos, which comprises the largest sub-basin of the PLP and is sub-divided into three different areas: the southeastern arm, the southwestern arm and the main central area.
- The central area of the system, forming a wide area with no regular playa surfaces.

- The basin of the Rio Casas Grandes in the Guadalupe Victoria area, forming the central-western part of the PLP.

- Three separate basins in the western area: Laguna Guzman, Laguna El Fresnal and Laguna Santa Maria.

- Laguna Palomas in the north part of the basin.

- The northern area of the PLP in the USA is represented by an arm that extends into southern Luna County (the Indian Basin) and the Mimbres Basin south of Deming, both in New Mexico (figure 2.1). The Mimbres Basin is not always considered hydrologically part of the PLPB (Reeves, 1969).

Hydrological recharge into the basins occurs for the most part during the summer months from July through September when monsoonal rains are frequent (Adams and Comrie, 1997). During the rainy season sediment recharge to the periphery and selected areas of the playas will occur if the rains are strong enough to cause fluvial sediment transport from the nearby alluvial areas. Widespread recharge to the entire playa surface caused by long-range fluvial transport is almost negligible or restricted to the small inlet deltas receiving sediments carried only by short traveled water flow. The lack of strong long-range sediment recharge to the playas is due in part to the ephemeral nature of the main streams discharging into the basins. Added to this effect, pluvial events in the current climatic regime are commonly not strong enough to cause water/sediment to travel down these streams all the way from the distant sources to reach the playa surface. Arid climate, long dry seasons, prolonged drought periods such as the basin experienced recently (Stahle et al., 2009), water diversion for agriculture, and highly permeable surfaces are also
contributors enhancing the extreme rarity of large-scale water/sediment recharge to cover the entire playa surfaces.

The limited amounts of surface water recharge and deep water tables cause most of the playas in the system to be categorized as dry playas (following the classification scheme of Rosen, 1994). A few of these playas might act as wet playas under this classification scheme due to the allocation of surface water during times of no rain. This water is derived from anthropogenic activities (mining or agriculture) and or groundwater discharge in the form of natural springs (e.g. Laguna Santa Maria). Specific areas of larger playas might also act as wet playas not necessarily due to groundwater recharge. Such an example is the western shoreline area of the Bolson de los Muertos, commonly inundated on a yearly basis for weeks and some times even months at a time (except during prolonged drought periods). The inundation caused during the monsoon season of the year 2006 is an example. This event marked a >100 year return period of extreme rainfall characterized by intense and frequent pluvial events (Gill et al., 2009) which caused a widespread inundation of the BDM basin. Almost 12 months after these rains some areas close to the shoreline still retained water. No groundwater level record for the shoreline of the BDM area is available, thus determining whether the shoreline of the Bolson de los Muertos behaves as a wet playa due to its groundwater or the seasonal inundations is uncertain.

Methods

Field geomorphic reconnaissance and sample acquisition

With targeted areas selected from analysis of remote sensing imagery pertaining to dates where dust plumes were observed in the region (Lee et al., 2009; Rivera Rivera et al.,
several field campaigns for geomorphic descriptions and sampling were conducted during 2005 - 2007. Detailed ground based descriptions of the different playas and their sediments and other characteristics were performed (see playa sample inventory below). During this period a total of 33 sediment samples corresponding to 11 different playas and sub-playa areas were collected and described (table 2.1 and figure 2.1).

Loose sediment samples were collected from the surface upper two centimeters utilizing a plastic spatula creating a wedge and taking care to only sample from the front of the wedge. Semi-consolidated samples (peds) were sampled as whole pieces with care not to disturb the original sediment strata and upper fine crusts (in some cases). Samples were collected in sealable plastic sampling bags, location and identification of each sample were marked on the plastic bag with indelible ink, and coordinates were recorded utilizing a handheld GPS unit. Samples were returned to the laboratory and allowed to air dry by opening the bags, then resealing them after drying. Samples were stored in the sealed bags in the laboratory except for when aliquots were removed for laboratory analyses.

Granulometry procedures

An adaptation of standard methodologies for granulometric laser diffraction analysis was employed following suggested procedures from Zobeck (2004) and Sperazza et al., (2004). The general procedure consisted of separating and weighing approximately 2 grams of sample for very fine grained textures and 5 grams for sand-rich samples in order to ensure proper obscuration of the laser beam. The sample was then poured into a plastic container containing a 5% solution of sodium hexametaphosphate to serve as dispersing agent. The plastic bottles were placed in an automatic shaker and dispersed overnight.
After completing dispersion, samples were analyzed utilizing the Hydro unit of a Malvern Mastersizer 2000 laser diffraction granulometer apparatus. Grain size plots were recorded for each of the samples. Random samples were analyzed more than once to ensure proper results. Calibration standards were also used during the analysis to ensure proper function of the Malvern Mastersizer.

**Elemental analysis procedures (PIXE)**

Elemental concentrations were determined by proton induced X-ray emission (PIXE) spectrometry. Samples were pulverized in a corundum mortar and pestle. An average of three to five grams of material was powdered for each sample and analyzed where sufficient amounts were available. An aliquot of approximately 0.2 to 1 g of each powdered sample was pelletized into a 2.5 cm disk between two Kapton films. PIXE analysis was performed by a General Ionex 4 MV tandem accelerator with a duoplasmatron. Data reduction was accomplished with a modified version of software developed at the University of Guelph (Campbell et al., 1993). The accuracy of the analyses was verified using USA National Institute of Standards and Technology Standard Reference Material 2711, Montana II Soil, which was pelletized and analyzed under the same conditions during the same run.

**Geochemical statistics**

Elemental (PIXE) data was analyzed via descriptive statistics. Dendrograms were plotted in order to assess the geochemical affinity between the different playas. Dendrograms were computed using the Pearson correlation and Ward’s method of
amalgamation utilizing commercial software. A crustal enrichment factor (EFc) was calculated in order to assess the concentration of individual elements and compare them to crustal backgrounds as well as to establish any possibility of anthropogenic enrichment for some of the playas. The EFc was referenced to aluminum using equation 1 and crustal reference values from Mason (1958).

\[
\text{EFc} = \frac{(C_x/C_{Al})_{\text{sample}}}{(C_x/C_{Al})_{\text{crust}}}
\]

where EFc is the crustal enrichment factor referenced to aluminum. \(C_x\) is the concentration of an individual element in the sample and the crust respectively and \(C_{Al}\) is the concentration of aluminum in the sample and the crust.

Results and Discussion

Sub-basins, areas and playas (figure 2.1)

Laguna de Patos

Laguna de Patos forms one of the smallest playas of the Pluvial Lake Palomas (PLP) extending N-S for close to 6.5 km and reaching 2.5 km at its widest point. It is located at 30° 44’ 45.3” N and 106° 29’ 45.4” W. This playa represents the southeasternmost extension of PLP adjacent to the southeast main basin of PLP the Bolson de los Muertos (BDM) basin, here referred to as SELP (southeast Lake Palomas). The playa forming the Laguna de Patos is presently separated from the SELP area by an approximately 1.5 km stretch of higher topography forming a hydrological barrier between the two (figure 2.2). The main transport route in the region is national highway 45 and passes along this stretch. This highway connects the town of Villa Ahumada (principal town in the area), approximately
~10 km south from Laguna de Patos, to Ciudad Juarez (the main urban area in the region) approximately 110 km to the north.

Laguna de Patos is seated atop a low-lying basin flanked by three main mountains. To the north lies the Sierra Candelaria, composed of Tertiary welded tuffs and granodiorites intruding Cretaceous limestones, surrounded by Tertiary conglomerates that forms the bajadas (SPP, 1983). To the southeast is the Sierra San Ignacio, formed by Tertiary igneous intrusive rocks, mainly trachytes, rhyolites and welded tuffs that once hosted a barite mine. These intrusives are surrounded by a bajada formed by Tertiary conglomerates (SPP, 1983). To the west of the Laguna de Patos is the Sierra Banco Lucero, mainly composed of Cretaceous limestones intruded by Tertiary andesites and basalts, rimmed by a Tertiary conglomerate bajada (SPP, 1983).

During the wet season (summer months) the Rio Del Carmen and other localized arroyos derived from the local sierras intermittently inundate the Laguna de Patos and the SELP segment of the PLP. The sediments derived from these sources accumulate in the playa forming graded beds of sand, silts and clays. The playa of the Laguna de Patos is a flat barren surface surrounded by widely spread mesquite (Prosopis sp.) anchored nebkhas seated atop an extensive sand sheet (figure 2.3). The surface of the playa is completely flat and lacks any roughness elements that might preclude wind erosion and/or coarser sediment (sand size) abrasion in the form of sandblasting and bombardment. Sediments forming the uppermost crust of the playa are present in the form of polygonal desiccation structures (peds) (figure 2.4). These ped structures are only 2-4 centimeters thick and commonly underlie loose, fine sediment aggregates. The peds in the Laguna de Patos playa (as in many other playas in the PLP) are intermittently covered by a thin (<5 mm) brittle,
upward-curled crust commonly formed by a finer clayey sediment fraction compared to the underlying sediments (figure 2.5).

One ped sample was collected from this playa and its sediment grain size distribution analyzed. The granulometric distribution of sample LDP-001 displays a skewed bimodal distribution, with the main peak centered at approximately .9 µm (very fine clay) and the second much smaller peak centered approximately at 100 µm (very fine sand) (figure 2.6). The clay fraction of this sample represents 90.4 percent of the total sample weight, while the silt fraction amounts to 9.2 percent by weight, fine sand sediments represent the remainder .4 percent. The mean sediment size of the sample is .8 µm with a standard deviation of 1.7, which classifies the sample as poorly sorted according to Folk's (1974) sediments size classification based on the standard deviation.

Sample LDP-001 was also analyzed by PIXE (particle induced x-ray emission) means in order to establish its elemental composition. Tables 2.2 and 2.3 display average elemental concentrations for all collected samples. The major elemental concentration for the Laguna de Patos is dominated by Si, comprising 25.8 percent of the total sample elemental makeup. Al, Ca and Fe concentrations follow with 8.0, 6.0 and 4.1 percent respectively. The rest of the major elements (Na, Mg, K, Ti and Mn) are present in concentrations below 3 percent. The minor elements are represented in the sample by S, Cl, V, Ni, Cu, Zn, Rb and Sr. Of these minor elements, only Cl is present in high concentrations (4090 ppm), which makes it appear as an enriched element for LDP with an enrichment factor coefficient of 21 (figure 2.7).

The playa of LDP has not been identified as a major mineral aerosol producer, possibly due to the playa’s small size and temporal limitations of the remote sensing
methodology utilized by other authors. Nevertheless the geomorphic, sedimentological and anthropogenic setting give LDP a moderate potential to act as a mineral aerosol producer whenever specific conditions are met, which may allow the playa or areas of the playa to act as dust emitting “hot spots” (Gillette, 1999). The playa surface is an unlimited source of occasionally loose and apparently easily deflatable clay rich (~90% by weight) sediments, with a flat surface free of roughness elements. The periphery of the playa represents a supply-unlimited source of coarser loose (sand size) sediments able to erode the playa surface by sandblasting and bombardment whenever the loose sand’s threshold velocity for aeolian movement is reached (Gillette and Chen 2001; Gill, 1996; Shao and Raupach, 1993). Adding to these effects, the use of the playa surface as a transport route by the local ranchers increases the surface disturbance, mechanical erosion and overall potential for dust emission from this playa. The surface of the LDP by itself often is hard and otherwise not easily eroded. The uppermost, thinnest crusts atop the LDP peds were slightly thicker compared to the curled upward crusts found in other playas of the PLP (figure 2.5). The slightly thicker and more consolidated crusts may have a diminishing effect on the dust production potential of the playa, counterbalancing the dust producing factors found in and around the LDP. For these reasons, the proposed potential of the LDP playa surface is only moderate compared to the rest of the PLP playas.

**Bolson de los Muertos**

The Bolson de los Muertos (BDM) Basin represents the southernmost extension of Pluvial Lake Palomas and forms the largest of the system’s sub-basins. The BDM extends from the south near Villa Ahumada, (Chihuahua, Mexico) approximately 90 km northward.
and reaches close to 25 km at its widest point near the Sierra de los Muertos (figure 2.2). The approximate center of the BDM is located at 31° 04’ 8.1” N and 106° 54’ 16.9’’ W. Some the fluvial areas immediately surrounding this basin are commonly used for agriculture and ranching mainly to the south where the Rio Santa Maria and Rio Del Carmen drain into the basin. The central-east and northeastern margin of the basin represents the contact between the playa surface and an extensive sand sheet seated atop a series of alluvial deposits gently dipping west from the surrounding mountains. This sand sheet and other related aeolian bedforms form a ~45 km long aeolian corridor where sand size sediments are transported from the BDM shoreline to the aeolian corridor depocenter formed by the Samalayuca Dunes (Dominguez Acosta et al., 2006; Dominguez and Langford, 2008). A fault escarpment formed by the El Camello fault with a NNW strike delimits the eastern margin of the BDM (figure 2.8). This fault forms the eastern boundary of the graben where the Bolson de los Muertos seats (Reeves, 1969). The south and western margins of the BDM are delimited by alluvial fans derived from the surrounding mountains.

Sierra Banco Lucero divides the southeastern area of the BDM into two separate playas, here termed southeast arm and southwest arm of the Bolson de los Muertos. The SE arm playa forms an inlet area for the Rio Del Carmen, while the SW arm playa along with the Santa Maria Basin form the inlet basins of the Rio Santa Maria (figure 2.2).

The SE arm area elongates approximately 30 km in a NNW direction and reaches almost 9 km at its widest point. The SE arm is flanked to the NNE by the Sierra Candelaria, composed of Tertiary welded tuffs and granodiorites intruding Cretaceous limestones, all of these surrounded by a bajada formed by Tertiary conglomerates (SPP, 1983). Approximately 20 km to the southeast is located the Sierra San Ignacio formed by Tertiary
igneous intrusive rocks, mainly trachytes, rhyolites and welded tuffs. These intrusives are also surrounded by Tertiary conglomerates (SPP, 1983). The western margin of the SE arm area is in close contact with Sierra Banco Lucero and its derived Tertiary conglomerates. Sierra Banco Lucero is mainly composed of Cretaceous limestones intruded by Tertiary andesites and basalts (SPP, 1983). The northern segment of SE arm area was home to “Salinas la Union,” a salt mining facility (Reeves, 1969; SPP, 1983). The mining claim for this area stated denounced by Diego Romo de Vivar in 1647, commencing the first colonial settling in the area (Ahumada Gobierno Municipal, 2009). Whether the mined salts were derived from seasonal growth or paleo‐deposits was not found. BLORT

The southwestern arm area of the Bolson de los Muertos or southwest Lake Palomas playa is similar in shape to the SE arm, elongating approximately 30 km in a NNE direction and reaching close to 9 km at its widest point. The eastern margin of this basin is in contact with aeolian deposits juxtaposed onto the alluvial fans derived from the western flank of the Sierra Banco Lucero and the Cerros Prietos formed by Tertiary intrusives and conglomerates. The central western flank of the Sierra Banco Lucero is host to a localized Tertiary granitic outcrop and Tertiary skarn deposits (SPP, 1983). To the south the SW arm area is delimited by the Cerro el Chile formed by Cretaceous limestones, Tertiary intrusives and conglomerates and a very localized Tertiary granite outcrop (SPP, 1983). The western margin of the SW arm is in contact with Quaternary alluvial deposits grading into the Cerros la Nopalera of very similar composition to the Cerro el Chile (except for the granite outcrop).

Both southern areas (SE and SW) connect to the central and main area of the Bolson de los Muertos (figure 2.2). This area forms the largest individual sub-basin area in the PLP
extending NNW for approximately 60 km and reaching ~25 km in width. As mentioned above, the eastern margin of this sub-basin forms the contact with an aeolian corridor and its sedimentary deposits. The whole western margin of the central BDM is delimited by a NNW aligned mountain range extending close to 70 km. This range is formed by a series of Sierras, including from south to north the Sierra la Nariz, Cerros la Morita, Cerros Bayos, Sierra el Malpais and Sierra San Blas, all a mixture of Cretaceous carbonates and clastics (shales) intruded by Tertiary igneous rocks along with deposits of Tertiary conglomerates and Quaternary basalts (SPP, 1983). The northern margin of the Central BDM grades down into an area covered by Quaternary alluvial deposits overlaying older lacustrine deposits of PLP. A now abandoned railroad track passes thru this area and was used to connect Ciudad Juarez (approximately 65 km NNE) to Estacion Guzman and the town of Casas Grandes, constituting one of the main transport routes of the past century.

Three large outcrops are found isolated within the central area of the BDM. The northernmost and larger is formed by the Sierra de los Muertos formed by Cretaceous limestones and Tertiary conglomerates on the eastern flank. The next outcrops to the south are formed by a series of nameless, smaller and dispersed Cretaceous limestone outcrops hosting a small Tertiary basalt outcrop at its southwestern flank. These outcrops are located at the Los Amargosos ranch.

The surface of the BDM appears to be a preferred area for the accumulation of water released by monsoonal rain events during the late summer months (figure 2.9). A series of arroyos draining the whole extent of the mountain ranges located at the western margin of the BDM including several smaller drainages form the eastern margin and the two main perennial river systems draining into the southern BDM (Santa Maria and Del Carmen)
form the major source of sediment recharge in to the different areas of the BDM (figure 2.2). These sediments accumulate on the playa surfaces in the form of graded beds ranging from clay and silts to small amounts of sand size sediments. In some of the peripheral areas of the basins abundant sand deposits and fine gravel size sediments also accumulate forming localized “Gobi” (stony) type deposits (figure 2.10) and/or shoreline (beach) related deposits (figure 2.11). These coarser sediments are derived from the contact with alluvial fan deposits mainly at the western margins and by the continued erosion of the exposed alluvial sediments from the El Camello escarpment along with the sand contributions from the delimiting shoreline beach and connecting aeolian corridor sand sheet deposits located at the eastern margin.

The surface of these playas is very flat and non-vegetated with lack of any considerable amounts of non-erodible elements. Polygonal desiccation structures ( PEDS) cover the vast majority of the surface, especially after the rainy season (figure 2.12). These PEDS may reach up to ~ 5 centimeters thickness and during times of prolonged drought they are underlain by loose sand size aggregates formed by fine (clay and silt size) sediments (figure 2.13). Whenever a disturbance of these crusted ped surfaces occurs, the loose aggregates are deflated and transported across the playa surface accumulating inside open ped margins or on the upwind side of the very scarce vegetation (tall grasses) that might be present (figure 2.14). During the dry season and especially during a prolonged drought, the ped surfaces show evidence of deflation with irregular surfaces exposing the inside of the ped sediments. During these times, the dry surfaces are very resistant to wind erosion with hardened barren crusts capping the underlying aggregate materials. At this point these surfaces can only be eroded by severe anthropogenic (or related) action
(vehicular or cattle activity) or to a lesser degree by the constant bombardment and sand blasting caused by the transport of the basins' marginal coarser sediments (figure 2.15) (Gill, 1996). Opposite to these conditions, during the rainy season and after the basins have received a reload of fresh sediments or the in-situ precipitation has caused the top sediments of the peds to rearrange (resettling of disturbed sediments) in a sort of textural reset, the playa surfaces reflect a different set of textural conditions. The ped tops are covered by a very thin (<2 mm) brittle crust formed by fine clay size sediments (figure 2.16). These thin clayey crusts are commonly curled upward when heated and dried by solar action, causing them to extend above the laminar boundary layer at the playa surface and becoming especially prone to aeolian transport caused by the crust-to-crust collisions as well as the loose sand-crust interaction (Glennie, 1970). These conditions commonly occur during the autumn and winter months after the rains have ceased (typically in October) and prior to the peak windy season (March thru April) before strong winds completely deflate the surfaces.

The large size of the BDM basin creates a dual playa type behavior. The larger extent of the playa surface does not show signs of continued inundation (except during the rainy season) such as caused by discharge of shallow groundwater. Thus the majority of the playa acts as dry playa (Rosen, 1994), a type of playa classified as a low mineral aerosol emitter if other erosion-promoting conditions are not present (Reynolds et al., 2007). On the other hand, the playa margins, with the possible exception of the northern margin, receive a larger quantity of water during rain events (compared to central areas) and retain larger inundated areas for longer time periods, as long as several months or more during particularly heavy rainy seasons (e.g. 2006) (figure 2.17). Due to this effect these marginal
areas might also have a higher water table as a response to the runoff and groundwater recharge from the surrounding delimiting mountains. These conditions (long lasting inundations and possible low water table) generate a wet playa behavior (Rosen, 1994), with or without the presence of a shallow (<5 m) groundwater table (Reynolds et al., 2007). The sediments and resulting crusts formed at these types of environments are generally considered to be easier to erode and emplace into the atmosphere (Reynolds et al., 2007). The crusts found on wet playas might have a high content of efflorescent salts (Cahill et al., 1996; Rao and Venkataratnam, 1991). These salts crystallize along with the fine playa clastic sediments forming very soft and easily erodible crusts referred to as “puffy” or “fluffy” depending on the relative crust strength (Reynolds et al., 2007). During one of the sampling campaigns these types of surfaces were noted and sampled at the central-eastern margin of the BDM (figure 2.18).

Several surface sediment samples were collected from distinct areas of the Bolson de los Muertos (table 2.1). In the SE arm area, 10 samples (SELP-001 thru SELP-010) were collected forming a west to east transect across the playa surface following the prevailing wind direction and transport, approximately through the central part of the playa. Two samples were collected from the SE and SW arms merging area at their northern edges (CLP 001 and 002) and four other samples form the central and eastern segment of the BDM (COR 003, 005 and 006 and BDM 004), where sample BDM 004 was collected during a resampling campaign after the 2006 rains (figure 2.1). These samples were analyzed with the aid of a laser granulometer in order to obtain the grain size frequency distribution of the sediments.
Granulometric charts from the SE arm area display three major sample behaviors. The first trend is represented by samples SELP 001, 002 and 003 (westernmost), where the first and last samples display a bimodal distribution, while SELP 002 exhibits a trimodal distribution (figure 2.19). What is characteristic of all three samples is the location and extent of the main peak centered from 4.5 to 3 μm respectively, with the secondary and smaller peaks centered at the very fine sand size (~100 μm) for all three samples and a third peak centered at approximately 800 μm (coarse sand) for the SELP 002 (figure 2.19). The weight percent clay in the samples ranges from ~65 (SELP 001 and 002) to 75 percent (SELP 003), while the silt percent by weight ranges from ~30 to 20 percent from the westernmost sample (SELP 001), downwind to sample SELP 003. The fine sand fraction does not reach 5 percent for samples 001 and 003, and only 7.3 percent for sample 002. This sample is also the only one with a traceable amount of coarse sand equivalent to 1.6 percent by weight. The mean distribution of these samples is 2.7, 3.5 and 2.1, with a 2.2, 2.6 and 2.2 standard deviation respectively, all of the samples well within the clay and very fine silt ranges and classify as very poorly sorted (VPS) according to Folk, (1974) classification.

The second trend in the SE area samples (SELP 004 thru 008) is described by an overall increase in the sand fraction where the secondary coarser sediment peaks contain a greater amount of sediments compared to the upwind samples. All of these samples display a very dominant bimodal distribution, formed by a major peak located in the clay (<2.5 μm) fraction, with the exception of SELP 005 whose major peak is centered at the very fine sand size fraction. The secondary peaks of these samples are located in the very fine sand size fraction (~100 μm), with the exception of SELP 005 whose grain size distribution is
inverted compared to the others (figure 2.20). With the exception of SELP 005, all other samples have 60 - 70 percent by weight clay size sediments. The silt fraction of these sediments ranges from 20 to 30 percent by weight and the sand size fraction ranges from 7 to almost 12 percent by weight. Only samples 004 and 008 have a traceable amount of coarse sand in them (<.7 percent). Sample 005 has an almost equal distribution of clay, silt and sand size fractions by weight percent, with values of 36.6, 30.5 and 32.9 percent by weight respectively. The mean grain size distribution for these samples ranges from 2.8 to 3.5 (except SELP 005 at 12.7) µm with a standard deviation below 3 for all of them.

Sample SELP 009 represents the grain size distribution of the downwindmost SELP area almost in contact with the surrounding eastern alluvial and sand sheet deposits, while sample SELP 010 represents the contact between the playa and alluvial sediments (figure 2.21). These two samples are generally coarser than the rest, with SELP 010 significantly coarser than SELP 009. The grain size distribution of sample 009 displays a diffuse trimodal distribution, where the clay and silt fractions makeup ~84.1 percent by weight (40.5 and 43.6 respectively) and the sand fraction only 16 percent. The mean grain size for this sample amounts to 7.2 µm with a 2.6 standard deviation, which classifies it as a VPS sample (Folk, 1974). The downwindmost sample (SELP 010) also displays a trimodal distribution with the larger peaks located in the fine to coarse sand size fractions, and a broad smaller peak at the clay and silt fractions. The sand fraction of these samples amounts to 56.6 percent by weight (48 fine sand and 8.6 coarse sand) while the silt and clay fractions amount to 24.7 and 10.4 percent by weight respectively. The mean grain size distribution of this sample is the coarsest of all with 75.2 µm and a standard deviation of 2.4, also classified as VPS (Folk, 1974).
Excluding the two easternmost samples (SELP 009 and 010), the other playa samples are dominated by the clay and silt fractions amounting to almost 90 percent by weight of the total sediment distribution, with a mean of 4.2 µm. The sediment grain size distribution of the SE arm area exhibits a progressional coarsening from west to east following the sediment’s downwind transport. This scenario suggests that the finer fraction is deflated with downwind transport concentrating the coarser sandier fraction. The atmospheric emplacement of these fine sediments as mineral aerosols is certainly a plausible explanation for these results.

The granulometry of the CLP 001 and 002 samples display a bimodal distribution with the major peak centered at 3.5 and 2.5 µm and the secondary peak centered at 80 and 150 µm respectively. The sediment fraction represented by the second peak of sample CLP 002 is coarser than CLP 001 and there is also a very diffuse peak at the very fine silt size (~12 µm) (figure 2.22). These differences are noted in the percent grain size distribution by weight. The clay fraction is slightly higher for CLP 001 with 69.4 percent by weight, while for CLP 002 amounts to 61.4 percent by weight. The silt and fine sand fraction of CLP 002 are slightly larger with 32.1 and 6.5 percent by weight respectively, compared to 28.2 and 2.4 percent by weight for sample CLP 001. The mean particle size of these samples is 2.3 µm for CLP 001 and 3.0 µm for CLP 002, with a 2.0 and 2.3 standard deviation respectively, which classifies them as VPS samples (Folk, 1974).

The last set of samples from the Bolson de los Muertos (BDM) is comprised of samples COR 005 and 006, which represent regular playa ped surfaces sampled in the central area of the BDM near the Sierra de los Muertos. Samples COR 003 and BDM 002 were sampled in the central-eastern margin of the BDM closer to the shoreline sandy beach.
deposits of the eastern margin (figure 2.1). All four samples display a trimodal particle size distribution, where samples COR 005, 006 and BDM 002 possess a major peak centered at 1.5 μm for the first two and approximately .9 μm for the last. The second and third peaks are centered at 110 and 15 μm for COR 005, 15 and 110 μm for COR 006 and 100 and 20 μm for sample BDM 002. Sample COR 003 is the coarsest of all with the main peak centered at 150 μm and the second and third peaks centered at 25 and 1 μm respectively. The noticeable coarsening of sample COR 003 is due to the close spatial location of the sample to the sandy beach deposits of the eastern shoreline, which form sandier ped structures compared to the upwind, more distant COR 005 and 006 samples. Sample BDM 002 is located in the vicinity of the BDM shoreline and does not reflect the coarser grain size distribution; this might be due in part to the sample being collected during 2007, a year after the heavy rains that represented the end of a severe and long drought in the region (Stahle et al., 2009). Comparing the clay fraction of the shoreline samples, it is noticeable that there is a difference in the location of the clay fraction peak, which is finer for BDM 002 (at .9 μm) and there is also a noticeable difference in the slope of the left arm of the clay curve (figure 2.23). The slope of the left arm of the BDM sample is considerably greater compared to the others. This is interpreted as a signal of the sediment recharge that occurred after the major rains of 2006 and/or a possible crust surface reset occasioned by the disruption, dispersion and consequent resettling of the finer particle atop these structures caused by the impacting force of the rain drops and hail common during summer storms.

The weight percent distribution of sediments in these samples is dominated by the clay fraction amounting to more than 50 percent by weight for the COR 005 (54.7%), 006
(71.9%) and BDM 002 (55.8%) samples (upwind playa samples and after-rains sample). The shoreline sample COR 003 only contains 23 percent by weight of the clay fraction and consequently is higher in silt and sand content (51% and 26.1% respectively). The silt content of the other samples is 35 percent and 26.1 percent by weight for COR 005 and 006 respectively, and 35.9 percent by weight for BDM 002. The sand fraction amounts to 10.3 percent for COR 005, 2 percent for COR 006 and 8.3 percent for BDM 002.

The BDM samples were also analyzed by PIXE (particle induced x-ray emission) in order to establish their elemental composition. Tables 2.2 and 2.3 display average elemental concentrations for all collected samples.

Mean elemental concentrations of the major elements from the Bolson de los Muertos (including SELP, CLP and COR samples) are dominated by Si, averaging 24.67 weight percent. The remaining major elements (Mg, Al, K, Ti, Mn and Fe) display very similar concentrations between the different areas of the BDM, except for Na and Ca in the COR samples which have lower concentrations compared to the SELP and CLP samples (table 2.2).

The minor elements present in the BDM include S, Cl, Ni, Cu, Zn, Ga, Br, Rb, Sr, Zr and Pb. From these elements Ni is only present in the CLP samples of the BDM. The COR samples display the least amount of minor elements with only measurable values for Cl, Zn and Sr (table 2.3).

Enrichment factor coefficients were calculated for the BDM samples. These factors show Cl values above average crustal values for all samples except for COR 006. The Cl enrichment factor coefficient (EFC) reaches as high as 523 for SELP 005 and observes the lowest enriched value for the COR 005 sample with 12 units, placing it just above the 10-
point mark for average crustal values. S and Br are the only other elements slightly enriched in these samples. S reaches an EFC score of 29 in sample SELP 005, while Br reaches a score of 14 and 15 for samples CLP 001 and SELP 005 respectively.

Different areas inside and preferentially at or near the margins of the Bolson de los Muertos have been identified as some of the major dust sources from the Pluvial Lake Palomas basins (Lee et al., 2009; Gill et al., 2007; Rivera Rivera et al., 2006). The southern and eastern marginal areas of the southwestern and southeastern arms, along with the central-east margin of PLP have been observed to produce large plumes of mineral aerosols that can be traced for several hundreds of kilometers downwind commonly to the E and NE (figure 2.24). These large events are possible because all or most of the key factors that contribute to the “hot spot” dust generation (Gillette, 1999) are met during times when high intensity winds cross the area.

The physiographic setting of the BDM sub-basins is another key factor that contributes to increase the potential of the BDM playas and their margins as major aerosol producers. The three sub-areas or basins of the BDM elongate in a general N, NW and NE direction, almost perpendicular to the prevailing wind direction from the SW, exposing a greater longitudinal surface area to the prevailing winds, thus increasing the potential for deflation. These basins are also delimited to the west (upwind side) by tall mountain ranges (especially the SELP and central-northern area), which form a sort of initial barrier for the southwesterly winds (figure 2.2). As these winds are compressed onto the upwind mountainside the air parcels are ramped and lifted high above the mountains, but as the air parcels commence to descend they are accelerated downward into the lee side of the ranges, where the playa surfaces of the BMD are located. This effect is called a hydraulic
jump (Doyle and Durran, 2002), and it may increase potential for wind deflation of the PLP playas, due to the physiographic arrangement of the basins derived from the Basin and Range topography of the region. Hydraulic jump and related fluid dynamic phenomena have been suggested to play a role in dust emissions from other hotspots, including the Sahara (Cuesta et al., 2009), Owens Lake / Owens Valley (Wurtele et al., 1993; Doyle and Durran, 2002), and the nearby White Sands of New Mexico (Haines et al., 2006) and Franklin Mountains which bisect El Paso (Reynolds and MacBlain, und.).

At ground level, most areas of the BDM playas possess only very scarce vegetation commonly present as small patches of grasses. The surfaces of these playas are very flat and barren, with lack of non-erodible elements, such as rocks or irregular topography (figure 2.12). The playas are not used for agriculture or cattle ranching, but several areas in the delimiting mountains and in the river inlets and fluvial deposits are used for these purposes. Most of the ranches are located to the west and south of the BDM, while the main transport route and town are located to the east of the BDM. This setting causes the playa surface to be used as a minor vehicular transport route connecting these ranches to the main town of Villa Ahumada. The lack of roughness elements and the mechanical erosion caused by the anthropogenic activity help increase the potential of these playas as dust emitters, by creating a smooth surface over which wind can maximize its speed and unlocking the fine sediments from their crust enclosures.

The sediment grain size distributions of the playas and their margins are one of the key factors for dust generation. The playa sediments average over 60 percent by weight of clay size sediments, and if added to the silt fraction they constitute an average of more than 85 percent by weight fine (dust) material. These quantities categorize the playas as
unlimited sources of fine materials. These materials might be trapped in the ped structures, but the presence of vast sources of loose, potentially saltating materials across the playa increases the erosion potential of these ped surfaces. The loose sand size sediments are abundant at the margins (all around) of the playas, derived from the alluvial fans, fluvial deposits and the adjacent sand sheets and sand dunes, eroding the playa surfaces by sandblasting and bombardment (Gill, 1996; Cahill et al., 1996).

Sediment textures found in some areas of the playas are also facilitators for dust generation. The efflorescent crusts found in some of the playa margins where the playa behaves as a wet playa, possess a lower threshold velocity compared to the ped surfaces, thus contributing to increase the dust generation potential (Cahill et al., 1996; Rao and Venkataratnam, 1991). Before deflation of the surfaces and after the rainy season the surface of the ped structures are covered by a thin, brittle crust formed by very fine clay size sediments that curl up when exposed to the sun and dry air (Glennie, 1970) forming easily eroded “flakes” (figure 2.16). These flakes are moved across the surface colliding with one another and with the loose sand, disintegrating them and releasing the fines as aerosols. All of these circumstances create the perfect setting for a “hot spot” of dust emissions (Gillette, 1999) as evidenced by the large dust outbreaks generated from these areas (figure 2.24). For this reason the playas and margins of the BDM are classified as major dust sources with very high dust generation potential.

Central area of the Pluvial Lake Palomas Basin

The central area of the Pluvial Lake Palomas is formed by a very extensive area with no clear shape and varied delimiting margins (figure 2.25). The center of the area is
approximately located at 31° 29’ 49” N and 107° 18’ 32.1” W. This basin extends close to 60 km in a NW direction from the south at the gradational margin with the Bolson de los Muertos until it reaches the international border near and east of Columbus, NM and Puerto Palomas, Chihuahua. Beyond this point the northern area of the PLP is locally referred to as the Indian Basin and is entirely located in the New Mexico, USA side (which lies outside the study area). The central area basin extends at its widest point for almost 35 km from west to east. The eastern margin of the basin is the best delimited as the El Camello fault escarpment (Reeves, 1969) has created an approximate 10 m relief separating the playa surface from the adjacent sand sheet and very extensive nebkha fields (figure 2.25). The southwestern margin of the basin is delimited by the Sierra San Blas (previously described) extending close to 20 km. The central-western area forms a diffuse margin where lacustrine sediments prograde in to fluvial mouth and fluvial channel deposits in the Guadalupe Victoria area as they have been deposited by the Rio Casas Grandes. The area displays a large fluvial delta with bars and spits formed by the fluvial deposits of the Rio Casas Grandes. The deposits in this area are considerably coarser than the rest and form a deflated desert pavement surface, which precludes dust emissions (figure 2.26). The northwestern margin is delimited from south to north by the Cerro el Fortin, Cerro la Rosina, Cerro el Gato and Cerro la Montura. The first two (El Fortin and La Rosina) are formed by Paleozoic limestones and Tertiary rhyodacites rimmed by Tertiary conglomerates. Cerro el Gato and La Montura are entirely composed of Quaternary basalts derived from several small volcanoes (INEGI, 1983).

With the exception of the Rio Casas Grandes, only minor streams and arroyos derived from the delimiting mountains form the only hydrological recharge for most of the
central area of PLP. The lacustrine and fluvial soils of these areas are widely used for cattle ranching and agricultural purposes. National highway 2 forms the major transport route transecting the central area from east starting at Ciudad Juarez, Chihuahua going westerly across the state line into the state of Sonora.

One sample (HWY02-001) was collected and analyzed from the lacustrine deposits of this area, in what appeared to be a degraded grassland area. The surface sediments of the lacustrine deposits are commonly present in the form of poorly developed ped structures and sometimes possess no structure at all. Tall grass vegetation tends to be more common in different areas, especially after rain events (figure 2.27). The lack of extensive and well-developed crust structures causes some areas to act as dust “hot spots”, aided by the presence of coarser (sand and fine gravel) deposits at the margins of the basin.

The grain size distribution of sample HWY02-001 displays a bimodal distribution with the major peak centered at ~12 µm and the second at approximately 120 µm (figure 2.28). Clay and silt size sediments form over 88 percent by weight of the sample, 44.5 and 44.4 respectively, with fine and medium sands forming the remainder. The mean grain size is 5.5 µm with a 2.4 standard deviation, which classifies the sample as very poorly sorted (VPS) according to Folk (1974).

Elemental concentrations were obtained for this sample (tables 2.2 and 2.3). The major element concentrations are very similar to other samples, only with Si reaching 30 percent making this the most siliceous sample of the basin. Conversely, Ca has the lowest value for the PLP samples with 2.17 percent. Minor elements present in this sample are Cu, Zn, Ga, Rb, Sr and Zr. All of the elemental concentrations are well within crustal averages (figure 2.7).
The western area of the basin has been observed to emit dust from discrete areas (figure 2.29). Prior to the 2006 major rain events, the area lacked vegetation and the surface appeared very degraded, thus possessing a high dust emission potential. After the rains the area recuperated extensive grass cover and dust emissions appeared to be less frequent. The anthropogenic activity of the area and the availability of loose coarse sediments around the basin give the area an increased potential for dust emissions, only opposed by the vegetation cover of some areas. The southernmost mountain (Sierra San Blas) might cause the downwind playa area to experience stronger wind currents due to the hydraulic jump effect, which might potentialize erosion on the downwind side. Overall the area is classified with a medium potential for dust emission, varying according to the rain or drought effects that may change this potential to low or high accordingly.

**Rio Casas Grandes Valley (Guadalupe Victoria area)**

The valley of the Rio Casas Grandes (CGR) in the area east of the Sierra de Boca Grande forms an area highly prone to dust emissions because of the available sediment types and the high agricultural land degradation that the region has experienced. The area is centered at $31^\circ 30' 31.3''$ N and $107^\circ 40' 30''$ W. The fluvial deposits of the CGR cover an area that once served as a basin of the PLP. The area forms a teardrop shape, initiating at the mountain pass where the CGR crosses the Sierra de Boca Grande, extending to the SW for approximately 30 km (figure 2.30). At its widest point (NW-SE) the area reaches almost 20 km and its confined to the east by the fluvial channel of the CGR, to the north by the Cerro El Gato (previously described) and to the west and southwest by the Sierra de Boca Grande formed by Paleozoic and Cretaceous limestones, rimmed by Tertiary conglomerates.
and scattered Quaternary basalts \textit{(INEGI, 1983)}. The fluvial deposits of the CGR valley have been extensively used as rich agricultural croplands (growing cotton, melons and vegetable crops), which form the main economic activity of the area. The valley is connected to the north and south by a two-lane road branching off from national highway 2, north to the border town of Palomas, Chihuahua.

Two samples were collected from two different adjacent surfaces. The first sample GV 001 corresponds to non-vegetated agricultural land and the second sample GV 002 correspond to an undisturbed vegetated area approximately 100 m north from the first.

The grain size distribution of the GV samples display a bimodal distribution represented by two peaks of similar height, with the finer sediment peak being broader compared to the coarser sediment peak. The fine fraction peaks are centered at 3 and 4.5 µm for GV 001 and GV 002, while the coarser peaks are centered at approximately 110 and 100 µm respectively (figure 2.31). The clay fraction of these samples amounts to 44.5 and 41.5 percent by weight for GV 001 and GV 002, while the silt fraction is smaller with 33.6 percent by weight for GV 001 and 40.8 percent for GV 002. The fine sand fraction reaches 19.1 and 15.8 percent by weight respectively and the coarse sand fraction is present with 1.5 and 1.1 percent by weight respectively. Average mean size of these samples is 8.0 µm for GV 001 and 7.9 µm for the GV 002. Both samples are classified as VPS \textit{(Folk, 1974)}, with a standard deviation of 2.9 and 2.7.

The two samples were analyzed by PIXE in order to establish elemental compositions. Mean elemental concentrations for all major elements are very similar to the rest of the PLP samples, with the possible exception of Na (.4 %) possessing the lowest value from all samples (table 2.2). The minor elements present in these samples are: S, Ni,
Cu, Zn, Ga, Rb, Sr, Zr and Pb (table 2.3). All of the elemental concentrations are well within average crustal values as described from the enrichment factor coefficients (figure 2.7).

The dust generation potential for this area is modulated by the agricultural practices used by the farmers (Lee et al., 2009). The soil grain sizes possess high amounts of fine clays and silts, and due to the agricultural disruption they are not enclosed by any type of crust. The agricultural fields are typically maintained in a barren, unvegetated state during the non-growing season, which is also the period of the highest winds. Vegetation is almost restricted to agricultural plants, with native vegetation occupying only very scarce areas in the valley. The physiographic setting of the valley may potentialize dust emission by the same hydraulic jump effect caused by the Sierra de Boca Grande and other ranges located upwind (west) of the valley and transverse to the regional prevailing wind direction from the SW. Dust emissions from this area are mostly likely to occur when the soils are not cultivated and the surface is left fallow with no roughness to increase threshold values. The agricultural fields are commonly barren during the windy season occurring in March and April as well as during the winter months which also experience occasional high wind events. The area currently has a high dust emission potential that would be affected by the type of agricultural practices used.

Laguna Guzman

Laguna Guzman is one of the best known lacustrine basins in the region. It is located approximately 17 km south from the intersection of national highway 02 and the road going north to Palomas, Chihuahua and Columbus, New Mexico. The center of the Laguna is located at 31° 16' 49.7'' N and 107° 27' 40.6'' W. The basin of Laguna Guzman forms the
hydrological sink for the fluvial deposits of the Rio Casas Grandes (CGR) (figure 2.32). During the first part of the last century the area of Guzman was used as a railroad station for the route connecting Ciudad Juarez (NW) and Casas Grandes, Chihuahua. The station and the few buildings constructed around it are now abandoned. Agriculture is common in the alluvial deposits forming the northern margin of the laguna, but nowhere as extensive as in the CGR valley. Livestock ranching is observed in the vicinity of the playa. When dry, the playa surface is used as a minor transport route by the locals.

The surface of Laguna Guzman forms an oval shape playa elongating approximately 13 in a NNW direction and reaching ~7 km at its widest point from NE to SW. To the north the playa surface is delimited by the coarser fluvial deposits of the CGR deposited by a series of small braided streams. The eastern margin of the playa deposits are delimited by Quaternary alluvial deposits originating from the western margin of the Sierra San Blas (previously described). The western margin of Laguna Guzman is delimited by more Quaternary alluvial deposits derived from the adjacent Sierra Las Lilas, formed by Paleozoic and Cretaceous limestones rimmed by Tertiary conglomerates (INEGI, 1983). The southern margin is delimited by Quaternary basalts and Tertiary conglomerates from the Cerro el Venado and the Cerros Prietos (INEGI, 1983).

The sediments that form the surface of Laguna Guzman are present in the form of extensive polygonal desiccation structures (peds) (figure 2.33) creating an extensive flat and barren surface free of any non-erodible elements. These peds form hard ~2-3 cm thick crusts, covered by thinly flat and curled micro-crusts formed by finer clay size sediments (figure 2.34). The areas marginal to Laguna Guzman possess a heterogeneous and coarser
sediment distribution representative of alluvial deposits. These areas commonly vegetated by creosote bush (*Larrea tridentata*) and other shrub type vegetation.

Two surface sediment samples were collected from this playa and their grain size distribution was analyzed. Sample LG 003 was collected before the major 2006 rain events, and LG 004 was collected during the later part of 2007.

The granulometric distribution of these samples is almost unimodal, with the bulk of the sample formed by clay and silt size sediments, with peaks centered at 2.5 and 7 µm for sample LG 003 and LG 004 respectively. Both samples possess a diffuse complementary peak in the fine sand size centered approximately at 110 µm (figure 2.35). A clear distinction in the clay percent by weight is evidenced from the two samples. The pre-rains 2006 sample LG 003 possesses 55.5 percent by weight clay, while the post-rains (2007) sample LG 004 increased its clay content to 76.3 percent by weight. This increase is a clear indication of sediment recharge into the playa and/or a top ped surface textural rearrangement of the finer material. The fine sediment recharge is also evident from the granulometric charts (figure 2.35), where the left arm of the fine sediment curve from sample LG 004 possesses a higher slope compared to the same arm from sample LG 003. Adding the silt fraction to these samples, LG 003 reaches 96 percent by weight of fine (clay and silt size) sediments, while LG 004 amounts to 98.6 percent by weight, with the remainder percent in the fine sand fraction. The mean grain size of these sediments is 3.4 µm for LG 003 with a standard deviation of 2.1, and 1.6 µm for LG 004 with a standard deviation of 1.9. The standard deviation of LG 004 classifies it as a slightly better sorted sample (poorly sorted) compared to LG 003 classified as very poorly sorted (*Folk, 1974*).
The major element concentrations of these samples are relatively similar to those from other basins, with none of the elemental concentrations outstanding as significantly high or low (table 2.2). The minor element concentrations display a similar behavior with all values falling within average crustal concentrations (table 2.3 and figure 2.7). The main difference between samples is the presence of As in sample LG 004 with a concentration of 12 ppm (within crustal values). The presence of As in the post-rain sample could indicate some type of arsenic removal from the system after it has been replenished by fresh sediment input. This removal could have occurred as As percolates deeper into the soil, or if As is deflated from the surface by aeolian action if it is concentrated in efflorescent type salts. In either case research is needed to test these hypothesis.

Several factors in the Laguna Guzman contribute to generate a dust “hot spot” potential for the sediments and surface structures present, although some factors may preclude intense emissions from occurring. Ephemeral vegetation cover, mostly in the form of tall grass after rain events, and the presence of hard deflated ped structures are both factors contributing to diminish the potential for dust generation from this playa. On the other hand, the presence of eroding agents both anthropogenic (and livestock-related) and natural in the form of loose sediments (sand size) in and around the playa contribute to dust generation from the very fine-grained ped structures. The release of fine sediments from these surfaces is likely increased during the time that the thin crusts are present atop the ped structures (figure 2.34). This usually occurs after the rainy season has passed and when the first strong winds occur (November to February). Laguna Guzman is characterized as having a medium to high dust generation potential, dependent on the extent of vegetation cover and the initial deflation of the thin micro-crusted surfaces.
Trans-Laguna Guzman

Laguna Guzman is separated to the south from the main body of Laguna El Fresnal by a small basalt outcrop. Right across this outcrop, a northern extension of Laguna el Fresnal is present. This area, although hydrologically connected to Laguna el Fresnal, is commonly not inundated continuously to the main body of El Fresnal. A small playa surface represents this area here referred to as the Trans-Laguna Guzman or TLG, centered at 31° 12’ 47.2” N and 107° 29’ 02.8” W (figure 2.32). The playa surface extends longitudinally for almost 6.5 km in a NNE direction, reaching only ~1.5 km at its widest point. To the north the TLG playa is delimited by a basalt outcrop forming the boundary with the Laguna Guzman. To the east the playa is in contact with Tertiary conglomerates and igneous intrusive rocks from the Cerro el Venado. The western margin is delimited by Quaternary alluvial deposits derived from some nameless Quaternary basalt deposits and the Cerro Bismarck formed by Tertiary granites intruding Cretaceous limestones (INEGI, 1983). The Cerro Bismarck is host to one of the largest mining facilities in the region, Minera Bismarck exploiting sphalerite ore for zinc (Haptonstall, 1994).

The playa of TLG is formed by a very flat and barren surface mainly free of roughness elements and vegetation. Hard ped structures dominate the playa surface and during the sampling campaigns no appreciable fine crusts were observed atop these peds. The alluvial deposits forming the western (downwind) margin of the playa form a source for saltating sediments that might contribute to dust generation from this playa.

Two samples were collected from this playa and analyzed for granulometry and elemental concentrations. Sample TLG 002 was collected in the year 2006 (pre-2006 rains)
and TLG 001 was collected in 2007 after the unusual 2006 rains. Sample TLG 001 was collected approximately 300 m west from the prior year sampling site, due to the still-high water level, which kept the whole extent of the playa inundated. Changing the sampling location caused the sampled sediments to be acquired from the playa margin, where coarser material was observed along with traces of efflorescent salts.

The granulometric distribution of TLG 002 is described by a bimodal distribution where the main peak is centered at 2 μm and the secondary peak at 110 μm (figure 2.36). Opposite to this, sample TLG 001 displays a trimodal distribution with two main peaks centered at 3.5 μm and 80 μm, while the third and coarsest is centered at 700 μm (figure 2.36). The clay fraction of sample TLG 002 amounts to 55.6 percent by weight, while for sample TLG 001 is decreased to 42.3 percent by weight. On the other hand, the silt fraction is larger for TLG 001 with 43.8 percent by weight, compared to 31.6 percent for TLG 002. Both samples possess similar percentages of fine sand with 12.3 and 11.3 percent by weight for sample TLG 002 and 001 respectively. A small fraction of coarse sand is also present in both samples, reaching .2 percent and 1.4 percent by weight for TLG 002 and 001 respectively. The mean grain size is smaller for the pre-rain inner playa sample with 4.2 μm, compared to the playa margin sample with a mean of 7 μm. Both samples are classified as VPS (Folk, 1974), due to the 2.8 and 2.7 standard deviation values (TLG 002 and 001). The sampling location with respect to the playa margin displays a clear difference between the two samples, where the playa margin sample is coarser and trimodal compared to the inner playa sample. As observed from other playas where post-rain samples were collected at or very near the prior year sampling point, the post-rain samples display a finer granulometry and augmented clay fraction.
The mean elemental concentrations of the TLG samples (tables 2.2 and 2.3) are within average values compared to the other regular playa samples, with only As in the TLG 001 sample slightly enriched scoring an enrichment factor coefficient of 11 points (figure 2.7).

The small area of the TLG playa and the observed hard ped structures with no visible superficial thinner crusts, contribute to lower the playa surface potential for dust emission. On the other hand, the lack of roughness elements in the playa surface and the upwind availability of coarser sediments (sand) contribute to the erosion of the playa surface by sandblasting and bombardment. These coarser sediments were not observed to be available in loose form (aeolian sands), instead they are part of the alluvial deposits, thus making their release in order to increase the surface erosion of the playa more difficult. These observations cause the TLG playa to be categorized with a low to medium dust generation potential, due to the lack of easily erodible elements and the supply restricted availability of eroding agents (Gillette and Chen, 2001).

**Laguna El Fresnal**

South of the TLG area is the main body of Laguna el Fresnal, centered at 31° 05’ 17.3” N and 107° 30’ 23.9” W. This basin hosts a playa surface that elongates for approximately 11 km from south to north and reaches almost 4 km at its widest point (figure 2.32). The playa of Laguna el Fresnal is inundated partially by the streams derived from the surrounding mountains both the east (Cerro el Venado and Sierra los Borregos) and west (Sierra el Fresnal, Cerro la Aguja and Cerros Bismarck). In the southern margin of the playa Rio Rincon de Chihuahua also inundates the playa surface. The rivers and streams
around the area are ephemeral, inundating the basins only during the wet season. The playa of Laguna el Fresnal has been observed to retain water even during the dry season (figure 2.37). This is possibly due to groundwater discharge from the Bismarck mine, which is released outside the mine premises, eventually reaching the playa of El Fresnal. Rancho El Fresnal is located in the southern margin of the playa (in the alluvial deposits); besides this ranch, no other major anthropogenic activity is noticeable adjacent to the playa. Extensive agricultural land is observed in the valley south from Laguna el Fresnal formed by the Sierra el Fresnal and Santo Domingo to the west and the Sierra los Borregos to the east.

The basin of Laguna el Fresnal is delimited to the west by Quaternary alluvial deposits derived from the Sierra el Fresnal composed of Quaternary basalts and Tertiary rhyolites and tuffs, and the Cerros la Aguja with similar composition adding trachytes and andesites (INEGI 1983). To the east the Laguna el Fresnal is delimited by an aeolian sediment blanket possibly derived from the playa erosion and conglomeratic alluvial fan deposits of the Cerro el Venado of similar composition to Sierra el Fresnal.

The playa surface of el Fresnal is flat and free of roughness elements. The areas of the playa that are not continuously inundated are covered by ped structures averaging 2-3 cm thickness and are overlain by vast amounts of thin, brittle crusts less than 5 mm thick. These crusts are formed by very fine sediments and curl upward forming almost cylindrical shapes (figure 2.38). Alluvial fan deposits to the west and aeolian sediments to the east delimit the margins of the playa.

Two samples were collected from this playa, sample LF 001 collected in 2006 prior to the rainy season and sample LF004 collected in 2007. A separate sample LF “Flakes” was
collected only from the thin curled crust atop the ped structures during the 2006 sampling campaign. Similarly to the TLG 001, the 2007 LF sample (LF 004) was collected approximately 800 meters NW from the prior year sample. LF 004 was collected from the inner margin of the highest playa extent, thus the sediment collected was clearly from a ped surface.

The granulometric distribution of the LF 004 and flakes samples display a bimodal distribution, with the main peaks centered at 1.8 µm for LF 004, and at 1.5 µm for the flakes sample. The second and smaller peak is centered at approximately 110 µm for the LF 004 sample and approximately at 13 µm for the flakes sample. The LF 001 sample displays a trimodal distribution with the main peak centered at 9 µm, with the second peak at 110 µm and the coarser peak centered at 1000 µm (figure 2.39). The clay fraction of these samples for the flakes and LF 004 samples is 73.7 and 80.1 percent by weight respectively and decreases to 51.2 percent by weight for the LF 001 sample. The silt fraction of these samples amounts to 26.3 percent by weight for the flakes sample, 41.8 percent for the LF 001 sample and 16.1 percent for the LF 004 sample. Silt and clay form the total grain size distribution of the flakes sample, while LF 001 possesses 3.4 percent fine sand and 1.4 percent by weight coarse sand. The fine sand percent of LF 004 amounts to 3.8 percent by weight with no coarser fraction present in this sample. The flakes sample collected prior to the main rain events of 2006 possesses the finest grain size composition of all, suggesting that the loose thin crust that forms atop the ped structures accumulates a greater percentage of the available fine material (clay and silts) discriminating any other coarser fractions. The relation between the two ped samples is similar to other pre- and post- 2006 samples, where the post-2006 samples display a principal peak centered in a finer size
compared to the pre-2006 samples. The left arm slope of the fine sediment curve is also
greater for the post-2006 sample, clear evidence of sediment recharge and/or possibly a
surface resettling caused by the frequent inundation of this playa.

The LF samples were analyzed by PIXE (particle induced x-ray emission) to
determine the elemental concentrations in these samples. The mean elemental
concentrations of the Laguna el Fresnal samples are displayed in tables 2.2 and 2.3. No
drastic elemental variations are observed for the major element concentrations in Laguna
el Fresnal. The minor element concentrations are slightly high for As in all samples as
observed from the enrichment factor coefficients (EFC), with values just above the 10-point
mark. Cl is also slightly enriched in the flakes sample with an EFC of 10.

The flat playa surface and lack of roughness elements along with presence of vast
amounts of thin crusts atop the ped structures and the availability of alluvial and aeolian
deposits at the margins of the El Fresnal playa are contributing factors for the generation of
dust from this playa. Similarly, the physiographic alignment of the playa with respect to the
downwind Sierra del Fresnal is a contributing factor for dust generation due to the
increased wind erosion potential posed by the hydraulic jump effect possibly occurring in
this area. On the other hand, the frequent playa inundation caused by the ground water
discharge from the Bismarck mine causes inundated areas of the playa to be non-emitters
of dust, effectively lowering the potential of the playa to act as a dust emitter. No significant
anthropogenic activity is observed around the playa except for the el Fresnal ranch in the
southern area. The resulting potential for mineral aerosol emplacement from this playa is
classified as low to medium, restricted by the frequency and extent of playa inundation.
**Laguna Santa Maria**

Laguna Santa Maria is located in a narrow valley formed to the east by the Sierra el Malpais and Sierra La Nariz, and to the west by the Sierra los Borregos and Cerro el Venado (previously described). The lake surface elongates from south to north for almost 15 km and maintains an approximate average width of 2.5 km (figure 2.32). The center of the laguna is located approximately at 31° 06’ 57.7” N and 107° 16’ 7.7” W. A considerable extension of the northern area of the lake might be inundated year round, due to the presence of two natural springs, the Ojos de Santa Maria located in the western side and the Manantiales de Valerio located in the eastern side. The larger and ephemeral fluvial input of this lake is present at the southern end, where the Rio Santa Maria discharges into the basin. The dry margins of the lake form the only areas where lacustrine sediments might be exposed. These areas may increase in size in the southern segment when the Rio Santa Maria is dry and as the waterline recedes. The lake margin forms a contact to the west with the conglomeratic deposits from the delimiting mountains. On the southeastern side the lake margin is in contact with aeolian deposits possibly derived from the erosion of the dry lakebed areas, and to the northeast with Tertiary intrusives and Quaternary basalts of the Sierra el Malpais (INEGI, 1983). The Santa Maria basin is a remote area with no major transport routes present. One dirt road connects the northern part of the basin to the Guzman area and the same road extends south out of the basin into an area close to the southwestern arm of PLP. During a field visit cattle ranching was observed at the ranch at the Ojos de Santa Maria, but no other anthropogenic activity was recognized. The dry playa margins observed in the lake formed gently sloped flat and smooth surfaces with no presence of roughness elements. Even though the water line was very close to the ped
surfaces, the substrate was dry and firm enough to allow walking on top of it. These surfaces displayed the presence of regular ped structures with average thickness around 3-4 cm (figure 2.40). In some areas these peds were overlain by abundant thin clay crusts curled upward. Further back from the water line and still in the playa margin, coarser sediment deposits displaying efflorescent salts and fine gravels were present (figure 2.41). Beyond this area, the deposits graded in to conglomeratic alluvial sediments with larger rock clasts and abundant vegetation.

Two samples were collected from this area, both gathered at the same location but representing distinct surfaces. Sample LSM 002 represents the flat, efflorescent salt-rich gravelly surface further away from the water line (figure 2.41). The second sample, LSM 003, represents the regular ped structures found closer to the water line (figure 2.42). Both samples were analyzed for grain size and elemental concentrations.

The granulometric distribution of LSM 002 displays a diffuse bimodal distribution, with the dominant peak centered at 150 \( \mu m \), accompanied by a broader and smaller peak at approximately 2 \( \mu m \) (figure 2.43). The clay fraction of this sample amounts to only 9.9 percent by weight, with a higher concentration of silts equivalent to 36 percent by weight. It is likely that the fine fraction of this sample might be under-represented due to the dissolution of the efflorescent salts as result of the dispersing treatment utilized to analyze the samples. The coarser fraction of this sample amounts to 46.8 percent by weight of fine sands, and 4.2 percent of coarse sands. The mean grain size of this sample is 50.5 \( \mu m \) (2.3 standard deviation) constituting one of the coarser samples found in the PLP system (but not accounting for the water-soluble salt component), with the only exception of sample SELP 010 with a mean of 75.2 \( \mu m \) (2.4 standard deviation).
The grain size distribution of sample LSM 003 is characterized by a bimodal distribution with the two peaks almost equally distributed and centered at 1.5 µm and 70 µm. Only a minimal trace (.2 percent by weight) of coarser material is present at approximately 650 µm (figure 2.43). The clay fraction of this sample amounts to 50.7 percent by weight, with 44.4 percent by weight of silt and 4.5 percent of fine sand. The mean grain size of LSM 003 is 4.3 with a standard deviation of 2.6, which classifies the sample as VPS (Folk, 1974) the same as LSM 002.

Mean elemental concentrations of the LSM samples are presented in tables 2.2 and 2.3. The mean concentrations of the major elements (Si, Al, Ca, Fe, K, Na, Mg, Ti and Mn) are similar to the rest of the other playas in the PLP. The minor element concentrations are slightly enriched in Cl (mean 2347 ppm) and As (mean 23 ppm) for the LSM 002 sample, as evidenced by the enrichment factor coefficient (EFC) scores (figure 2.7) of 23 (Cl) and 13 (As). Sulfur is also slightly high in concentration, compared to other playas with 4197 ppm, but this value is within crustal averages with an EFC of only 6.

The basin and surface of the Laguna Santa Maria is parallel to the upwind topographical barrier formed by the Sierra los Borregos and Cerro el Venado, which are in turn perpendicular to the prevailing wind direction. This relation might contribute to increase the wind erosion from the dry lake areas as the hydraulic jump effect increases the wind speeds downwind of the mountains. The flat and smooth surfaces of the dry playa margins along with the lack of vegetation and other roughness elements contribute to increase the dust generation potential of the LSM. At smaller scale the ped surfaces contain very large amounts of fine clay and silt sediments (~95 % by weight), which create an extended supply of fines available for erosion. The erosion of these fine sediments can be
caused by the release of saltating particles from the upwind conglomeratic alluvial deposits and the coarse sand deposits in the upwind playa area. These deposits, represented by LSM 002, might be easily available for saltation downwind if released from the soft matrix that the efflorescent salts form. These salts can be easily deflated, consequently releasing the saltating fraction, which would be transported downwind across the ped surfaces acting as eroding agents by means of sandblasting and bombardment. On the other hand, the constant inundation of areas of Laguna Santa Maria and the consequent water-level limited exposures of dry surfaces constitute key factors constraining the dust generation potential of the Laguna. During the field campaign the water level of the Laguna was high and the exposed playa surfaces were limited. For this reason, the dust generation potential of the Laguna Santa Maria is described as medium, restricted by the inundation extent of the playa.

Laguna Palomas

Laguna Palomas (part of the Pluvial Lake Palomas) is located in the northernmost extension of Pluvial Lake Palomas inside Mexican territory. This semi-circular playa surface extends close to 2.5 km in diameter with center at 31° 42’ 11.4” N and 107° 34’ 44.2” W (figure 2.30). The playa is only several kilometers east from the principal paved road that connects the town of Palomas and the national highway 2 to the south. The town of Puerto Palomas is located approximately 9.5 km north of the Laguna Palomas. Other than the town of Palomas and the adjacent road, the only other visible signs of anthropogenic activity near the playa area were a few scattered ranches along the highway. Laguna Palomas forms a small and restricted sub-playa of the northwestern PLP. This playa is
almost entirely surrounded by the Quaternary basalt flows of Cerro el Gato to the west, and the Quaternary alluvial deposits of the Cerro la Rosina formed by Paleozoic limestones and Tertiary intrusives rimmed by Tertiary conglomerates (INEGI, 1983). The hydrologic recharge to this playa is formed by a few small arroyos derived from the surrounding mountains; no other major fluvial system discharges into this playa. During the field campaign, no access was granted to the playa surface (inundated at the time), which resulted in the collection of one sample from one of the main arroyos discharging into the playa from the south. The sample was collected approximately 2 km south of the playa surface and it was taken from the fine loose sediments at the surface.

Granulometric and elemental analysis were conducted for sample LPAL 005. The granulometric distribution of this sample displays a bimodal distribution with the principal peak centered at 250 µm and the secondary peak centered approximately at 2 µm (figure 2.44). The fine sediment fraction of this sample is formed by clay with 20 percent by weight and silt with 16.1 percent by weight. The coarser fraction is dominated by fine sands constituting 63.7 percent by weight and a very small trace of coarse sand with only .2 percent by weight. The rich sand content of the sample is expected due to its fluvial nature, depleted of the finer material that is transported downstream into the playa.

Major and minor elements concentration in sample LPAL 005 displays no outlier values compared to the rest of the playa samples (table 2.2 and 2.3). Only arsenic stands out in the enrichment factor coefficients with a score of 9, which is still considered within average crustal values (figure 2.7).

No clear determination of the LPAL playa dust generation potential can be drawn, due to the lack of in situ observations of the playa, the sediments and structures, as well as
direct analysis of the playa sediments. The collected sample would serve only as an approximation to the elemental concentrations expected in the playa.

**Laguna Seca**

Laguna Seca is the only playa included in the study that is not part of the Pluvial Lake Palomas *per se*. This playa was included in the study, due to observations from satellite imagery of dust plumes generated from this area (Lee et al., 2009; Rivera Rivera et al., 2006). The Laguna Seca is located approximately 6 km southwest from the town of Ascension, Chihuahua. The surface of the playa forms a semicircular shape approximately 7 km in diameter and is centered at 31° 02’ 47.2” N and 107° 54’ 35.1” W (figure 2.45). The areas around the playa are intensely used for agricultural purposes and the playa serves as a runoff sink for these agricultural lands. The playa is also hydrologically recharged from the north by a tributary stream of the Rio Casas Grandes (CGR) called El Federico, and also receives runoff from the arroyos flowing from the nearby mountains of the Sierra el Fresnal (east), Cerro la Aguja and Cerro la Tecolota (ENE). Only the SW margin of the playa is delimited by Cerros el Paraje formed by Tertiary tuffs (INEGI, 1983). The rest of the playa is delimited by Quaternary alluvial deposits derived from the nearby mountains, as well as fluvial deposits from the CGR. Several dirt roads are observed around the playa serving the surrounding farming areas.

The surface of the Laguna Seca is fairly flat and barren and presents some low-lying areas that are preferentially inundated (especially to the NE). The non-inundated areas display poorly developed ped structures, which are not extensive throughout the surface. These peds are very thin (<5-7 mm) and overlay a harder and coarser substrate that is not
fractured (figure 2.46). Scarce shrub type vegetation is present in these surfaces (figure 2.47). The inundated areas display a sediment gradient at its dry margins. The outer extent of the margin is dominated by a gravelly sandy surface forming “Gobi” type deposits (figure 2.48). These deposits become finer–grained, dominated by sands, as they get closer to the inundated margin (figure 2.49). Once at the margin with the inundated area the sediments become finer and are present in the form of clay and silt aggregates. These aggregates are overlain by an efflorescent salt crust a few millimeters thick (figure 2.50). The salt crust may be generated either as a response to the runoff inundating the playa or as response to a shallow groundwater table.

Three samples were collected from these surfaces. Sample ASC 001 corresponds to the dry areas of the playa, and samples ASC 002 and 003 correspond to the sediments closer to the inundated parts of the playa. Sample ASC 002 was collected from the efflorescent salt crust atop the aggregate layer, and sample ASC 003 was collected from the loose aggregates underneath the efflorescent crust.

The granulometric distribution of these samples is varied. Sample ASC 001, which represents the thin peds, displays a diffuse trimodal distribution with a dominant peak centered at 5.5 µm and the second and third diffuse peaks located approximately at 65 µm and 700 µm respectively (figure 2.51). The clay fraction of this sample amounts to 53.5 percent by weight, while the silt fraction amounts to 38.3 percent, thus the fine sediment fraction (clay and silt) reaches just over 90 percent by weight of the total sample. The coarser sand fraction is divided with 6.3 percent of fine sands and 1 percent by weight coarse sands.
Sample ASC 002 represents the efflorescent salt crust. The granulometric distribution of this sample displays a trimodal distribution with a dominant peak centered at 400 µm, and the second peak centered at 3.5 µm. The third peak is diffuse and almost incorporated to the coarser peak. This peak is centered at approximately 70 µm (figure 2.51). The clay fraction of this sample reaches only 22.3 percent by weight and the silt fraction 25 percent. The sediment fraction forming the bulk of this sample is formed by fine sand amounting to 50 percent by weight. The coarse sand fraction is present with 2.7 percent by weight. The fine fraction of this sample is under-represented due to the dissolution of the efflorescent salts as result of the dispersing treatment utilized to analyze the samples.

Sample 003 represents the underlying aggregates. This sample displays a bimodal distribution with the dominant peak centered at 150 µm. The second peak is centered at 2.5 µm (figure 2.51). The clay fraction of this sample amounts to 43.5 percent by weight, while the silt fraction reaches 26.8 percent. The fine sand fraction is present with 29.7 percent by weight.

Elemental concentrations of this playa are quite different for sample ASC 001 and the wet playa related samples ASC 002 and 003. The concentration values of sample ASC 001 are all well within crustal average values, as noted from the enrichment factor coefficients (EFC) (figure 2.7). The other two samples possess anomalous concentrations for some of the minor and trace elements present. Sample ASC 003 is slightly enriched in sulfur with a EFC of 13, but is highly enriched in arsenic, bromine and chlorine with EFC values of 27, 74 and 146 respectively. These scores indicate anomalous concentrations,
which exceed average crustal values. The individual concentrations of these elements are: S 5750 ppm, As 46.9 ppm, Br 192.9 ppm and Cl 25410 ppm.

Sample ASC 002 pertaining to the efflorescent salt crust displays the most enrichment of elements and is also depleted of most of the major elements with values that reach up to an order of magnitude less compared to regular playa sediments. Si, which is the dominant element in all samples commonly averages concentration over 20 percent, but in sample ASC 002 reaches only 2.4 percent. This trend is similar (less drastic) for all other major elements except for Na, which is enriched in the efflorescent sample with an EFC of 137 and a concentration of 32.7 percent. Most of the enriched minor elements display more drastic EFC values, with the exception of vanadium with an EFC of 10 and a concentration of 94.7 ppm. V is only found in one other playa, the Laguna de Patos, although there is well within average crustal values. The other enriched elements are Mo with an EFC score of 641 and a concentration of 54.3 ppm, Mo is only found in this sample; S with an EFC score of 778 and a concentration of 34250 ppm; As with EFC of 1287 and concentration of 218 ppm; Br with EFC of 2718 and concentration of 690 ppm; and Cl with EFC of 10913 and a concentration of 18.4 percent (figure 2.7).

These anomalous values are likely indicative of anthropogenic enrichment (pollution). The area surrounding this playa is widely used for agricultural purposes, and the region has had a long tradition as a major cotton producer. The runoff from some of these agricultural lands appears to reach this playa. Arsenic compounds known as organic arsenical herbicides are commonly used as herbicides and some of them are specifically targeted as cotton defoliants (EPA, 2009).
The playa of the Laguna Seca sits atop a wide-open basin, with a fairly flat surface. No major mountains are located immediately upwind from the playa. Vegetation is present in some areas but is mostly scarce. In the wet playa areas, vegetation is not present. The dry areas of the playa are used as transport route connecting the agricultural lands around the playa. The availability of abundant loose sand deposits within the playa area contributes to the erosion of the finer sediment surfaces including the efflorescent salts. These efflorescent salts can be easily deflated due to their fragile nature (Reynolds et al., 2007; Cahill et al., 1996). This scenario influences the potential of the playa to act as a dust producer. Only the thin crusting on some of the dry areas and the random vegetation cover acting as roughness elements help reduce the dust generation potential of the playa. For these reasons the playa areas of the Laguna Seca are classified with a medium to high potential for dust emissions, only restricted by the density of vegetation. Special attention is called to the possible transport of hazardous elements such as As when the efflorescent crusts are deflated. This area is directly upwind (SW) from the major urban areas of El Paso, Texas and Ciudad Juarez, Chihuahua.

Conclusions

Pleistocene Pluvial Lake Palomas is located in the Chihuahuan Desert near and generally upwind of the border towns of Ciudad Juarez (Mexico) and El Paso (USA). The sub-basins of PLP have just recently been described as major producers of mineral aerosols. The aerosols produced in this region are transported locally for tens to hundreds of kilometers, and in long-range transport high in the atmosphere for thousands of kilometers reaching as far as the northeast coast of the United States and Canada. The fine
<PM10 particles (particles with diameter less than 10 microns) produced from these areas can be of major concern for respiratory health related problems as well as to transport and infrastructure.

Pluvial Lake Palomas (PLP) could have inundated a surface of 7700 square kilometers by Wisconsinan time. At present time the PLP is divided into eight, mostly closed hydrological sub-basins and areas, represented by: The Laguna de Patos, the Bolson de los Muertos, the central area of PLP, the Rio Casas Grandes Valley (at Guadalupe Victoria area), the Laguna Guzman, Laguna el Fresnal, Laguna Santa Maria and Laguna Palomas. One external basin (Laguna Seca) in the area of Ascension, Chihuahua was also investigated. Conditions present in most of these basins and related playas can form the “perfect storm” scenario for the production of mineral aerosols derived from the playa surfaces and their margins.

The physiographic setting of these basins in the classic Basin and Range topography is a potential contributor to increase the aerosol production and emplacement into the atmosphere. Most of these basins elongate in a north-northwestern direction, maximizing the surface area exposed to the prevailing southwesterly winds. The majority of the basins are bounded by high mountains in their upwind side. These mountains are oriented perpendicular to the prevailing SW winds and might contribute to increased wind erosion of the playa surfaces by increasing the wind speed as the wind accelerates downward on the downwind side of the mountains due to the hydraulic jump effect.

Ground level conditions on most of these playas also form an important factor increasing the dust emission potential. Most playa surfaces are represented by large flat areas, with smooth surfaces containing none to very scarce vegetation in most cases. Other
types of non-erodible elements are also absent. The surface of most of these playas is
composed of a few centimeters thick crust of ped structures, greatly varying in size. The
bulk grain size composition of these peds is largely dominated by fine grain size sediments
in the clay and silt size range commonly forming over 90 percent by weight of the total
sediments in these peds, with clays accounting for up to 40 - 60 percent by weight of the
total. Below these peds loose fine sediments forming sand size aggregates are commonly
found. These aggregates are locked from aeolian deflation due to the capping action of the
peds. The ped structures by themselves are highly resistant to wind deflation, unless other
external and/or surface erosional elements contribute to the disruption and/or erosion of
these surfaces. During certain times of the year before the peak of the windy season in
early spring, some of the playas are covered by small, thin and brittle surface crusts formed
by very fine sediments (<10 µm). These crusts commonly curl upward surpassing the
laminar boundary layer at the soil surface, becoming exposed to the wind, and making
them available for aeolian transport.

The sediments forming the playa surfaces have a great potential as mineral aerosol
sources, although not by themselves. Most of the playas are bounded by almost unlimited
sources of sand and fine gravels derived from the contiguous alluvial fan and fluvial
deposits, and aeolian deposits such as extensive sand sheets, abundant nebkha fields and
other types of dunes. The sediments derived from these deposits are able to move across
the playas and their margins by saltation (only the sand fraction) and to a lesser degree by
creep (coarser sands and fine gravel), under high wind speeds. These sediments form
eroding agents dislodging the fine clays and silts in the ped structures and flakes by means
of sandblasting, sand bombardment and inter-flake collision mechanisms. Other
mechanical erosion mechanisms are also present in the area and contribute to the
disruption of the ped structures. Anthropogenic erosion in the form of vehicular transport,
and cattle are also commonly present in and around some of the playas (figure 2.15). Other
types of soft sediment crusts are also found in the marginal areas of certain playas. These
easily erodible crusts are formed by efflorescent salts, and get deflated with the windy
season's first strong winds.

Elemental concentrations of sediments in some of these playas might pose a serious
added concern to aerosols emplaced from these playas and their margins. Some
efflorescent crusts of these playas possess high concentrations of elements posing potential
health hazards for persons exposed to the deflated aerosols. High concentrations of As, Br,
Mo and V were found in the efflorescent salt crusts of one of the playas (Laguna Seca). This
playa sits directly downwind from the major urban area in the region, the Paso del Norte
border community (El Paso, Texas and Cd. Juarez, Chihuahua) approximately 150
kilometers to the northeast, and also from other major cities in Texas and possibly beyond.
High concentrations of Cl, As, S and Na are common throughout the playa sediments. These
elements when transported to different places might contribute to ecosystem degradation
by salinization.

This study intended to provide a preliminary assessment of the specific sedimentary
and geochemical characteristics of the sediments from the playas and their related margin
areas that form the mineral aerosol sources in the Pluvial Lake Palomas basin. Future
research in this area would include documentation of surface threshold velocities, detailed
clay mineralogical analyses, sediment geochemical signatures from REE and isotopes,
correlation of these aerosols with atmospheric samples collected downwind, and volumetric estimates of emplaced aerosols.

More extensive research in the area is required in order to fully understand the mechanisms contributing to dust generation and atmospheric emplacement of mineral aerosols in the region, including the different sediment sources outside the playas and their margins (e.g. alluvial and fluvial deposits). The continued research will in turn contribute to quantify and improve the numerical modeling of aerosol generation and distribution around the region and the globe, an aspect that is of prime necessity in a time of concern regarding climate change, where one of the greatest incognita is the precise behavior of mineral aerosols in the atmosphere.
References
Dominguez Acosta, M., Gill, T. E., Schmidt, R. H., Jr., 2006. The Lake Palomas – Samalayuca Dunes corridor system, Chihuahua, Mexico. Sixth International Conference on Aeolian Research, University of Guelph, Ontario Canada, program and abstracts, p. 80


INEGI (Instituto Nacional de Estadística, Geografía e Informática, México.), 1983. Carta Geológica (Geological Map), Ciudad Juárez, 1:250,000. Hoja (Sheet) H13-1


SPP (Secretaria de Programacion y Presupuesto, México), 1983. Carta Geológica (Geological Map), Casas Grandes, 1:250,000. Hoja (Sheet) H13-4


### Tables

#### Table 2.1. Sample inventory and descriptions.

<table>
<thead>
<tr>
<th>Playa/Area</th>
<th>Samples</th>
<th>Sediment Types</th>
<th>Remarks</th>
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<tr>
<td>Laguna De Patos</td>
<td>LDP 001</td>
<td>Ped structures</td>
<td>Hard ped with thinly-crusted up-curl ed flakes. (Figure 2.2)</td>
</tr>
<tr>
<td>Bolson de los Muertos / Southeast arm</td>
<td>SELP 001-010</td>
<td>Ped structures and playa margin deposits</td>
<td>Samples 001 thru 008 are from playa peds, Samples 009 and 010 are from margin deposits. (Figure 2.2)</td>
</tr>
<tr>
<td>Bolson de los Muertos / South-central area</td>
<td>CLP 001-002</td>
<td>Ped structures</td>
<td>Samples from merging area of SELP and SWLP. (Figure 2.2)</td>
</tr>
<tr>
<td>Bolson de los Muertos / Aeolian Corridor</td>
<td>COR 003, 005 and 006; BDM 002*</td>
<td>Ped structures</td>
<td>COR 005 and 006 from inner playa peds, COR 003 and BDM 002 from shoreline area. *2007 sample. (Figure 2.2)</td>
</tr>
<tr>
<td>Central Lake Palomas</td>
<td>HWYO2 001</td>
<td>Ped structures</td>
<td>Undifferentiated basin in central Lake Palomas. (Figure 2.25)</td>
</tr>
<tr>
<td>Rio Casas Grandes Basin / Guadalupe Victoria</td>
<td>GV 001 and 002</td>
<td>Crusted soil surface</td>
<td>GV 001 from agricultural land, GV 002 from undisturbed land. (Figure 2.30)</td>
</tr>
<tr>
<td>Laguna Guzman</td>
<td>LG 003 and 004*</td>
<td>Ped structures</td>
<td>*LG 004 sampled in 2007. (Figure 2.32)</td>
</tr>
<tr>
<td>Laguna Fresnal / Transition to Laguna Guzman</td>
<td>TLG 002 and 001*</td>
<td>Ped structures and margin deposits</td>
<td>TLG 001 sampled from playa margin, *2007 sample. (Figure 2.32)</td>
</tr>
<tr>
<td>Laguna El Fresnal</td>
<td>LF 001, LF Flakes and LF 004*</td>
<td>Ped structures and thinly-crusted up-curl ed flakes</td>
<td>LF 001 from ped structures, LF Flakes from thinly-crusted up-curl ed flakes and *LF 004 from ped structures, 2007 sample. (Figure 2.32)</td>
</tr>
<tr>
<td>Laguna Santa Maria</td>
<td>LSM 002* and 003*</td>
<td>Ped structures and margin deposits - efflorescent salts</td>
<td>LSM 003 from gravelly-salty crust, *2007 samples. (Figure 2.32)</td>
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<tr>
<td>Laguna Palomas</td>
<td>LPAL 005*</td>
<td>Stream sediments</td>
<td>Sample d from stream sediments ~2km away from playa surface, *2007 sample. (Figure 2.30)</td>
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<tr>
<td>Laguna Seca</td>
<td>ASC 001*, 002* and 003*</td>
<td>Ped structures, aggregates and efflorescent salt crust</td>
<td>ASC 001 from peds structures, ASC 002 from efflorescent crust and ASC 003 from clay aggregates, *2007 samples. (Figure 2.45)</td>
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Table 2.2. Major element mean concentrations from the Pluvial Lake Palomas samples. All concentrations in percentages, ± is the range between the maximum and minimum values, 0 value indicates there is only one sample.

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<tr>
<th>Playas</th>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
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<tr>
<td>LDP</td>
<td>2.0±0</td>
<td>2.8±0</td>
<td>8.0±0</td>
<td>25.8±0</td>
<td>2.8±0</td>
<td>5.9±0</td>
<td>0.3±0</td>
<td>0.06±0</td>
<td>4.18±0</td>
</tr>
<tr>
<td>SELP</td>
<td>4.02±0.99</td>
<td>1.6±0.26</td>
<td>3.59±1.19</td>
<td>22.76±4.45</td>
<td>2.30±0.68</td>
<td>5.91±5.8</td>
<td>0.30±0.04</td>
<td>0.05±0.02</td>
<td>2.26±0.73</td>
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<tr>
<td>CLP</td>
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<td>1.78±0.76</td>
<td>6.40±3.23</td>
<td>25±1.25</td>
<td>2.31±0.19</td>
<td>7.73±1.17</td>
<td>0.32±0.02</td>
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<td>2.46±0.53</td>
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<tr>
<td>COR</td>
<td>2.98±0.24</td>
<td>2.28±0.22</td>
<td>6.99±0.24</td>
<td>25.32±1.32</td>
<td>2.36±0.04</td>
<td>4.28±0.87</td>
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<tr>
<td>Tot BDM</td>
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<td>1.89</td>
<td>0.33</td>
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<tr>
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<td>9.04±0</td>
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<td>2.17±0</td>
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<tr>
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<td>0.46±0.05</td>
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<td>22.78±1.14</td>
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<td>2.83±0.04</td>
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<td>LG</td>
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<td>2.02±0.22</td>
<td>6.99±0.69</td>
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Table 2.3. Minor element mean concentrations from the Pluvial Lake Palomas samples. All concentrations in percentages, ± is the range between the maximum and minimum values, 0 value indicates there is only one sample.

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<th>Playas</th>
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<td>18±0</td>
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<td>87±8</td>
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<td>12±0</td>
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<td>629±77</td>
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Figure 2.1. General location of Pluvial Lake Palomas, its sub-basins and general areas prone to mineral aerosol emissions. Red dots indicate general sampling localities within each sub-basin and or area. Approximate coordinates: Southeastermost area, north 30° 45’ 04.4”, west 106° 35’ 52.6”; Southwestermost area, north 30° 40’ 31.4”, west 106° 57’ 50.1”; Central-westernmost area, north 31° 33’ 37.1”, west 107° 48’ 22.2”; Northernmost area, north 32° 13’ 20.2”, west 107° 29’ 26.5”.

Figures
Figure 2.2. General location of the Laguna de Patos, Bolson de los Muertos, and surrounding major physiographic features. C-LN, Cerros la Nopalera; S-MP, Sierra el Malpais; L-SM, Laguna Santa Maria; SW arm, southwestern arm of the Bolson de los Muertos; SE arm, southeastern arm of the Bolson de los Muertos; S-CA, Sierra de la Candelaria; S-SI, Sierra San Ignacio; S-BL, Sierra Banco Lucero; S-LN, Sierra la Nariz; S-SB, Sierra San Blas; S-LM, Sierra los Muertos; S-SA, Sierra de Samalayuca. Center of the image approximately at: north 30° 57’ 31.1”, west 106° 51’ 28.2”. 
Figure 2.3. Laguna de Patos and the surrounding sand sheet covered by mesquite (*Prosopis* sp.) anchored nebkha dunes.
Figure 2.4. Playa surface of the Laguna de Patos, surface is flat, barren and covered by desiccation polygon structures. Vehicle tracks in the middle of the image and very small dust plume in the far center of the image.
Figure 2.5. Thinly crusted up-curved flakes on the Laguna de Patos.
Figure 2.6. Sample LDP 001 granulometry.
Figure 2.7. Enrichment factor coefficients (EFC) related to aluminum. Values calculated according to equation 1. Only elements with scores above 10 for one or more of the playas are shown. Numbers indicate EFC values out of the presented scale.
Figure 2.8. Image looking east into the shoreline area of the Bolson de los Muertos. The image depicts the margin between the lacustrine sediments, the shoreline, and the sand sheet deposits. The approximately 3 meters of relief from the playa surface to the sand sheet are caused by the El Camello fault escarpment, which runs from north to south along the eastern margin of the Pluvial Lake Palomas (PLP).
Figure 2.9. MODIS (Moderate Resolution Imaging Spectroradiometer) Aqua image from August 7 2006. The image displays band combination 721, which highlights inundated or high humidity areas in turquoise color. Deeper standing water is displayed in darker blue-purplish color. Notice that regardless of the large inundation resulting from the >100 year return period rains, the area does not inundate homogeneously and deeper water is retained near the fluvial inlets in the playa. Center of the image approximately located at: north 30° 59’ 49.3”, west 106° 42’ 31.7”.
Figure 2.10. Easternmost marginal area of the southeast arm area of the Bolson de los Muertos. Fine and medium gravelly deposits resembling Gobi type surfaces. Sediments derived from interaction of alluvial fans and playa deposits.
Figure 2.11. Sand deposits from the shoreline beach of the Bolson de los Muertos at the aeolian corridor area.
Figure 2.12. Playa surface of the southeast arm area of the Bolson de los Muertos. Surface is flat, barren and free of any roughness elements. Ped structures dominate the landscape of the playa. Sierra Banco Lucero in the background.
Figure 2.13. Disturbed ped structures exposing loose sand size, clay and silt aggregates easily deflated once exposed.
Figure 2.14. Loose sand size, clay and silt aggregates traveling on top of the playa surface. In this case they are accumulated on the windward side of small grass bunches.
Figure 2.15. Cattle going across a playa surface, an example of mechanical erosion along with vehicular transport.
Figure 2.16. Thinly crusted up-curved flakes atop ped structures.
Figure 2.17. PLP area of the Bolson de Los Muertos at the Rancho El Sancho. This area of the corridor appears to be a recurrent inundation area during prolonged rain events. After the intense rains that occurred intermittently during the summer of 2006 through the end of the year, the area retained water for several months at a time.
Figure 2.18. Area of “puffy” sediments at the central-eastern shoreline of the Bolson de los Muertos. Vehicle in the image could not be driven across the surface due to sinking of upper crust and the wetness of the substrate. Image captured in April 2007.
Figure 2.19. Granulometric distributions of samples SELP 001 (top), SELP 002 (middle) and SELP 003 (bottom).
Figure 2.20. Granulometric distributions of SELP samples, from top to bottom, SELP 004 (top), 005, 006, 007, and 008 (bottom).
Figure 2.21. Granulometric distributions of samples SELP 009 (top), and SELP 010 (bottom).
Figure 2.22. Granulometric distributions of samples CLP 001 (top), and CLP 002 (bottom).
Figure 2.23. Comparative granulometric distributions of samples BDM 002 (Red), and COR 003 (Green).
Figure 2.24. Major dust plume (November 27, 2005) generated from the Bolson de los Muertos and surrounding playas and fluvial deposits. Main plumes originating from SW arm area, SE arm area and the fluvial deposits of the Rio Del Carmen (Image from MODIS satellite Terra). Center of the image approximately at: north 31° 05’ 33.27”, west 106° 21’ 44.6”. 
Figure 2.25. Location of the central area of the Pluvial Lake Palomas and major physiographic features (ASTER image). Center of the image approximately at: north 31° 29' 44.1", west 107° 16’ 15.4".
Figure 2.26. Desert pavement surface in the central Lake Palomas area, caused by deflation of the fluvial deltaic deposits of the Rio Casas Grandes.
Figure 2.27. Vegetated area of the Central Lake Palomas. This image is from 2007 after the heavy rains of 2006. During 2006 prior to the rains this area was visited and sampled (HWY02 001) and at this time no vegetation was observed.
Figure 2.28. Granulometric distribution of sample HWY02 001 from the Central Pluvial Lake Palomas.
Figure 2.29. Dust storm generated near highway 02 at the western margin of the Central Pluvial Lake Palomas, notice the drop in topography created from the El Camello fault escarpment.
Figure 2.30. Location of the Rio Casas Grandes Valley at Guadalupe Victoria and the Laguna Palomas (ASTER image). Center of the image approximately at: north 31° 35’ 22.5”, west 107° 34’ 32.2”.
Figure 2.31. Granulometric distributions of samples GV 001 (top), and GV 002 (bottom).
Figure 2.32. Location of the Laguna Guzman, the TLG area, Laguna El Fresnal and Laguna Santa Maria, along with the major physiographical features of the area (ASTER image). L-GZ, Laguna Guzman; TLG, Trans- Laguna Guzman; L-F, Laguna El Fresnal; L-SM Laguna Santa Maria. Center of the image approximately at: north 31° 04′ 27.3″, west 107° 23′ 52.1″.
Figure 2.33. Playa surface of the Laguna Guzman.
Figure 2.34. Ped structures overlain by easily deflated, very thin crusts of fine clayey material.
Figure 2.35. Comparative granulometric distribution of LG 003 (Green-2006) and LG 004 (Red-2007) samples.
Figure 2.36. Comparative granulometric distribution of TLG 002 (Green-2006) and TLG 001 (Red-2007) samples.
Figure 2.37. Playa surface of Laguna El Fresnal during the year 2006 (top) with water present in the distance, and during the year 2007 (bottom) with the water line approximately 800 meters from where it was the prior year.
Figure 2.38. Playa surface of the Laguna El Fresnal (top) covered by thinly crusted clayey flakes forming cylinders as shown in the close up image (bottom).
Figure 2.39. Granulometric distribution of samples from Laguna El Fresnal. On top a comparative graph of samples LF 004 (red – 2007) and LF 001 (green - 2006). On the bottom the granulometry of the thinly crusted flakes.
Figure 2.40. Dry margins of the Laguna Santa Maria, margins display ped structures in some cases with thin crust atop the peds. These areas are flat and barren.
Figure 2.41. Gravelly deposits and efflorescent salts contiguous and upslope from the ped surface, not yet in the alluvial deposits.
Figure 2.42. Thin crusted curled flakes on top of peds at the Laguna Santa Maria.
Figure 2.43. Granulometry of the Laguna Santa Maria samples. LSM 002 (top) a gravelly crust with efflorescent salts, LSM 003 (bottom) ped structures.
Figure 2.44. Granulometric distribution of Laguna Palomas sample LPAL 005.
Figure 2.45. Google Earth image displaying the location of the Laguna Seca (southeast of Ascension). Laguna Seca is the only playa included in this study which is not part of the Pluvial Lake Palomas Basin. Center of the image approximately at: north 31° 03’ 11.3”, west 107° 52’ 17.8”. 
Figure 2.46. Thin ped structures atop un-fragmented substrate in Laguna Seca. These peds represent sample ASC 001.
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Figure 2.50. Efflorescent salt crusts at the water line contact, these sediments represent sample ASC 002.
Figure 2.51. Granulometric distributions for samples ASC 001 (top), ASC 002 (middle) and ASC 003 (bottom).
CHAPTER 3
The Pluvial Lake Palomas – Samalayuca Dunes Aeolian Corridor, Northern Chihuahua, Mexico

Abstract

Pleistocene Pluvial Lake Palomas (PLP) is connected to the Samalayuca Dunes (SMD) field by an aeolian sediment corridor extending over 45 kilometers in an easterly direction. This aeolian corridor system is located in the central Chihuahuan Desert approximately 45 kilometers south of the Ciudad Juarez, Chihuahua, Mexico – El Paso, Texas, USA metropolitan area. Mineral aerosols emplaced from these areas are responsible for frequent air quality violations in western Texas, northern Chihuahua and far beyond, making it one of the principal sources of aeolian dust in the Chihuahuan Desert. The geomorphology of the corridor displays a varied arrangement of forms progressing downwind along with the sediment genesis from the lacustrine environment of the PLP to the depositional dune forms of the SMD field. These forms include from west to east along the downwind transport direction: playa surfaces dominated by polygonal desiccation peds, a shoreline environment displaying “puffy” efflorescent crusts and beach sand deposits, a series of barchan dunes and barchanoid ridges, parabolic dunes, a very extensive sand sheet underlying all geoforms, a series of widely distributed nebkha (coppice) fields, scattered deflationary pans and localized small playas, and the complex dune forms of the Samalayuca Dunes field represented by interference pattern straight crested dunes, star dunes, megastar dunes and relict transverse ridges. A progressional geomorphic, granulometric, and geochemical description of the sedimentary forms of the
Palomas-Samalayuca aeolian corridor system is presented, following their genesis from source to depocenter at the base of the Sierra del Presidio and Sierra de Samalayuca. ASTER and Landsat remote sensing data correlate the spectral signatures across the aeolian corridor. Granulometric analyses obtained using a laser particle sizer display a complex distribution of sediment grain size representative of the dual (lacustrine and aeolian) nature of the sediment sources for the corridor. Geochemical (elemental) data obtained using PIXE analysis and statistical analysis of the data reveal a good correlation of elemental concentrations between samples of similar geomorphic affinities, as well as a dual trend of elemental concentrations with downwind transport. Elements derived from resistant minerals (e.g. Si) are enriched downwind while easily degraded elements are deflated upwind before ever reaching the sediment depocenter at the Samalayuca Dunes.

**Introduction**

Pluvial Lake Palomas (PLP) is connected to the Samalayuca Dunes (SMD) by a heterogeneous geomorphic and sedimentologic aeolian corridor where lacustrine and aeolian sediments are transported from their source at the PLP to their depocenter at the SMD (figure 3.1). This aeolian corridor extends downwind for over 45 kilometers following aeolian sediment transport and genesis from source to depositional site. The system is located in the north central Chihuahuan Desert, about 65 kilometers (to the center of the corridor) due south from the Ciudad Juarez, Chihuahua (Mex) – El Paso, Texas (USA) metroplex area (figure 3.1). The region is characterized by an arid climate with high temperatures reaching up to ~40 °C during the summer months from June thru September and low temperatures dropping below the freezing point during the winter months.
Precipitation in the region is limited and usually restricted to the monsoonal rains occurring during the hot summer months. Regional prevailing winds are from the W and SW with a wind direction change over the winter months to more NW winds. These types of conditions are typical of the central Chihuahuan desert (Schmidt, 1994).

The PLP-SMD corridor system is among the few aeolian corridors that have been described. Examples of aeolian corridors include: in North America, corridors in the Mojave desert - Kelso dunes field (Kocurek, et. al., 1999), the Algodones dunes field (Derickson, et. al., 2007), globally the largest corridor system located in the Sahel - Saharan desert (the largest aeolian dust producer in the world) (Bristow, 2005; Moreno, et. al., 2006) and the Hexi corridor in China (major producer of long range transported dust to North America) (Xunming, et. al., 2007).

Paleo-lacustrine and modern aeolian sediments deposited at the shorelines of the Pleistocene (post-Kansan) Pluvial Lake Palomas (Reeves, 1969; Hawley, 1993; Kennedy and Hawley, 2003) are transported through the connecting corridor to the Samalayuca Dunes in a west to east direction following the predominant wind direction. Lacustrine PLP sediments were deposited in a structural basin of the Basin and Range physiographic province during large pluvial and fluvial events dating back to past glacial maximums when PLP could have inundated a closed basin surface of up to 7700 square kilometers during Wisconsinan time (Reeves, 1969; Hawley, 1993; Kennedy and Hawley, 2003).

The bulk of the coarser aeolian sand fraction of the sediments (the Samalayuca Dunes) stops approximately ~4 kilometers before reaching orographic barriers at the base of the Sierra de Samalayuca and Sierra del Presidio (Dominguez and Langford, 2008). These two
orographic barriers are oriented perpendicular to the prevailing wind direction and rise almost 600 meters from the surrounding basin surfaces, increasing their effectiveness as aeolian barriers (INEGI, 1983) (figure 3.2).

The finer sediment fraction clays and silts (<PM10, particulate matter less than 10 microns in diameter) derived from the corridor and its members are likely entrained to the atmosphere as mineral aerosols and transported from a few kilometers locally to thousands of kilometers at a larger scale, reaching as far as Canada (Prospero, et. al., 2002; Gill, et. al., 2006; Rivera Rivera, et. al., 2006; Lee, et. al., 2009). These <PM10 sediments usually contribute to air quality violations in the Paso del Norte metropolitan area (El Paso, TX and Ciudad Juarez, Chih) and can cause major infrastructure and transportation hazards as well as health (respiratory) illnesses to the people frequently exposed (Gill, et. al., 2007; Novlan, et al., 2007; Rivera Rivera, et al., 2009).

The progressional transport of sediments is indicated by the presence of distinct geomorphological features. These features include from source to depositional site: The playa (lacustrine) surfaces and shoreline deposits where sediment structures are found in the form of playa peds (polygonal desiccation structures) (figure 3.3A), shoreline sandy peds (figure 3.3B), shoreline “puffy” efflorescent crusted surfaces (figure 3.3C) and sandy beach deposits (figure 3.3D). Gobi type deposits are found at the boundary between the playa and the surrounding fluvial and alluvial deposits (figure 3.3E). An extensive sand sheet is found throughout the corridor (figure 3.3F). Barchan and barchanoid ridge sand dunes are located adjacent to the western corridor margin (figure 3.3G). Parabolic dunes are distributed along the western margin of the corridor (figure 3.3H). Nebkhas or coppice dunes (figure 3.3I) are widely distributed throughout the corridor especially the central
and eastern parts except in the two corridor end members (the playa surface and the Samalayuca Dunes). Deflated surfaces or pans are scattered throughout the corridor forming interdune areas and exposing older fluvial and alluvial deposits of the Bolson de los Muertos (figure 3.3J). Finally, the major dune forms of the Samalayuca Dunes include straight crested perpendicular interference pattern dunes (figure 3.3K), megastar dunes or draas, and large relict transverse ridges (figure 3.3L).

These classes are described and characterized based on their geomorphological classification affinity obtained by field and remote sensing descriptions of the different geoforms. Other analysis utilized for description is granulometry, which was obtained for 15+ samples distributed along the corridor corresponding to the distinct geomorphic classes present. Elemental geochemical analyses of these samples were also obtained by means of particle induced X-ray emission (PIXE) methods (Dominguez and Gill, 2007) and are used to classify and assess the geochemical relation among samples pertaining to the different geoforms.

The size and mass load of transported sediments makes this corridor and important sedimentomorphic feature of the area. Characterization of the PLP - SMD aeolian corridor provides a unique chance to integrally describe this aeolian system inside the Chihuahuan desert for the first time and at the same time classify the dust (mineral aerosols) producing potential of each individual geoform.
Methods

Remote sensing procedures

Preliminary assessment of the corridor system and its geomorphic classes was conducted by remote sensing methods. A series of high-resolution (30 meter pixel) ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images were analyzed in order to have a first look into the system. Digital image enhancing techniques were applied to remotely sensed level 2 atmospherically corrected ASTER data using commercial software ENVI ®. The applied processes were performed in order to generate an initial recognition and spatial description of the different geomorphological and sedimentological characteristics of the targeted areas. Three distinct target areas were selected on the basis of sediment provenance; first the sediment source corresponding to the lacustrine sediments of the Pluvial Lake Palomas (PLP), second the Samalayuca Dunes (SMD) forming the sediment depocenter and last the area corresponding to the connecting aeolian corridor. These areas posed an increased level of image processing and characterization difficulty, because the corridor end members (lacustrine and dunes) appear as extremely bright reflectors in the targeted ASTER images (figure 3.4). As a result, non-processed images hardly display any differences between these areas, wrongfully suggesting that they might possess homogeneous sedimentary compositions. Similarities are even carried out to the spectral signatures between the lacustrine and aeolian sediments where no major spectral differences are noticed (figure 3.5). Different approaches for image manipulation were tested including band combinations, unsupervised and supervised classification, principal component analysis and the use of
established geological indexes. Results were varied with the supervised classification and
the integration of three geological indices resulting in the best image aid for corridor
geomorphic classification (figures 3.6 and 3.7).

The supervised classification technique was performed utilizing spectral signatures for
the three target areas, lacustrine, aeolian and corridor deposits. These signatures were
acquired from field samples utilizing a spectroradiometer in controlled laboratory
conditions. A minimum distance mechanism was utilized as classification procedure (figure
3.5 and 3.6).

Development of a sediment index was obtained by the application of three different
geological indices, which relate to the physical characteristics of the target areas. Indices
used were aimed to aid in the identification of saline deposits and clayey sediments related
to the lacustrine deposits of the PLP and help identify the presence of vegetation in the
corridor. With the identification of these elements the aeolian component of the corridor
would be distinguishable from the lacustrine one.

The first index was derived from Landsat TM bands 4 and 5, which may used to map
Landsat TM bands 4 (0.76 - 0.90 µm) and 5 (1.55 - 1.75 µm) are spectrally analogous to the
ASTER bands 3 (0.76 - 0.86 µm) and 4 (1.60 - 1.70 µm) respectively. A weighted ratio of
these bands was calculated according to equation 1.

Equation 1

\[ \frac{(B3-B4)}{(B3+B4)} \]

where B3 and B4 correspond to ASTER bands 3 and 4 respectively.

The second index corresponds to the Normalized Difference Vegetation Index (NDVI),
commonly used to map vegetation. The NDVI is a modified ratio of the near infrared (0.7 -
1.3 µm) to the visible red (0.63 - 0.69) bands. These correspond to the wavelengths of bands 3 and 2 (0.63 - 0.69 µm) from ASTER. NDVI index is calculated from the weighted ratio of these bands according to equation 2.

\[
\text{Equation 2} \quad \frac{(B3-B2)}{B3+B2}
\]

The third index is a modified ratio from ASTER bands 4, 2 and 3, where clayey soils are displayed as bright reflectors in bands 4 and 2, while they are relatively obscured reflectors in band 3 (Kariuki, et al., 2006). This index was calculated according to equation 3.

\[
\text{Equation 3} \quad \frac{(B4+B2)}{B3}
\]

where B2, B3 and B4 correspond to ASTER bands 2, 3 and 4 respectively.

Three separate images were derived from each calculation. The collection of index images was incorporated into a single RGB image where the NDVI index was allocated to the red channel, the salinity index to the green channel and the last clay index was allocated to the blue channel (figure 3.7).

**Field geomorphic reconnaissance and sample acquisition**

With targeted areas selected from remote sensing results, several field campaigns for geomorphic descriptions and sampling were conducted during 2005 - to 2007. Detailed ground based descriptions of the different geoforms were performed (see geomorphic classes below). During this period a total of 17 samples corresponding to 10 different geomorphic classes were collected and described (table 3.1 and figures 3.2 and 3.3).

Loose sediment samples were collected from the surface upper two centimeters utilizing a plastic spatula creating a wedge and taking care to only sample from the front of the wedge. Semiconsolidated samples (peds) were sampled as whole pieces with care not
to disturb the original sediment strata and upper fine crusts (in some cases). Samples were collected in sealable plastic sampling bags, location and identification of each sample were marked on the plastic bag with indelible ink, and coordinates were recorded utilizing a handheld GPS unit. Samples were returned to the laboratory and allowed to air dry by opening the bags, then resealing them after drying. Samples were stored in the sealed bags in the laboratory except for when aliquots were removed for laboratory analyses.

**Granulometry procedures**

An adaptation of standard methodologies for granulometric laser diffraction analysis were employed following suggested procedures from Zobeck (2004) and Sperazza, et. al., (2004). The general procedure consisted of separating and weighing approximately 2 grams of sample for very fine grained textures and 5 grams for sand rich samples in order to ensure proper obscuration of the laser beam. The sample was then poured into a plastic container containing a 5% solution of sodium hexametaphosphate to serve as dispersing agent. The plastic bottles were placed in an automatic shaker and dispersed overnight. After completing dispersion samples were analyzed utilizing the Hydro unit of a Malvern Mastersizer 2000 laser diffraction granulometer apparatus. Grain size plots were recorded for each of the samples. Random samples were analyzed more than once to ensure proper results. Calibration standards were also used during the analysis to ensure proper function of the Malvern Mastersizer.
Elemental analysis procedures (PIXE)

Elemental concentrations were determined by proton induced X-ray emission (PIXE) spectrometry. Samples were pulverized in a corundum mortar and pestle. An average of three to five grams of material was powdered for each sample and analyzed where sufficient amounts were available. An aliquot of approximately 0.2 to 1 g of each powdered sample was pelletized into a 2.5 cm disk between two Kapton films. PIXE analysis was performed by a General Ionex 4 MV tandem accelerator with a duoplasmatron. Data reduction was accomplished with a modified version of software developed at the University of Guelph (Campbell, et al., 1993). The accuracy of the analyses was verified using USA National Institute of Standards and Technology Standard Reference Material 2711, Montana II Soil, which was pelletized and analyzed under the same conditions during the same run.

Geochemical statistics

Elemental (PIXE) data was analyzed via descriptive statistics, correlation coefficients and analysis of clusters. Dendrograms were plotted in order to assess the geochemical affinity both among elements and suggested geomorphic classes in order to propose feasible geochemical signatures pertaining to the distinct geomorphic forms. Dendrograms were computed using the Pearson correlation and Ward’s method of amalgamation utilizing commercial software. A crustal enrichment factor (EFc) was calculated in order to assess the concentration of individual elements and compare them to crustal backgrounds as well as to establish any possibility of anthropogenic enrichment for some of the
geoforms. The EFc was referenced to aluminum using equation 4 and crustal reference values from Mason (1958).

\[ EFc = \frac{C_x/C_{Al}}{\text{sample}} / \left( \frac{C_x/C_{Al}}{\text{crust}} \right) \]

where EFc is the crustal enrichment factor referenced to aluminum. \(C_x\) is the concentration of an individual element in the sample and the crust respectively and \(C_{Al}\) is the concentration of aluminum in the sample and the crust.

**Results and discussion**

**Remote sensing analysis**

The supervised classification image (figure 3.6) resulted in the categorization of the three targeted sediment spectrums across the corridor (lacustrine, undifferentiated corridor sediments and major non-vegetated dunes). In the image the lacustrine component appears in a red color and overwhelmingly depicts the Pluvial Lake Palomas (PLP) margins (SW corner). Relatively small patches of red areas appear scattered throughout the corridor. A clear interpretation of the geomorphic class that these patches pertain is not clear, but there is a strong possibility that they might reflect deflated areas or localized hydrological sinks in the form of small playas where finer (clay-silt) sediments are accumulated or exposed.

The major component of the image is depicted in blue and corresponds to the undifferentiated aeolian corridor sediments. These sediments are dominated by sand sheet deposits and nebkha (coppice) dunes (figure 3.6). This class is extensive in the area and throughout the region overlaying the surfaces of the surrounding basins (Langford, 2000).
The next component of the image is shown in green color, it strongly depicts the presence of non-vegetated sand dunes. This class shows a great result in outlining the two main bodies of the Samalayuca Dunes field (SMD), as well as the barchan and other sand dunes located parallel to the eastern PLP margin. According to this classification these sand deposits should be related, although elemental cluster analysis, geomorphic classification and granulometric analysis show that these sediments are in fact different. The reason for this discrepancy is probably due to a main difference between these two classes (at large scale), which is the presence of vegetation for the sand sheet and nebkhas (blue) and its absence in the major dune forms (figure 3.6). Finally the unclassified areas appear in black color and they comprise the main mountains in the area including their associated coarser alluvium deposits.

The three individual monochromatic images generated from the sedimentological indices do a good job at classifying distinct areas across the corridor, although the depicted classes were not always consistent with the initially proposed ones. The proposed salinity index perfectly denoted the lacustrine and alluvial fan deposits as bright reflectors contrasting to the darker areas from the rest of the image, which include all the aeolian sediments, vegetation and bedrock (figure 3.8). The NDVI index darkened much of the targeted areas (as expected) and highlighted the vegetated portions of the image. From this image abundant vegetation can be depicted in specific areas of the corridor, mainly at the mountains and nebkha fields as well as in localized drainage systems flowing off the mountains; very little vegetation is shown in the lacustrine sediments (figure 3.9). All of these are areas where vegetation is expected. The NDVI index is important in order to factor out the vegetation signature from the rest of the targeted geomorphic features. The
image resulting from the proposed clay index did not successfully highlight the lacustrine deposits as expected (figure 3.10), instead it created the opposite effect from the salinity index. This unexpected result gives a contrasting approach between the two images (salinity and clay indices).

The RGB image that includes the three sedimentological indices displays a greater variability of geomorphic classes as described in the geomorphic classification (figure 3.7). This diversity represents a more realistic approach to the composite nature of the corridor system. The resulting image is able to clearly discern the two end members of the system (lacustrine sediments and sand dunes), and at the same time differentiate features in the middle segment of the corridor. Vegetated areas in the mountains, alluvial fans and fluvial drainages are also well distinguished. The lacustrine sediments of the PLP appear in a bright green and yellowish color along with the alluvial fans derived from the nearby mountains. Non-vegetated sand deposits of the Samalaya Dunes field and the other major dune forms near western margin of the corridor appear in tones of blue. Sand sheet deposits and nebkha fields are displayed in color ranging from purple to dark pinks. As mentioned before this signature is consistent with the presence of vegetation. Mountain areas present a higher presence of pink colors in their flanks while the ridges are displayed in a more dark purple color.

**Geomorphic Classes**

**Lacustrine playa surfaces**

The lacustrine playa surface sediments are for the most part free of vegetation and present in the form of polygonal desiccation structures (peds) (figure 3.3A and 3.3B). These
peds dominate the surface of the playa away from the shoreline. Ped surfaces are commonly desiccation-cracked for the dry season, conditions that last most of the year except for the summer months from July through September when monsoonal rains are frequent (figure 3.11). During the rainy season sediment recharge to the periphery and selected areas of the playas might occur if the rains are strong enough to cause sediment transport from the nearby alluvial areas. Widespread recharge to the entire playa surface caused by long-range fluvial transport is almost negligible or restricted to the small inlet deltas receiving sediments carried only by short traveled water flow. The lack of strong long-range sediment recharge to the playas is due in part to the ephemeral nature of the main streams discharging into the basin (Rio Santa Maria and Rio Del Carmen). Added to this effect, pluvial events are commonly not strong enough to cause water/sediment to travel all the way from the distant sources to reach the playa surface. Arid climate, long dry seasons, prolonged drought periods, water diversion for agriculture and highly permeable surfaces are also contributors enhancing the extreme rarity of large-scale water/sediment recharge to cover the entire playa surfaces (figure 3.12).

Ped structures at the surface average only a couple centimeters thickness, although they can greatly vary in size. Below these peds loose fine sediments forming sand size aggregates are commonly found. These aggregates are locked from aeolian deflation due to the capping action of the peds unless they are disturbed by mechanical weathering mechanisms such as precipitation, animals, humans and vehicles (common in the area). Figure 3.3B displays a ped area, with a possible small area disturbed by cattle. Before the windy season peaking in the early spring (Novlan, et al., 2007), these peds contain small, thin and brittle surface crusts formed by very fine sediments (<6 μm). These crusts
commonly curl upward surpassing the laminar boundary layer at the soil surface, becoming exposed to the wind, and making them available for aeolian transport (figure 3.3A) (Nicholson 1988). The collision between the wind transported surface crusts, the dislodged sand size aggregates from underneath them, and the erosion caused by sandblasting are common causes contributing to the dislodgement of fine aerosols from otherwise deflation resistant playa surfaces (Cahill, et. al., 1996; Gill, 1996; Gillette, 1999).

**Shoreline deposits**

Lacustrine shoreline sediments at the western corridor margin cover an area of a few tens of meters lakeward away from the boundary between the alluvial-sand sheet deposits and the flat playa surface. A fraction of the sediments eroding from this area are transported by aeolian action downwind into the corridor. The remainder of the shoreline sediments are accumulated in the shoreline at the El Camello fault escarpment (Reeves, 1969), which delineates the eastern margin of the PLP. The topographical relief caused by the escarpment reaches a maximum height of 3 meters from the lower playa surface. This relief helps to trap some of the eroding coarser sediments from the shoreline beach area. At the same time the relief may contribute to the erosion and deposition of coarser sediment (fine gravel) from the escarpment alluvial and fluvial deposits into the shoreline area (figure 3.13).

The shoreline area of the corridor along with other sub areas of the PLP have been recognized as a frequent source for mineral aerosols derived from the PLP basin (Prospero, et. al., 2002; Gill, et. al., 2006; Rivera Rivera, et. al., 2006, 2009; Gill, et. al., 2007; Lee, et. al., 2009). The heterogeneous mixture of sediments ranging from clays and silts to fine gravel,
along with the presence of efflorescent salt rich surfaces form prime conditions for the aerosol generation (figures 3.3B, 3.3C, 3.3D, 3.3E). This is enhanced by the non-limited supply availability of fine sediment (<20 µm) fractions that form the bulk of the aerosols emplaced into the atmosphere (Gillette and Chen, 2001). Crusted surfaces such as these resist wind erosion to a greater extent compared to other non-crusted desert surfaces (Cahill, et. al., 1996; Gill, 1996; Gillette, 1999), but in this case several specific factors contribute to the frequent generation of aerosols in the area. Among these factors are: the absence of non-erodible elements in the flat, barren, vegetation free playa surfaces; the presence of thin, loose and brittle crusts that curl-up and form atop the ped structures and loose fine sediments; the availability of loose sand acting as an abrading or sandblasting agent; the presence of very fragile easily erodible “puffy” surfaces; and anthropogenic disturbance (ranching activity) in the area.

The corridor’s shoreline sediments can be divided into three distinct categories based on their sediment texture and granulometry.

**Shoreline sandy peds**

The first category and more distal from shore (westward) consist of sandy clay-silt rich desiccation polygons (peds) morphologically similar to the inner playa peds (figure 3.3B). These desiccation polygon structures sit in area of the corridor that is commonly inundated during major monsoonal rain events, thus recharging the fine sediment load more often than their distant counterparts towards the center of the playa. The frequent (yearly except for drought periods) inundation of the shoreline area also causes the accumulation of evaporite salts, which contribute to the softening of the ped crusts facilitating their
deflation once dried. These peds possess a greater fraction of sands compared to their inner playa counterparts (see granulometric description). This coarsening of the sediments is related to their spatial location next to the lacustrine beach, which possesses major sand accumulations. The same spatial relation with the sand sheet and alluvial surfaces exposed by the escarpment increases the presence of coarse material and its inclusion in the peds. Another factor contributing to the coarsening of these peds is that they are located at the downwind margin of the playa, thus receiving a vast amount of the saltating fraction eroded from the upwind margin and all across the playa surface.

**Efflorescent salt surfaces**

A “puffy” (Reynolds, et. al., 2007) crust composed of efflorescent salts and a heterogeneous mixture of clastic sediments forms the second category. These sediments heterogeneous grain size distribution includes the presence of fine gravel clasts and an almost equal concentration of sand and clay-silt sediments plus efflorescent salts (figure 3.3C). This combination makes these surfaces extremely soft and easily erodible by wind, as has been demonstrated at other playas (Cahill, et al., 1996). During the dry season walking on these sediments would cause the surface to break and sink a few centimeters. This type of textural arrangement is common of wet playas as described by Cahill, et al. (1996) and Reynolds, et. al. (2007), where fluctuation of a shallow ground water level (<5 meters) facilitates capillary rise of the groundwater accumulating percolated evaporite salts at the surface and creating a “puffy” texture crust. The Bolson de los Muertos (BDM) basin, as the western corridor member is known, covers the south central part of the Pluvial Lake Palomas (PLP) and is the largest of its sub-basins. The large extent of the
playa (basin) causes it to behave as a dry playa (following the classification scheme of Rosen, 1994) for most of its extension. One exception to this general behavior is the shoreline area of the corridor system, commonly inundated on a yearly basis for weeks and some times even months at a time (except during prolonged drought periods). An example of this occurred during the summer monsoon of 2006, which marked a \( \geq \) 100 year return period of extreme rainfall in the Chihuahua-Texas-New Mexico border region characterized by intense and frequent pluvial events (Gill et al., 2009). These rains caused a widespread inundation of the BDM basin. Almost 12 months after these rains some areas close to the shoreline still retained water (figures 3.11 and 3.12). No groundwater level record for the shoreline area is available, thus whether the shoreline of the Bolson de los Muertos behaves as a wet playa due to its ground water level is uncertain. A possible explanation is then the monsoonal inundations of the area, where long-standing excess runoff water contributes to the salt accumulation on these surfaces. The southeastern part of the PLP hosted an evaporite mining facility for several years called “Salinas la Union” (Reeves, 1969). Whether the salts mined from this area were deposited by modern monsoonal rains and high evaporation rates or represented paleo-deposits of a lake environment is unknown.

**Beach sand deposits**

The third textural category is comprised of loose and semi-consolidated beach sand deposits of the shoreline. These sands display traceable amounts of fine sediments (clays and fine silts) accumulating possibly as grain coatings due to the close relation to the playa
ped surfaces. These sand deposits are possibly the primordial sand source for the corridor (figure 3.3D).

Ostracod shells are found in the sediments forming all three shoreline textures with a higher concentration of shells found in the sandy shoreline deposits and diminishing away from the shoreline, both towards the center of the playa and into the corridor. At this point it is uncertain whether the ostracod shells are fossil remains or modern varieties. Very small (fine sand size) calcareous oolites are also found within these sediments specifically in the sandy deposits close to the shoreline.

**Stony deposits and deflated surfaces**

Sparsely distributed along the shoreline and the surrounding alluvial-sand sheet boundaries are stony (“Gobi” or “gibber”) type deposits where gravel size clasts are present loose on the surface or embedded in a clayey sand matrix (Cooke, 1970) (figure 3.3E). These deposits may be derived from the coarser sediment alluvial fans, which surround and underlay most areas of the corridor system. The alluvial sediments display gentle westerly sloping surfaces originating from the nearby mountains and bedrock outcrops. Aeolian deposits commonly overlay these alluvial fan surfaces. The alluvial fan deposits cap the Bolson de los Muertos (basin) fill, deposited by older alluvial and fluvial systems like the inflow of the ancestral Rio Grande during the late and middle Quaternary (Hawley and Kottlowski, 1969) and the rivers draining the highland watersheds bordering the northeastern Sierra Madre Occidental (the Casas Grandes River, Santa Maria River and Del Carmen River), along with the southern ranges of the Datil-Mogollon transition zone province drained by the Mimbres river (Hawley, 1993, Kennedy and Hawley, 2003). The
alluvial deposits are sparsely exposed along the corridor and are mainly only visible at the El Camello fault escarpment that forms the eastern margin of the PLP (Reeves, 1969) and in arroyo cuts and deflated surfaces forming localized flat low-lying desert playa surfaces. These surfaces are randomly distributed throughout the corridor and vary in size (area) from a few to several hundred square meters. Some of these deflated surfaces form the interdune areas for the major dune forms in the corridor (except the Samalayuca Dunes).

Sand Sheet

Sand sheet deposits form a distinct geomorphic feature in the corridor and are mainly composed of very fine to medium size sand fraction. This thin layer (<2 meters thick) of aeolian clastic sediments overlays the alluvial fan deposits in which the corridor system seats (figure 3.3F). The sand sheet is extensively distributed from the eastern margin of the Pluvial Lake Palomas (PLP) to the edges of the Samalayuca Dunes (SMD). This sand sheet serves as the base for other sand derived aeolian features found along the area and along with the deflated surfaces forms the growing base for most of the vegetation found in the corridor.

Major dune forms

Other distinct geomorphic forms in the corridor are represented by at least six types of sand dunes. These are distributed across the entire length of the corridor and are present in discrete areas dominated by only one or two dune forms, with the exception of nebkhas (coppice dunes), which are common throughout the corridor (Dominguez, et. al., 2006, Dominguez, et. al., 2008).
**Barchan and Barchanoid ridge dunes**

Following the aeolian transport path along the prevailing W-SW winds, the western area of the corridor near the margin of the PLP is host to a series of small discontinuous dune fields extending parallel to the shoreline (SSE-NNW) for an extension close to 35 kilometers (figure 3.6). These fields are found within the first three kilometers east from the shoreline. They are dominated by small to medium size barchan dunes reaching over 30 meters from horn to horn for some dunes and less than ~4.5 meters height, with horns oriented towards the east (figure 3.3G). In some of the dune fields where sediment supply is greater the barchan dunes evolved into barchanoid ridges transverse to the prevailing wind direction. Sediments forming these dunes are composed of light colored siliceous sands ranging from very fine sand to medium size and containing ostracod shells and calcareous oolites. In some areas these sediments appear to be the initial source of the next downwind geomorphic feature represented by parabolic dunes.

**Parabolic dunes**

The next dominant dune form is found from the shoreline and the barchan and barchanoid ridges, still in the western margin of the corridor. This form is composed of simple and compound parabolic dunes with dune noses “migrating” downwind in an easterly direction. These dunes appear to increase size with downwind transport. The smaller arm dunes (closer to shoreline) are present as simple forms with well-defined dune fronts and arms extending just over one kilometer in length. Some of these dunes might be considered as compound forms because some of the arms are shared between dunes. The
next downwind and larger parabolic dunes reach arm lengths up to 3.5 kilometers, all of them with due west to east arms alignment. Some of the parabolic dunes fronts (noses) have coalesced to form compound and complex dunes, effectively enlarging the size of the dune front (figure 3.3H). For one specific case the dune front, which extends for almost 3 kilometers (and about 900 meters wide) paralleling the shoreline may have transformed into a small dune field of barchanoid ridges with average lengths close to 100 meters.

**Nebkha dunes**

Nebkhas or coppice dunes, which are a characteristic landform of the Chihuahuan Desert (e.g. Buck et al. 1999; Langford, 2000; Rango et al., 2000) form one of the most abundant and widely distributed dune forms found throughout the corridor (figure 3.3I). These dunes dominate the central and eastern areas of the corridor (although not restricted to them) and are the more abundant dune form in the region overlaying the basin floors of the Mesilla Bolson, Hueco Bolson and the Bolson De Los Muertos (where the corridor seats). In regional areas of non-active sources and supply limited sediments, coppice dunes (as commonly referred in the region) are most likely derived from local sand sources formed by deflation surfaces where short distance traveled sand is trapped by vegetation as in the case of the coppice dunes of the Mesilla Bolson (Langford, 2000) just north of the corridor. The coppices in this corridor setting differ from this scenario, because the sand sources in the shoreline are active and transported across the corridor. Thus, depending on the location of the coppices or coppice fields, the major sources might be the shoreline deposits accompanied by the extensive sand sheet sediments and to a lesser degree the deflated surfaces scattered throughout the corridor. Coppice dunes vary
in size from a few tens of meters to dunes as tall as 3 meters above the surrounding sand sheet. These coppices are usually aggregated in groups of a few individuals resembling islands of coppices, or larger accumulations forming vast nebkha fields. The vegetation anchoring the coppices contributes to the accumulation of other sediment size fractions besides sand. Such is the case of clay and silts, which are trapped by vegetation and possibly accumulated as sand grain coatings (Bullard, et. al., 2007).

**Samalayuca Dunes**

The Samalayuca Dunes form the aeolian depocenter of the corridor. These dunes form an extensive sand sea trapped in its transport path by the Sierra de Samalayuca and the Sierra del Presidio (Reeves, 1969; Schmidt and Marston, 1981; Dominguez, et. al. 2008). The Sierra de Samalayuca is composed by partially metamorphosed sedimentary rocks of uncertain age and the Sierra del Presidio is formed by Cretaceous carbonate rocks (INEGI, 1983). These two barriers prevent the bulk of the sand deposits to continue their easterly migration (figure 3.2). A mountain pass is found at the southern part of the Sierra del Presidio where some sand does escape to the Bandejas Basin. The Samalayuca Dunes extend close to 30 kilometers in a SSE to NNW direction with a width of 14 kilometers in an E to W direction for the main body of sand. A second and smaller sand body is found WNW of the main body, extending almost 9 kilometers in a NW direction and reaching approximately 3.5 kilometers width in a NE direction (figures 3.1 and 3.2).
Straight crested dunes

Three main dune forms comprise the Samalayuca dune field. The first, youngest, most abundant and widely distributed is a perpendicular interference pattern of straight crested dunes (figure 3.3K). These dunes are composed by one set of long (few kilometers) dunes oriented from north to south and a second set of shorter (<200 meters) transverse dunes oriented from west to east. The crest of the NS dunes commonly faces towards east reflecting the sand transport from the prevailing wind direction (W-SW), while the crest of the WE dunes varies facing direction from north to south and are commonly rounded instead of sharp indicating the variable secondary wind directions, blowing from the north and south (Schmidt and Marston, 1981). Where the interference pattern forms an “in-line” arrangement of the E-W dunes on both sides of a larger N-S dune, a four-armed star pattern dune forms, and in some areas a true star dune forms if the accumulation of sand is increased, although these patterns are distributed throughout the field, true star dunes are not as abundant (Dominguez, et. al. 2008).

Megastar dunes

The second and older dune form is composed of megastar dunes or draas, which occur as separate dunes reworking the easternmost relict transverse dune ridge. This ridge forms a complex dune arrangement and is oriented SSE to NNW. The megastar dunes are commonly formed by a main crest oriented roughly NS and intersected by several auxiliary or secondary crests at oblique angles from it (figure 3.3L). The main crest may extend for up to one kilometer, while the secondary crests will reach close to half a kilometer length. Megastar dunes increase in overall size and complexity from south to north. Along with
some superimposed reversing dunes, the megastar dunes form the highest dune forms in the field surpassing ~120 meters from the surrounding interdune areas (Dominguez, et. al. 2008).

**Relict transverse dunes**

The last and oldest dune type is formed by the remnants of a series of very large transverse ridges, which form the “skeleton” of the dune field. These ridges extend for lengths that may reach up to 15 kilometers (at the center of the field) and are oriented in a general NNW direction fanning out from the south. They are separated at an average distance of 1 kilometer and are approximately 50 meters tall underlying all the other dune forms in the field (Dominguez, et. al., 2008).

**Granulometric Analysis**

The overall distributions of sediment grain size fractions across the corridor are controlled by the sediment’s deposition, erosion, transport and atmospheric emplacement mechanisms acting on the particles from source to depocenter along the corridor. Grain size distribution of sediments range from clay to medium sands and rarely to coarse sand, with the presence of fine gravel clasts in some specific surfaces. These gravels were noted and described in the field, but are not accounted for in the following granulometric description due to analytical limitations of the utilized equipment, which has a maximum grain size limit of 2 mm. Regardless of this limitation the bulk of the sediments falls well below the 2 mm limit, with the only exception of the already noted scarce fine gravel clasts found in the shoreline area of the corridor.
Playa surfaces

Finer sediments formed by clay and silt fractions dominate the playa surfaces with only minor amounts of fine sand present. These sediments represent the graded settling of the suspended load at the lacustrine depocenter in very low energy conditions. COR 005 and 006 samples correspond to regular playa peds (figures 3.2 and 3.3A). The grain size distribution for these samples is similar between them (figure 3.14A and 3.14B), where the clay fraction reaches up to 72 percent by weight in COR 006 and 55 percent in COR 005. The silt fraction is present in similar weight percentages for both, comprising almost one third of the total weight. The fine sand fraction is also present in both, although it makes a ten percent contribution to COR 005 and only ~2 percent for COR 006. The two samples display a trimodal distribution with the main peaks centered at about 1.6 μm for both. A second peak present in both samples and with similar reach is centered at the silt fraction at about 15 μm. The third peak lays in the fine sand fraction at about 110 μm and as reflected in the weight percent is much smaller for COR 006 (figure 3.14B). This fine sand peak is the main difference between the two samples, which otherwise possess similar sediment distributions. Both samples have a mean grain size in the clay fraction, below 4 μm (3.8 and 1.8 μm for COR 005 and 006 respectively), with a standard deviation of 2.7 and 2.1 respectively. This classifies them as very poorly sorted (VPS) (Folk, 1974) sediments. These differences imply that even within a specific geomorphic class, sediment distribution may not be entirely homogeneous, instead the large areas covered by these playas give rise to varied sediment distributions representative of local factors (e.g. preferred location or distance from recharge sites and/or local topographical differences). As discussed above,
this sediment distribution dominated by clays and silts (~90 percent by weight and more) generates an increased potential for atmospheric mineral aerosol emission as is demonstrated by the frequency and regularity of dust emissions from these playas (Rivera Rivera, et. al., 2006; Gill, et. al., 2007; Lee, et. al., 2009). Dust generation potential is enhanced (or permitted) by the presence of coarser erodible agents such as sand, found both encrusted within the fine sediments and loose at the margins of the playas, which can saltate and aid in grinding, suspending and “sandblasting” the finer materials (Shao and Raupach, 1993; Cahill et al., 1996).

**Shoreline deposits**

Shoreline deposits are dominated by heterogeneous mixtures of sediment sizes, where silt and fine to medium sand make up the bulk of the sediment fraction with a diminished amount of clay and the presence of coarser sand and fine gravel clasts especially closer to the shoreline margin. COR 002, 003 and 004 samples correspond to shoreline deposits (figures 3.3B, 3.3C and 3.3D). The three textures of the shoreline are classified in the same geomorphic category due to their spatial relation, regardless of some granulometric and elemental distinctions among them. These differences arise from their close relation the other contiguous geomorphic classes either upwind or downwind from the shoreline. The upwind shoreline sediments located at the playa surface, display strong resemblance to their regular playa ped counterparts. While the “puffy” sediments, which are also seated in the playa surface closer to the beach, display similar sediment size distributions, the presence of salts apparently precludes the formation of clear ped structures. The downwind beach sediments are not directly seated in the playa surface, but are adjacent to
it. This spatial location differentiates them significantly in grain size distribution and elemental concentrations from their upwind shoreline counterparts, due to the distinct geomorphic setting they are found on (beach environment) and their closer relation to the sand sheet and alluvial sediments downwind.

**Shoreline sandy peds**

Sample COR 003 is the westernmost sample from the shoreline approximately 30 meters away from the playa-beach boundary (figure 3.3B). It is described as a sandy ped sample due to the increased silt and sand fractions in the sample, compared to the regular playa ped samples (COR 005 and 006). The bulk size fraction for this sediment lays in the silt size reaching 50 percent by weight, while the clay and fine sand fraction reach 23 and 26 percent respectively. The mean grain size reaches 14 µm in the fine silt size with a standard deviation of 2.6 classifying it as very poorly sorted sediment (VPS) (Folk, 1974).

Similarly to the other ped samples (005 and 006), COR 003 displays a trimodal distribution, only this sample as a whole is skewed towards the coarser sizes. The largest and most abundant fraction of sediment peaks at 150 µm in the fine sand size. The second largest peak is centered at 25 µm, while the smallest one lies at 1.5 µm (figure 3.15B).

**Efflorescent salt crusts**

Sample COR 002 is located at the playa-beach boundary and represents the “puffy” surfaces (figure 3.3C). It is composed of a soft, thin crust with presence of fine gravel clasts. This sample exhibits a “diffuse” trimodal distribution where the finer fraction (clay <4 µm) is present, although it does not exhibit a single clear peak, it still comprises up to 32
percent by weight of the total sample. This fraction is tightly clustered to the silt fraction, which comprises the bulk of the sample (similar to COR 003) reaching 54 percent by weight. The last size fraction present is the fine sand and represents 14 percent by weight. The sample grain sizes range from .2 µm to 400 µm, similarly to sample COR 003, with a mean of 7.9 µm and a standard deviation of 2.48 classifying the sample as VPS sediments (Folk, 1974). The largest peak is centered about 15 µm and along with the finer fraction forms the bulk of the sample. The second peak is centered close to 120 µm in the fine sand fraction, while the last very broad peak is centered at about 2 µm (figure 3.15A). These grain sizes represent only the clastic granulometry for this sample, because the ionic efflorescent salt fraction of the sample was put in to solution by the dispersing procedure implemented to analyze the sample.

**Beach deposits**

Sample COR 004 represents the sandy beach deposits (figure 3.3D). This sample displays a bimodal distribution ranging from 0.3 µm to 800 µm making it the sample with the largest range distribution and the one containing the coarsest sediments (excluding gravel size) from the entire corridor system (figure 3.15C). The bulk of the sample is found at the fine sand fraction making up 76 percent of the total sample by weight, with a peak centered at ~180 µm. The silt and clay fractions are present in smaller percentages and grouped into a very broad peak, with the silt fraction comprising 19 percent and the clay fraction comprising only a 4.4 percent by weight. This sample has a mean grain size distribution at 71 µm, with a standard deviation of 1.6 classifying it as a poorly sorted sample (PS) (Folk, 1974). This grain size distribution is indicative of the geomorphic
environment in which the sample is present. A considerable amount of sands, especially the coarser fractions (up to ~800 µm) are accumulated and retained at the beach margin by the “El Camello” fault escarpment, which creates a barrier up to 3 meters high (figure 3.13). The immediate presence of finer material upwind from the beach (peds and efflorescent crusts) supplies the finer material that forms the tail in figure 3.15C. The apparent small concentration of fine material in this sample is counterintuitive to the vast supply of fine material adjacent to it. This relation might be explained by the sand’s texture, which is unconsolidated and trapped in the escarpment (to a certain degree). This scenario promotes the sand inter-grain collisions (sand blasting) dislodging the finer material clays, silts and fine sands, thus making them available for aeolian transport downwind on to the corridor and emplacing the finest sediments in to the atmosphere (Gomes, et. al., 1990).

Shoreline deposits in this area have been identified by remote sensing means to be a recurrent and major mineral aerosol producer for the system (Gill, et. al., 2007). The presence of a non-supply limited source of fine materials (playa deposits) along with the equally non-supply limited availability of abrading agents (sand deposits) and the presence of the soft, easily erodible “puffy” areas, are conditions that converge to form the “perfect storm” for aerosol production and emplacement (Gillette, 1999).

**Deflated surfaces**

Two deflated surfaces (pans) were sampled and analyzed, samples COR 010 and 001 correspond to this category (figure 3.3J). These surfaces are composed by a heterogeneous mixture of sediment sizes ranging from clay to fine sand. The sediments found in these deflated surfaces possess a trimodal distribution with the main peak centered at
approximately 110 µm. The second peak is centered at ~18 µm, while the last and broader peak is centered at 3 µm, all of them for both samples (figure 3.16). COR 001 is slightly coarser than COR 010, with the bulk of the sediments in the fine sand comprising 43 percent by weight, while the same fraction in the other sample only comprises 22 percent. The silt sediment fraction comprises over 40 percent by weight for both samples, where COR 010 is enriched with 49 percent and COR 001 with 42 percent. Similarly to the fine sand, the samples are slightly different in the clay fraction where COR 010 is enriched with 27 percent, while COR 001 contains 14.5 percent. COR 010 is the upwind sample and has a mean of 12.3 µm with a standard deviation of 2.6. COR 001 located a few kilometers downwind from the later, has a mean of 28.9 µm with a standard deviation of 2.2. Both samples are classified as very poorly sorted, reflecting their alluvial nature and the presence of large amounts of loose sand size sediments around them. The sediment distribution of these surfaces allows for some potential mineral aerosol emission due to the fair concentration of fines and the presence of sand size erodible agents incrusted in the sediment surface and loose around them. These deflated surfaces commonly display a hardened substrate only able to generate dust emission by the mechanical erosion of the saltating load present in vast amounts.

**Sand sheet**

The widespread sand sheet deposits of the corridor are characterized by a heterogeneous unimodal sediment distribution, and are represented by COR samples 007, 009, 011 and 012 (figure 3.3F). These samples are tightly clustered between the fine sand and silt fractions, with the absence of the clay fraction in all of them. The fine sand fraction
(FS) forms the bulk of the sediments for these samples, ranging from 68 percent by weight to 86 percent. COR 007 (68.6 % FS) and 009 (68 % FS) are located upwind from samples COR 011 (86.3 % FS) and 012 (80 % FS), where a clear spatial relation is evident for this samples, with the corresponding silt fraction decreasing downwind. The two upwind samples contain 31 and 32 percent of silt by weight, while the downwind samples decrease in silt size sediments reaching 13 and 20 percent respectively (COR 011 and 012). The mean values for these sediments follow the downwind decrease of silts (probably through aeolian winnowing) with the upwind samples having smaller means of 77 and 75 µm respectively, compared to the downwind samples, which increase their mean to 98 and 90 µm respectively. Peaks for these samples are centered at ~160 µm for COR 007 and 009 and ~180 and 200 µm for COR 011 and 012 (figure 3.17). These samples are classified as moderately well sorted sediments with standard deviations ranging from 0.55 to 0.59. This sediment distribution is possibly due to the loss of fine fraction with transport across the corridor. The material could either be deposited in localized structures such as interdune areas, trapped by vegetation (barchans) or emplaced into the atmosphere as dust. The mobile nature of these sands is reflected in the absence of the clay fraction, where the inter-grain collisions would remove any trace of the clay size sediments.

**Major dune forms**

**Barchan and Barchanoid ridges**

The near shoreline barchan dunes and barchanoid ridges display a very homogeneous granulometry, with the fine sand size fraction forming the bulk of the sediments. Sample COR 008 exemplifies the granulometric distribution of a barchan dune. This sample
displays a well-sorted unimodal distribution ranging from 70 µm to 450 µm from very fine to medium sand size range. The fine sand makes up 82 percent by weight of the sediments, while the rest (~18 percent) falls in the silt size fraction. The mean sediment concentration is 85 µm and the peak is centered at ~180 µm (figure 3.18). The standard deviation of the sample is 0.48 thus the sample is classified as well sorted. The granulometric distribution and sorting of this sample is common for the sand samples in the corridor where the clay fraction is absent, with the exception of the nebkhas.

**Nebkhas**

The sediment grain size distribution this category is represented by a bimodal heterogeneous assemblage of sediments ranging from submicron size (~0.4 µm) clays to ~500 µm medium sands. The bulk of the sediments comprise fine and medium size sands reaching 79 percent for COR 013, 93 percent for COR 014, and 78 percent by weight for COR 015 (figure 3.19). The sediments’ silt fraction comprises up to 20 percent for COR 015 and 18 percent for COR 013, while COR 014 only reaches 3 percent. The finest grain size fraction (clay) is largest for COR 014 with 3.6 percent, while COR 013 contains 1.8 and COR 015 only comprises 1 percent. The mean is largest for COR 014 at 99 µm, while the mean for COR 013 and 015 is 84 µm and 81 µm respectively. The standard deviation is greater for COR 014 with 1.38 classifying it at the boundary between moderately sorted and poorly sorted, followed by COR 013 with 1.0 classified as poorly sorted and COR 015 with 0.75, classified as moderately sorted. Along with COR 004 (beach sand), the nebkhas are the only sand samples in the aeolian corridor which display a clear bimodal distribution dominated by a main sand peak followed by a small tail of fine clay and silt size sediments. This might
suggest a source relation between the two sediment types due to the similar size distribution, although the elemental analyses do not reflect this relation. A plausible explanation as mentioned in the geomorphic descriptions, is the capturing and adhesion of clay and silt size particles as coatings on the sand grains. The mechanisms would be different for both, where nebkhas might trap these fine sediments by the filtering action of the flora anchoring them (Ravi et al., 2007), while the beach sands will be constantly subjected to the fine sediment presence due to the very close spatial relation with them (lacustrine sediments on the playa surface).

**Samalayuca Dunes**

The sands of the Samalayuca dunes possess the most highly sorted sediments in the entire corridor. These sands range from 120 µm to 450 µm total grain size distribution. Both samples (SM 022A and SM 003B) are very tightly clustered with peaks at about 200 and 230 µm (figure 3.20). Fine sand makes the bulk of the sample with 99.8 percent by weight for sample SM 022A and 99.1 percent for sample SM 003B. The remainder 0.1 and 0.8 percent correspond to the silt fraction respectively. Both samples have a standard deviation of 0.38 with means at 121 µm and 109 µm respectively. They are classified as well sorted sediments even though the class break is at 0.35, so they are at the boundary with very well sorted sediments. This grain size distribution is evidence of the depocenter condition of the Samalayuca dunes for the sand fraction of the corridor sediments where the sand size sediments accumulated at the dunes have been transported the furthest and all the fines have been depleted. The minor difference in grain size distribution between

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these samples is due to the local geomorphic class of each one, where SM 022A pertains to a megastar dune or draa and SM 003B corresponds to a straight crested dune.

**Elemental analysis**

Mean elemental concentrations established for the distinct geomorphic forms are presented in figures 3.21 and 3.22. These figures are separated into major elements and minor elements. A total of 21 elements were detected (Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, S, Cl, Ni, Cu, Zn, Ga, As, Rb, Sr, Zr, Ba and Pb) and values are presented in percent for the major elements and parts per million (ppm) for the rest.

From the major elements group Si possesses the higher concentrations as expected for this type of clastic aeolian environment averaging close to 30 percent with maximum values reaching just over 40 percent for the major dune forms of the Samaluyuca Dunes field. This Si enrichment denotes the mature state of the sands that form these dunes largely depleted from other elements leaving the more surface stable Si (SiO$_2$) as the bulk constituent. The remainder elements on the major element group are present with averages well below 10 percent, where Al, Ca and Na exhibit the higher concentrations. Al is mainly concentrated in the playa and shoreline deposits, followed by the deflated surfaces. Interestingly these geoforms possess the finest grain sizes in the corridor. Ca and Na display a similar behavior, with the difference that Ca is higher in the deflated surfaces compared to the playa and shoreline deposits. This might be related to the formation of pedogenic calcic soils (caliche) found in desert soils of the corridor. The remainder elements from the major group (Mg, Ti, Mn, Fe and K) follow similar trends with higher concentrations at the playa, shoreline and deflated surfaces diminishing towards the
sediment depocenter (SMD) (figure 3.21). The concentrations of the major elements are well within crustal average values with EFc scores below five points (figure 3.23).

Cl and S dominate minor and trace element concentrations, with outlier values (exceeding 2σ from the mean) in two shoreline samples (COR 003 and 004) corresponding to the “puffy” and beach sand deposits. These samples greatly exceed chlorine and arsenic crustal average values with EFc scores above 10 and reaching a maximum of 94 points for Cl and 12 for As. In other circumstances these high EFc scores might indicate anthropogenic enrichment of the samples. In this instance the samples pertain to “puffy” surfaces with high efflorescent salt concentrations (see description above) thus the high EFc values might be adequate (Levy, et. al., 1997; Lupankwa, 2006). Another factor contributing a possible explanation is high mobility in solution of these elements, which get dissolved and accumulated by fluvial and groundwater transport until they reach the hydrological sinks represented by the playa areas. The rest of the minor and trace elements concentrations are well below the average crustal values with EFc scores below 5 points.

Besides Cl and As, S is the only other element that outstands in the EFc graph (figure 3.23), but their values remain below 10 EFc points. Cl values are higher for the shoreline deposits followed by the playa peds and deflated surfaces, and are not detected in the rest of the geomorphic forms. This circumstance reflects the concentration of salt related elements at the shoreline margin of the corridor where ground water discharge and/or the long-standing inundation of the surface contributes to the accumulation of such elements forming a wet playa scenario as described by Reynolds et. al. (2007). The absence of these elements in the rest of the corridor samples suggest the easy deflation of the “puffy” surfaces and their subsequent depletion in downwind sediments might reflect the null
transport along the corridor and in situ (shoreline) atmospheric emplacement of the very fine sediments containing these elements.

A comparison of elemental concentrations for the different samples pertaining to the same geomorphic categories displays similar values among them. This confirms that the proposed geoforms are for the most part geochemically homogeneous. The main exceptions are the shoreline samples, which do reflect some geochemical variations among them. Pb and Ba are the only elements absent in all of the shoreline samples. Ni, Cu, Ga, As and Zr were not detected in sample COR 004 corresponding to sandy beach deposits. As and Ni are also absent in the sandy ped sample (COR 003). These elements, Ni, Cu, Ga, As and Zr are all present in the “puffy” crust sample (COR 002). Cl and As (COR 002) are the only elements that display concentrations higher than average crustal values (figure 3.23). Cl displays the highest concentration in sample COR 004 (beach sand) with 10900 ppm compared to 7270 ppm in sample COR 003 (sandy ped) and 2130 ppm for sample COR 002 (“puffy” crust). As (15.7 ppm) is only present in the “puffy” sample (COR 002). Shoreline deposits are described as a heterogeneous mixture of sediments and diverse textural classes going from sandy peds to “puffy” crust to beach sands (see geomorphic classification above), a condition that is reflected (and expected) by the elemental variations displayed among these samples.

Elemental concentrations of the playa samples COR 005 and 006 are similar among them with values for the detected elements Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, Cl, Zn and Sr well within crustal averages (figure 3.23). Chlorine in sample COR 005 is the only exception with a concentration of 2080 ppm (EFC 12.2) compared to sample COR 006 with a concentration of 365 ppm. Sample COR 005 located closer to the center of the playa.
Sand sheet samples (COR 007, 009, 011 and 012) also display elemental concentration similarities among the detected elements (Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, Cu, Zn, Ga, As, Rb, Zr, Ba, Pb and S). Concentrations of these elements are all within crustal averages (figure 3.23). Elemental differences between these samples are only observed for a few elements. Ca is present in all samples, but its concentration displays a decrease along downwind transport from sample COR 007 (closest to shoreline) with a value of 5.7% to 1.4%, 1.2% and 0.8% for samples COR 009, 011 and 012 (furthest downwind sample) respectively. Sample COR 009 is the most distinct of all, with Cu (3.7 ppm) and S (487 ppm) present only in this sample. As is only present in downwind samples COR 011 (7.8 ppm) and COR 013 (8.2 ppm), while Pb (17.1 and 12.7 ppm) and Ba (795.7 and 708.5 ppm) are only present in the first two upwind samples COR 007 and 009.

Nebkha (coppice) dune samples (COR 013, 014 and 015) possess similar elemental concentrations for most of the detected elements, Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, S, Ni, Zn, Ga, As, Rb, Sr, Zr and Pb. Differences between samples are evidenced by S (262.2 ppm) and As (6.0 ppm) only present in the upwindmost sample COR 013. Ni (10.2 ppm) on the other hand is only present in sample COR 15. Pb (11.9 ppm) is present in samples COR 014 and 015 with very similar concentrations.

The major dune form samples are almost identical for the Samalayuca dune samples (SM022A and SM003B), and distinct with respect to the barchan (COR 008) sample located closer to the shoreline. Of the twenty-one analyzed elements, Cl, Ni, Cu and As are absent from all samples. The Samalayuca dunes samples differ only in the presence of S (290.9 ppm), detected in sample SM003B. Compared to the Samalayuca dune samples, the barchan dune sample COR 008 is depleted in Pb and S. This sample displays higher concentrations...
of Ca (3.7 %), Mn (173 ppm) and Sr (408 ppm) compared to the Samalayuca dune samples (Ca 0.2 and 0.3 %, Mn 56 and 52 ppm, and Sr 99 and 97 ppm respectively for SM022A and SM003B). The higher concentrations of these elements in the near shoreline sample (COR 008) are evidence of enriched carbonate components near the shoreline and their subsequent depletion with transport from source to depocenter at the Samalayuca dunes.

Elemental concentrations of the deflated surface samples (COR 010 and 001) are very similar among them. Ni, As and Ba are the only elements absent from these samples. The upwind sample COR 010 exhibits a slightly higher concentration of Cl (1100 ppm) and S (830.2 ppm) compared to COR 001 (Cl 296 ppm and S 439.9 ppm).

Associations among elements were obtained using cluster analysis. These analyses were performed utilizing individual elements and individual geoforms as separate variables in order to assess the affinity among elements and among geomorphic classes separately. Clusters resulting from elemental associations are related to the mineralogical signatures of the sediment parent rocks, while geomorphic clusters relate the affinity of the different samples to be grouped into specific geomorphic classes.

The elemental dendrogram (figure 3.24) plots 16 out of the 21 detected elements due to a software restriction on missing values for individual variables. Si, Ba, Pb, As and Ni are not displayed in figure 3.24. To overcome this problem several dendrograms were generated in order to establish a meaningful cluster representation. This dendrogram displays five clusters, although a sixth might be considered.

The first and most populated cluster is formed by the elements Na, Mg, Zn, Mn, Fe and Ti. This association is characteristic of mafic igneous rocks and some derived sedimentary rocks and sediment loads. These rock and sediment associations are
representative of lithologies commonly found throughout the corridor sediment source areas, mainly in the form of extensive and widely distributed extrusive igneous rocks (Tertiary basalt flows) and derived sediment load. The next cluster is formed by Al and K, elements commonly found in feldspars and other aluminosilicate minerals, constituents of silicate rocks common to the area and derived clay minerals which form the bulk of the lacustrine component of the corridor. Ca and Sr form the next cluster; both elements are common carbonate rock components such as limestone and dolomite. These elements also possess chemical similarities such as similar radii (one below the other in the periodic table) allowing for the possibility of Sr substituting for Ca in certain mineralogical ionic exchange (e.g. Apatite (strontium-apatite: (Sr, Ca)$_5$(PO$_4$)$_3$(F,OH)). The next cluster is formed by Cl and S which display a strong association common to some evaporite related minerals such as halite (NaCl) and mirabilite (Na$_2$SO$_4$) commonly found in continental evaporite deposits including wind-erodible playa sediments in the Basin and Range region derived from discharge of shallow saline groundwater, such as at Owens Lake (Levy et al., 1999; Gill et al., 2002). Some Cl salts also related to calcium (linked at a higher distance) are also common minerals found in desert playas. The next cluster is composed of Ga and Zr associated to Rb and Cu. This cluster accommodates most of the missing elements (Pb, Ni and As) when plotted in different dendrograms. This cluster is representative of metallic elements (except for As) and several ore related minerals associating As to Pb, Ni, Cu and Ga found in literature (Webminerals database, 2009).

The second dendrogram (figure 3.25) plots the individual samples forming clusters related to specific geomorphic categories. Linking distances for this dendrogram are significantly small reflecting the tight association between samples. Samples COR 005 and
006 form the first cluster, both samples being tightly linked and correspond to regular playa ped sediments. This cluster is in turn linked to the second cluster formed by samples COR 002 and 003, which represent the “puffy” crusts and sandy shoreline peds, two of the sediment textures found in the shoreline deposits. Samples COR 005, 006, 002 and 003 all are located in the lacustrine segment of the corridor and are all fine grain size. Samples COR 004 and 007 subsequently linked to 008 form the next cluster. Geomorphically these samples correspond to beach sand, sand sheet and barchan dunes deposits respectively. Their association displays an apparent conflict in geomorphic association. This can be explained by their closely related spatial location within a segment of less than 1.5 kilometers long. This close spatial relation is significantly strong to overprint the chemical geomorphic association seen for the other samples. Over this 1.5 kilometers length COR 004 is the upwind sample (source) closely related to the next downwind sand sheet sample COR 007 located less than half a kilometer from the first. These two are in turn located approximately one kilometer apart from the next downwind sample. The close spatial proximity of the samples restricts the chemical elements to be geomorphically sorted by distance traveled, leading to similar chemical signatures resulting in tight clustering. Corridor samples 010 and 001 form the next cluster. These two samples correspond to deflated surfaces. The next cluster is formed by COR samples 009, 011, 012 and 013 subsequently clustered to COR 014 and 015. The sub-cluster formed by samples 009, 011 and 012 corresponds to sand sheet deposits (along with sample 007), while the cluster formed by 014 and 015 correspond to nebkha samples. Sample 013 is described a nebkha sample, but it was collected at the bottom of the dune form near the contact with the surrounding sand sheet, hence the chemical association to the sand sheet samples. The
The close relation of these samples is also evidence of a tight chemical association between nebkhas and the sand sheet deposits that underlay them. The last cluster is formed by the two Samalayuca Dunes field samples, which form the closest linked cluster.

At the highest linking distances three general cluster signatures are evident (figure 3.25). The first and most distinct (more isolated) is represented by sand samples distant from the source (non-shoreline related). This cluster contains three of the sand sheet samples (COR 009, 011 and 012), the three nebkha samples (COR 013, 014 and 015) and the two Samalayuca dune samples (SM026A and SM 003B). These samples are all dominated by the sand fraction and form the downwindmost samples in the corridor. Clustering of these samples might be evidence of a chemical depletion of elements with transport across the corridor. One of the other two high distance clusters corresponds to shoreline related sand deposits (COR 004, 007 and 008), linked to the deflated surfaces (COR 010 and 001) samples. The first cluster is found with in the first 1.5 km away from the shoreline, while the second (deflated surfaces) exceeds these distance. Both of these clusters are linked to the lacustrine sediment cluster (COR 002, 003, 005 and 006) (figure 3.25). Except for the deflated surface cluster, which is found at a greater distance from the shoreline, all other samples are spatially related to the shoreline. With only a couple of exceptions (samples COR 009 and 001 out of order), the general distribution of samples and containing clusters across the dendrogram from left to right corresponds to the downwind distribution of sediments from source to depocenter. These associations depict a clear chemical signature for lacustrine related sediments and the loss of this signature as the sediment progresses downwind across the corridor.
Conclusions

An aeolian corridor extending approximately 45 kilometers in an easterly direction forms part of the Pluvial Lake Palomas – Samalayuca Dunes system. The corridor is located in the central Chihuahuan desert approximately 45 km south of Cd. Juarez Chih. Mexico – El Paso, Texas, USA. The aeolian corridor connects the mixed-size lacustrine sediments of Pleistocene Pluvial Lake Palomas to the sand size sediments’ depocenter at the Samalayuca dunes. The finer fraction (clays and fine silts) of sediments in the lacustrine deposits are eroded and deflated at the western margin of the corridor and eventually emplaced as mineral aerosols into the atmosphere and transported from a few up to thousands of kilometers downwind.

The geomorphology of the corridor is represented by (source) a heterogeneous mixture of lacustrine sediments including sandy and fine-grained peds, “puffy” efflorescent crusts and sandy beach deposits all pertaining to the shoreline environment. Localized stony (“Gobi”) type deposits are found at the margin of the lacustrine system, possibly derived from the erosional contact between the lacustrine and the alluvial deposits that underlay the corridor. The center part of the corridor is covered by a series of sandy landforms within an extensive sand sheet that forms the base for a series of dunes extending east downwind across the corridor. Nebkha fields are present in most of the corridor area forming the most common dune form in the region. Barchan dunes and barchanoid ridges form the westernmost dune types, followed by very large parabolic dunes. The transported sand accumulates in the Samalayuca Dunes field forming complex patterns of interfering
straight crested dunes, star dunes, megastar dunes and relict transverse ridges. Across the corridor the alluvial deposits are exposed in the form of deflationary pans or in arroyo cuts.

Samples from most of these geoforms were collected and analyzed in order to describe their granulometric and elemental compositions as they progressed downwind across the corridor. The sediment size distribution is tightly correlated among samples of similar geoforms, where playa peds are dominated by clay and silt sediment grain sizes, with small amounts of fine and medium sands forming the poorest sorted geoforms in the corridor. Downwind from the playa, the shoreline environment becomes sandier with the peds and “puffy” crusts still retaining small amounts of clays and silts. The beach sand deposits are dominated by sand size fractions with a small fine sediment tail formed by clays and silts (potentially representing a coating of fine sediments on the sand grains due to their close proximity with the playa surface). Across the center part of the corridor sediment sizes are dominated by sands, changing only slightly in grain size, sorting and shapes of the granulometric curves as they progress downwind towards the Samalayuca dunes. The Samalayuca dunes possess the best sorted sands of the system, a result of the sands’ mature state as they have reached their depocenter.

The nebkhas form the only exception to this trend: similarly to the beach deposits, they also display a small tail of fine (clay and fine silt) sediments. Differing from the beach deposits there are no major playa surfaces across the corridor (only a few small and isolated ones). Thus the fine tail of the nebkhas must have a different source. A likely explanation, as has been demonstrated elsewhere in the Chihuahuan Desert (Ravi et al., 2007) is the capturing of fine (clay and fine silt) materials in the nebkhas due to the trapping and filtering effect of the mesquite and other vegetation that anchors these dunes.
allowing the nutrient-richer fines to settle under the vegetation cover atop of the sands and eventually mixing with or forming a coating layer in the sand grains, creating a positive-feedback “island of fertility” in the nebkha in which the finer sediments are more hospitable for the growth of dust-trapping vegetation (Schlesinger et al., 1990).

The geochemical data and statistical analysis corroborate geomorphic and granulometric associations within and along the corridor. Samples pertaining to similar geomorphic classes are tightly clustered when their elemental concentrations are analyzed by cluster analysis. With the exception of three near shoreline samples (COR 004, 007 and 008) all other samples fall in to the corresponding cluster represented by the proposed geoform. Elemental concentrations across the corridor display two major tendencies along downwind transport. All analyzed elements display a decrease in concentration from source to depocenter exhibiting the deflation of sediments and mineral degradation caused by downwind transport. Si is the only element displaying an opposite trend, resulting from the enrichment of the element due to the resistate nature of quartz and its presence as the coarsest grains. Si (SiO$_2$) is accumulated in the sands of the Samalayuca dunes and forms the highest concentrated element in the corridor, with concentrations an order of magnitude greater compared to other elements. With the exception of Cl and As in a few shoreline samples, the concentration of all other elements in the corridor are well within crustal average values. No evident anthropogenic enrichment is evidenced in the field or in the literature for concentration of the shoreline samples. On the other hand, Cl and As possess a high mobility in solution, thus they tend to be concentrated in the hydrological sinks in this case represented by the shoreline deposits. Evidence of this is the wet playa
(Rosen, 1994) behavior of the shoreline, where efflorescent salt crusts are present possibly accumulating the Cl and As of the samples.

Several opportunities for future research are present in the corridor system, ranging from dune dynamics to detailed aerosol emission potential of each distinct geoform and detailed geochemical (REE and isotopic) fingerprinting of the corridor sediments in order to better assess sediment provenance and transport.
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### Table

Table 3.1. Sample inventory and descriptions

<table>
<thead>
<tr>
<th>Sample</th>
<th>Geomorphic class</th>
<th>Figure</th>
<th>Remarks</th>
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<td>COR-005</td>
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<td>Playa</td>
<td>3A</td>
<td>Regular playa ped sample</td>
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<td>3C</td>
<td>Soft “puffy” crust (efflorescent crust)</td>
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<td>Shoreline</td>
<td>3B</td>
<td>Sandy ped crust</td>
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<td>Shoreline</td>
<td>3D</td>
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<td>Barchan dune</td>
<td>3G</td>
<td>Near shoreline small dune fields</td>
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<td>Sand Sheet</td>
<td>3F</td>
<td>Sand sheet deposits</td>
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<td>Sand Sheet</td>
<td>3F</td>
<td>Sand sheet deposits</td>
</tr>
<tr>
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<td>Deflated surfaces</td>
<td>3J</td>
<td>Deflated surfaces</td>
</tr>
<tr>
<td>COR-010</td>
<td>Deflated surfaces</td>
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<td>Deflated surfaces</td>
</tr>
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<td>3I</td>
<td>Individual nebkha</td>
</tr>
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<td>Nebkhas</td>
<td>3I</td>
<td>Sample from nebkha cluster</td>
</tr>
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<td>Individual nebkha</td>
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<td>3K</td>
<td>Megastar dune</td>
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<td>SM-003B</td>
<td>Major Dunes</td>
<td>3L</td>
<td>Straight crested dune</td>
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Figure 3.1. General location of the Pluvial Lake Palomas – Samalayuca Dunes Corridor System. Center of the corridor at approximately located at: North 31° 13’ 33.34”; West 106° 42’ 06.09” (NASA satellite image viewer image).
Figure 3.2. Corridor sample locations and key physiographic features.
Figure 3.3. Geomorphic forms and sediment textures of the corridor system: A).- Regular playa peds of the Bolson de los Muertos; B).- Sandier peds located closer to the shoreline; C).- Soft crusted sediments with gravel clasts, “puffy” surface; D).- Shoreline beach sand deposits; E).- “Gobi” type deposits at the playa sand sheet margin; F).- Sand sheet deposits (notice in the background the two small nebkhas and the playa surface).
Figure 3.3 (continued). Geomorphic forms and sediment textures of the corridor system: G).- Barchan dunes and barchanoid ridges atop the sand sheet located near the western corridor margin; H).- Parabolic dunes in the upwind segment of the corridor (ASTER image); I).- Nebkha field, individual dunes are anchored by mesquite (*Prosopis sp.*) trees; J).- Deflated or barren surface cutting through and surrounded by sand sheet deposits; K).- Straight crested (NS) and large megastar dunes in the Samalayuca Dunes field; L).- Megastar dunes with radiating sinuous arms.
Figure 3.4. Unprocessed ASTER satellite image displaying the corridor system, notice the high reflectance displayed by the two end members (Pluvial Lake Palomas and Samalayuca Dunes sediments) and larger interior corridor dunes (parabolic).
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Figure 3.6. Supervised classification from a processed ASTER image. The selected regions of interest are: lacustrine sediments of PLP (red), aeolian sand deposits of SMD and scattered dunes subparallel to PLP shoreline (green) and undistinguished corridor sediments (blue).
Figure 3.7. Sedimentomorphic index. The image is derived from combination of three different geo-indexes. Clayey lacustrine component and fine alluvial sediments appear as green and yellow colors. The major dune forms of the SMD and those sub-parallel to the PLP shoreline appear as light blue pinkish and reddish color are combination of vegetation cover and nebkhas.
Figure 3.8. Salinity index. The image denotes the lacustrine and alluvial fan deposits as bright reflectors contrasting to the darker areas from the rest of the image, including all the aeolian sediments, vegetation and bedrock.
Figure 3.9. NDVI index (Normalized Difference Vegetation Index). The image depicts the presence of vegetation in fluvial channels, nebkhas fields and atop mountains. Scarce vegetation is also evident in small areas of the lacustrine sediments.
Figure 3.10. Proposed clay index. Originally oriented to highlight the fine lacustrine sediments, the image highlights the clastic (sand) sediments pertaining to the sand sheet and other sand deposits.
Figure 3.11. PLP area of the Bolson de Los Muertos at the Rancho El Sancho. This area of the corridor is recurrently inundated during prolonged rain events. After the intense rains that occurred intermittently during the summer of 2006 through the end of the year, the area retained water for several months at a time.
Figure 3.12. MODIS Aqua (Moderate Resolution Imaging Spectroradiometer) image from August 7 2006. The image displays band combination 7 2 1, which highlights inundated or high humidity areas in turquoise color. Deeper standing water is displayed in darker blue-purplish color. Notice that regardless of the large inundation resulting from the >100 year return period rains the area does not inundate homogeneously and deeper water is retained near the fluvial inlets in the playa.
Figure 3.13. Image looking east into the shoreline area of the Bolson de los Muertos. The image depicts the margin between the lacustrine sediments the shoreline and the sand sheet deposits. The approximately 3 meters of relief from the playa surface to the sand sheet are caused by the El Camello fault escarpment, which runs from north to south along the eastern margin of the Pluvial Lake Palomas (PLP).
Figure 3.14. Playa peds granulometric distribution. A).- COR-005 sample displaying a clear trimodal distribution dominated by fine (clay and silt) sediments with a small fraction of fine and medium sand present. B).- COR-006 sample with peaks at the same general size fractions as COR-005, but not as well defined. This sample is overall dominated by the fine size fraction, with very few sand.
Figure 3.15. Shoreline sediments granulometric distribution; A).- COR-002 shoreline “puffy” or efflorescent salt deposits. This sample displays a trimodal distribution dominated by silt and sand size sediments (soluble salts might have dissolved into solution due to the dispersing process utilized in the analysis, thus creating an underrepresentation of the size fraction). B).- COR-003 shoreline sandy ped deposits similarly to COR-002, displaying a trimodal distribution dominated by the sand and silt fractions. C).- COR-004 shoreline sandy beach deposits, dominated by sand fraction sediments, with a small trace (tail) of fine sediments evident in the clay and silt fraction sizes, possibly due to clay and silt coatings on the sand grains.
Figure 3.16. Deflated surfaces granulometric distribution. Sample COR-001 is representative of the two deflated surfaces samples collected in the corridor. These samples display a frequency distribution dominated by the fine and medium sand size fraction with a smaller peak at the silt size fraction extending into the clay fraction.
Figure 3.17. Sand sheet sediments granulometric distribution. Sample COR-007 is representative of all four sand sheet corridor samples. The distribution of the sand sheet sediments is unimodal with a single sharp peak located in the fine sand.
Figure 3.18. Barchan and barchanoid dunes sediment granulometric distribution. COR-008 represents the barchan dunes located almost adjacent and parallel to the eastern corridor margin. The sample displays a unimodal distribution with the peak located in the fine to medium sand size fraction similar to that of the sand sheet sediments.
Figure 3.19. Nebkha dunes sediment granulometric distribution. Sample COR-014 is representative of the nebkha dunes corridor samples. All three samples possess a grain size distribution dominated by a large peak in the fine to medium sand size fraction (slightly coarser than barchan and sand sheet grains) forming the bulk of the sample. A second very small peak is located in the clay and silt fractions forming a tail for the coarser peak. This tail of fine sediment might be due to the filtering effect of the nebkha vegetation, which would collect airborne fines (clays and silts) and settle them atop the sand grains as a clayey sand grain coat.
Figure 3.20. Samalayuca dunes (SMD) sediment granulometric distribution. Sample SM026A is displayed as representative of the SMD sand distribution. The sample displays a unimodal distribution with a sharp peak located in the fine to medium sand similar to the sand component of the nebkha sediment. The Samalayuca dunes samples are the best sorted samples in the corridor.
Figure 3.21. Major elemental mean concentration values obtained by means of PIXE (particle induced x-ray emission) analysis (Si values are scaled down by a factor of 10 for better graphical representation). Si is by far the most abundant and highest concentrated element in the corridor. Si is also the only element whose trend increases downwind towards the Samalayuca dunes; this is explained by the resistate and coarse nature of quartz and its subsequent accumulation in the SMD. The rest of the elements except for Ca display a constant decrease in concentration with transport downwind along the corridor. Ca is slightly enriched in the denudated soils, but then decreases again.
Figure 3.22. Minor elemental mean concentration values obtained by means of PIXE (particle induced x-ray emission) analysis (Cl values are scaled down by a factor of 10 for better graphical representation). Cl forms the highest concentrated minor element in the non-pure sand samples and its increased in the shoreline deposits. All elements display a decreasing tendency as they progress downwind across the corridor. Rb and Zr values remain fairly constant throughout the corridor. Ba and S values are not connected across the coppice dunes, because they were not detected in the samples.
Figure 3.23. Enrichment factor coefficients (related to Al) for the corridor samples (see table 1 for sample-geoform association). Cl and As are the only elements that have an enrichment factor >10, which might indicate irregular enrichment of these elements. The highest enrichment factors occur for playa related samples possibly explained by the high mobility in solution of these elements and resulting accumulation in the playas, which acts as hydrological sinks.
Figure 3.24. Dendrogram of elemental cluster analysis. Individual elemental concentrations are clustered to assess the affinity among variables. Five clusters are evident from this analysis with Mg, Zn, Mn, Fe and Ti forming the first cluster very tightly linked, along with Na linked at a greater distance. Al and K form the second cluster. The third cluster is formed by Ca and Sr and the fourth cluster is formed by Cl and S. The last cluster is formed by Ga, Zr, Rb and Cu.
Figure 3.25. Dendrogram of geoforms cluster analysis. Sample concentrations are clustered in order to assess the affinity among geomorphic forms. Six clusters are evidenced from this analysis. The first contains samples COR 005 and 006, both playa peds. The next cluster contains samples COR 002 and 003, both located at the shoreline and with high clay and silt concentrations. The next cluster is formed by samples COR 004, 007 and 008, which belong to different geoforms (beach, sand sheet and barchan dunes deposits). COR 10 and 001 form the next cluster and represent deflated surfaces. COR samples 009, 011, 012 and 013 form the next, where the samples 009, 011 and 012 belong to sand sheet deposits and 013 is a sample from the basal part of a nebkha close to the interdune area.

Samples 014 and 015 form the next cluster (also linked to the previous), also corresponding to nebkha samples. The last and tightest cluster is formed by the two Samalayuca dunes samples, SM026A and SM003B.
CHAPTER 4

Geomorphology of the Samalayuca Dunes, Northern Chihuahua, Mexico

Abstract

The Samalayuca Dunes are one of the largest and least studied sand seas of North America. They are located in northern Chihuahua, Mexico approximately 45 km south of El Paso, Texas and Cd. Juarez, Chihuahua on the USA-Mexico border. Sands that form these dunes are derived from the sandy shoreline deposits of Pleistocene Pluvial Lake Palomas and its successor playas in the Bolson de los Muertos. These sands are transported eastward across an aeolian corridor and accumulate as echo dunes upwind of the Sierra de Samalayuca and the Sierra del Presidio. Unlike other dune fields in the region (e.g. White Sands, NM), which are influenced by a unidirectional wind regime (mainly from the SW), the morphology of the Samalayuca Dunes is influenced by a complex wind regime, with effective winds from different directions, where the predominant direction is from the West-southwest accompanied by two other secondary directions, one from the North and the other from the South. This variation from the regional wind patterns (SW) may be due to the local topographic effects of the nearby mountains, which deflect and funnel the wind. Morphology of the active dunes is dominated by straight crested sets of dunes oriented almost perpendicular to each other with a general NS and EW crest orientations. These dunes are 4-5 m high with crests spaced at approximately 66 m for the NS trending crests and 53 m for the EW crests respectively. They were previously described as an “Akle” pattern, but are in fact a nearly perpendicular interference pattern. These active dunes are superimposed in a compound and complex arrangement on the remnants of much larger
north-northwest trending megadunes that fan-out from south to north-northwest within the dune field. These relict aeolian ridges are spaced at an average distance of 1 km and are approximately 50 m high. The easternmost ridge is an active set of at least 15 megastar (draas) and reversing dunes up to 120 m tall increasing in size and complexity from south to north. Northeast trending along crest flow is evident from the eroded topographic lows flanking these active dunes and is a major factor shaping these ridges.

**Introduction**

The Samalayuca Dunes (SMD) field is one of the most iconic and beautiful geologic landmarks of the Chihuahuan desert. Unfortunately they are also one of the largest and least studied sand seas of North America. The dunes of Samalayuca are located in northern Chihuahua, Mexico approximately 45 kilometers south of the USA-Mexico border (figure 4.1).

The first bibliographic record of the Samalayuca Dunes was compiled over 400 years ago, by Spaniard colonizers who first adventured through the region as they traveled north along the “Camino Real Paso del Norte” (Schmidt and Marston, 1981). Compared to its closest and widely described dune field of White Sands, NM in the USA (Langford 2002 and 2003, Kocurek 2007), some 150 km north of the SMD, the Samalayuca Dunes have had less than a handful of broad descriptions. The most detailed was by Schmidt, and Marston, 1981. Webb (1969) described the dunes as “nondescript piles of sand with irregular and inconsistent shapes” anchored by irregular bedrock outcrops buried underneath the sand. Reeves (1969) presented a brief mention of the dunes as the Pluvial Lake Palomas saltating fraction sediment depocenter. Schmidt and Marston (1981) proposed two distinct dune
morphologies, an extensive “agle” pattern and large “echo” dunes. Based on gravity and magnetic data, Schmidt and Marston proposed an aeolian controlled dune forming mechanism, instead of Webb’s basement control. Access to new high-resolution imagery and extended field observations have led to a new geomorphological and physical description of the SMD field.

The Samalayuca Dunes, excluding the extensive and largely vegetated surrounding sand sheet and nebkha fields (Dominguez, et. al., 2006.), covers an approximate area of 136.8 km$^2$. The field can be best described by separating it in two bodies of active dunes (figure 4.1). The main body of dunes is located the furthest downwind, adjacent to the Sierra del Presidio, and occupies an approximate area of 113.2 km$^2$. This field is elongate to the NNW, and is approximately 24 km long and 15 km at its widest point. The eastern (downwind) margin of the main body of dunes is parallel to the western (upwind) side of the Sierra del Presidio and maintains an almost constant distance of approximately 4 km from the active sand margin to the base of the mountain (figure 4.1). The second and smaller body of dunes is located upwind (west) from the main body adjacent to the Sierra de Samalayuca and occupies an approximate area of 23.6 km$^2$. The field is approximately 9 km long to the NNW direction and close to 6.5 km wide from west to east at its widest point. This western field maintains an approximate distance of 2 to 2.5 km from the downwind active sand margin to the southwestern margin of the Sierra de Samalayuca (figure 4.1).

The Samalayuca Dune Field sits atop a Late Tertiary extensional basin of the Basin and Range physiographic province, characterized by continuous NNW trending mountain ranges intercalated by flat low lying basins (Reeves, 1969., Hawley, et. al., 2000., Kennedy
and Hawley, 2003) The SMD field is flanked to the ENE by Cretaceous limestones of the Sierra del Presidio (~1870 m amsl) and partially metamorphosed sandstones of the Sierra de Samalayuca (~1750 m amsl) (age of these sediments is uncertain) (INEGI, 1983). Approximately 6 km to the south the SMD is flanked by a few small Quaternary basalts and Cretaceous limestone outcrops of the Cerros la Morita. Further south (~4 km) outcrop the Tertiary intrusives of the Cerros las Felipas and the Sierra las Conchas. Approximately 13 km south from the SMD is located the very prominent mountain range of the Sierra Candelaria (~1900 m amsl) formed by Tertiary granodiorites (INEGI, 1983). The sierras of Samalayuca, Presidio and Candelaria along with the above mentioned ranges form wind barriers responsible for the formation and shape of the Samalayuca Dunes (figure 4.1). Upwind (west) from the Samalayuca Dunes lies an aeolian corridor extending ~40 km downwind in an easterly direction (Dominguez, et. al., 2006). The aeolian corridor sits atop a gentle west-sloping surface formed by a series of alluvial fans and localized flat low lying desert playa surfaces. These surfaces are scattered throughout the corridor and only exposed along the cuts of ephemeral arroyos and within the playas themselves. Almost all of the corridor is covered by a thin (~3 m thick) sand sheet overlaid in most areas by extensive nebkha fields and scattered active dunes. The corridor dune forms include barchan and barchanoid ridges as well as parabolic dunes (Dominguez, et. al., 2006). The western margin of the corridor is defined by the boundary with the ~200 km long (NNW to SSE) and >27 km wide (E to W) Pleistocene Pluvial Lake Palomas (PLP) (Reeves, 1969; Kennedy and Hawley, 2003). These lacustrine shoreline sand deposits of the PLP are interpreted as the source sediments for the sand deposits across the corridor and the Samalayuca Dunes (Reeves, 1969; Schmidt and Marston, 1981; Dominguez and Gill, 2007).
Aeolian transport of sand across the corridor and into the dunes is locally achieved by the presence of a multi-directional wind pattern derived from the interaction of the prevailing regional wind direction from the SW and the (seasonal) variable wind directions from the north and south (Schmidt and Marston, 1981) (figure 4.2). The prevailing westerly wind vectors might be deflected upwind from the SMD as those vectors interact with the topographical highs created by the Sierras de Samalayuca and Candelaria. The northern Sierra de Samalayuca deflects the SW wind vectors curving them around it, while the southern Sierras de la Candelaria and Las Conchas will cause a similar wind deflection around them (figure 4.3). These wind vector deflections causes a funneling of the winds as they enter the SMD area, which might in fact be responsible for the non-linear (funnel shape) upwind shape of the field (figure 4.1). The Sierra del Presidio plays a prime role in the Samalayuca Dunes formation as sands accumulate close to the upwind side of the Sierra at a constant distance of approximately 4 km. This effect is achieved by the decrease in wind competence as wind rises in order to pass the range summit at ~1870 m amsl that forms the approximately 600 m of relief from the surrounding basin surface (~1250 m amsl) (INEGI, 1983). The Sierra del Presidio also plays an important role in the apparent symmetry or rectilinear form of the downwind SMD margin and the formation of some of the easternmost and larger dune forms in the field, by creating a reversing (eddy like) wind flow, which is deflected back from the NE towards the SMD (figure 4.3).

At the southernmost part of the field, the Sierra del Presidio exhibits two mountain passes where the range crest is at basin floor level. These passes known as Puerto el Sabinoso and Puerto Ancho (from north to south) serve as escape routes for the SMD sediments (figures 4.1 and 4.3). The exiting sediments accumulate downwind in the
Bandejas basin at the margin with the Bandejas arroyo. At this site the sands accumulate in a small ~5 km long (west to east) and ~1 to 1.5 km wide dune field. The sand accumulated at this site may then be transported downwind by aeolian action along the western-northern margin of the Sierra de San Ignacio (>1780 m amsl). Some of these sands are ultimately removed from the aeolian system and transported downstream by hydraulic action along the Arroyo de Las Bandejas ultimately reaching the southeast flowing Rio Grande/Bravo (figure 4.1).

Methods

Geomorphological parameters (crest-to-crest spacing and crest orientations) for the Samalayuca Dunes (SMD) were obtained with the use of new remote sensing imagery. These parameters are useful factors in classifying dune distributions within fields and as a means of comparison between dunes of different fields (Lancaster, 1988, Ewing, 2006). ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and Landsat imagery available from NASA at 30 m resolution was utilized to perform band combinations and observed field scale variations (figure 4.1). Quick Bird imagery publically available from Google Earth, with a high (sub-meter) resolution for the “true” color composite was utilized to classify small-scale features for the different dune types (figures 4.5 and 4.6). Google Earth georectified images and the program’s measuring capabilities were utilized to measure the physical parameters described (crest to crest spacing and length, area of the field and overall dimensions) (figure 4.4). Five east-to-west cross-sections across the field were plotted in order to measure the crest-to-crest spacing of the NS straight crested dunes. Similarly four NS cross sections were utilized to measure the
crest-to-crest spacing of the E-W trending dunes. The last and northernmost NS cross section was not measured due to the faint crest images of the EW dunes caused by the rounded nature of these crests, thus making correct measurement difficult. The area of the field was approximated by placing geometrical figures (parallelograms and triangles) of known dimensions across the field images (figure 4.4). Common software (Excel) was utilized to compute and plot statistical measurements for crest-to-crest spacing frequency distributions. Rockware software (Rock Works) was utilized to plot wind rose diagrams of the digitized crest orientations and calculate standard statistics. A total of 3115 crest segments were digitized for the roughly NS and EW oriented dune patterns.

Satellite data was ground truthed and the northern, western and southern areas of the dunes were visited and sampled. A loop across the northern segment of the field, approximately 10 km long, led to the acquisition of topographical cross sections using a handheld GPS device. Data was analyzed by the GPS proprietary software. All five common forms of dunes found in the SMD were visited in the field and described.

**Geomorphology and Physical parameters**

The Samalayuca Dunes exhibit a complex interrelation of at least five different dune forms. These dunes are created and maintained by the topographical and atmospheric (wind directions) conditions present in and around the field. Each of the individual forms interacts in a compound and/or complex manner with the other forms. Compound forms occur when a specific type of dune interacts with similar forms to create a larger dune. Complex dunes form through interaction of different dune forms. These relations are exemplified when a dune form is overlaid by one or more different dune forms both
geomorphically and chronologically (Lancaster, 1995; Kocurek, et. al., 2005; Ewing, et. al., 2006). The Samalayuca dunes contain both compound and compound/complex dune forms.

Sets of perpendicular straight crested dune patterns dominate the field surface. These dune patterns display a dominant north-south oriented dune set interlaced by a secondary and shorter east-west dune set (figure 4.5). Scattered throughout the field where the right straight crested dune patterns coalesce in an “aligned” position a four to five-armed star dune pattern emerges (figure 4.6). Across the main body of dunes the presence of a set of five very large and older, transverse dunes forms the “skeleton” of the field and serves as base for the complex interaction of these dunes and the other forms (figure 4.7). The eastern area of the field is dominated by the tallest of all dune forms in the SMD, a NNW chain of multi-arm mega star dunes (draas) rising over 120 m from the surrounding interdune areas, seated atop in a complex interrelation with the relict transverse dunes and climbing straight crested dunes (figure 4.8).

**North to south straight crested dunes**

The N-S straight crested dunes form the most common and widespread dune form in the Samalayuca Dunes field (SMD) (figure 4.5). These dunes, which resemble “crescentic ridges” from Lancaster, (1995) or “transverse ridges” from McKee (1979), display a clear and sharp crest oriented NS with a well defined and short brink and avalanche face commonly facing east.

These type of dunes are common throughout the world’s sand seas and constitute the dominant forms in several large scale dune fields such as the Thar Desert, the Takla
Makan, and Tengger sand seas (in Asia); and the Jafurah, Nafud and parts of the Rub’ al Khali (in Saudi Arabia and the northern Saharan Desert) (Fryberger, et. al., 1981). In North America, they range from very wide spread to common in most sand seas (Lancaster, 1995) including those in the Chihuahuan Desert (White Sands, NM and Samalayuca Dunes, Chih.).

The orientation of the dunes and their crest are a response to the local westerly prevailing winds (Schmidt and Marston, 1981). These straight crested dunes reach heights of approximately 5-7 m from the surrounding interdune areas and vary in length across the field. The longest continuous dunes occur mainly in the northern segment of the main body of dunes, reaching up to 1.5 km long. Dunes in the eastern and southern segment of the (main) field might be as short as ~160 m, but the average dune length reaches up to 500 m in length. Dune defects in the forms of tuning forks are common in the field and represent normal dune response to variations in the wind patterns (Beveridge, et. al., 2006). A total of 286 crest-to-crest spaces were measured in five different EW cross sections (figure 4.4). The crest-to-crest spacing averages 66 m and the maximum and minimum lengths reached 124 and 22 m respectively with a standard deviation of 17 m (figure 4.9).

The straight crested dunes both NS and EW form the topmost and smaller form of dunes in the SMD. These dunes are the youngest features in the field and respond to the seasonal changes in wind directions and atmospheric conditions. These active dunes are superimposed atop larger and older dunes, with which they form compound and complex dune relations (Kocurek, et. al. 2005; Beveridge, et. al. 2006; Ewing, et. al. 2006). The NS straight crested dunes, when atop the transverse (NNW oriented) relict dunes form a compound relation with them (figure 4.6). Both forms are generally transverse to the prevailing westerly winds even though they operate and respond in very different scales of
time and magnitude. These same dunes appear as climbing dunes atop the mega star dunes (draas), in this case forming a complex relation with them due to the effect of the very large star dunes on local wind patterns. When either of these compound or complex relations occurs the NS dune orientation is slightly shifted as the dunes start to climb atop the larger forms (figure 4.10). The crests are deflected from their original NS patterns to more NNE on the upwind side of the larger structures and NNW on the downwind side of the underlying dunes. The average crest-to-crest spacing also increases as these dunes interact more closely with the larger forms.

**East to west straight crested dunes**

The east to west straight crested dunes are oriented transverse to the secondary local wind regimes from the north and south (figure 4.11, figure 4.12). A distinct characteristic of these dunes in response to the bidirectional and opposite winds is the lack in some cases of well-defined and sharp crests. This is exemplified by the presence of rounded dune tops with absence of brink and avalanche faces (figure 4.11). In other cases the crest of these dunes will have a sharp crest with brink and avalanche face facing either north or south as a result of a recent strong wind. Similar to the conjugate NS dunes, the EW dunes reach heights up to approximately 5 m from their interdune areas. The length of these dunes varies across the field where the longest dunes reach lengths of ~225 m while the smaller ones will reach approximately 50 m. The average length of these dunes is 66 m corresponding with the average crest to crest spacing of the NS conjugate dunes. The maximum lengths for these dunes are reached when two or more EW crests intersect across one or more NS dunes, giving the appearance of a single and extended dune crest.
generally aligned EW. The crest-to-crest spacing of 194 dunes was measured across three NS cross sections oriented perpendicular to the general dune orientations. The crest-to-crest spacing of these dunes averages 53 m with maximum measured at 102 m and a minimum of approximately 26 m, with a standard deviation of 14 m (figure 4.13). Similarly to the NS dunes the EW crest to crest spacing and crest orientations increase and are deflected as these dunes interact closer with other larger underlying forms.

Throughout the field the EW and NS dune intersections occur in two different ways. One of these occurs as a crossing, “in-line” pattern where contiguous EW crests on both sides of a NS ridge are aligned and extend across the NS ridge without apparent deflection, creating the appearance of a single continuous and longer EW crest. An area containing several pairs of these NS and EW intersections will form rectangular patterns resembling a chessboard-like appearance (figure 4.5). The second intersection pattern is a “staggered” pattern where contiguous EW crests are not aligned and are truncated by the NS crests creating the appearance of a steplike pattern.

Interdune areas formed by these intersecting patterns are another characteristic feature of the field. They form bowl-shape deep hollows widespread across the entire field creating the appearance of square honeycomb patterns (figures 4.5 and 4.11). These bowls may reach depths of 5-7 meters exposing in some areas consolidated older dune strata (figure 4.14).

The EW dunes form complex dune pattern arrangements with the older and larger structures underneath them. This relation is exemplified when the EW dunes sit atop the larger relict transverse dunes and as they climb on some of the mega-star dunes.
Star dunes

Star dunes of different sizes are distributed across the field. Some of the smaller and incipient star dunes possess a four-arm morphology generated by the onset intersection of EW and NS straight crested dunes (figure 4.15). As these intersecting patterns accumulate more sediments, the center area (star vertex) continues growing, developing a sharp peak giving rise to an incipient four or five armed star dune (Werner, 1995) (figure 4.6). Apparently from this field the larger forms of star dunes might increase the number of arms as they grow larger and interact with other nearby straight crested dunes. These larger forms commonly occur in complex relation seated atop and reworking the larger mounds formed by the relict transverse dunes. Star dunes increase in size and complexity as they position on top of higher areas of the relict transverse dunes. These star dunes may exhibit five to six arms commonly formed by a NS crest intersected by one or more EW crest and/or oblique versions of the same EW crests, and reach length up to approximately 300 m (figure 4.6). The arms of these dunes respond to all three local wind directions (westerly, northerly and southerly), but as they start to grow larger or seat atop higher areas, localized self-induced flows commence to reshape them, thus creating the oblique orientations of some of their arms.

Relict transverse dunes

At large scale the main body of dunes displays a set of five large transverse dune ridges underlying all other dune types in the field. The SMD relict transverse ridges extend across the field almost parallel to the eastern downwind field margin striking in a general
NNW to SSE direction and transverse to the westerly prevailing winds (figure 4.7). These ridges display an average ridge to ridge spacing of ~1 km with the inter-ridge areas occupied by deep basins. The height of these ridges from the lowest basin floor to the top of the consecutive ridge is approximately 50 m (figure 4.16).

Transverse ridges fan out from the south with a V-shaped vertex, and with one exception they do not intersect at their northern terminations (figure 4.17). Three of these vertices connect or give rise to all five transverse ridges. The southernmost vertex is the origin point of the two longest ridges, the eastern ridge and the second upwind ridge. A second vertex is found in the lower central area of the SMD field and serves as the origin point for the inner two ridges. The third vertex is not a true origin point but instead appears more as a ridge splay for the two western most ridges (figure 4.7).

The upwind ost ridge extends almost 11 km from the south with a NW strike. Past the ridge’s center towards the NW, a V shape splay is found giving rise to the second upwind ridge. An approximate distance of 980 m separates these two ridges.

The second ridge is the most distinct from the rest; it extends almost 10 km, but its strike direction forms an arc-like pattern. The southern half of this ridge is parallel to the other NNW consecutive ridges, while the northern half is deflected to a more northerly strike. This northern segment does not display a continuous linear pattern; instead, it appears to be segmented, formed by a series of three northerly segments connected by two smaller NNW segments. The northernmost reach of this ridge connects with the easternmost and longest ridge forming a closed loop shape (figure 4.7).
The third ridge from west to east follows a NNW strike and extends for almost 7 km; it is separated from the preceding ridge by an approximate distance of 1140 m. This ridge has an origin point in the central vertex where it is connected to the fourth ridge. The fourth downwind ridge extends for almost 9 km in a general NNW direction and is separated by an approximate distance of 920 m from its preceding upwind ridge.

The last and farthest downwind ridge is the longest one, extending for almost 17 km in a general NNW direction. This ridge, which is also the best defined, includes the highest topographical point in the SMD, with superimposed star mega dunes that reach heights over 120 m above the surrounding interdune areas.

The NW body of dunes against the Sierra de Samalayuca exhibits a similar type of ridge located at the upwind most part of the field and extending for almost 6 km in a general NNW direction forming a straight-up Z shape (or “lightning bolt” shape). Similar to the main body of dunes, this ridge forms the highest topographical point in the NW field (figure 4.7).

Due to their size and stratigraphic relations, these transverse ridges are interpreted as the prime relict forms representing the structural skeleton of the Samalayuca Dunes (SMD) field. A similar dune forming scenario is present in other large and old dune fields, where relict linear dunes form the base structure for other younger superimposed dune forms; an example of this is the El Gran Desierto dune field in Sonora, Mexico (Beveridge, 2006).
Megastar dunes

Megastar dunes (or large star dunes) are commonly found in desert sand seas in Africa, Asia and North America. In North America descriptions of these dunes have been made for the El Gran Desierto, Kelso, Dumont and Eureka dune fields (Sharp, 1966; Lancaster, 1995; Beveridge, 2006). Around the world’s dune fields megastar dunes form less than 10% of the dune forms in sand seas that contain them, commonly forming the highest dune forms in these areas (Lancaster, 1995). These type of dunes commonly occur in areas that represent sedimentological depositional centers (Lancaster, 1983) as is the case of the SMD field, where sediments are trapped by the sierras of Samalayuca and del Presidio. These dunes may be formed by the transitional development of complex dune forms. In the case of the El Gran Desierto, they develop from the complex interaction with crescentic dunes, while in the Namib Desert they form by the complex interaction with linear dunes (Lancaster, 1995). In many of these sand seas the large star dunes or megastar dunes form linear clusters or chains of dunes, which respond to multi-directional or complex wind regimes (McKee, 1966 and 1979).

Megastar dunes of the SMD field display similar geomorphologic characteristics as other large star dunes found around the world. In the SMD field a north-northwest oriented chain formed by at least 15 multi-arm mega-star dunes (draas) dominates the desert landscape, forming the tallest dune forms. These dunes change in size, form and complexity as they progress northward from their origin, overall getting larger and more complex by adding more arms. The chain of megastar dunes originates at the southern end with the presence of several 5-6 armed simple star dunes (figure 4.6). These forms start to develop more complex shapes as they progress northward. These dunes are commonly composed
by a single tall and sharp main crest (pyramid-like) generally oriented NNW, intersected by smaller oblique crests and smaller climbing dunes (figures 4.8 and 4.10).

The southernmost megastar dune differs from the common dune pattern due to the semicircular pattern formed by the main crest extending over 1 km long. This main crest is intersected by over six other oblique crests oriented NS, EW and SW-NE, extending up to 500 m from the main crest (figure 4.18). The second megastar dune (NNW from 1st) is representative of the general pattern with a main crest extending approximately 670 m in a NNW direction and intersected by at least 5 oblique crests (SW-NE) reaching almost 500 m long (figure 4.19a). The main crest of the third megastar dune is also oriented NNW and extends approximately 580 m. This crest is intersected by other oblique crests generally oriented NE and reaching up to 400 m long (figure 4.19b). The next megastar dune (4th) is oriented NNW for the main crest and extends approximately 1200 m. The main crest is intersected by several NE crests at its upwind face and SE crests at the downwind face. The longest crest intersecting this dune reaches close to 600 m (figure 4.19c). The fifth megastar dune does not display a clear dominant crest, instead it appears to be formed by a series of E, NE, N and SE crests resembling a dendritic pattern. The largest crest extends approximately 750 m in a NE direction (figure 4.19d). The sixth megastar dune possesses a well defined pattern formed by a main crest oriented NNW and approximately 1220 m long, intersected by several (>15) oblique crests. These intersecting crests are generally oriented NE on the upwind side of the megastar and a combination between NE and SE oriented crests in the downwind side of the dunes. The larger intersecting crest reaches over 600 m long (figure 4.19e). Similarly to the previous dune, the seventh megastar displays a NNW oriented main crest extending approximately 940 m and intersected by
~10 oblique crests generally oriented NE on the upwind side and E to SE on the downwind side (figure 4.19f). These intersecting remainder dunes are not described in full due to the lack of high-resolution imagery for the quadrant that contains them, nevertheless the general orientation of the main crests and comparative lengths are displayed in figure 4.8. Megastar dune eight has a general north orientation and extends approximately 890 m, similarly to the other dunes: this dune displays several oblique intersecting arms generally oriented NE on the upwind side and E and SE on the downwind side of the main crest. The next megastar dune (9th) is also oriented in a mostly northward direction, extending for over 1100 m. The main crest is intersected by several oblique crests, one of which might form a separate mega-crest extending close to 1000 m in a NE direction. Megastar dune 10 extends approximately 1000 m in a mostly NNE direction. Dune number 11 next is oriented in a slightly NNW direction and extends for approximately 820 m. The remaining dunes (northernmost) start to decrease in size maintaining the intercepting crests and overall shape. Dunes 12, 13 and 14 extend for approximately 500 to 650 m in a general northward direction. Dune 15 is the only one offset from the main chain of dunes. This dune lies due east from dune 11 and extends for approximately 590 m in a general NNE direction (figure 4.8).

Overall, the first 7 dunes’ main peaks are separated from adjacent mega-dune peaks by distances ranging from 320 m up to 850 m in a NNW direction. After dune 7, the main crests are arranged in an en echelon pattern where the offset is perpendicular to the main crest, but the northern and presiding southern terminations overlap. The NW body of dunes displays a single megastar dune oriented NNW and extending approximately 900 m (figure 4.8).
At least 14 megastar dunes of the Samalayuca Dunes field sit atop the downwindmost relict transverse ridge forming a complex dune interaction (both geomorphic and chronological) between the two distinct forms. Added to this complexity, climbing dunes are found superimposed on both structures. The large megastar dunes appear to be currently reworking the older and larger structure because of its stratigraphic arrangement. Similarly, the climbing dunes rework the sediments from the flanks of the megastar dunes.

Megastar dunes might form by the ongoing accumulation of sand derived from the interaction of multiple wind directions caused by the coalescence of the prevailing local westerly winds in conjunction with the localized eddy like currents generated at the upwind base of the mega-stars. Added to these wind currents are the presence of localized “backward” northeasterly winds generated by the shadow effect of the Sierra de Samalayuca and the secondary opposing local wind directions both from the north and south.

Conclusions

The Samalayuca Dunes field (SMD) is the largest active, non-nebkha dune field in the central and southern Chihuahuan Desert and is also one of the largest dune fields of North America. At the same time the Samalayuca Dunes has been previously only generally described and there is little prior information regarding their origin and geomorphology. With the aid of new high-resolution satellite imagery (Quickbird, ASTER and Landsat), software and field campaigns, a new and more detailed description of this field is presented.
The very fine to medium sand size sediments forming this field are derived from the eastern lacustrine paleo-shorelines of Pleistocene Pluvial Lake Palomas and its related playas at the Bolson de los Muertos (Reeves, 1969). The aeolian sediments travel east across a ~40 km long aeolian corridor to be deposited at the upwind base of the sierras of Presidio and Samalayuca (Dominguez, et. al., 2006).

The SMD field covers a total area of ~136.8 km$^2$ and is separated into two bodies of sand ranging approximately 24 km long and 15 km wide for the main body covering an area of 113.2 km$^2$, and 9 km long by 6.5 km wide for the second (NW) body with an approximate area of 23.6 km$^2$.

The shapes and patterns of these forms respond to a complex wind regime dominated by the prevailing local westerly winds in conjunction with secondary north and south winds. Some of these dune forms are modified by the presence of localized wind currents caused by the topographical effects of other larger forms or their own. Five major types of dune forms are present in the SMD field. They include an intersecting perpendicular set of two straight crested dunes generally oriented NS and EW with an average crest to crest spacing of 66 and 53 m respectively and reaching lengths varying from ~200 to 1300 m for the NS and 120 to 230 m for the EW dune crests. These dunes form two intersecting patterns described as in-line and staggered. They overlay all other dune forms in the field forming the younger and most widespread dune forms. Star dunes formed by four to five arms are distributed across the field where an in-line intersecting pattern develops overlaid on a topographical high formed by a relict dune ridge. A set of five very large transverse relict ridges forms the base skeleton of the SMD. These ridges extend for several kilometers in a general NNW direction and maintain an average crest to
crest distance of 1 km. Seated atop the eastern most relict ridge is a NNW oriented chain of megastar dunes formed by at least 15 dunes. Each dune is composed of a main crest averaging approximately 1 km long, generally oriented NNW and intersected by a series of oblique secondary crests averaging a few hundred meters long. The crests of these dunes form the highest points in the field reaching over 120 m from their surrounding interdune areas.

The spatial and stratigraphic interaction between the SMD dunes forms a complex arrangement, where one or more dune forms are superimposed atop a different form, creating the intricate nature of Samalayuca Dunes field.

Field and dune dynamics, granulometric and geochemical distributions and refinement of physical parameters at field and dune scale are only some of the remaining topics needed to be researched in order to attempt to fully understand this extraordinary geologic monument.
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Figure 4.1. Regional location and physiographic setting of the Samaluyuca Dunes field, northern Chihuahua, Mexico. (Center of the field approximately located at N 31° 15’ 49”, W 106° 23’ 43”).
Figure 4.2. Frequency of wind direction for the local Samalayuca area (left) and for the region (right). (From Schmidt and Marston, 1981).
Figure 4.3. Conceptual wind vector model responsible for the formation and shape of the Samalayuca Dunes field. Dark blue arrows indicate the local prevailing westerly wind direction while lighter blue arrows indicate the secondary north and south directions. Red arrows indicate the resulting topographically influenced wind vectors.
Figure 4.4. Polygons used to calculate the area of the Samalayuca Dunes field and NS and EW cross sections used to measure the crest to crest distance of the straight crested dunes (Image and data modified from Google Earth).
Figure 4.5. Crests of NS and EW straight crested dunes forming onset perpendicular interference patterns (Image modified from Google Earth).
Figure 4.6. Five armed star dunes originating atop the southern most extension of a relict ridge by the intersection of NS and EW crests (Image modified from Google Earth).
Figure 4.7. NNW Relict transverse ridges displaying step like progression (or en echelon) pattern. These ridges form the underlying skeleton of the Samalayuca Dunes field and represent the older preserved dune features.
Figure 4.8. Main crests directions and lengths of the megastar dunes. General orientations are N and NNW, except for crest 1, which displays a semicircular crest and dune 5 with no apparent main crest.
Figure 4.9. Frequency distribution histogram of the north to south dunes crest-to-crest spacing, average is 66 m and 17 m standard deviation.
Figure 4.10. Northernmost megastar dunes with intersecting oblique arms, climbing dunes and surrounding NS and EW straight crested dunes (image looking north).
Figure 4.11. NS straight crested dunes (into the plane of the image) and their conjugate EW straight crested dunes (across the image). Note the smooth round crests. Large megastar dunes at the upper left with intersecting arms and climbing dunes (image looking due south across the field).
Figure 4.12. Wind rose diagram of straight crested dunes in a selected study area of the field. Notice the strong EW component due to a larger count of crests due to their overall smaller size compared to the longer (smaller count) NS crests.
Figure 4.13. Frequency distribution histogram of the east to west dunes crest-to-crest spacing, average is 53 m and 14 m standard deviation.
Figure 4.14. Consolidated paleodune strata exposed in some deep interdune areas. Scarce clay lenses are observed embedded in the strata, which displays an Fe red oxidation coloration.
Figure 4.15. Small four-armed star dune in the northern segment of the field. The star dune pattern forms as the intersecting NS and EW crests accumulate more sediment.
Figure 4.16. Topographic cross section showing two relict ridges (left most) and the eastern most relict ridge overlain by a megastar dune. Average spacing between ridges is 1 km and 50 m average height, except for eastern ridge exceeding 120 m height.
Figure 4.17. Aerial photograph of the dunes field. Notice the funnel shape of the upwind field margin and linear shape of the downwind margin. Relict ridges at the center of the field and megastar dunes atop eastern most ridge (north is towards the upper right corner).
Figure 4.18. Southernmost (1st) megastar dune displaying a semicircular main crest and several NS and NE trending oblique intersecting crests (Google Earth image).
The Pluvial Lake Palomas – Samalayuca Dunes system in the Chihuahuan Desert of North America is composed of three individual sub-systems that represent different sediment states along a downwind aeolian transport path. This transport path follows the sediments’ genesis from the initial lacustrine depositional site at the Pluvial Lake Palomas, through a ~45 km stretch formed by an aeolian corridor, until sediments are deposited at the Samalayuca Dunes sand sea. The Pluvial Lake Palomas – Samalayuca Dunes system is one individual geosystem where each of the parts is intimately connected to each other and the mechanisms or disruptions acting on one part of the system have an effect on the rest of the parts.

A detailed geomorphologic, sedimentologic and elemental concentration analysis was conducted in all the different areas and geoforms of the individual sub-systems. Results elucidate the present state of the system, and the intricate interrelation of the sediments and geoforms along this lacustro-aeolian system.

The upwind lacustrine segment of the system (Pleistocene Pluvial Lake Palomas Basin) is formed by a series of open and closed hydrologic sub-basins and undifferentiated areas. The majority of these basins exhibit flat, barren playa surfaces delineated by fluvial and alluvial deposits. The surface sediments of these playas are characterized by possessing poorly to very poorly sorted sediments. The bulk sediment fraction of these playas is dominated by very fine sediments in the range of clays and fine silts (< 20 – 30 µm) commonly amounting to more than 50 % of the total sediment fraction by weight. The
remainder is commonly formed by the coarser silt fraction and sand size sediments in the very fine to medium sand size fraction.

Elemental concentrations of these sediments indicate for the most part mean concentrations that are within average crustal concentration values. Only a few elements outstand by possessing high concentrations, which suggest enrichment of these elements beyond average crustal values. Chlorine (Cl), Arsenic (As), Sulfur (S) and Bromine (Br) to some extent, are commonly enriched in playa sediments specially when sampled at or near the playa margins. These elements display their higher concentrations in playa surfaces exhibiting efflorescent salt crusts, suggesting a concentration effect of the efflorescent salts. One specific playa outstands as displaying the highest elemental concentrations from all the analyzed areas. The Laguna Seca is the only playa included in the study that is not part of the Pluvial Lake Palomas Basin per se. This playa sits in a sink area for one of the Rio Casas Grandes tributaries atop fluvial and alluvial deposits. The area is also one of the major agricultural regions in northern Chihuahua. Two of the samples collected from this playa (ASC 002 (efflorescent salt crust) and 003 (loose aggregate deposits)) display highly anomalous concentrations of Cl, Br, As, S, Mo, and Na. Enrichment factor coefficients (calculated for all samples) of these samples display values that greatly exceed the 10 units mark, above which anomalous enrichment is considered. Cl (10,913 units), Br (2,718 units) and As (1,287 units) are the three highest enriched elements from these samples.

The grain size distribution of sediments forming these playa surfaces, the presence of coarser (sand and fine gravel size) loose sediments at the margins of the playas, the formation of thinly up-curled clayey crusts and efflorescent crusts atop the playa surfaces, the lack of considerable amounts of roughness elements and the flat, barren nature of most
of the playas among other factors, coalesce to form the “perfect storm” scenario for the erosion and atmospheric emplacement of the fine sediment fraction (<20 µm) as mineral aerosols. Mineral aerosols emanated from the playas, alluvial and fluvial areas of Pluvial Lake Palomas are commonly transported very long distances impacting downwind urban areas such as the binational Paso del Norte metroplex and beyond.

The central-eastern margin of the Pluvial Lake Palomas is connected to the aeolian corridor sub-system, which extends approximately 45 km in an easterly direction following the prevailing wind direction from the W-SW. This aeolian corridor is geomorphologically represented by a series of geoforms that evidence the transport of sand and to a lesser degree clay and silt size sediments across its surface. Discarding the playa surface of the Bolson de los Muertos, the geomorphology of the aeolian corridor is represented from the upwind shoreline area to the downwind Samalayuca Dunes by the following geoforms.

Shoreline deposits from the eastern margin of the Pluvial Lake Palomas, which comprise the most heterogeneous geoform from the aeolian corridor. These deposits are represented by three distinct sediment types. The upwindmost type is formed by polygonal desiccation structures similar to the regular playa surfaces, where a large fraction of the sediments are represented by clay and silts. Opposite to the regular playa surfaces, these peds contain a greater fraction of sand size sediments (up to 25 % by weight, compared to ~15 % for the regular playa surfaces), evidence of the shoreline environment that they are found in. Next downwind are found soft efflorescent salt “puffy” crusts, which do not form well-defined polygonal desiccation structures. These sediments contain up to 80 % by weight of the clay and silt fractions. The downwindmost shoreline geoform is represented by beach deposits, dominated by fine sand size sediments amounting to almost 75 % by
weight. Oppositely to the previous shoreline forms (classified as very poorly sorted), the beach deposits are classified as poorly sorted due to the greater dominance of the sand size sediments.

Sediments from the shoreline are eroded and transported downwind in different ways depending on their size fraction. The very fine (<20 µm) sediment fraction is commonly emplaced into the atmosphere in the form of mineral aerosol (dust) plumes, where most of the load is transported out of the system. A small fraction of the fine sediments (<20 µm) are trapped by vegetation inside the aeolian corridor and deposited on the coarser (sand size) sediments anchored by the vegetation, such is the case of vegetated nebkha dunes. The coarser sand size sediments eroded from the shoreline are transported downwind by saltation and give rise to the other aeolian geoforms present in the corridor.

Barchan dunes and barchanoid ridge dunes are present near the eastern margin of the aeolian corridor. These dunes are found forming small fields distributed semi-parallel to the NNW trending Bolson de los Muertos eastern margin. Sand size sediments (mean grain size 85 µm) forming these dunes are classified as well sorted.

Parabolic dunes are found almost adjacent to the barchan dune fields. These dunes display long (> 1 km) arms extending in an easterly direction following the prevailing wind direction (W-SW). The front or noses of these dunes form in some cases small dune fields represented by transverse barchanoid ridge-like dunes. In some areas these dune fronts coalesce to form a larger front representing compound dunes interrelations.

Three types of aeolian geoforms are ubiquitous in the aeolian corridor. A widespread sand sheet formed by moderately well sorted sand size sediments (average mean 85 µm) forms the aeolian base for all the other aeolian geoforms. A second
widespread geoform is represented by nebkha (coppice) dunes. These dunes are present almost from the lacustrine – aeolian margin all the way to the periphery of the Samalayuca Dunes. The sediment distribution of nebkha dunes is dominated by sand size (mean grain size 88 µm) fraction. Along with the beach sediments, the nebkha dunes are the only geoform that displays a small “tail” of very fine sediments accompanying the dominant sand size fraction. The presence of these clays and silts is possibly related to fine sediment coatings on the sand grains and/or trapping by fines by vegetation. Deflated surfaces or localized small desert playas represent the other geoform that is randomly present across the aeolian corridor. Deflated surface sediments possess a wide distribution of grain sizes, which are very poorly sorted, similarly to the playa and shoreline sediments. Deflated surfaces represent “windows” into the alluvial sediments that underlay the aeolian corridor.

The downwindmost area of the corridor is host to the largest dunes present in the system, the Samalayuca Dunes. These dunes represent the depocenter for the saltation sediment fraction that has been transported across the corridor. Sand size sediments (mean grain size 115 µm) accumulate at the upwind base of the Sierra de Samalayuca and Sierra del Presidio. These dune sediments represent the last sediment maturation state of the aeolian corridor, where the sand size fraction possesses a narrow unimodal distribution of well to very well sorted sediments.

Sediment maturation state across the corridor is also evidenced by the elemental concentrations of the different geoforms present in the corridor. The upwind source shoreline and playa sediments display overall higher elemental concentrations for most of the detected chemical elements. This behavior is expected for the “fresh” immature
sediment load found at the source area. Across the aeolian corridor elemental concentrations decrease for most elements, evidencing the chemical depletion and continued maturation state of these sediments. Sediments at the Samalayuca Dunes display an overall lower elemental concentration among corridor samples, representing the end maturation state of these sediments. Individually, Silica (Si) is the only element that displays a contrary tendency to this depletion. Si is enriched at the Samalayuca Dunes as a consequence of the resistate nature of quartz (SiO$_2$) and is also evidence of the sand’s mature chemical state. Throughout the aeolian corridor some elements outstand for displaying high concentrations in specific geoforms compared to others. Such is the case of Cl and S, which are highly concentrated in the shoreline and are mainly depleted from the rest of the geoforms. These salts and evaporite related elements are considered evidence of the wet playa behavior for the shoreline area of the Bolson de los Muertos, and are also strong evidence of the elemental depletion across the corridor. Ca and Sr possess higher concentrations in the deflated surfaces compared to other geforms. These two elements are key indicators of carbonate compositions. Their presence in the deflated surfaces is evidence of the alluvial nature of these sediments, derived from the nearby Cretaceous carbonate outcrops abundant in the area.

The Sierra de Samalayuca and Sierra del Presidio give rise to one of the most iconic landmarks of the Chihuahuan Desert, “Los Medanos de Samalayuca” (the Samalayuca Sand Dunes). Sediments transported across the aeolian corridor are accumulated in this sand sea forming complex and intricate dune interrelations. The Samalayuca Dunes have had a short scientific research trajectory limited to one previous publication (Schmidt and Marston, 1981) and a few secondary mentions in other research. The complex geomorphology of the
dunes is evidenced in this research by the use of new remote sensing platforms and detailed ground truth descriptions.

The geoforms of the Samalayuca Dunes are represented by five key dune types. The smaller and most widespread of these dune types is represented by sets of east-west oriented straight crested dunes, which intersect other longer sets of north-south oriented straight crested dunes. These two dune types form almost perpendicular intersecting patterns seated atop in a complex arrangement with the other dune forms. In areas where the intersecting of these dunes occurs in an “in-line” setting, a cross-like pattern emerges. This pattern might continue to develop augmenting size and forming simple and small four armed star dunes. Whenever this “in-line” intersection occurs in a complex manner with a larger underlying form, the simple star dunes might develop into larger and more complex forms by adding additional arms and augmenting the overall size. Underlying all dune forms in the sand sea are present a set of relict transverse dune ridges that elongate from vertices originating in the southern extensions of the field. These N to NNW oriented ridges extend for up to 17 km forming the base skeleton of the Samalayuca Dunes field. The downwindmost of these relict transverse ridges is overlaid in a complex interrelation by megastar dunes, forming the tallest dune forms in the field rising over 120 m from their surrounding interdune areas. The megastar dunes are composed of a main crest generally oriented in a N-NW direction forming a pyramidal shape. These crests are intersected by multiple oblique secondary crests or arms with general W to E and SW to NE orientations on the upwind sides, and W to E and NW to SE orientations on the downwind side. These megastar dunes align in a chain-like arrangement for the most part progressing to an en echelon pattern in the northern extension.
The Samalayuca dunes respond to a diverse wind regime generated by the orographic effects of the delimiting sierras and the internal large dune structures. The local wind regime affecting the dune field is dominated by a prevailing W to E direction, complemented by secondary N and S directions. Megastar dunes might form by the ongoing accumulation of sand derived from the interaction of multiple wind directions caused by the coalescence of the prevailing local westerly winds in conjunction with the localized eddy-like currents generated at the upwind base of the megastars. Added to these wind currents are the presence of localized “backward” northeasterly winds generated by the shadow effect of the Sierra de Samalayuca and the secondary opposing local wind directions both from the north and south.

Overall this research contributes to a better understanding of dust sources and ground conditions of these sources in the Chihuahuan Desert of North America, along with the identification of a previously undescribed aeolian corridor and a detailed geomorphological description of the all the dune forms present in the Samalayuca Dunes. These contributions are specifically represented by:

- The identification and detailed geomorphic description of a major and previously un-identified mineral aerosol producing area in North America, the Pluvial Lake Palomas Basin and its related alluvial and fluvial areas.
- The identification of internal granulometric and sedimentologic features that coalesce to create conditions favoring mineral aerosol emission in the system. These features are similar to other major dust-producing areas around the globe (Sahel-Sahara, Taklamakan, Owens dry Lake and others).
• An assessment of the external sedimentological conditions present at the margins of the Pluvial Lake Palomas, which aid to potentialize the production of mineral aerosols.

• Preliminary identification of elemental concentrations, which can be used for source profiling mineral dust emissions from the Pluvial Lake Palomas basin and sub-basins, and identification of elements in the aerosols which might pose health hazards to the downwind communities from this system, specifically the binational Paso del Norte metroplex.

• Possibility of better global aerosol modeling due to a better understanding of ground conditions for this system, which can be compared to other similar systems worldwide.

• Discovery and description of a new aeolian corridor system, its geoforms and the sediments’ elemental and granulometric trends.

• Discovery and description of two new dune forms in the Samalayuca Dunes.

• Revised and detailed description of two other previously identified dune forms in the Samalayuca Dunes.

• First in-depth description of the Samalayuca Dunes’ physical parameters.

• Analysis of the complex and compound dune form interrelations in the Samalayuca Dunes system.

• An overall contribution to broaden the scientific knowledge and understanding of the northern Chihuahuan Desert region.
Reference

APPENDIX A

Grain size frequency distribution curves for the Aeolian Corridor system samples.

SM 003B

SM 022A

COR 001

COR 002
## APPENDIX B

**PIXE (particle induced X-ray emission) elemental concentration for the Pluvial Lake Palomas Basin samples**

(Concentration of major elements (yellow) in percent, minor elements (green) in parts per million)

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APPENDIX C
PIXE (particle induced X‐ray emission) elemental concentration for the Aeolian Corridor samples
(Concetration of major elements (yellow) in percent, minor elements (green) in parts per million)

260


CURRICULUM VITA

Miguel Domínguez Acosta was born on August 31, 1975 on Monterrey, Nuevo León, México. The only son of Maria Esther Acosta Díaz and Alberto Domínguez Rodríguez, Miguel concluded his high school studies at the Centro de Bachillerato Tecnológico industrial y de servicios 114 in Ciudad Juárez Chihuahua, the year of 1993. He entered at the University of Texas at El Paso in the year of 1994, where he obtained a degree in geological sciences, with a minor in chemistry in May of 2000. The last four year of the BS he worked for the geological science department as a grader and professor assistant. Miguel entered the graduate program in Geological Science in the fall of 2000, and obtained his masters of science degree in December 2002, presenting a thesis entitled: Geochemical Mapping of Southwestern New Mexico, an Assessment of the Regional environmental Status. During his graduate studies he continued working in the Geological Science department as a teaching assistant. Miguel became a full time professor at the Universidad Autonoma de Ciudad Juarez in the year 2003 and continues to teach and research in this institution. He entered the Geological Sciences Doctoral program at UTEP in the fall of 2005, where he continued working as a teaching and research assistant, as well as teaching two introductory geological science classes. Miguel has presented his doctoral research in several international conferences including Canada, the U.S. and Mexico.

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