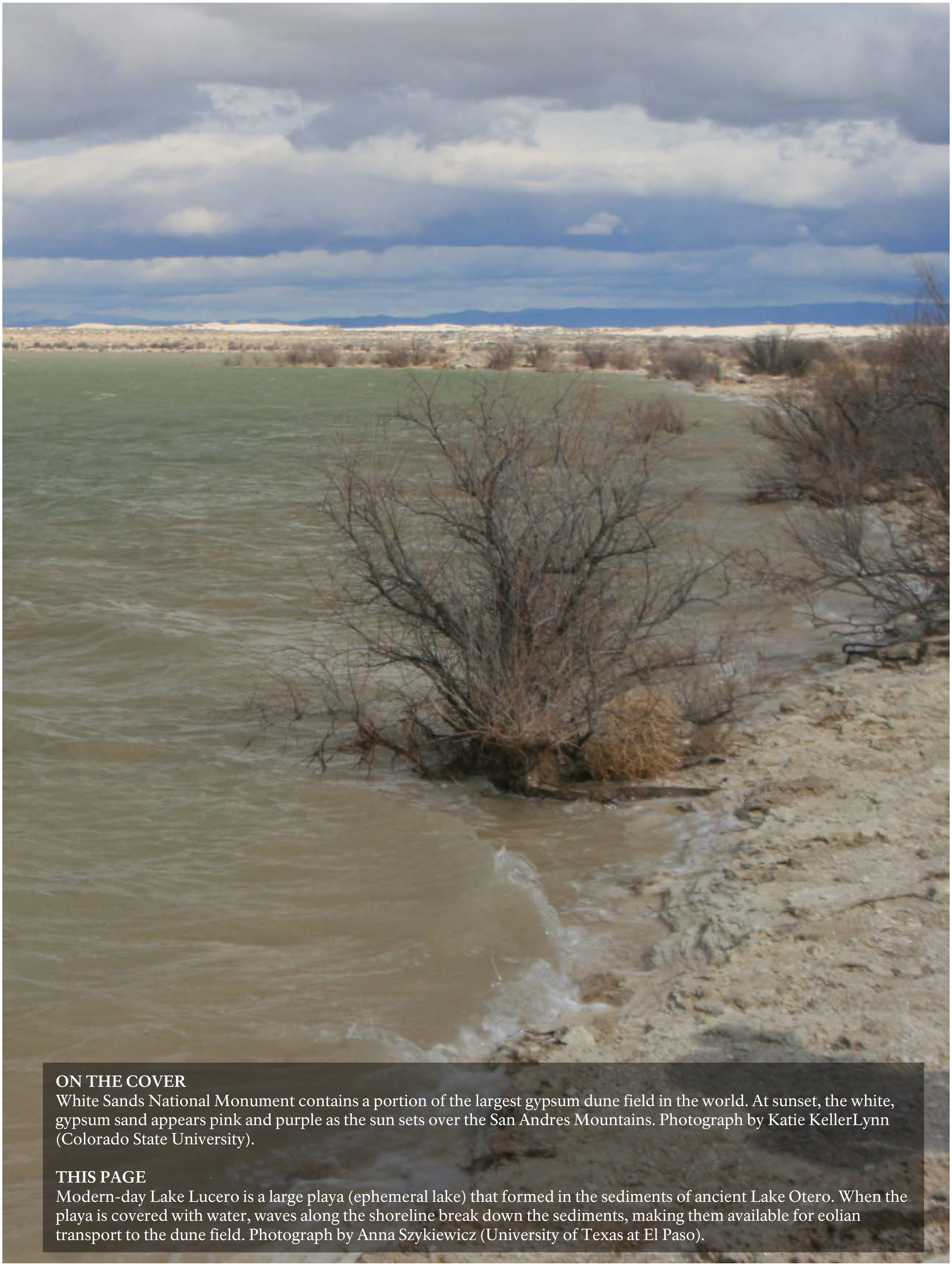
**National Park Service**
**U.S. Department of the Interior**

**Natural Resource Stewardship and Science**

# White Sands National Monument

## *Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2012/585



**ON THE COVER**

White Sands National Monument contains a portion of the largest gypsum dune field in the world. At sunset, the white, gypsum sand appears pink and purple as the sun sets over the San Andres Mountains. Photograph by Katie KellerLynn (Colorado State University).

**THIS PAGE**

Modern-day Lake Lucero is a large playa (ephemeral lake) that formed in the sediments of ancient Lake Otero. When the playa is covered with water, waves along the shoreline break down the sediments, making them available for eolian transport to the dune field. Photograph by Anna Szykiewicz (University of Texas at El Paso).

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## *Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2012/585

National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

October 2012

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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# Executive Summary

*This report accompanies the digital geologic and geomorphic map data for White Sands National Monument in New Mexico, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This report was prepared using available published and unpublished geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report.*

This Geologic Resources Inventory (GRI) report was written for resource managers at White Sands National Monument to assist in science-based decision making and resource management. This report also may be useful for interpretation. The report discusses geologic issues at White Sands National Monument, distinctive geologic features and processes within the national monument, and the geologic history leading to the national monument's present-day landscape. The report provides a glossary, which contains explanations of technical, geologic terms, including terms on the map unit properties tables (see "Geologic Map Data" section). Additionally, a geologic time scale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top (fig. 6). In the "Geologic Map Data" section, overview graphics illustrate the geologic map of Seager et al. (1987) and the geomorphic map of Fryberger (2001b), which served as source data for the White Sands National Monument digital geologic data set (see Attachment 1). In addition to these two maps, the online publication *Geological Overview of White Sands National Monument* (Fryberger 2001a) was a primary resource in preparing this report. Map unit properties tables for the geologic and geomorphic maps summarize features, characteristics, and potential management issues associated with the rocks and unconsolidated deposits at White Sands National Monument.

White Sands National Monument contains a portion of the largest gypsum dune field in the world (Talmage 1933; McKee 1966). The entire dune field covers 712 $km^2$ (275 $mi^2$). Most of the dune field, about 60%, is located within White Sands Missile Range, which surrounds White Sands National Monument. The national monument hosts about 200 $km^2$ (115 $mi^2$) of the dune field.

Described as part of a "wet eolian system," the White Sands dune field is shaped by eolian (wind-related) processes and groundwater hydrology. The two principal features in White Sands National Monument—the gypsum dunes and playa—typify these processes, attesting to past and present eolian and pluvial (precipitation-related) activities and groundwater discharge. In New Mexico, the Pleistocene Epoch (2.6 million–11,700 years ago) was characterized by pluvial lakes, such as Lake Otero, that were the result of wet conditions and heavy rainfall. The White Sands dune field formed since the Pleistocene Epoch during a series of events involving deflation (removal of loose material via eolian processes). Modern playa Lake Lucero is an outcome of regional aridity during the Holocene Epoch (the last 11,700 years). Progressive changes in climate to present-day arid conditions caused pluvial lake waters to recede and lake beds to dry, making sand-size sediment available for eolian transport into the dune system.

The White Sands dune field consists of a core of barchan dunes flanked on the north, south, and east by parabolic dunes. An active Holocene lake basin, with Lake Lucero and other smaller ephemeral lakes or "playas," and a scour platform, from which gypsum is deflated, occur west of the dune field. An area of alluvial deposits—called "piedmont-slope deposits," "coalescing alluvial fans," or the "bajada" by various investigators—flanks the San Andres Mountains to the west of the active Holocene lake basin. These alluvial deposits are an avenue for water runoff and sediment input onto the active Holocene lake basin during storms.

Geologic issues of particular significance for resource management at White Sands National Monument were identified during the 2003 geoindicators and 2007 geologic resources evaluation (GRE) meetings; these programs were precursors to the Geologic Resources Inventory (GRI) Program, administered by the NPS Geologic Resources Division. Geologic issues identified during these meetings include the following:

- Groundwater. Groundwater is inseparable from the geologic features and processes of the White Sands dune field. The groundwater system at White Sands National Monument is probably an integration of two systems—the larger groundwater system of the Tularosa Basin, and a shallow, perched groundwater system within the dune field. Exactly how these two systems interact and influence each other is unknown, but under investigation.
- Surface Water. About 105 km (65 mi) of intermittent streams enter White Sands National Monument from the San Andres Mountains on the west. These streams have created a feature of coalescing alluvial fans called a "bajada" on the western side of the national monument. During rainfall events, storm water and alluvial sediments are washed through the bajada and onto the active Holocene lake basin, and storm water fills Lake Lucero and other low places on the playa. The Lost River is the only intermittent stream to enter the national monument from the east.

- Erosion. Erosional processes exacerbated by anthropogenic activities are a concern for resource managers at White Sands National Monument. Erosion-related issues include culverts on adjacent White Sands Missile Range, which concentrate flow and intensify erosion of archeological sites; corridors of buried fiber optic cables, which create pathways ideal for transporting storm water flow; and past land-use practices such as grazing, which denuded vegetation and increased sediments available for storm water runoff and eolian transport.
- Debris Flows and Rockfall. Debris flows in the bajada on the western side of White Sands National Monument are a safety concern as they have killed people on White Sands Missile Range and in a nearby Bureau of Land Management (BLM) campground. Most of the material transported through the bajada is small in size. However, large boulders occasionally roll down the slopes of the bajada onto the boundary road in White Sands National Monument. Such boulders have knocked out sections of the national monument's perimeter fence.
- Paleontological Resources. Fossil track sites of Pleistocene mammals, primarily proboscidean (mammoth or mastodon), are the most significant paleontological discovery at White Sands National Monument to date, and represent one of the largest concentrations of Cenozoic fossil tracks within the United States and possibly the world. Significant trackways have been found on Alkali Flat and the southern shoreline of Lake Lucero.
- Climate Change. Climate change could have a dramatic effect at White Sands National Monument, mainly as a result of longer and more severe droughts. Climate-related issues include the magnitude and frequency of dust storms, changes in sand transport rates, and activation or stabilization of areas of sand dunes. Ancient Lake Otero, which covered the Tularosa Basin as a result of wetter conditions during the Pleistocene Epoch (2.6 million–11,700 years ago), provides a geologic scenario for understanding abrupt changes in climate. Lake Otero sediments within White Sands National Monument preserve the latest part of the history of Lake Otero, leading to development of Lake Lucero and Alkali Flat during drier conditions of the Holocene Epoch (the past 11,700 years).
- Monitoring Eolian Processes. Lancaster (2009)—the chapter about eolian features and processes in *Geological Monitoring* (Young and Norby 2009)—highlighted 10 vital signs for monitoring eolian systems, discussed study design, and provided case studies of monitoring within arid landscapes. This information may be useful in developing a monitoring program at White Sands National Monument. In 2012, researchers from the University of Texas at Austin were preparing a dune monitoring protocol for the Chihuahuan Desert Network and White Sands National Monument that used light detection and ranging (LIDAR).
- Infrastructure and Gypsum Sands. An awareness of eolian processes and the saline groundwater system is necessary for developing sustainable infrastructure in areas of gypsum sand. Issues at White Sands National Monument include blowing sand, for example across the paved portion of Dunes Drive; the corrosive nature of saline groundwater for infrastructure; the possibility of gypsum dissolution in the presence of freshwater, creating sinkholes; and gypsum's ability to adhere to surfaces and become "glue" within machinery, windows, and doors.
- Tamarisk. Also called "salt cedar" because it is well suited for areas of saline ("salty") groundwater, tamarisk (*Tamarix* spp.) has invaded many interdune areas, where water is near the surface, in the White Sands dune field. These nonnative plants change local wind patterns and impact eolian processes. Tamarisk has also invaded the Lost River area, where it is threatening pupfish (*Cyprinodon tularosa*) habitat.
- White Sands Missile Range. White Sands Missile Range surrounds White Sands National Monument. As a result, much of the land surface in the vicinity of the national monument is administered by the Department of Defense and closed to public access. The national monument is administered by the National Park Service. Issues related to the proximity of the missile range include exacerbated erosion, contaminated runoff, and unexploded ordnance.
- Mining and Energy Development. Past mining activities left minor impacts within White Sands National Monument. Nature is taking its course, breaking down sediments and removing traces of sodium carbonate ("soda ash") and gypsum quarries, a plaster of paris plant, and a trail to a salt mine. The Department of Defense investigated, but has not developed, the oil and gas potential at White Sands Missile Range.
- Seismic Activity. Seismic risk at White Sands National Monument is low. However, faults are notable geologic features in the vicinity, including the Alamogordo fault at the base of the Sacramento Mountains east of the national monument, and the San Andres fault west of the national monument.

Geologic features of particular significance for resource management at White Sands National Monument include the following:

- Geomorphic Areas. Fryberger (2001b)—the geomorphic map for White Sands National Monument—divided the dune-field system into four geomorphic areas: (1) an active Holocene lake basin (geomorphic map unit symbol *ahlb*), which holds modern Lake Lucero; (2) a scour platform (*sp*), which is an area of net sediment erosion; (3) the barchanoid dune field (*bdf*), which contains the primary, active White Sands dunes; and (4) marginal parabolic dunes (*mpd*), which occur north, south, and east of the active dune field. Also included on the geomorphic map are "miscellaneous geomorphic features" such as alluvial fans (*allvl_fan*), outcrops of ancient Lake Otero (*lo_outcrops*), and yardangs (*yrdng*).

- Alluvial Deposits. Large geomorphic features deposited by running water, including sheet flow and more channelized flow, are conspicuous on the White Sands landscape. These features include the alluvial fans on the western side of White Sands National Monument, which coalesce to form the bajada. The bajada, also called “piedmont slope,” distributes water and sediments onto the playa, has distinct plant communities and soil types, and is the recharge area for the basinwide groundwater aquifer.
- Source of Gypsum Sand. Hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$), commonly referred to by its geologic name “gypsum,” is ubiquitous across the White Sands landscape. The ultimate source of the gypsum sand that makes up the dunes is the Permian (299 million–251 million years ago) rock that underlies and flanks the Tularosa Basin, in particular the Yeso Formation (geologic map unit Py). Geologic map units such as older gypsiferous basin-floor deposits and lake beds (Qbfg), gypsiferous lake deposits (Qlg), inactive gypsum dunes (Qegi), and active gypsum dunes (Qega) cover White Sands National Monument and attest to the widespread nature of gypsum.
- White Sands as an Analogue for Mars. The origin of domes and mounds on Mars is under debate, but the sulfate ($SO_4$)–rich character of crystal pedestals/domes on Alkali Flat makes White Sands a provocative terrestrial analogue for the formation of the sulfate-rich eolian outcrops on parts of Mars. In addition, the Olympia Undae dune field on Mars appears to have many of the same morphological features as the dunes of White Sands; recent exploration by orbital spacecraft has shown that gypsum-rich, windblown sand dunes are present on that planet.
- Biological Soil Crusts. Biological soil crusts are indicators of ecosystem stability, health, and climate change. They occupy an intermediate ecological position between active dunes and vegetated surfaces at White Sands National Monument, and are critical to plant growth because they fix nitrogen into the system and bind soil. Biological soil crusts can either promote water infiltration (on silty soils) or increase runoff (on sandy soils). Both these attributes are important for the dune ecosystem.
- Geothermal Features and Processes. Hydrothermal waters are a characteristic of basins along the Rio Grande rift. Based on the presence of thermophilic bacteria strains and hydrothermal minerals in the soil, some investigators have hypothesized the existence of active discharge of hydrothermal fluids onto the playas near White Sands. However, investigators have yet to detect any hot-spring activity within the White Sands dune field.

# Acknowledgements

*The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.*

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geological surveys, local museums, and universities in developing GRI products.

The GRI Program would like to thank the participants at the 2003 geoindicators and the 2007 geologic resource evaluation (GRE) meetings (see Appendix). These meetings were instrumental in developing the process now used by GRI scoping teams in identifying significant geologic issues, features, and processes within National Park System units. Thanks very much to David Bustos (White Sands National Monument) for his assistance during GRE scoping, and the report-writing and review processes, as well as for providing many of the photographs used in this report. Also, thanks to Trista Thornberry-Ehrlich (Colorado State University) for creating many of the graphics in this report.

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# Introduction

*This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of White Sands National Monument.*

## Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

## Park and Regional Setting

On 18 January 1933, outgoing President Herbert Hoover proclaimed 57,867 ha (142,987 ac) of gypsum sand in south-central New Mexico as "White Sands National Monument." White Sands Missile Range, which is administered by the U.S. Department of Defense, surrounds the national monument and hosts the majority of the dune field (fig. 1).

In the early 1940s, the U.S. government deemed this part of New Mexico as ideal terrain for military operations (Houk and Collier 1994). The first atomic-bomb test detonation was made at the Trinity Site, which is now a national historical landmark located on White Sands Missile Range. Just after the attack on Pearl Harbor in 1942, the Alamogordo Bombing and Gunnery Range was established. The Alamogordo Army Air Base, also established in 1942, was used for aircrew training during World War II. In 1945, White Sands Proving Ground was set aside. In 1958, the gunnery range and proving ground were consolidated and renamed White Sands Missile Range. The Alamogordo Army Air Base was renamed Holloman Air Force Base after World War II.

Since the 1940s, a military presence and security measures in the White Sands area have safeguarded many natural resources from anthropogenic impacts. Although issues do occur as a result of the nearby military operations (see "White Sands Missile Range" section), much of the land surface in the vicinity of White Sands National Monument is not publically accessible. The national monument is administered by the National Park Service.

The White Sands dune field, including portions in both the missile range and national monument, is situated within the Tularosa Basin between the San Andres and Sacramento mountains (fig. 1). Major geomorphic features of the area include extensive floors of intermontane basins, such as the Tularosa Basin; contiguous piedmont slopes, or bajada; and upland areas, including mountain ranges (e.g., San Andes and Sacramento) and high plateaus, with steep bounding escarpments. Present-day basin floors are characterized by discontinuous ephemeral drainageways, widespread eolian deposits, and numerous closed depressions with ephemeral lakes called "playas." In the recent geologic past, however, basins were occupied by extensive perennial lakes and/or large fluvial systems (Hawley 1993).

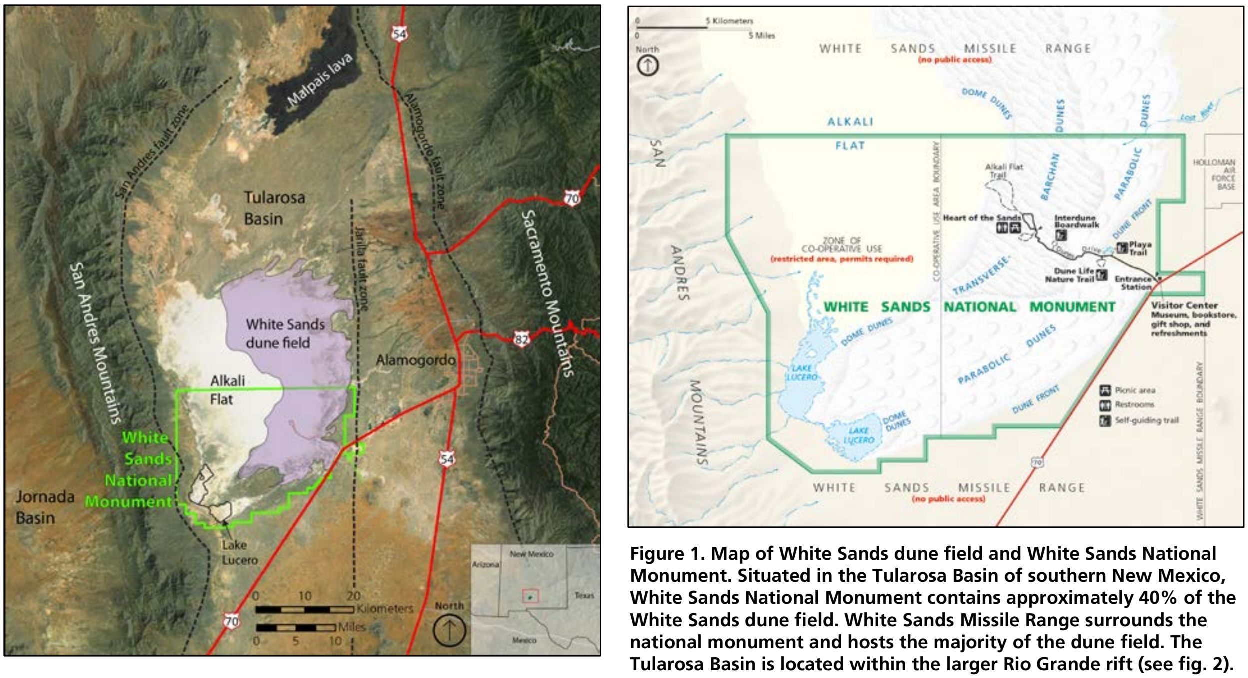

**Figure 1. Map of White Sands dune field and White Sands National Monument. Situated in the Tularosa Basin of southern New Mexico, White Sands National Monument contains approximately 40% of the White Sands dune field. White Sands Missile Range surrounds the national monument and hosts the majority of the dune field. The Tularosa Basin is located within the larger Rio Grande rift (see fig. 2). Left map by Trista Thornberry-Ehrlich (Colorado State University) after Kocurek et al. (2007). Right map by National Park Service.**

The Tularosa Basin is a "closed basin," without an outlet for surface drainage. Some groundwater discharges into the Hueco Basin to the south. Rates of groundwater discharge are slow enough that the water table is near the surface (McLean 1975; Basabilvazo et al. 1994). Structurally, the Tularosa Basin is part of the Rio Grande rift, which is "the single most striking topographic feature of New Mexico" (Price 2010, p. 13). This deep-seated tear in Earth's surface stretches for more than 1,000 km (620 mi), from Colorado to Chihuahua, Mexico, intersecting New Mexico and Texas along its length. The Rio Grande rift represents an ongoing episode of east–west crustal extension that began about 40 million years ago (Price 2010).

The Tularosa Basin is one of nine basins along the Rio Grande rift (fig. 2). In general, each basin is made up of half grabens (down-dropped blocks) that formed as a result of the pulling apart of Earth's crust. Crustal movement along the rift exposed Precambrian (4.6 billion–542 million years ago) and Paleozoic (542 million–251 million years ago) rocks on the edge of the Tularosa Basin in the uplifted Sacramento Mountains to the east and the San Andres Mountains to the west. These same rock units underlie the basin. When crustal movement exposed the strata along the graben perimeter, meteoric waters (derived from precipitation) began dissolving the soluble evaporite rocks, such as gypsum, and transporting the solutes (dissolved material) into the basin (Allmendinger and Titus 1973).

During wetter conditions of the Pleistocene Epoch (2.6 million–11,700 years ago), the Tularosa Basin was the site of a sequence of large pluvial lakes, the most recent known as Lake Otero. Infilling of the Lake Otero basin left sediments, including laminated clays and silts, gypsum-rich marls, limestone, and massive silts containing large gypsum crystals. Progressive changes in climate to present-day arid conditions caused pluvial lake waters to recede and lake beds to dry, making sand-size sediment available for eolian transport into the dune system.

Today, these sediments are exposed in gullies and incised by at least 20 playas (Langford 2003). The largest of the playas, Lake Lucero (fig. 3), consists of three sub-basins in the southern part of White Sands National Monument. Gypsum exposed in Lake Otero sediments (geomorphic map units *sp_los* and *lo_outcrops*) provides the main source of sand for the White Sands dune field (Fryberger 2001a) (fig. 4). Sand-sized grains from evaporite material along the shores of modern Lake Lucero are a secondary source; finer grained material is transported beyond the dune-field system (Fryberger 2001a) (fig. 5). Refer to figure 6 for a geologic time scale and summary of events in the geologic history of White Sands National Monument.

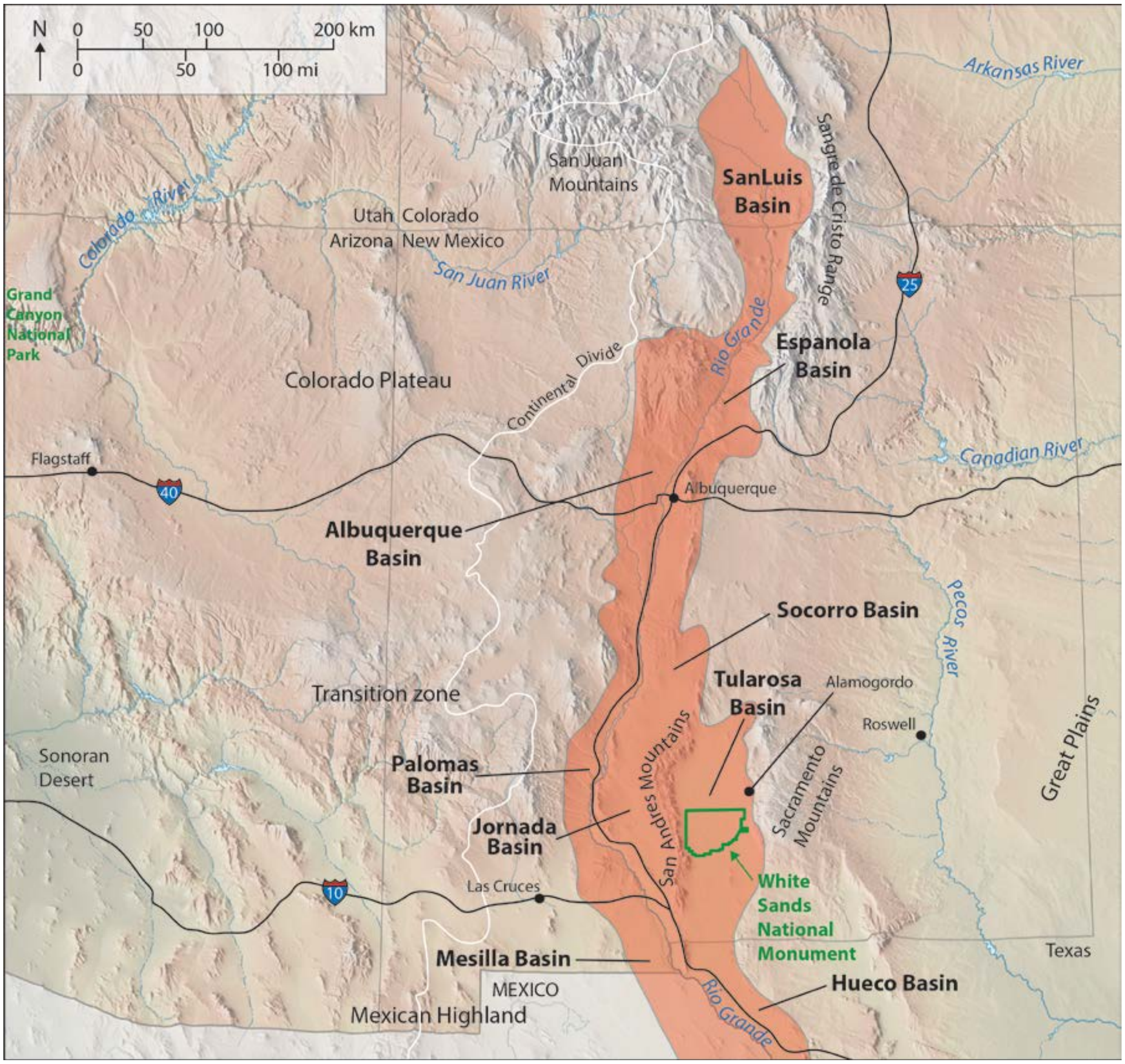

**Figure 2. Basins along the Rio Grande rift. The Tularosa Basin is one of nine basins along the Rio Grande rift. The orange shading on the figure denotes the Rio Grande rift. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Connell et al. (2005). Base map by Tom Patterson (National Park Service).**

**Figure 3. Ephemeral Lake Lucero. Dry much of the time, the playa of Lake Lucero becomes filled with water as a result of heavy precipitation and runoff from the San Andres Mountains and bajada west of White Sands National Monument. Under wet conditions, the lake may cover an area of 26 km$^2$ (10 mi$^2$), as shown here in 2004. National Park Service photograph.**

**Figure 4. Ancient Lake Otero sediments. The sediments of ancient Lake Otero (*sp_los*) provide gypsum sand to the White Sands dune field. Outcrops of these sediments (*lo_outcrops*) break down into sand-sized grains available for eolian transport. Photograph by David Bustos (White Sands National Monument).**

**Figure 5. Modern Lake Lucero sediments. Much of the sediment (white gypsum and halite crusts) produced by evaporation of modern Lake Lucero is fine grained and becomes transported beyond the dune system. Photograph by David Bustos (White Sands National Monument).**

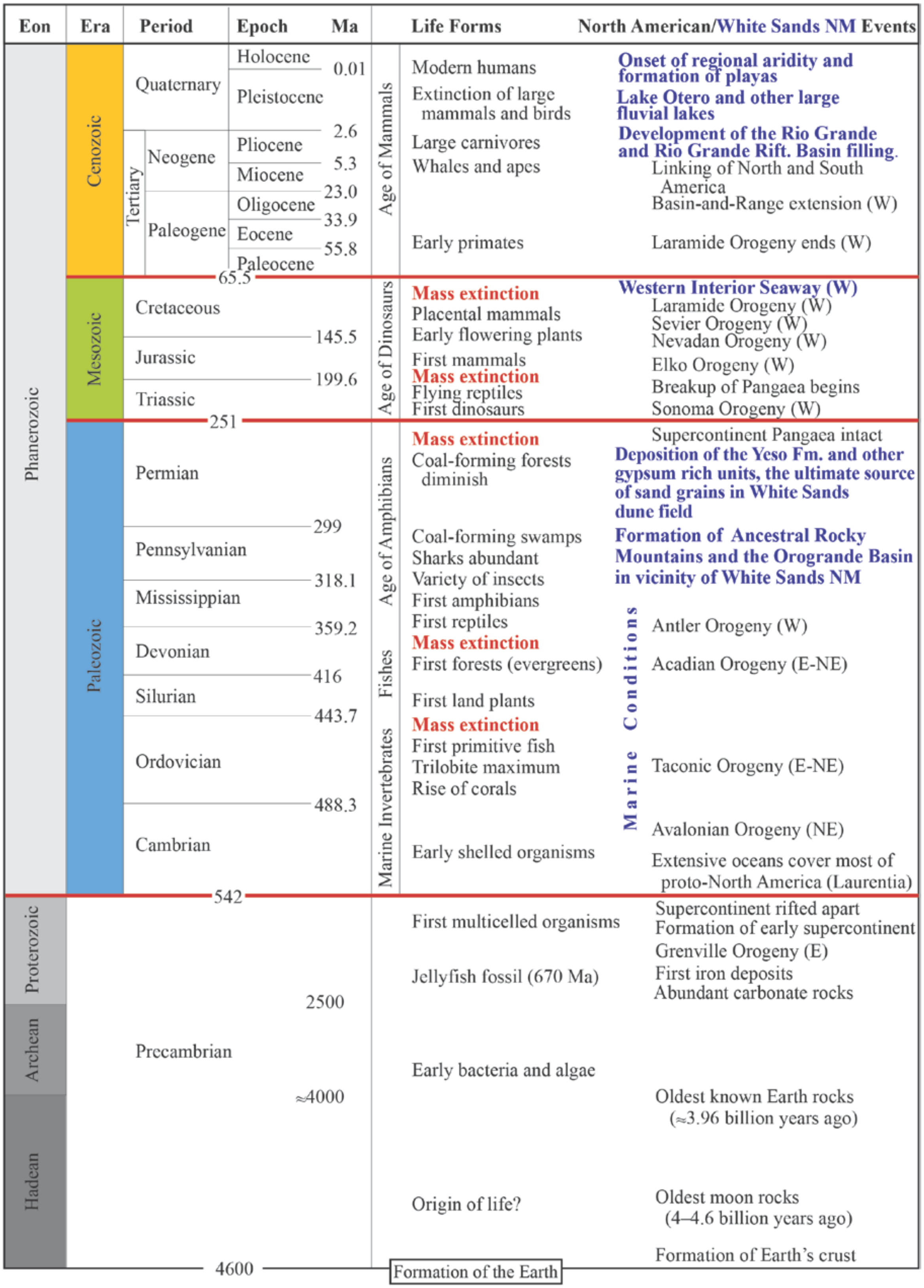

**Figure 6. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. Boundary ages are in millions of years (Ma). Red lines indicate major boundaries between eras. Major life history and tectonic events occurring on the North American continent and significant events for White Sands are included (in purple). Compass directions in parentheses indicate the regional location of individual geologic events. Graphic design by Trista Thornberry-Ehrlich (Colorado State University), adapted from geologic time scales published by the U.S. Geological Survey (http://pubs.usgs.gov/fs/2010/3059/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/ics%20chart/09_2010/StratChart2010.pdf).**

# Geologic Issues

*The Geologic Resources Division held a geologic scoping meeting for White Sands National Monument on 14 November 2007 to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes those discussions and highlights particular issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.*

In order to include geologic resources in the National Park Service's inventory and monitoring effort, the Geologic Resources Division proposed the geoindicators concept (Berger and Iams 1996) as an option for gathering information about geologic features and processes within the National Park System. In 2003, a geoindicators meeting was conducted at White Sands National Monument, and a geoindicators report was prepared (KellerLynn 2003). In 2007, during a Geologic Resource Evaluation (GRE) scoping meeting, participants developed a mapping plan, and identified issues, features, and processes of significance for resource management at White Sands National Monument (KellerLynn 2008a). The names of the participants at these meetings are listed in the appendix. Since that time, the Geologic Resources Inventory (GRI) has evolved and now links digital geologic data with issues, features, and processes associated with geologic resources within National Park System units. Discussions during the geoindicators and GRE meetings at White Sands National Monument identified the following geologic issues of management concern:

- Groundwater
- Surface Water
- Erosion
- Debris Flows and Rockfall
- Paleontological Resources
- Climate Change
- Monitoring Eolian Processes
- Infrastructure and Gypsum Sands
- Tamarisk
- White Sands Missile Range
- Mining and Energy Development
- Seismicity

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing many of these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. The NPS Geologic Resources Division initiated and funded the development of *Geological Monitoring* to provide guidance for resource managers seeking to establish the status and trends of geologic resources and processes within the National Park System, and to advance the understanding of how geologic processes impact ecosystem dynamics. Each chapter of *Geological Monitoring* covers a different geologic resource and includes recommendations for monitoring, including expertise, personnel, equipment, approximate cost, and labor intensity of suggested methods.

### Groundwater

Generally speaking, Geologic Resources Inventory (GRI) reports do not provide in-depth information about groundwater resources. Typically, resource management issues related to groundwater are beyond the scope of GRI reports, and are addressed by the NPS Water Resources Division. However, at White Sands National Monument, groundwater is inseparable from the geologic features and processes of the White Sands dune field.

The groundwater system at White Sands National Monument is complex, and much about it is unknown. Furthermore, a comprehensive model of the overall system has not been produced. In 2003, geoindicators participants thought that park managers and researchers would be able to "telescope" to the scale of the national monument from a basinwide model in preparation by the U.S. Geological Survey at that time. The resulting report, Huff (2005), simulated groundwater flow models of the Tularosa Basin, but the focus of the study was on the non-saline part of the basin-fill aquifer. Huff (2005) estimated rates of groundwater recharge and withdrawal to determine the effects of current and anticipated water use, which is indeed valuable information for park managers in order to respond in an informed way to the growth and development in the Tularosa Basin. Nevertheless, the playa and dune system of White Sands were not part of the model simulations of Huff (2005), namely because local faults were thought to separate the regional groundwater system from the shallow groundwater aquifer within the dune field (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012).

Analysis of recent scientific literature and reports for and by the National Park Service suggest that the groundwater system at White Sands National Monument is an integration of two systems—the larger groundwater system of the Tularosa Basin, and a shallow groundwater system within the White Sands dune field. As summarized by KellerLynn (2003, 2008a), exactly how these two systems interact and influence each other is unknown, but under investigation by researchers at the

New Mexico Institute of Mining and Technology (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012).

### Basinwide Groundwater System

The basinwide groundwater system is composed of basin fill derived by erosion of the uplifted terrain surrounding the basin, and fluvial deposits of the ancestral Rio Grande (Huff 2005). The various lithologies of the basin-fill deposits collectively form the basin-fill aquifer. The thickness of the basin-fill aquifer ranges from less than 30 m (100 ft) over areas of uplifted bedrock to greater than 1,200 m (3,930 ft) in the deepest parts of the basin (Huff 2005). These deposits include the Camp Rice Formation (geologic map unit symbol Qcp) and piedmont-slope deposits (Qpo, Qpg, Qpa, and Qpy) mapped by Seager et al. (1987). Piedmont-slope deposits are unconsolidated coarse- to fine-grained alluvial fans, which coalesce and form the bajada that rims the basin. The deposits grade basinward into finer grained alluvial, lacustrine, and eolian materials (see "Alluvial Deposits" section).

In the vicinity of White Sands National Monument, recharge enters the basin-fill aquifer by infiltration of intermittent, surface water flows into coarse sediment near the proximal end of alluvial fans. Underflow along stream channels associated with larger sub-basins also contributes recharge (Huff 2005). Precipitation falling on the basin floor probably does not contribute significantly to groundwater recharge, because of low precipitation and high evaporation rates in the Tularosa Basin (Huff 2005).

At White Sands National Monument, the most conspicuous feature of the basinwide groundwater system is Lake Lucero, which is concentrated in the deepest part of the active Holocene lake basin (geomorphic map unit symbol *ahlb*) and holds groundwater discharge. As noted in the 2003 geoindicators report, the relative proportions of water in Lake Lucero supplied by groundwater, surface water runoff, and precipitation are unknown (KellerLynn 2003). However, hydrologic investigation by researchers from the New Mexico Institute of Mining and Technology was addressing this question in 2012 (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012).

In order to understand the interrelationships among groundwater, Lake Lucero, and dune processes, geoindicators participants recommended monitoring the lake level and salinity of Lake Lucero, and suggested that a team of subject and resource experts be formed to develop a monitoring plan. Data gained through monitoring would help answer many questions, including the following, which were suggested by geoindicators participants in 2003: (1) What salts are produced in Lake Lucero? (2) When are they produced? (3) What are the relative amounts of groundwater and surface water? (4) How do changes in lake level affect salinity? (5) How do lake levels correspond to the regional aquifer and to potential perched aquifer(s) of the dune field?

### Dune-Field Groundwater System

In addition to the basinwide groundwater system, a shallow groundwater system appears to be perched within the White Sands dune field. Geoindicators participants discussed this dune-field system as the "unsaturated zone." Fryberger et al. (1988) referred to a "near-surface water table." Porter et al. (2009) noted "shallow water levels beneath the dunes," and reported a difference of 24 m (80 ft) in water elevation between the shallow water levels within the dune field and the deeper, regional aquifer. This difference supports the possibility of a shallow, perched aquifer within the dune field. Furthermore, during the geoindicators meeting, Bill Conrod—a natural resource specialist at White Sands National Monument from 1996 to 2005—described "abundant moisture in the sand above the aquitard." The "aquitard" is an impermeable layer that isolates the sand above from the general (basinwide) aquifer below. Conrod speculated that the aquitard was a layer of clay that underlies the gypsum dunes; it is presently exposed at a depth of about 8 m (25 ft) in the picnic-loop area of the national monument (Porter et al. 2009). Similarly, Kocurek et al. (2007) suggested that the perched water table within the White Sands dune field is a result of the contrast in permeability between the relatively porous dune-field sediment accumulation and the underlying, less porous strata of Lake Otero.

Throughout the entire White Sands dune field, the level of the groundwater fluctuates seasonally, reaching a low point in the summer due to intense evaporation (Schenk and Fryberger 1988). During the winter, surface water runoff is probably the cause of interdune ponding, for example in the Heart of the Sands area (Kocurek et al. 2007). Langford et al. (2009) measured the depth to groundwater within the White Sands dune field and found an average of 53 cm (21 in) at sites within the barchanoid dune field (bdf), and an average of 135 cm (53 in) at sites within the marginal parabolic dunes (mpd).

### Groundwater Interactions

How changes in the basinwide groundwater system will affect the perched aquifer within the dune field is not known (KellerLynn 2003). However, Porter et al. (2009) speculated that the perched aquifer would not be subject to groundwater pumping of the basinwide groundwater system. Water in the dunes probably exists as vadose (unsaturated) water, not as phreatic (saturated) water that could be pumped (Steve Fryberger, consultant, written communication, 29 March 2012). Investigators speculate that the water in the dune-field system is mainly meteoric (rainfall), whereas water just a short distance below is tied to the regional groundwater table. Meteoric water enters the dunes and infiltrates rapidly then seeps out at the base of the dunes, raising the water table.

As part of the hydrologic investigation by the New Mexico Institute of Mining and Technology, a pump test is scheduled for summer 2012 to look at conductivity (groundwater movement between the regional and perched, dune field aquifers) (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012). The hydrologic investigation by the New Mexico Institute of Mining and Technology has already provided some intriguing data about groundwater in the dune field. It appears that the water directly beneath the dunes is fresh and only 50 to 200 years old, while the water only 1.5 m (5 ft) away can be brackish and 500 to 2,000 years old (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012). Fryberger et al. (1983) observed similar, close-range separation of vadose and phreatic waters in eolian systems in Saudi Arabia.

Because the source of moisture for the dune-field system is most likely meteoric, evapotranspiration and recharge from precipitation are probably more significant factors for change within the dune-field system than regional groundwater pumping (Porter et al. 2009). Mean annual precipitation at White Sands National Monument is 25 cm (10 in), as measured in nearby Alamogordo, New Mexico. The effective evapotranspiration rate is eight times that much, approaching 203 cm (80 in) per year as a result of hot, dry, and windy environmental conditions (Porter et al. 2009).

Porter et al. (2009) noted that employees at White Sands National Monument have been measuring depth to groundwater (groundwater elevations) in eight wells at the national monument since 1997. Well data reflect climatic factors, including precipitation and evapotranspiration. In addition, water samples for these wells can be tested for hazardous chemicals (Bennett and Wilder 2009) (see "Surface Water" section). Notably, all of these wells tap the shallow, perched water table within the dune-field system. No wells at the national monument have been drilled into the basinwide groundwater system, though one of the wells is located near Lake Lucero. Porter et al. (2009) highlighted the significance of the location of wells at the national monument because data collected from within or outside the dune field would likely entail entirely different water budget considerations.

### Groundwater and Eolian Processes

A primary significance of the shallow groundwater system is its control of eolian processes within the dune field. Two basic mechanisms control the availability of material for eolian transport—cohesion and cementation (Fryberger 2001a). Cohesion (damp sand sticking together) forms larger "clumps" of sand, too large for eolian processes to move. Rainfall and a rise in the water table provide the necessary moisture for cohesion. Cementation also reduces the amount of loose sand available for transport. Cementation occurs when shallow, sulfate-rich ("saline") waters evaporate. Evaporation causes pore water within dune sediments to be supersaturated with respect to gypsum, which coats and binds sand grains together. The amount of cement increases with depth (Schenk and Fryberger 1988), though cementation of gypsum also occurs near the surface, creating a crust that is resistant to deflation (removal of loose material by wind).

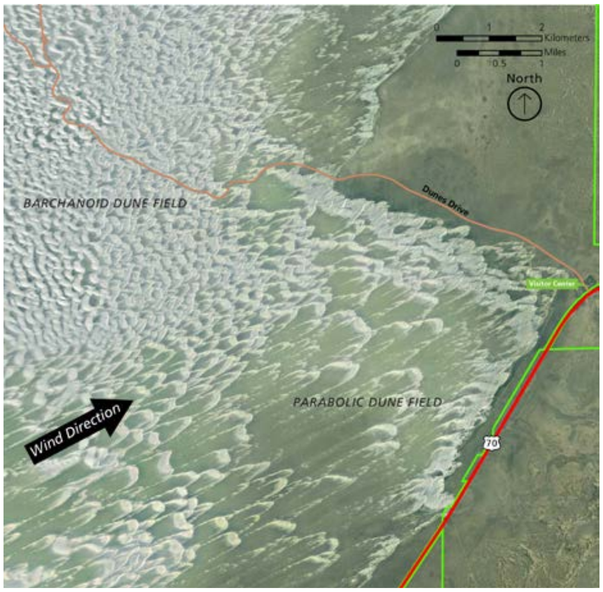

**Figure 7. White Sands dune field. At White Sands National Monument, marginal parabolic dunes, shaped like the mathematical curve of the same name, fringe the barchanoid dune field, which is composed of crescent-shaped dunes (see figs. 24 and 28). The primary wind direction at White Sands National Monument is from southwest to northeast. ArcGIS imagery compiled and annotated by Jason Kenworthy (NPS Geologic Resources Division).**

### Groundwater and Dune Morphology

Langford et al. (2009) suggested that groundwater salinity controls dune morphology. Parabolic dunes form in topographically high areas of the White Sands dune field (fig. 7), and eolian sediments within the parabolic dunes have accumulated above the water table, which is, on average, 135 cm (53 in) below the interdune surface. Meteoric freshwater (from precipitation) accumulates in the dune sediments above the water table, allowing vegetation growth. Vegetation, in turn, anchors sand, creating the parabolic form. By contrast, barchan dunes form in areas deflated to the saline groundwater table (fig. 7); these areas are devoid of vegetation (Langford et al. 2009). On average, the depth to the water table in the barchanoid dune field is 53 cm (21 in), and water is three times more saline than in areas of parabolic dunes. Langford et al. (2009) reported total dissolved solids of 5,000 mg/L in the barchan dunes and 1,600 mg/L in the parabolic dunes. As a result of the interactions among salinity, topography, and vegetation, parabolic dunes appear to be "freshwater dunes," while barchan dunes are "saline water dunes." Another dune morphology hypothesis is that the various types of dune forms, such as barchan and parabolic, at White Sands are the result of a decreasing rate of sand transport from west to east across the dune field (McKee 1966). Reitz et al. (2010) made a similar interpretation but applied new technology since McKee's time, that is, light detection and ranging (LIDAR)—a method that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses. The measured interval is converted to distance. The production of high-resolution digital elevation maps from LIDAR has resulted in a better understanding of the physical and chemical processes that shape landscapes. LIDAR data show a decrease in sediment transport from west to east across the White Sands dune field, which allows plants to take hold, become established, and stabilize the dune field (Reitz et al. 2010).

### Surface Water

About 105 km (65 mi) of intermittent streams enter White Sands National Monument from the San Andres Mountains to the west. Surface water runoff is very important to the dune-field system in this area (Steve Fryberger, consultant, written communication, 29 March 2012). For example, Lake Lucero floods immediately following rains in the mountains. This causes huge freshwater inputs to the active Holocene lake basin, including Lake Lucero and the other smaller lakes that make up the playa. In addition, sediment is washed down the alluvial fans during rainfall events. Although short lived, floods are significant events that drive sedimentation and cause "freshwater events" (Steve Fryberger, consultant, written communication, 29 March 2012) (see "Alluvial Deposits" section).

In contrast to the western side of White Sands National Monument, the Lost River is the only intermittent stream to enter the national monument from the east (fig. 8). With the exception of Lost River, surface water flow and its associated sediment input do not reach the playa (Lake Lucero) or scour platform (Alkali Flat) from the east because the dune field intercepts it. Furthermore, on the eastern side of the national monument, shifting sand associated with eolian processes has the ability to change the course of streams, thus affecting riparian habitat. Pupfish (*Cyprinodon tularosa*)—a state-listed threatened species—live in the Lost River, and in 2003 (at the time of the geoindicators meeting), no pupfish inhabited the national monument. However, as a result of migrating dunes, the course of the Lost River had changed by 2007 (the time of the GRE scoping meeting), bringing pupfish with it. Pupfish still enter the national monument with high rain events (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012).

Lost River is also affected by human activities. Population growth in the Alamogordo area, and the associated increase in water use, has lowered water levels of the Lost River (KellerLynn 2003, 2008a). Ranching activities also dewater the Lost River. Spring boxes in the Sacramento Mountains intercept water that historically would have flowed into Lost River (KellerLynn 2003, 2008a). In addition, Lost River is now infested with hundreds of acres of tamarisk (see "Tamarisk" section). Each tree can use as much as 380 L (100 gal) of water a day, or several million gallons per acre per year (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012). Invasion of tamarisk threatens to dry up the pupfish habitat at White Sands National Monument (National Park Service 2007).

Annual rainfall cycles, which include extreme storm events, are the primary driver of surface water flow at White Sands National Monument. Annual rainfall cycles also impact cyanobacteria blooms, plant and animal species, and the playa system (KellerLynn 2003). During wet periods, surface water runoff becomes concentrated in the Lost River channel, and as a result, the Lost River may transport perchlorate (a component of rocket fuel) into White Sands National Monument (KellerLynn 2003, 2008a). The source area of the perchlorate is a 16-km- (10-mi-) long, high-speed track for rocket tests at Holloman Air Force Base; the track is on the Lost River playa (KellerLynn 2003, 2008a).

**Figure 8. Lost River. The ephemeral Lost River is the only stream to flow into White Sands National Monument from the east. The water-filled portion of the channel in the photograph is approximately 0.3 m (1 ft) wide. Seager et al. (1987) mapped two geologic map units in this area: (1) older gypsiferous basin-floor and distal slope deposits (Qpg), and (2) younger piedmont-slope deposits (Qpy). The Lost River channel erodes into these deposits. Photograph by Katie KellerLynn (Colorado State University).**

The ephemeral nature of surface water at White Sands National Monument makes sampling difficult, and typical methods for monitoring fluvial systems may not apply. In order to adequately record "vital statistics" such as quantity, quality, and duration of surface water, a specialized approach is likely needed at White Sands National Monument. Monitoring would need to focus on summer storm events, during which the majority of annual precipitation falls. Because the storms are localized, however, availability of a team, organized and ready to dispatch at a moment's notice, may have the best opportunity for success. As an alternative, crest stage gages could be used to measure streamflow in remote areas (KellerLynn 2003, 2008a).

Lord et al. (2009)—the chapter about monitoring fluvial systems in *Geological Monitoring* (Young and Norby 2009)—provided information for designing an effective program for monitoring streamflow, and includes a number of pertinent questions that managers at White Sands National Monument may find useful in preparing or revising a monitoring plan. Contact the NPS Water

Resources Division (Fort Collins, Colorado) for assistance monitoring surface-water flow at the national monument.

### Erosion

Erosional processes exacerbated by anthropogenic activities are a concern for resource managers at White Sands National Monument (KellerLynn 2003, 2008a). In particular, archeological sites on the western side of the national monument have been impacted by human-induced erosion as a result of the construction of culverts on adjacent White Sands Missile Range (fig. 9). The Huntington Site, for example, has experienced accelerated erosion and downcutting (KellerLynn 2003, 2008a). This site was the location of a village near a permanent water source about 1100 CE (Common Era, preferred to A.D.) (Eidenbach 2010).

**Figure 9. Culverts at White Sands Missile Range. Changes in natural drainage patterns, for example by raised roadways and culverts at White Sands Missile Range, have changed surface water flow and exacerbated erosional processes, threatening archeological resources in adjacent White Sands National Monument. Photograph by Katie KellerLynn (Colorado State University), taken by permission during the 2003 geoindicators meeting.**

Additionally, the installation of fiber optic cables has created pathways ideal for concentrating and transporting storm water. The development of fiber optic lines has exacerbated erosion to archeological sites in the national monument (KellerLynn 2003, 2008a). Future repair, replacement, and addition of fiber optic lines are expected, and have the potential to introduce new damage to park resources (KellerLynn 2003, 2008a). Past land-use practices may also be drivers of increased erosion, for example, the introduction of invasive plants and animals, and fire suppression (Pete Biggam, National Park Service, soil scientist, written communication, 11 January 2008). Historic ranching practices led to overgrazing, in turn causing erosion. Impacts of overgrazing include loss of fine plant material and the transformation from grasslands (typical in the 1800s) to shrublands (typical today) (KellerLynn 2003). In general, shrublands reflect increased aridity and greater potential for erosion (KellerLynn 2003).

In the vicinity of the west-side bajada, several areas of gully erosion along the trail to Lake Lucero are of interest because of the information that these freshly exposed lake beds may yield, such as Pleistocene fossils (see “Paleontological Resources” section). Exposures of Lake Otero beds along the trail to Lake Lucero may provide interpretive opportunities during ranger-led walks. Contact the New Mexico Bureau of Geology and Mineral Resources for research in this area.

### Debris Flows and Rockfall

Most of the precipitation at White Sands National Monument comes during sudden storm events (KellerLynn 2003). High amounts of precipitation can induce mass wasting (gravity-driven processes), in particular, activating debris flows in the bajada on the western side of the national monument. Debris flows are a safety concern, as they have killed people on White Sands Missile Range and in a nearby Bureau of Land Management (BLM) campground (KellerLynn 2003, 2008a).

Most of the material transported through the bajada is gravel, sand, or silt. However, large boulders occasionally roll down the slopes of the bajada onto the boundary road in White Sands National Monument. Such boulders have knocked out sections of the national monument’s perimeter fence (KellerLynn 2008a).

Wieczorek and Snyder (2009)—the chapter about monitoring slope movements in *Geological Monitoring* (Young and Norby 2009)—described various types of slope movements and mass-wasting triggers, and suggested five methods and “vital signs” for monitoring slope movements: (1) types of landslides, (2) landslide triggers and causes, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessing landslide hazards and risks. Resource managers at White Sands National Monument may find this information useful for monitoring mass wasting within the bajada.

### Paleontological Resources

In the past decade, information about paleontological resources at White Sands National Monument has gone from basic to booming, with anticipation for more fossil discoveries (and greater understanding) in the future. In 2003, Greg McDonald, paleontologist for the NPS Geologic Resources Division at that time, summarized the paleontological resources at White Sands National Monument for the geoindicators report (KellerLynn 2003). In 2007, Vincent Santucci and colleagues from the National Park Service compiled available paleontological information and references for White Sands National Monument and other parks in the Chihuahuan Desert Network (Santucci et al. 2007).

#### Fossil Trackways

Since 2007, investigators have discovered hundreds of fossilized tracks throughout the national monument in addition to those already found, greatly expanding the number of track sites known from the Tularosa Basin

**Figure 10. Fossil tracks. Approximately 18,000 to 30,000 years ago, Pleistocene animals, for example mammoth or mastodon, traveled to and from ancient Lake Otero, leaving their tracks in the sediments. Recent discoveries of hundreds of fossilized tracks throughout the national monument have greatly expanded the number of track sites known from the Tularosa Basin. Photographs by David Bustos (White Sands National Monument).**

(Bustos 2011a). Fossil track sites are the most significant paleontological resources at White Sands National Monument to date, and may represent one of the largest concentrations of Cenozoic fossil tracks within the United States and possibly the world (Bustos 2011a) (fig. 10). Significant vertebrate tracks and trackways have been found on Alkali Flat and the southern shoreline of Lake Lucero (Lucas et al. 2007; Kesler 2011).

The fossilized tracks are primarily *Proboscipeda panfamilia*, produced by Pleistocene proboscidean (mammoth or mastodon). The fossil tracks are from large carnivores (felids or canids) and artiodactyls (even-toed ungulates) (Santucci 2012). The majority of these ancient animals left their footprints as they traveled to and along the shorelines of ancient Lake Otero and surrounding wetlands (Bustos 2011a). Based on radiocarbon dating of plant fragments in the Lake Otero strata in which the tracks occur, Allen et al. (2006) provided an estimated age of 31,000 years before present for the trackways on the west side Lake Otero, and 18,000 before present from core samples associated with the trackways on the east side Lake Otero taken in May of 2012.

At the request of park managers, in May 2012, investigators from the Natural Resources Conservation Service (NRCS), who were conducting a soil survey at the adjacent White Sands Missile Range, dug five trenches adjacent to the monument exposing different stratigraphic layers in the area of one of the trackways at the national monument. Researchers from the New Mexico Bureau of Geology and Mineral Resources sampled and analyzed materials from these trenches (fig. 11). Many of the samples looked promising for organic materials and microfossils that would aid in refining radiometric ages and determining environmental conditions at the time of deposition (Santucci 2012).

**Figure 11. Lake Otero strata. In May 2012, the Natural Resources Conservation Service (NRCS) dug five trenches at different stratigraphic positions in the sediments adjacent to White Sands National Monument. Researchers from the New Mexico Bureau of Geology and Mineral Resources sampled and documented these sediments. Organic materials (dark layers) and microfossils may help researchers refine the timing of deposition and determine the conditions of the depositional environment. Photograph by Vincent Santucci (NPS Geologic Resources Division).**

#### Body Fossils

Lake Otero sediments also likely contain "body fossils" of Pleistocene vertebrates, invertebrates, and plants. Vandiver (1936) reported the occurrence of fossil bones and teeth of a mammoth from within the boundaries of White Sands National Monument. Vandiver (1936) also described some external molds of plants at the national monument. These are apparently the remains of cacti and other plants that were replaced or encrusted by gypsum crystals.

Investigators have found Pleistocene fossil vertebrates and mollusks at a number of localities just north of the national monument within White Sands Missile Range (Lucas et al. 2002; Morgan and Lucas 2002). These fossils were recovered from clays within Lake Otero strata (Lucas and Hawley 2002). The vertebrate fossils from Alkali Flat and Alkali Spring on the White Sands Missile Range include mammoth (*Mammuthus columbi*), extinct horse (*Equus conversidens*), and western camel (*Camelops hesternus*), as well as several species of small vertebrates (frog, lizard, snake, vole, muskrat, and mouse) (Gary Morgan, New Mexico Museum of Natural History and Science, assistant curator of paleontology, written communication, 27 June 2012). The fossils were derived from three different lithologic units of Lake Otero strata—a bed of green gypsiferous clay, and two units consisting of gypsum sand and coarse gravelly sand. Finding similar fossils at White Sands National Monument is certainly possible, if not probable (Gary Morgan, written communication, 27 June 2012).

Based on the same geologic units to the north of the national monument, 2007 scoping participants (see Appendix) proposed that fossil pupfish, amphibians, and snails may occur within the national monument's boundaries. Indeed, since the 2007 meeting, Lake Otero sediments within the national monument have yielded bones and scales, possibly of pupfish (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, written communication, 16 May 2008).

#### Microfossils

Lake Otero sediments also contain microfossils such as ostracodes and diatoms. Bruce Allen (New Mexico Bureau of Geology and Mineral Resources) separated microfossils from Lake Otero sediments and obtained radiocarbon ages from a sequence of lake beds. The lake beds span two episodes of lake formation and intervening erosion, and range in age from more than 40,000 years ago to about 15,000 years ago. Microfossils provide important paleoecological information for determining past climate and environmental conditions at White Sands National Monument (see "Climate Change" section).

#### Future Discovery and Investigations

Recent discoveries of fossil resources at White Sands National Monument highlight the probability of future discoveries. Although a thorough, field-based inventory has yet to be conducted at the national monument, some work has begun using Geoscientists-in-the-Parks (GIP) and Youth in Parks (YIP) funding sources. For instance, two students from New Mexico State University began documenting the fragile fossil trackways in summer 2011. Because professional paleontologists are interested in studying the trackways and other paleontological resources, an opportunity for mentoring and collaboration between students and professionals in the field may be possible at White Sands National Monument.

The paleontological resources at White Sands National Monument continue to be of interest to researchers. Paleontologists at the New Mexico Museum of Natural History and Science would be willing to assist the National Park Service with a field-based paleontological survey in the future (Gary Morgan, written communication, 27 June 2012). Furthermore, Bruce Allen (New Mexico Bureau of Geology and Mineral Resources) would be interested in continuing a study of fossil microinvertebrates in Lake Otero sediments (KellerLynn 2008a).

#### Monitoring

The fossil tracks at White Sands National Monument occur in the gypsiferous playa muds of Lake Otero sediments. The fossils undergo rapid deterioration once they are exposed at the surface deposition (Santucci 2012). Santucci et al. (2009)—the paleontological resources chapter in *Geological Monitoring* (Young and Norby 2009)—described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. In order to fully document, age date, and understand the geology, stratigraphy, and paleoenvironment associated with the fossil trackways, the National Park Service (White Sands National Monument) and the New Mexico Institute of Mining and Technology established a task agreement to accomplish paleontological resource research in the monument. The NPS Geologic Resources Division provided funding to support the geologic field work and evaluation identified in the task agreement.

### Climate Change

A topic of great importance today is how quickly large changes in climate, referred to as "abrupt climate change," can occur (Committee on Abrupt Climate Change, National Research Council 2002). These types of changes are very large, 10°C (18°F) or larger, and fast (years to decades). The pace of change is startling—1°C (1.8°F) per year, which is 100 times faster than today's warming (Jim White, Institute of Arctic and Alpine Research [INSTAAR], director, e-mail communication, 17 January 2012). An awareness of the timing of past climate-change events may help resource managers prepare for future changes at White Sands National Monument.

Changes in eolian systems attributed to the effects of climate variability on annual to decadal time scales include changes in the magnitude and frequency of dust storms (Middleton 1989), sand transport rates (Lancaster and Helm 2000), and activation or stabilization of areas of sand dunes (Wolfe 1997). At White Sands National Monument, climate change could have a dramatic effect on the dune system. For instance, more frequent, intense, and longer-lasting droughts would result in a drop in the water table, in turn impacting dune movement and formation (Rip Langford, University of Texas at El Paso, professor, written communication, 9 April 2012). Such droughts could result in a larger deflation area, less vegetation to stabilize existing dunes, and changes in dune morphology. Reactivation of dunes could occur, with potentially larger dunes forming. Finally, less runoff available to feed Lake Lucero could create more dunes moving out of the active Holocene lake basin (KellerLynn 2008a).

Researchers from the New Mexico Bureau of Geology and Mineral Resources and White Sands Missile Range proposed that ancient pluvial lakes, such as Lake Otero, which formed during times of exceptionally heavy rainfall, are tools for understanding climate change (Allen 1994). However, because of security precautions at adjacent White Sands Missile Range, ancient Lake Otero has not been as accessible for scientific investigations as other pluvial lakes in New Mexico. Consequently, an understanding of the history of Lake Otero is not as comprehensive as that of Lake Estancia to the north. Studies at Lake Estancia—including Bachhuber (1990), Behnke and Platts (1990), Frenzel (1992), Allen and Anderson (1993, 2000), Anderson et al. (2002), and Menking et al. (2004)—have demonstrated the wealth of information contained in pluvial lake sediments. For instance, shoreline locations and elevations show past fluctuations in lake levels when climate was wetter than today. Bioturbated (organism-disturbed) sediments document the presence of aquatic worms and other bottom-dwelling organisms, which colonized the lake basins as waters freshened and expanded. Various species of ostracodes indicate changes in salinity when ancient lake waters either freshened and expanded, or were saltier and lower (Allen 1994).

In 2003, geoindicators participants noted that similar studies of Lake Otero sediments would provide equally valuable information (KellerLynn 2003). In 2012, core samples were taken at White Sands National Monument that may reveal greater information about Lake Otero (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012). While the proportion of Lake Otero sediments preserved at White Sands National Monument is small compared to the overall size of the lake (and the area contained within White Sands Missile Range), the portion within the national monument is critical because it preserves the latest part of the history of Lake Otero, leading to the development of playa Lake Lucero.

Except that Lake Lucero is younger and much smaller than Lake Otero at its maximum, the relationship between Lake Otero and Lake Lucero is unclear (Fryberger 2001a). Much remains to be discovered about the "transition" between the deposition of Lake Otero sediments and the present-day playa deposits (Fryberger 2001a).

For additional information regarding climate change and the National Park Service, including the NPS Climate Change Response Strategy, refer to the NPS Climate Change Response Program website (http://www.nature.nps.gov/climatechange/index.cfm, accessed 12 October 2012). Karl et al. (2009) summarized climate change impacts by region across the United States. Loehman (2010) provided talking points to understand the science of climate change and the impacts to arid lands.

### Monitoring Eolian Processes

Eolian processes involve erosion, transportation, and deposition of sediment by wind. Erosion in eolian landscapes is natural, and deflation is a primary reason for the existence of the White Sands dune field. However, changes in supply and availability of sand, vegetation cover, and soil moisture can affect eolian processes and the landforms they create. Such changes may be induced by land-use or climate alterations, including impacts to vegetation cover by grazing pressure or trampling, and increased sediment availability due to disturbance by animals or off-road vehicles (see "Climate Change" section).

Lancaster (2009)—the chapter about eolian features and processes in *Geological Monitoring* (Young and Norby 2009)—provided a brief introduction to eolian processes and landforms, and highlighted 10 vital signs: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) area of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state, (9) rates of dune migration, and (10) erosion and deposition patterns of dunes. The discussion of each vital sign provided estimated costs of the monitoring methods, a complexity rating for each method, an explanation of methodologies, and recommended timing of monitoring activity. Lancaster (2009) also discussed study design and case studies, including the Desert Winds Project at Gold Spring, Arizona, and Jornada, New Mexico, now administered by the Desert Research Institute. This information may be useful for resource management and monitoring at White Sands National Monument.

Gary Kocurek (University of Texas at Austin) is preparing a protocol for dune monitoring using light detection and ranging (LIDAR) at National Park System units in the Chihuahuan Desert Network. LIDAR is a highly accurate mapping method and will provide the first 3D topographic data of the White Sands dune field (Yost 2009). The purpose of this project is to collect data that will help determine similarities in shape and size of dunes, detect trends in the direction of migration, and observe interactions between dunes. By conducting multiple LIDAR surveys, researchers can detect changes over time, including the migration rate of dunes, changes in shape related to the wind regime, and the dynamic exchange of sediment between dunes and the substrate over which they migrate (Yost 2009).

### Infrastructure and Gypsum Sand

At present, infrastructure at White Sands National Monument includes Dunes Drive (fig. 12); eight administrative, visitor, and service structures, including the historic visitor center built by the Civil Works Administration (CWA); a fence that surrounds the national monument; trails and boardwalks; a picnic area and restroom at Heart of the Sands (fig. 13); and primitive backcountry campsites.

**Figure 12. Dunes Drive. The National Park Service "plows" Dunes Driver in order to make the dune field more accessible to visitors. Because eolian processes constantly erode and transport the gypsum sand, continuous maintenance is required. Plowing the road has lowered the land surface in the vicinity of Dunes Drive, resulting in flooding and road closures during wet periods. Photograph by Katie KellerLynn (Colorado State University).**

An awareness of eolian processes and the saline groundwater system is necessary for developing sustainable infrastructure in areas of gypsum sand. For example, Dunes Drive requires regular maintenance to keep it accessible for visitors. The road is paved with asphalt for approximately 3 km (2 mi) from U.S. Route 70 to the edge of the dune field. Sand blows across and collects on the surface of the pavement, which staff at the national monument regularly clears. Beyond the paved portion, Dunes Drive enters the dune field, and the road is constructed of compacted gypsum (fig. 12). Staff at the national monument maintains the gypsum portion by

**Figure 13. Flooded picnic area. Development in eolian landscapes must take into consideration special conditions caused by blowing sand, changing levels of the water table, and the corrosive nature of saline groundwater. The photograph of the flooded picnic shelters was taken on 7 September 2006 at White Sands National Monument. National Park Service photograph.**

Developing sustainable infrastructure in gypsum sands also requires an understanding of the mineral gypsum. According to Robert G. Myers (White Sands Missile Range, now retired), gypsum sand is a real problem for corrosion, especially in association with water. Add temperature and wind, and gypsum becomes "glue" (Robert G. Myers, White Sands Missile Range, geologist, e-mail communication to Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, 23 January 2012). Such glue can coat vehicles to the point of being unable to open the doors (Robert G. Myers, e-mail communication to Dave Love, 23 January 2012). Furthermore, gypsum "glue" is one of the reasons that the space–shuttle landing strip at White Sands Missile Range was a problem when it was second in line after Edwards Air Force Base in the early 1980s (Robert G. Myers, e-mail communication to Dave Love, 23 January 2012).

Additionally, in the presence of freshwater, dissolution of gypsum is a problem. Dissolution frequently occurs in the cemented gypsic and calcic soils of the Tularosa Basin, resulting in collapsed areas with little or no prior surface indication (Pete Biggam, National Park Service, soil scientist, written communication, 11 January 2008). Openings such as desiccation cracks or animal burrows provide starting points where water collection causes significant subsurface dissolution. Buried water and utility lines, and poorly compacted construction excavations, provide a less-dense matrix that increases water infiltration and saturation below grade. Inadvertent leaks of water lines exacerbate this condition. The water, whether from natural sources or unnatural leaks, dissolves the gypsum (Pete Biggam, written communication, 11 January 2008). One noteworthy example at White Sands National Monument is the formation of a sinkhole in the maintenance area parking lot in 1975 (fig. 14). The sinkhole developed as a result of a leaking water line. Air conditioner leaks can also cause sinkholes (KellerLynn 2008a). At White Sands National Monument, and nearby developed areas such as the Holloman Air Force Base, dissolution of gypsum is undercutting the edges of parking lots and curbs, and impacting utility trenches and buildings (KellerLynn 2003, 2008a). The national monument's historic visitor center appears to be subsiding, possibly as a result of dissolution. However, the building's mass and soil compaction are likely the cause (Pete Biggam, written communication, 11 January 2008a). Stabilizing the visitor center and mitigating further water leaks are important with respect to the overall maintenance of park facilities.

Other units in the National Park System with sand dunes—such as Padre Island National Seashore in Texas (KellerLynn 2010a), Assateague Island National Seashore in Maryland (Schupp in review), and Great Sand Dunes National Park and Preserve in Colorado (Graham 2006a)—share similar issues of shifting sands, and may have mitigation techniques applicable for the blowing sands of White Sands National Monument. Citations for those parks' Geologic Resources Inventory reports are listed. Also, scoping cooperators suggested contacting

Gary Kocurek (University of Texas at Austin) and David Loope (University of Nebraska) for guidance on developing and maintaining infrastructure in eolian, gypsum sands (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, and Steve Fryberger, consultant, e-mail communications, January 2012).

**Figure 14. Sinkhole. Because gypsum readily dissolves in freshwater, leaky water lines can cause dissolution and collapse. Collapse occurred, creating a sinkhole, in the maintenance area parking lot at White Sands National Monument in 1975. National Park Service photograph.**

### Tamarisk

Tamarisk (*Tamarix* spp.) was introduced into the United States as a wind break in the early 1850s. The exotic plant is also called "salt cedar" because it is well suited for areas with saline ("salty") groundwater. At White Sands National Monument, tamarisk has invaded many interdune areas, where groundwater is near the surface (fig. 15). The plants threaten to choke out native vegetation. Tamarisk also threatens the pupfish (*Cyprinodon tularosa*) population at White Sands National Monument, which naturally occurs in only a few springs and one stream (Lost River) in the Tularosa Basin (see "Surface Water" section).

In addition, tamarisk impacts eolian (dune) processes. It creates giant vegetative pedestals by drying out the surrounding dune, which then rapidly erodes away. Pedestals can reach 15 m (50 ft) high (fig. 16). Moreover, tamarisk changes local wind patterns and causes "unnatural" dune formation by trapping sand in front of the "natural" dune field. If multiple dunes were allowed to be established, the entire dune system could be disrupted (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012).

The National Park Service has a program in place to reduce or eliminate tamarisk, but tamarisk is difficult to eradicate. It re-sprouts readily after cutting or burning.

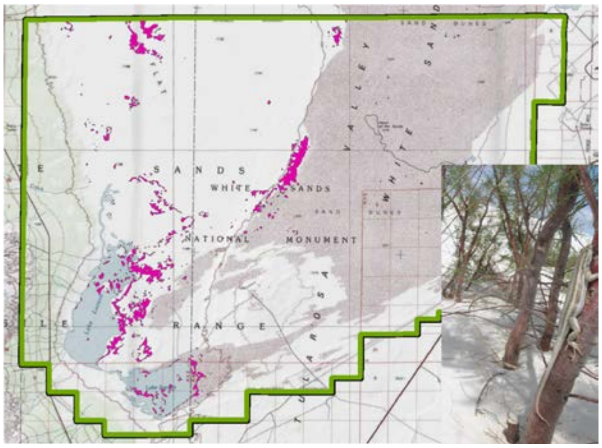

**Figure 15. Tamarisk invasion. Tamarisk (see fig. 16) has invaded many interdune areas, where water is near the surface. The pink color on the figure marks areas of invasion at White Sands National Monument. These nonnative plants change local wind patterns and impact eolian processes by lowering the water table. National Park Service graphic.**

**Figure 16. Tamarisk pedestal. Invasive tamarisk, which was introduced into the American Southwest in the 1850s to serve as wind breaks, creates giant vegetative pedestals by drying out the surrounding dune, which then rapidly erodes away. Photograph by David Bustos (White Sands National Monument).**

### White Sands Missile Range

After the attack on Pearl Harbor in 1942, military operations commenced in what is now White Sands Missile Range, and continue to the present day. White Sands Missile Range surrounds the national monument, and NPS operations must take into account regularly scheduled military tests. Dunes Drive is periodically closed for periods of up to three hours during testing at the missile range. Most significantly, unexploded ordnance, which inadvertently lands in White Sands

National Monument, is an ongoing safety concern for visitors and staff.

An unusual phenomenon at the national monument is the creation of impact craters from errant bombs. A particular geologic curiosity associated with bomb impacts is melted gypsum, essentially an anthropogenic fulgurite. Within the national monument, natural fulgurite forms via lightning strikes on dune-ridge tops (fig. 17). Lightning penetrates the ground and melts the sand along the path of the strike, creating branches or rods below ground and crusts on the surface. Fusion also may vaporize the center of fulgurite, resulting in a tube. Bomb explosions create similar features.

**Figure 17. Lightning strike. When lightning strikes a dune, fulgurite—a glassy tube or crust that is produced by fusion—may form. National Park Service photograph.**

Military-owned roads and culverts upslope of the national monument are of particular management concern for White Sands National Monument. These roads and culverts have changed the surface-water flow regime of Department of Defense (DOD) and National Park Service (NPS) lands (KellerLynn 2003, 2008a). Surface water flow originates in the bajada along the western boundary of the national monument. Roads serve as berms that inhibit surface flow across Alkali Flat, and culverts concentrate flow and induce erosion (see "Erosion" section).

### Mining and Energy Development

No abandoned mineral lands (AML) sites are listed for White Sands National Monument in the NPS AML database, which is maintained by the Geologic Resources Division (accessed 9 December 2011). However, legacies of mining include quarries for sodium carbonate ("soda ash") and gypsum, a plaster of paris plant, and a trail to a salt mine at White Sands National Monument. These features predate establishment of the national monument. Disturbances at these sites are minimal, and no reclamation is required (KellerLynn 2008a). Nature is taking its course: the sediments are breaking down naturally, removing traces of mining activities.

Though never developed, the Department of Defense investigated oil and gas potential at White Sands Missile Range. No oil and gas leasing occurs at White Sands National Monument.

Finally, rocks related to mineralization in the Organ and Orogrande mining districts west and south of White Sands National Monument, were mapped by Seager et al. (1987). These units [plutonic rocks (Tis), non-foliated rhyolite intrusive (Tri), and intermediate-composition plutonic rocks (Tii)] are associated with Oligocene volcanism (see "Geologic History" section). Dikes and stocks of these units intrude older rocks, for example the Pennsylvanian Lead Camp (PNlc) and Panther Seep (PNps) formations, and the Permian Hueco (Ph) and Abo (Pa) formations (Seager et al. 1987). In addition, Silurian Fussleman Dolomite (SOfm) hosts barite, fluorite, and base-metal deposits (Seager et al. 1987). These deposits crop out in the Organ mining district in the Organ Mountains west of the national monument (Seager 1981). Precambrian rocks, also in the Organ district, host gold-copper-quartz mineralization. Based on scoping discussions (KellerLynn 2003, 2008a), however, mining operations in these districts are not known to impact park resources.

### Seismic Activity

Scoping participants concluded that seismic risk at White Sands National Monument is low (KellerLynn 2008a). However, faults and the down-dropped are notable geologic features in the vicinity of the national monument. The Alamogordo fault at the base of the Sacramento Mountains bounds the eastern side of the Tularosa Basin; the San Andres fault bounds the western side (fig. 1). Both faults have associated seismic events. The central segment of the Alamogordo fault has an estimated minimum slip rate of 0.11 mm (0.004 in) per year; the southern segment of the San Andres fault has a slip rate of 0.15 mm (0.006 in) per year (Machette 1987).

A wealth of information about seismic activity and earthquake hazards is available for resource managers at White Sands National Monument. For instance, Braile (2009)—the chapter in *Geological Monitoring* (Young and Norby 2009) about earthquakes and seismic activity—described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. The nearest seismic stations to White Sands National Monument are southeast of Socorro, New Mexico, and at Dagger Draw near Carlsbad, New Mexico.

In addition, the U.S. Geological Survey (USGS) has earthquake information available for New Mexico at http://earthquake.usgs.gov/earthquakes/states/index.php?regionID=31 (accessed 17 January 2012). This USGS online information includes earthquake histories, Quaternary faults and folds, seismicity maps, seismic hazard maps, notable earthquakes, recent earthquakes, and links to local institutions. The bureau published catalogs of earthquake activity for New Mexico and bordering areas that cover the time period 1869–2004 (Sanford et al. 2002, 2006).

# Geologic Features and Processes

*Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in White Sands National Monument.*

In a general west-to-east direction across White Sands National Monument, the geomorphic map (Fryberger 2001b) separates the White Sands dune field into four active geomorphic areas:

- Active Holocene Lake Basin
- Scour Platform
- Barchanoid Dune Field
- Marginal Parabolic Dunes

Fryberger (2001b) also mapped "miscellaneous geologic features," which generally occur beyond these four geomorphic areas, though some of these features developed within these areas (see Geomorphic Map Unit Properties Table).

The discussion that follows is structured using these basic geomorphic areas, but makes connections to the geologic map of Seager et al. (1987). The map unit properties tables (in pocket) summarize the connections between Fryberger (2001b) and Seager et al. (1987).

In addition to these four geomorphic areas, a widespread alluvial deposit on the western side of the active Holocene lake basin is a conspicuous feature on the White Sands landscape. This feature is composed of alluvial fans that coalesce to form a bajada (fig. 18). Seager et al. (1987) mapped this feature as piedmont-slope deposits (geologic map unit symbols Qpy, Qpa, Qpo, Qcp, and Qpg), which are alluvial (deposited by running water) rather than eolian (windblown) in nature. The pediment-slope deposits occur at the base of the San Andres Mountains.

Other geologic features and processes of interest at White Sands National Monument include the following:

- Source of Gypsum Sand
- White Sands as an Analogue for Mars
- Biological Soil Crusts
- Geothermal Features and Processes

### Active Holocene Lake Basin

The active Holocene lake basin (geomorphic map unit symbol *ahlb*) is situated on the upwind, southwestern side of the White Sands dune field. This area extends north to south along the base of the alluvial fans (see "Alluvial Deposits" section), and upwind of the scour platform (see "Scour Platform" section). The active Holocene lake basin is characterized by several large playas, including North Lake Lucero (*ahlb_nll*) and South Lake Lucero (*ahlb_sll*), and many other smaller hollows, depressions, or low areas that periodically host standing water.

**Figure 18. Bajada. Also referred to as piedmont-slope deposits or coalescing alluvial fans, the bajada on the western side of White Sands National Monument is a primary geomorphic feature on the landscape. The bajada developed at the base of the San Andres Mountains, and it drapes across the mountain front in this photograph. The field-trip participants are standing on the active Holocene lake basin, just east of the bajada. The high albedo of selenite is very apparent on the playa surface. Photograph by Katie KellerLynn (Colorado State University).**

The extent and position of the active Holocene lake basin is defined by tectonics, and was created by downward displacement along the faults that bound the Tularosa Basin. The margins of Pleistocene and older alluvial fans that were deposited at the base of the San Andres Mountains delineate the western, down-dropped margin of the Tularosa Basin. These older fans are partly lithified, and consist of sands and gravels eroded from the nearby mountains (see "Alluvial Deposits" section). Modern drainages have formed on these older fans, and actively strip sediments and deliver them to the margin of the active Holocene lake basin (Steve Fryberber, consultant, e-mail communication, 7 September 2012).

On a smaller scale, the location of individual playas within the active Holocene lake basin reflects various processes including local faulting and wind scour. In addition, fluvial avulsion (shifting of channels) and associated sheet flow influence the location of individual playas. As a result of avulsion at the front of older alluvial fans, where a channel enters the break in slope / lower gradient of the playa surface, entry points to the playa may no longer receive sediment, resulting in subsidence and inversion (Steve Fryberger, consultant, e-mail communication, 7 September 2012).

An interesting feature of the active Holocene lake basin is the combination of freshwater and saline-water processes that occur at or near the surface. Because meteoric (rain) water is fresh, it is distinct from the saline groundwater system. When flooding occurs, the saline system is temporarily overwhelmed at the surface by the input of freshwater (Steve Fryberger, consultant, written communication, 29 March 2012). When meteoric waters evaporate from the playa, freshly dissolved gypsum (hydrous calcium sulfate, $CaSO_4 \cdot 2H_2O$) and halite (sodium chloride, NaCl) are re-precipitated, and either incorporated into the playa's strata or removed by the wind (fig. 5). The crystals and minerals created by the evaporation of meteoric waters can be quite different from those precipitated by saline groundwater (Steve Fryberger, consultant, written communication, 29 March 2012).

In addition to groundwater discharge at Lake Lucero (see "Groundwater" section), the presence of water in the active Holocene lake basin is related to elevation and the frequency of flooding (Fryberger 2001a). Lake Lucero lies in the lowest part of the basin and floods more frequently than higher lakes to the east and north. During flooding events, meteoric water flows down the alluvial fans or falls directly on the active Holocene lake basin. Ponding, though temporary, also occurs at the terminus of freshwater inflows from drainages down alluvial fans (see "Alluvial Deposits" section).

### Lake Otero Strata

As mapped by Seager et al. (1987), the deposits that underlie the active Holocene lake basin are gypsiferous lake deposits (Qlg). More recent investigations have identified these deposits as sediments of ancient Lake Otero (fig. 19), which covered the area during the Pleistocene Epoch and predates the modern playa system. These deposits represent gypsum sedimentation in the culminating phase of Lake Otero, as the system dried out with the onset of regional aridity during the Holocene Epoch. Lake Otero strata consist of laminated clays and silts, as well as gypsiferous marls, limestone, and massive silts containing large gypsum crystals (Langford 2003). The sediments of ancient Lake Otero also include greenish lacustrine shales (Fryberger 2001a). The coarse crystalline detrital gypsum was probably deposited in an evaporite playa or a very shallow lake. Shale layers probably represent the lake during more freshwater conditions (Steve Fryberger, consultant, written communication, 29 March 2012).

### Ancient Lake Otero and Modern Lake Lucero

At its maximum extent, ancient Lake Otero was 1,204 m (3,950 ft) above sea level and covered 2,000 $km^2$ (770 $mi^2$) (Allen 2005). At some time following the latest deposition of Lake Otero sediments, widespread wind scour occurred, deflating the basin in which modern Lake Lucero now exists.

Modern Lake Lucero It is a dry playa, with damp sediments beneath the surface. Occasionally summer storms furnish enough precipitation and runoff to cover the playa surface with standing water (Allmendinger and Titus 1973). As a result of flooding, Lake Lucero can cover up to 26 $km^2$ (10 $mi^2$) (National Park Service 2010) (fig. 4).

Modern Lake Lucero is composed of a central muddy area that Fryberger (2001a) referred to as a "saline mudflat." The mudflat consists of black or brownish muds with some sand, commonly haloturbated (churned by salt-crystal formation) and sometimes bioturbated (churned by organisms). Fans and other alluvial deposits, consisting mainly of quartz sands and some gypsum recycled from underlying Pleistocene deposits, occur along the western edge of this saline mudflat. Sediments of the fans intertongue with sediments of the saline mudflat.

Lake Lucero provides habitat for invertebrates such as diatoms, ostracodes, foraminifera, and fairy shrimp. Migrating birds also use the lake and shoreline. Spadefoot toads, which burrow into the lake sediments during dry periods, "erupt in song" when wet conditions return. Because Lake Lucero is an important component of the White Sands ecosystem, contaminated runoff from missile-range tests on Alkali Flat is a particular management concern (see "White Sands Missile Range" section). Lake Lucero is accessible through White Sands Missile Range during ranger-led walks (National Park Service 2010).

### Other Features of the Active Holocene Lake Basin

In addition to Lake Otero strata, individual playas (geomorphic map unit symbol *ahlb_ap*), sand sheets (*ahlb_ss*), patchy sand (*ahlb_ps*), and more active sandy areas (*ahlb_masa*) are features of the active Holocene lake basin. The active Holocene lake basin also hosts some parabolic dunes (*ahlb_fab*) and deposits of quartz called "quartz clastic wedges" (*ahlb_qcw*), which spill onto the playa surface during storms. Most of the individual playas have rims of eolian sand that form sand sheets or coppice dunes. Coppice dunes are mound-like accumulations of sand, forming around vegetation. Eolian sand sheets are sandy plains, formed by wind processes, commonly occurring on the margins of dunes or between dune belts. Fryberger (2001b) mapped sand sheets within the active Holocene lake basin (*ahlb*) and marginal parabolic dunes (*mpd*) (see "Marginal Parabolic Dunes" section). Sand sheets are important transitional features, from one geomorphic area to another, or from dune-interdune systems to non-eolian fluvial or lacustrine deposits. At White Sands National Monument, sand sheets, which are commonly vegetated, occur between clusters of active parabolic dunes, such as the open areas southwest of the visitor center. Also, sand sheets occur along the downwind margin of Alkali Flat and around the NE 30 observation station, which serves as a distinctive landmark on the otherwise flat landscape composed of sand sheets (fig. 20).

**Figure 19. Active Holocene lake basin. Much of the time, ephemeral Lake Lucero is dry, but after heavy precipitation and runoff, water can cover the playa, creating a lake up to 26 $km^2$ (10 $mi^2$) (fig. 4). The active, modern lake basin has been scoured into the sediment of ancient Lake Otero (left photos). When the playa is covered with water (right photo), wind erosion and the action of waves break down the Lake Otero sediments, making these available for eolian transport. Photographs by David Bustos (White Sands National Monument).**

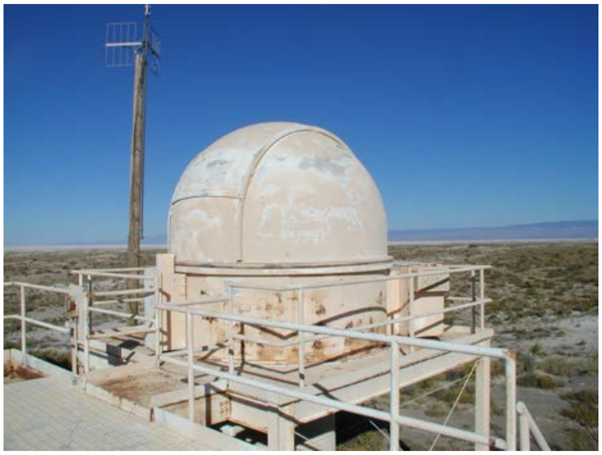

**Figure 20. NE 30 observation station. Situated on the highest point in White Sands National Monument, the NE 30 site has become a geographic landmark in the flat White Sands landscape. The station is surrounded by sand sheets. Photograph by Katie KellerLynn (Colorado State University).**

### Scour Platform

Toward the east, the active Holocene lake basin (ahlb) gives way to the scour platform (sp), which is known as "Alkali Flat" at White Sands (fig. 21). The scour platform is an area of net sediment loss, with erosional features such as deflation surfaces (*sp_fe_ds* and *sp_d?*). The scour platform is primarily composed of beds of Lake Otero (*sp_los*), which eolian processes erode, supplying the dunes with fresh sand. Some truncated dunes (*sp_todd_d*) and a few active parabolic dunes (*sp_fab*) also occur on the scour platform, as well as areas of patchy active sand (*sp_pas*), which are indicative of wind scour.

With respect to the surficial deposits mapped by Seager et al. (1987), gypsiferous lake deposits (Qlg) and basin-floor deposits and lake beds (Qbfg) are the main units that cover the scour platform. Some active gypsum dunes (Qega) also scatter across the area. Fryberger (2001a) correlated Qlg with Lake Otero; Qbfg predates Lake Otero.

Figure 21. Alkali Flat. Alkali Flat typifies the scour platform at White Sands National Monument. It is an area of net sediment loss. As shown in the photograph, the San Andres Mountains rise above the scour platform on the western side of the national monument. National Park Service photograph.

The presence of paleontological resources is a distinctive feature of the scour platform (see "Paleontological Resources" section). As older sediments are exposed by eolian processes, fossilized animal tracks have been uncovered (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012). Other features of the scour platform (discussed below) include yardangs (*yrdng*), zibar dunes (*sp_zd*), and scattered low domelike dunes (*sp_sldd*). In addition, crystal pedestal or domes occur on the scour platform (see "Crystal Pedestals/Domes" section).

### Yardangs

White Sands is a premier U.S. site for erosional ridges called yardangs (*yrdng*), which can be up to 6 m (20 ft) high and 40 m (130 ft) wide. These landforms are made of soft but coherent material, often in the shape of a boat's hull, though the variety at White Sands is great (Steve Fryberger, consultant, e-mail communication, 25 December 2007) (fig. 22).

The tendency for yardang formation within the White Sands dune field is probably a result of (1) the persistent regime of wind scour, especially downwind of Lake Lucero; and (2) the cemented nature of the gypsum sands in some places (Schenk and Fryberger 1988). The sands are cemented well enough to support these steep aerodynamic forms, but not so much that the wind is unable to erode them (Fryberger 2001a).

Yardangs exist on the southern margins of the scour platform, in some locations of marginal parabolic dunes, and downwind of Lake Lucero. Particularly fine examples occur along the eastern side of South Lake Lucero; these are mapped in the GIS data and labeled on figure 23.

### Zibar Dunes

"Zibar" is an Arabic term for low, rolling sands, commonly poorly sorted, that have greater topographic relief than sand sheets but less than dunes (Steve Fryberger, consultant, written communication, 28 March 2012). For a discussion of sand sheets, see the previous section "Other Features of the Active Holocene Lake Basin." Zibar dunes (*sp_zd*) are commonly found in the Middle East's vast deserts, between the famous megadunes of the region. Zibar dunes tend to be more coarse-grained than most dunes. A distinctive feature of zibar dunes is that they do not develop slip faces. A slip face is the steeply sloping surface on the lee side of a dune that stands at or near the angle of repose of sand. Whenever the angle of repose is exceeded and sand falls down the slip face, a dune advances downwind.

Figure 22. Yardang. White Sands is a premier U.S. site for erosional ridges called yardangs. These photos show different views of the same yardang. The sands are cemented well enough to support steep aerodynamic forms, but not so much that the wind is unable to erode them. Photographs by Steve Fryberger.

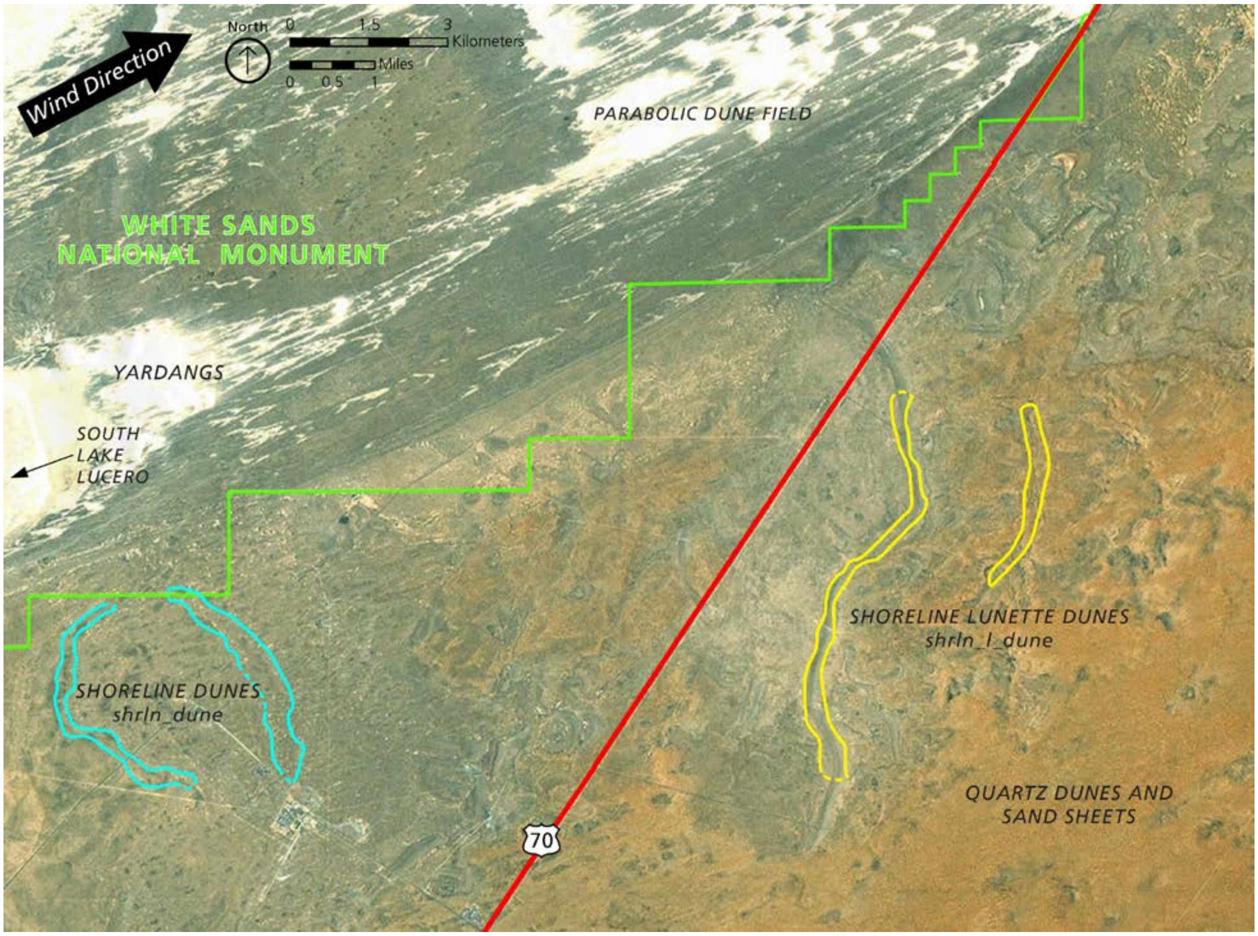

**Figure 23. Yardangs, shoreline dunes, and lunette dunes. Yardangs, shoreline dunes, and lunette dunes are miscellaneous geomorphic features as mapped by Fryberger (2001b). A triangular-shaped yardang field stretches to the northeast of South Lake Lucero. Lunettes occur primarily to the south of White Sands National Monument, and are shown at the bottom of the figure as crescent-shaped features that may have formed along the shorelines of ancient Lake Otero. The reddish color at the lower, right corner of the figure represents quartz dunes and sand sheets. ArcGIS imagery compiled and annotated by Jason Kenworthy (Geologic Resources Division). Map units from Fryberger (2001b).**

### Dome Dunes

Generally speaking, dome dunes are low domes of well-sorted sand. Steve Fryberger and colleagues have trenched dome dunes at White Sands National Monument and found slip face cross-bedding (Steve Fryberger, consultant, written communication, 29 March 2012). McKee and Douglass (1971) measured the rate of movement for dome dunes at White Sands National Monument as 7.3–12 m (24–38 ft) per year; this is the highest rates of dune movement for dunes at White Sands. McKee and Douglass (1971) referred to dome dunes as "embryonic," and this dune form is completely transitional with barchan dunes (Steve Fryberger, consultant, written communication, 29 March 2012) (fig. 24). Fryberger (2001b) mapped dome dunes (*sp_sldd*) on the scour platform at White Sands National Monument.

Scoping participants observed that fewer dome dunes appeared to be forming at White Sands than in the past (KellerLynn 2008a). This may be a climate-related development (see "Climate Change" section), which could lead to the eventual loss of dome dunes from the White Sands landscape (KellerLynn 2008a).

### Crystal Pedestals/Domes

Crystal pedestals—also referred to as "crystal domes" (see Szynkiewicz 2010b)—are distinctive features on the scour platform. These curious pipe-like accumulations of coarse gypsum reach 3 m (10 ft) high and 3 m (10 ft) wide (Anna Szynkiewicz, University of Texas at El Paso, research assistant professor, written communication, 20 March 2012). These pedestals/domes are distinctively aligned on Alkali Flat, and are characterized by cementation resulting from the growth of large gypsum (selenite) crystals around and within the domes (fig. 25). The selenite crystals protected these features from erosion during periods of extensive deflation during the Holocene Epoch (the last 11,700 years) (Szynkiewicz et al. 2010b).

Investigators have proposed that crystal domes formed where deeply circulating groundwater interacted with rocks of early-Permian age in the Tularosa Basin (fig. 26). The alignment is due to the existence of faults, which serve as pathways for fluids from the subsurface (Szynkiewicz et al. 2010b). The precipitated minerals built up on the surface of the scour platform as a result of groundwater seepage along these fractures. Hydrogen

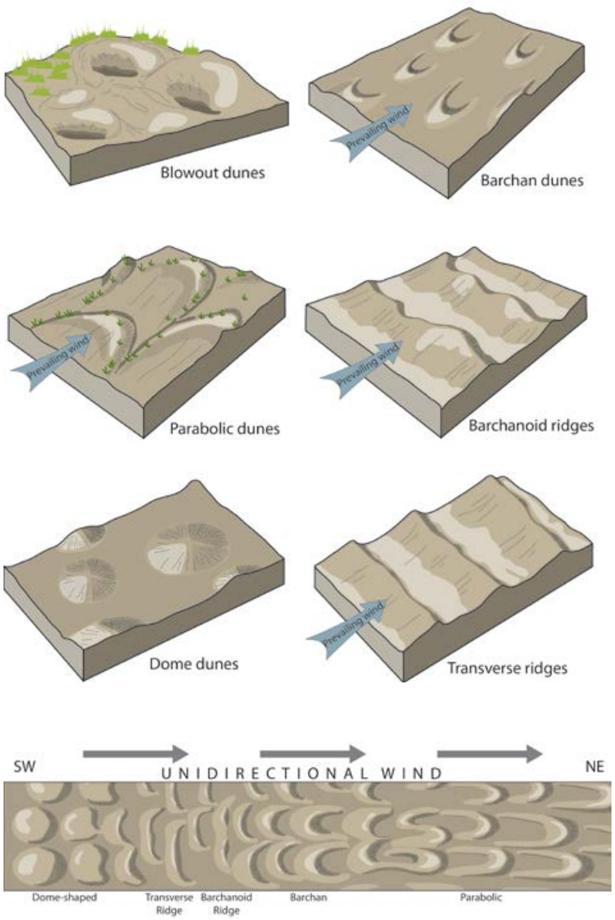

**Figure 24. Types of dunes at White Sands National Monument. The primary types of dunes at White Sands National Monument are barchan and parabolic dunes, with some dome dunes. Dome dunes are an embryonic form of other dunes such as barchans. Blowout dunes are comparable to parabolic dunes, but without the parabolic "arms." Transverse ridges and barchanoid ridges also form in the White Sands dune field. Sand supply, wind direction, and interactions among groundwater salinity, topographic elevation, and vegetation growth affect dune morphology. The lower graphic illustrates barchanoid dune morphologies. Graphics by Trista Thornberry-Ehrlich (Colorado State University) after Fryberger et al. (1990) and McKee (1983).**

and sulfur isotopes from the selenite crystals within the pedestals/domes indicate that the groundwater originated as precipitation in the surrounding highlands, which infiltrated deeply into the bedrock beneath the basin and was returned to the surface along preexisting faults (Szynkiewicz et al. 2010b). For related discussions of this process, see "Source of Gypsum Sand" and "White Sands as an Analogue for Mars" sections.

### Barchanoid Dune Field

The barchanoid dune field (*bdf*) comprises most of the modern, active White Sands dune field, and is a major component of the White Sands' ecosystem and the species within it. The dune field hosts more than 25 endemic plant and animal species, and associated micro-habitats for these species (Bustos 2011b). A specific example of the dune field's influence on ecology is the color of some local populations, for example the bleached earless lizard (*Holbrookia maculata ruthveni*), which have adapted to match the sand (fig. 27).

The barchanoid dune field was mapped as one unit—active gypsum dunes (Qega)—by Seager et al. (1987). The geomorphic map of Fryberger (2001b) divided the barchanoid dune field into four subunits: (1) a central sand ridge (*bdf_csr*), (2) barchan dune-outliers (*bdf_bd_o*), (3) barchan dunes-active (*bdf_bd_a*), and (4) possible barchan dunes? (*bdf_b?*). When creating the geomorphic map for White Sands, Fryberger (2001b) mapped "barchan dunes?" and other "possible features" from air photos, which are indicated by "?" on the data. These areas have not been ground checked (Steve Fryberger, consultant, written communication, 29 March 2012).

Barchan dunes at White Sands National Monument average 8–12 m (26–39 ft) in height (Ewing and Kocurek 2010), and move between 1.8 and 4.0 m (6 and 13 ft) per year (McKee and Douglass 1971). Barchans are crescent-shaped dunes with the convex side facing the wind; the "arms," also called "wings" or "horns," of the dunes face downwind (figs. 24 and 28).

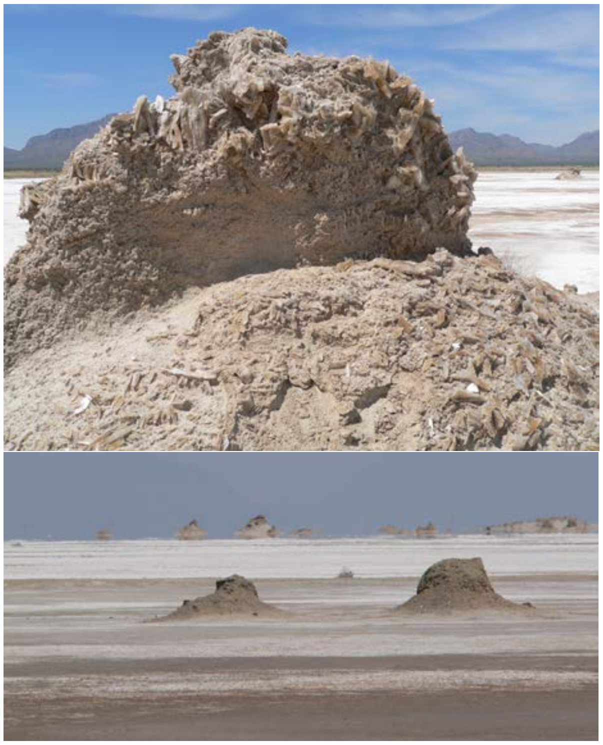

**Figure 25. Crystal pedestals/domes. Rising up to 3 m (10 ft) above the surface of Alkali Flat, crystal pedestals, also called "crystal domes," are composed predominantly of coarse crystals of selenite gypsum. Linear alignment of the domes suggests groundwater discharge onto the scour platform along fractures in the subsurface. Photographs by David Bustos (White Sands National Monument).**

The orientation of the barchan dunes indicates migration to the northeast under dominant winds from the southwest (fig. 29). In actuality, some seasonality in the wind regime occurs. During the late winter and spring, winds from the southwest and west are strongest. During the fall and winter, winds from the north-northwest occur. Winds from the south-southeast occur during the late spring and summer (Kocurek et al. 2007).

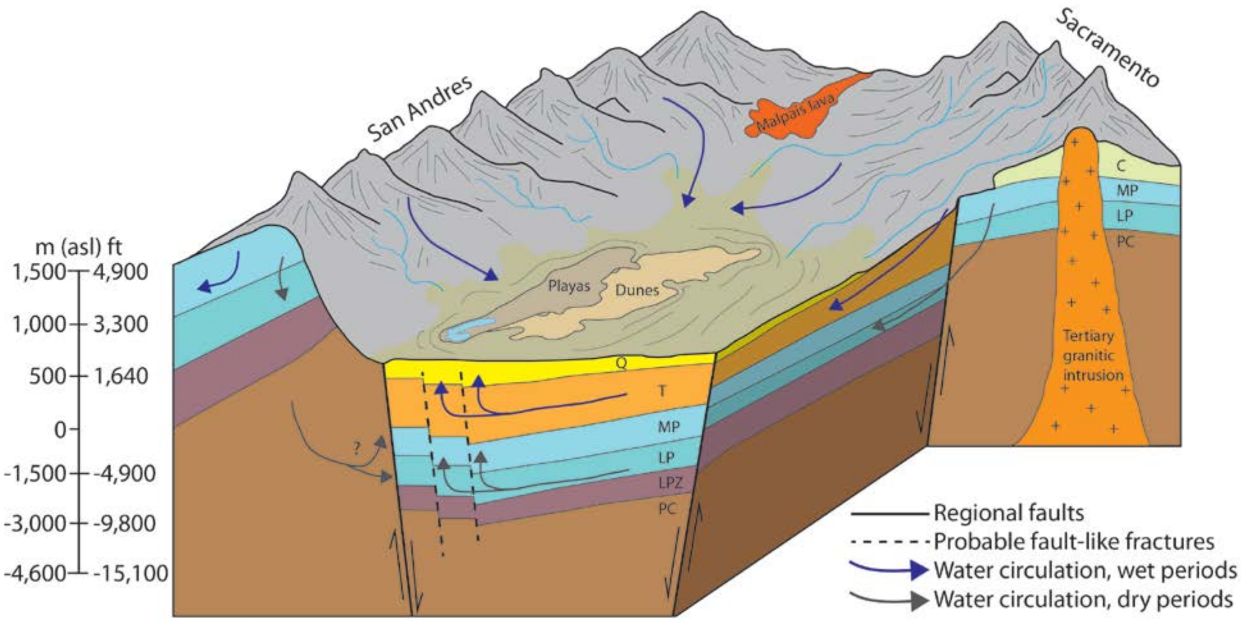

**Figure 26. Groundwater flow. A conceptual model of the Tularosa Basin shows groundwater flow under varied climate conditions (wet and dry). During wetter climatic conditions, groundwater flow originates at higher elevations in the San Andres and Sacramento mountains. Q = Quaternary basin fill. T = Tertiary basin fill. C = Upper Cretaceous sedimentary strata. MP = middle Permian evaporitic strata. LP = lower Permian evaporitic strata. LPZ = lower Paleozoic sedimentary strata. PC = Precambrian crystalline rocks. From Szynkiewicz et al. (2009), modified by Trista Thornberry-Ehrlich (Colorado State University).**

**Figure 27. Bleached earless lizard. The dune field is a primary component of the White Sands ecosystem, affecting its inhabitants. Some local populations have adapted to match the white, gypsum sand, including bleached earless lizard (*Holbrookia maculata ruthveni*). National Park Service photograph.**

**Figure 28. Barchanoid dune field. Crescent-shaped barchan dunes make up most of the active White Sands dune field. Photograph by David Bustos (White Sands National Monument).**

Recent work by Ewing and Kocurek (2010) on the dynamics of the dune field has revealed some previously unrealized dune-to-dune interactions; in particular, crest lines, which connect the highest points of dunes, break apart and recombine on a time scale of decades. Investigators and park managers had no idea this was occurring (David Bustos, White Sands National Monument, biologist, written communication, 18 April 2012). Researchers chose crest lines as a morphological feature to characterize the interactions among dunes because crest lines are large-scale, slow-evolving forms from which the rearrangement of preexisting states can be documented. Researchers can measure variations in the length of crest lines and the spacing between crest lines.

Time-series images of the White Sands dune field show that large-scale, fully developed, eolian crescentic dunes do not simply migrate in isolation, but rather interact with each other in organized patterns (Ewing and Kocurek 2010). Crest lines may merge together laterally or link at their ends, which are examples of constructive interactions that give rise to a more organized pattern in the dune field. By contrast, a crest line may break apart or split, which pushes the system to a more disorganized state. Also, crest lines may break apart then migrate downwind and attach or collide, which is a process that is neutral in overall pattern development but causes significant changes within a dune (Ewing and Kocurek 2010).

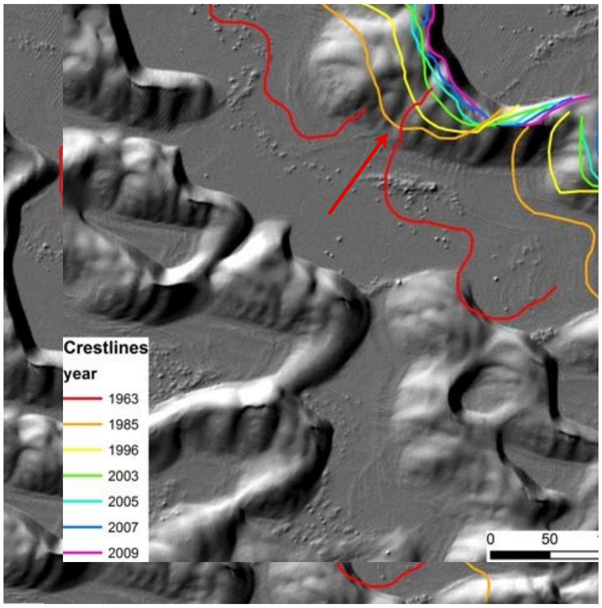

**Figure 29. Migration of dunes 1963–2009. The dunes at White Sands National Monument migrate both to the northeast and east because of the variable wind regime. The colored lines on the image indicate seven locations of the crest line of a migrating dune between 1963 and 2009. The image shows the Heart of the Sands area of White Sands National Monument. LIDAR image by University of Texas at Austin.**

### Marginal Parabolic Dunes

Marginal parabolic dunes (*mpd*) fringe the southern and eastern edges of the barchanoid dune field (*bdf*) at White Sands National Monument. The boundary between the barchanoid dune field and the marginal parabolic dunes is marked by damp interdunes (see "Interdunes" section). Parabolic dunes, whose shape mimics the mathematical curve of the same name, have a central mass of sand and long arms that extend upwind (figs. 7 and 24). Commonly the arms are anchored by vegetation. This landform contrasts barchan dunes, which have shorter arms that extend downwind (figs. 7 and 24).

Fryberger (2001b) mapped both active (*mdp_aap*, *mpd_ap*, and *mpd_pd*) and inactive areas of parabolic dunes. Inactive dunes, mostly parabolic (*i_dune_p*), which are a "miscellaneous geomorphic feature," occur primarily south of the barchanoid dune field. Abundant active parabolic dunes (*mpd_aap*) occur mostly in the dune field north of the national monument, though active small parabolic dunes (*mpd_asp*) occur in a northeast–southwest transect between Lake Lucero and the visitor center, and at other scattered locations (see Overview of Digital Geomorphic Data). In White Sands National Monument, active parabolic dunes move 0.6–2.4 m (2–8 ft) per year (McKee and Douglass 1971). Parabolic dunes on the eastern margin, farthest from the source of sand, show no movement to a maximum amount of movement of 1.5 m (5 ft) per year (McKee and Douglass 1971). Fryberger (2001b) mapped quartz dunes (*mpd_qd?*) and quartz sand (*mpd_qs?*) among the marginal parabolic dunes in the northeastern corner of the national monument; Seager et al. (1987) identified these features as part of the distal piedmont-slope deposits (Qpg).

### Interdunes

Interdunes occur everywhere there are dunes (Gary Kocurek, University of Texas at Austin, professor, written communication, 24 March 2012). Typically, interdunes are flat-lying areas surrounded by dunes, but they have many forms: erosional, damp, dry, wet, evaporitic, vegetated, slightly vegetated, or unvegetated (Frygerber 2001a). The type of dune that surrounds an interdune, as well as the dune's movement, influences the interdune's form. The many forms of interdunes are often indicative of the influence of groundwater, with respect to salinity and moisture (fig. 30). In the Heart of the Sands area, for example, interdunes experience constant cycles of change, becoming flooded as a result of a rise in the water table following winter rains, remaining damp for a period of time, then becoming evaporitic as water evaporates. When the water table falls, salts are deposited near the surface.

The geomorphic map for White Sands National Monument (Fryberger 2001b) does not include an "interdune" map unit. This is because they are part and parcel of dune areas. Moreover, interdunes are commonly overridden by moving dunes, obscuring their positions. From a mapper's perspective, interdunes are "a fluid kind of entity;" as dunes move, the interdunes would move on the map; whereas the "barchanoid dune field" as a unit does not change position much. As such, the barchanoid dune field (bdf) is a "mappable entity," whereas interdunes are not (Steve Fryberger, consultant, written communication, 29 March 2012). Creating a map showing interdune types (e.g., dry, wet, damp, or erosional), possibly by geomorphic area, could be a future mapping project. Mappers would need to develop criteria specific to White Sands for defining an appropriate framework and process (Steve Fryberger, consultant, written communication, 29 March 2012).

The most common type of interdune within the barchanoid dune field at White Sands is evaporitic (Fryberger 2001a). This type of interdune is dominated by salt crusts and salt ridges, which form in areas of intense evaporation. The growth of salt crystals creates a rough surface, with shallow pans separated by salt ridges (Fryberger 2001a). These crusts create a hardened surface that can resist eolian erosion. Crusts form within the upper 0.5–5 cm (0.2–2 in) of the interdune surface and consist of interlocked salt crystals. Salt crusts are ephemeral phenomena. Salt crusts change with precipitation and evaporation, and at times may be easily eroded. Below the salt crust, algae and lichen grow as part of a biotic soil crust (Shields et al. 1957) (see "Biological Soil Crusts" section).

Figure 30. Interdunes. The flat-lying areas between dunes, called "interdunes," may be erosional, depositional, damp, dry, wet, evaporitic, vegetated, slightly vegetated, unvegetated, or a combination thereof. The variety of interdunes at White Sands is great. The interdune in the upper photograph is dry and slightly erosional, but also slightly vegetated. The interdune in the lower photograph is wet and partly erosional/partly depositional. These photographs were taken in May 2007. The lower photograph shows remnants (ponding on the left) of a heavy monsoon season in 2006, when the groundwater table rose above the surface and flooded the interdune in winter 2006–2007. The elongated deposits on the right in the lower photograph indicate the extent of flooding and formed after water evaporated. Photographs by Anna Szynkiewicz (University of Texas at El Paso).

Salt ridges are bumpy, ripple-like structures that develop near the surface of the interdune as a result of evaporation and precipitation of dissolved salts. At White Sands, salt ridges are accompanied by the growth of mats of microorganisms and algae (Kocurek et al. 2007). According to Fryberger et al. (1988), algal mats at White Sands exist nearly everywhere the sand is wet or very damp. Interestingly, when the interdunes are water saturated, the algae release gas bubbles that produce vesicular ("bubbly") sand in the upper tens of millimeters of sediment (Fryberger et al. 1988). Algae appear most active during "freshwater flooding" events (Steve Fryberger, consultant, written communication, 29 March 2012). Many of the interdunes record "flood and dry" sequences, resulting from flooding following winter rains, in addition to rise and fall of the saline groundwater table. Dark layers in some interdune trenches record past algal layers (Steve Fryberger, consultant, written communication, 29 March 2012) (fig. 11).

### Miscellaneous Geomorphic Features

Fryberger (2001b) noted and mapped miscellaneous geomorphic features associated with the White Sands dune field. These features generally exist beyond the four contiguous geomorphic areas. They include such features as Lake Otero sediments (*lo_outcrops*), shoreline dunes (*shrln_dune*), shoreline lunette dunes (*shrln_l_dune*), and sabkhas (*sabkha*).

#### Lake Otero Sediments and Selenite Crystals

Notable outcrops of Lake Otero sediments (*lo_outcrops*) occur on the western shore of Lake Lucero. These outcrops help to define the limit of the active Holocene lake basin, including the Lake Lucero playa system and related areas of modern flooding.

A distinctive feature of these outcrops is selenite (the large crystal variety of gypsum) (fig. 31). In the outcrops at White Sands, selenite crystals form a horizon between lacustrine and alluvial deposits, which Allmendinger and Titus (1973) suggested was a clue to the crystals' origin. They proposed Laguna Madre as a modern analogue for selenite-crystal growth at ancient Lake Otero. Laguna Madre—a portion of which is in Padre Island National Seashore in Texas—is the largest hypersaline lagoon in the world, extending 445 km (277 mi) from the mouth of Corpus Cristi Bay in Texas to the Rio Soto La Marina in Tamaulipas, Mexico (Tunnell and Judd 2002; KellerLynn 2010a).

**Figure 31. Selenite and gypsum. Hydrous calcium sulfate ($CaSO_4 \bullet 2H_2O$), commonly known by its geologic name "gypsum," occurs in a variety of forms at White Sands National Monument, including silt- and sand-sized grains, small crystals (see fig. 32), and selenite, which is the large-crystal variety of gypsum. Selenite crystals are commonly 15 cm (6 in) or longer. Sand-sized grains of gypsum, which are transported by eolian processes, make up the dunes at White Sands. Silt-sized particles are worked into lacustrine sediments or blown beyond the dune-field system. Photographs by David Bustos (White Sands National Monument).**

Similarities in the formation of the selenite deposits at Laguna Madre and Lake Otero include the following: (1) both developed in an environment of high evaporation, (2) both developed into large crystals and rosettes (fig. 32), (3) both formed in saline-water environments, and (4) both incorporated sand-sized particles while displacing finer grained materials (Allmendinger and Titus 1973).

### Shoreline and Lunette Dunes

Shoreline dunes (*shrln_dune*) and shoreline lunette dunes (*shrln_l_dune*) are other miscellaneous geomorphic features at White Sands National Monument. Both types of dunes occur at the southern edge of the national monument and record the location of past shorelines.

Circular lakes will commonly have a dune on the downwind half of the lakeshore, suggesting in planform the shape of the moon, thus the term "lunette." The crescent- or half-moon shapes are distinctive on aerial photographs (fig. 23). The curve of the lake determines the shape of the dune. The exposed shoreline is the immediate source of sand for the lunette dunes, which seem to be non-migratory, probably as a result of cementation and vegetation. Most of the lunette dunes at White Sands are probably older than the present active dune field, and have been somewhat eroded (Fryberger 2001a).

**Figure 32. Gypsum rosette and crystals. An analogue for the formation of gypsum in ancient Lake Otero is Laguna Madre in Texas and Mexico. The selenite deposits in both these bodies of water developed into large crystals and rosettes. The left photograph is of a gypsum rosette from the Laguna Madre area of Padre Island National Seashore. The photo on the rights shows gypsum crystals at Lake Lucero. National Park Service photograph (top) available online at http://www.nps.gov/pais/naturescience/geologicformations.htm (accessed 19 September 2012). National Park Service photograph (bottom) by David Bustos (White Sands National Monument).**

### Sabkhas

The Arabic term “sabkha” refers to flat salty areas, often partly flooded by tides, along the coast of the Arabian Gulf (Fryberger et al. 1983). There are also continental sabkhas, such as Umm As Samim (“Mother of Poisons”) in Oman, which have formed where water and evaporites (sediments deposited from solution as a result of evaporation) collect in a basin with centripetal drainage. In these areas, eolian and other types of deposition occur near the water table. If the water table is rising, sediments accumulate, commonly through a series of build-and-erode events. In the Middle East, such places are characterized by high evaporation-to-rainfall ratios, and precipitation of salts from seawater forms evaporites that become incorporated into sediment packages near the water table. Marine (tidal) flooding will sometimes dissolve these evaporites—especially salt (halite), which is very soluble; less so with gypsum and calcite—until the next evaporation cycle builds them up again (Steve Fryberger, consultant, written communication, 29 March 2012).

Outside the Middle East, the term “sabkha” has been applied more generally to any evaporitic, flat, depositional environment where windblown, tidal, or fluvial sediments accumulate. Thus sabkhas may be freshwater or saline, but the sediment packages still resemble Middle Eastern sabkhas (Steve Fryberger, consultant, written communication, 29 March 2012).

The online publication *Geological Overview of White Sands National Monument* (Fryberger 2001a) used the concept of a sabkha as a means for describing and understanding subsurface sediment packages at White Sands National Monument. The term “sabkha” needs clarification for use at White Sands National Monument, in particular the distinction between “eolian sabkhas,” where sediments are mainly wind-deposited, and “generic sabkhas,” in which the sediment is not deposited primarily by wind. The work of Handford (1981), which proposed a scheme for classifying sabkhas, may be helpful in clarifying the use of the term at White Sands (Steve Fryberger, consultant, written communication, 29 March 2012).

Although not included as a map unit within the boundaries of White Sands National Monument, the geomorphic data set shows prominent mapped sabkhas north of the national monument, between the barchanoid dune field (bdf) and marginal parabolic dunes (mpd). According to Steve Fryberger, most of the sabkahs within the national monument are too small in area or too complex in the field to be individually mapped. Furthermore, distinguishing the extent and thickness of these features, particularly in the absence of trenches, is difficult in the flat terrains of the scour platform (sp) and active Holocene lake basin (ahlb) (Steve Fryberger, consultant, written communication, 29 March 2012). Nevertheless, these deposits are a significant feature at White Sands National Monument, and were highlighted in Chapter 6—“Sand Sheets and Eolian Sabkhas”—of Fryberger (2001a). This publication identified sabkhas as forming on Alkali Flat and the margins of Lake Lucero, and noted many sabkha-like sediments throughout the national monument; some are eolian, grading from dry and erosional on the eastern side of the playa, to damp or wet downslope/westward towards the ephemeral lakes (Steve Fryberger, consultant, written communication, 29 March 2012).

### Alluvial Deposits

Large geomorphic features deposited by running water include coalescing alluvial fans on the western side of White Sands National Monument. As is typical of alluvial deposits, the deposits at White Sands are located where gradient decreases suddenly at a mountain front; a major change in carrying capacity occurs, with water slowing down and dumping its entrained sediment. At White Sands, alluvial deposits have built up over time, as a result of repeated flooding events. Up to 20 cm (8 in) of rainwater can fall in an hour's time during sudden storm events. Water flows down these deposits as channelized flow and sheet flow, transporting water and sediment through the alluvial deposits and onto the active Holocene lake basin.

Fryberger (2001b) mapped alluvial deposits on the western side of White Sands National Monument as "alluvial fans" (*allvl_fan* and *o_allvl_fan*). Seager et al. (1987) mapped these deposits as "piedmont-slope deposits" (Qpa, Qpy, and Qpo). Seager et al. (1987) also mapped the Camp Rice Formation (Qcp and QTcu) as part of some of the alluvial deposits on the western side of the national monument. In semiarid and desert regions of the Southwest, the term "bajada" is often applied to alluvial deposits at the base of mountain ranges. The bajada at the base of the San Andres Mountains on the western side of White Sands National Monument is the recharge area for water to the basin-fill aquifer (see "Groundwater" section), and has distinct plant communities and soil types (KellerLynn 2003, 2008a).

Huff (2005) characterized these deposits as part of the basin-fill aquifer within the larger Tularosa Basin. The basin fill is made up of material eroded from the surrounding mountains and deposited as fluvial sediments within the ancestral Rio Grande basin. Unconsolidated, coarse-to fine-grained, coalescing alluvial-fan deposits surround the basin and grade toward the center of the basin into progressively finer-grained fluvial and lacustrine deposits (Huff 2005).

### Source of Gypsum Sand

Seager et al. (1987) mapped many gypsum-rich deposits and dunes within White Sands National Monument, including older gypsiferous basin-floor deposits and lake beds (Qbfg), gypsiferous lake deposits (Qlg), inactive gypsum dunes (Qegi), and active gypsum dunes (Qega). These units attest to the ubiquitous nature of gypsum across the landscape.

In the Tularosa Basin, the formation of gypsum—hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$)—is associated with long-term, complex interactions among climate, tectonic activity, and the hydrologic cycle that involves a geochemical recycling of sulfur (chemical symbol S) from older rocks that underlie and flank the closed basin (Szynkiewicz et al. 2009, 2010a) (fig. 26). Allmendinger (1971) identified the Permian (299 million–251 million years ago) Yeso Formation (Py) as the primary source of gypsum; 275-m- (900-ft-) thick deposits of this formation occur in the Tularosa Basin (Seager et al. 1987). Infiltrating precipitation and runoff, primarily at the margins of the basin, dissolve the sulfate ($SO_4$) in these Permian rocks, and solutes (dissolved sulfate ions) are transported by surface water runoff and groundwater to low-elevation areas covered by playas and lakes (Szynkiewicz et al. 2010a). During the Pleistocene Epoch, dissolved sulfate ions accumulated in pluvial Lake Otero, which extended across the Tularosa Basin (Herrick 1904; Allmendinger 1971; Seager et al. 1987). The fluids that accumulated in the lake had inherited the sulfur-isotope signature of the rocks that they had dissolved (Szynkiewicz et al. 2009). The "signature" or value is defined as the ratio of two naturally occurring sulfur isotopes, $^{34}S/^{32}S$, relative to a standard ratio, the Vienna Cañon Diablo troilite (VCDT) (see Krouse and Coplen 1997). Because variation in sulfur isotope ratios is small, the ratios are expressed as

δ (delta) in parts per thousand (‰); the value is expressed as $\delta^{34}S$. Sulfur isotope signatures of rocks in the Tularosa Basin show relatively wide variations of $\delta^{34}S$, as much as 14‰. Using these values, geologists have been able to interpret the origins of the gypsum in the lake sediments and the dune field.

As a result of regional aridity during the Holocene Epoch, Lake Otero dried up, leaving sediments composed of sulfate-rich, evaporite rocks such as gypsum. Szynkiewicz et al. (2010a) used sulfur isotope variation of the Lake Otero sediments to reconstruct the spatial evolution of the White Sands dune field. The sediments of Lake Otero that are exposed as outcrops in the active Holocene lake basin show a continuous increase of $\delta^{34}S$ from 11.3‰ to 13.8‰ from bottom to top. This pattern, in turn, corresponds well to an overall increase of $\delta^{34}S$ from southwest to northeast across the dune field, following the prevailing wind direction (Szynkiewicz et al. 2010a). With respect to the evolution of the dune field, this means that the source of the eastern parabolic dunes was deflation of sediments from the top of the lake bed sequence, marked by the highest $\delta^{34}S$ values, while the sand source of the barchan dunes, which are the core of the dune field farther west, was lower/older Lake Otero sediments, marked by lower $\delta^{34}S$ values (Szynkiewicz et al. 2010a). These findings show that the 7-m- (23-ft-) high sediment outcrops of Lake Otero strata are likely the major source of gypsum sand to the White Sands dune field. Furthermore, the dune field evolved as a result of stepwise deflation of these previously stored sediments, with the eastern parabolic dunes forming before the brachanoid dune field (see "Geologic History" section).

Other sources of gypsum sand include younger evaporite beds of playa lakes such as Lake Lucero (Kocurek et al. 2007) (fig. 5). Although Kocurek et al. (2007) and Rip Langford (written communication, 9 April 2012) stress that the relative amounts of different sediment sources to the dune field are still unknown, the isotopic findings of Szynkiewicz (2010a) provided definitive evidence that points toward Lake Otero beds. Furthermore, with respect to physical, geomorphic processes, the Lake

Lucero deposits are not a primary source for at least two reasons, according to Fryberger (2001a). First, modern Lake Lucero is a damp playa, with groundwater near the surface that inhibits the erosion of new sand for dune formation (see "Groundwater" section). Second, most freshly precipitated gypsum on the Lake Lucero playa occurs as silt-sized particles, which are generally transported by wind beyond the dune system. Another secondary source is recycled sand from older dune deposits (*sp_todd_d*) (Fryberger 2001a) (fig. 33).

**Figure 33. Old dunes. Sand recycled from older (inactive) dunes (geologic map unit symbol Qegi) is a secondary source of fresh sand to the White Sands dune field. Photograph by David Bustos (White Sands National Monument).**

Interpreting the large selenite crystals as a source of gypsum sand is tempting (see, for example, "Historical Perspective of Surface Water and Groundwater Resources in the Chihuahuan Desert Network, National Park Service" [Porter et al. 2009]). However, Fryberger (2001a) suggested that because the rate of weathering of these large selenite crystals is so slow, they are not a source of fresh gypsum to the dunes. This was confirmed by the work of Szynkiewicz et al. (2010b), which showed that the large selenite crystals have distinctively higher $\delta^{34}$S compared to the average $\delta^{34}$S of gypsum in the White Sands dune field. Fryberger (2001a) suggested that the significance of these crystals is the geomorphic role they play in maintaining the extensive lake-bed terraces on the western side of Lake Lucero, which protect the underlying lake beds from further wind erosion.

### White Sands as an Analogue for Mars

White Sands National Monument is of interest to scientists studying landforms on other planets. John Grutzinger of the Jet Propulsion Laboratory (JPL) Mars Mission has studied features at White Sands (Steve Fryberger, consultant, written communication, 29 March 2012), as have other researchers from NASA, the University of California at Davis (UC Davis), Indiana University, and University of Texas at El Paso. Chavdarian and Sumner (2006)—researchers from UC Davis—studied cracks and fins in the sulfate-rich sands at White Sands National Monument because they look remarkably similar to features seen by the Mars rover *Opportunity*. Moreover, Anna Szynkiewicz and colleagues are analyzing features and processes at the national monument as potential terrestrial analogues for Mars. At the time of field work, Szynkiewicz was at Indiana University; in 2012 she was at the University of Texas at El Paso. Of particular interest are the crystal pedestals/domes on Alkali Flat (see "Crystal Pedestals/Domes" section). Findings regarding the formation of the crystal pedestals/domes may illuminate details about the makeup and formation of similar-looking Martian domes and mounds.

Additionally, the crystal pedestals/domes at White Sands may aid analysis and interpretation of remote-sensing images of Mars. In particular, it may be possible to infer some details of Martian domes and mounds from the differences in albedo (reflectivity) of various types of gypsum associated with the crystal mounds on Alkali Flat. The fine-grained evaporite minerals scattered around the domes on Alkali Flat give the brightest albedo because of the larger exposure of mineral surfaces for the reflection of sunlight. The coarse-grained crystals of gypsum are characterized by considerably lower albedo (Szynkiewicz et al. 2010b).

The origin of domes and mounds on Mars is under debate, and data about the mineralogy and internal structure of these features are limited (Szynkiewicz et al. 2010b). However, the sulfate-rich character of the crystal pedestals/domes at White Sands makes them a provocative terrestrial analogue for the sulfate-rich eolian outcrops on parts of Mars. The crystal pedestals/domes at White Sands appear at the lowest elevations of Alkali Flat, where the hydraulic gradient between the recharge area and the basin floor is sufficient for groundwater upwelling at structurally localized points, that is, along faults. If upwelling water existed on Mars in the past and the upwelling was located in areas that are or were structurally similar to White Sands, it is possible that similar dome formation could have occurred on Mars (Szynkiewicz et al. 2010b).

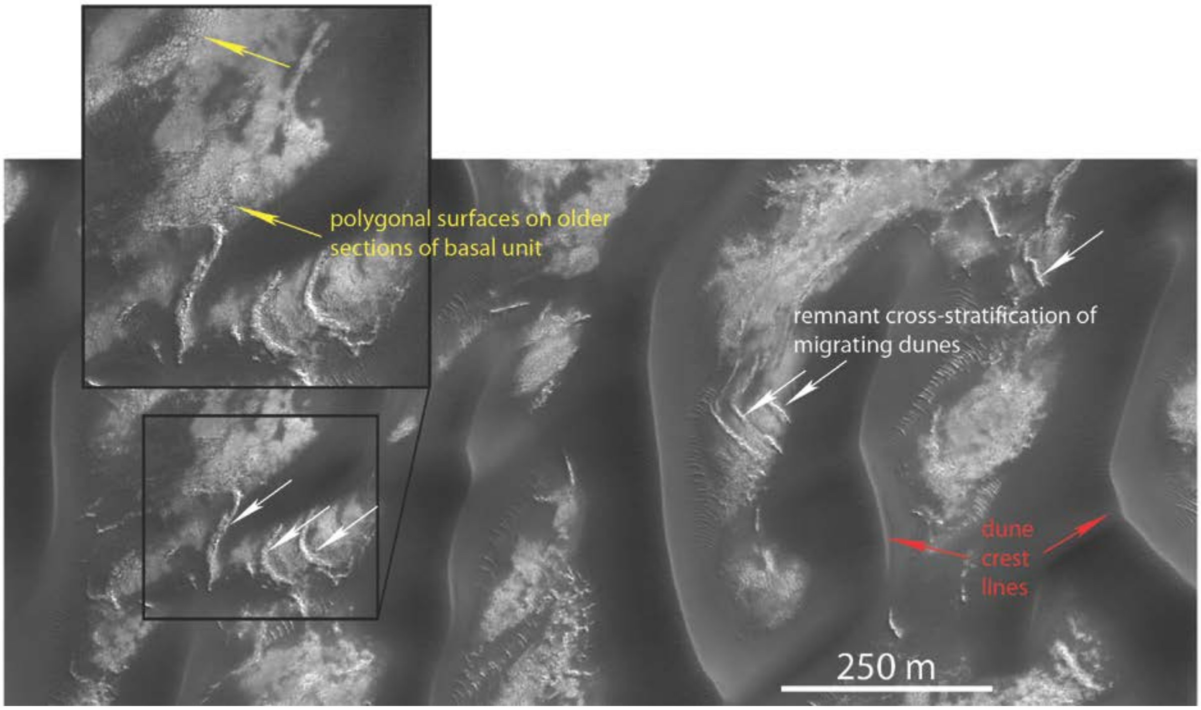

**Figure 34. Olympia Undae dune field. The White Sands dune field is a possible analogue for many dune features on Mars. This satellite image shows the gypsum-rich Olympia Undae dune field near the north pole of Mars. The long, linear features (with shadows) are the crest lines of dunes (red arrows). The gray and white areas between the crest lines are interdunes. Note the "waves" of cross-bedded strata in the interdune areas of Olympia Undae (white arrows). These features show similarities to the cross-bedded strata in the interdunes of the White Sands dune field. HiRISE image (PSP_009898_2615) available at http://hirise.lpl.arizona.edu/PSP_009898_2615 courtesy of NASA/JPL/University of Arizona, modified by Anna Szynkiewicz (University of Texas at El Paso).**

According to written communication by Anna Szynkiewicz (20 March 2012), recent exploration of Mars by orbital spacecrafts has shown that gypsum-rich, windblown sand dunes are present on Mars (fig. 34). These dunes—the Olympia Undae dune field—are located near the north pole of Mars, where NASA's *Phoenix Lander* recently measured ground temperatures as low as -97°C (-142°F). The Olympia Undae dune field is much bigger than the White Sands dune field and encompasses about 385,000 $km^2$ (150,000 $mi^2$), which is an area slightly larger than the state of Montana. Unlike White Sands, Olympia Undae has very dark color because it is composed of sand made of basalt, which is a rock much like the Carrizozo lava beds just north of White Sands. Whereas gypsum comprises nearly 100% of the sand at White Sands, gypsum comprises only about 30% of the Olympia Undae sand on Mars. This amount of gypsum is important because gypsum can only form in the presence of liquid water, which means water, and maybe life, were present on the surface of Mars at some time in the past.

The Olympia Undae dunes also have many of the same morphologic features as the dunes at White Sands, including sharp crest lines, steep slip faces, and wind ripples. Moreover, images of Mars show features that look like corrugated interdune areas, like those at White Sands.

At White Sands, interdunes often are indicative of the influence of groundwater, whereas on very cold Mars, interdunes are likely related to thawing of ice and subsequent freezing of the ground (Anna Szynkiewicz, University of Texas at El Paso, research assistant professor, written communication, 20 March 2012).

### Biological Soil Crusts

Biological soil crusts are also known as cryptogamic, microbiotic, cryptobiotic, and microphytic crusts, leading to some confusion (U.S. Geological Survey 2006). The names are all meant to indicate common features of the organisms that compose the crusts. The most inclusive term is probably "biological soil crust," as this distinguishes them from physical crusts without limiting the crust components to plants. Whatever name is used, there remains an important distinction between these formations and physical or chemical crusts. Biological soil crusts are formed by living organisms and their by-products, creating a crust of soil particles bound together by organic materials. Chemical and physical crusts, such as salt crusts, are inorganic features.

According to geoindicators participants, biological soil crusts at White Sands National Monument occupy an intermediate ecological position between active dunes and heavily vegetated surfaces. Biological soil crusts are indicators of ecosystem stability, health, and climate change. They are critical to plant growth because they fix nitrogen into the system and bind soil. Biological soil crusts can either promote water infiltration (on silty soils) or increase runoff (on sandy soils). Filaments of cyanobacteria are hydrophobic, so crusts made of cyanobacteria promote lateral redistribution of water. These attributes are important for the dune ecosystem (KellerLynn 2003).

Biological soil crusts at White Sands National Monument appear robust (KellerLynn 2003, 2008a). According to Curtis Monger (New Mexico State University), crusts in sulfate-rich soils form quickly (within a few years), so disturbances, for example from foot traffic, are less likely to create long-term problems (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, written communication, 16 May 2008).

Various sources of information pertaining to the biological soil crusts at White Sands National Monument include (1) data from vegetation plots in White Sands Missile Range, (2) data from Holloman Air Force Base, (3) data from a study of ATV tracks in 2000 and 2002 in the national monument, and (4) airborne visible/infrared imaging spectrometer (AVIRIS) imagery from the University of Texas at El Paso. Geoindicators participants suggested development of a database of this information in order to analyze what is known about resilience, recovery rates, spatial distribution of various types of biological soil crusts, and overall spatial distribution. This is a potential project for a Geoscientist-in-the-Parks (GIP) participant. Lisa Norby (NPS Geologic Resources Division) is the contact for the GIP Program. Information is available at http://nature.nps.gov/geology/gip/index.cfm (accessed 18 September 2012).

Analysis of AVIRIS and other satellite imagery for White Sands may be useful in developing a groundwater model that applies remote sensing (Barud-Zubillaga and Schulze-Makuch 2001a, 2001b). Such imagery could help monitor soil moisture and indicate the presence of the shallow groundwater table (Scheidt et al. 2010) (see "Groundwater" section). A possible research scenario could use samples of the biological soil crusts, which are growing in a laboratory setting at New Mexico State University. Investigators "image" these samples to obtain the spectra of wet samples. After the spectra are obtained, watering ceases, and investigators image the crusts as they dry. In this way, a database is established to help interpret satellite imagery. The AVIRIS image is for one point in time. However, the information gained from this method may extend to other satellite platforms that are more commonly available than AVIRIS. Contacts for information about biological soil crusts include Hildy Reiser (NPS Chihuahuan Desert Network), Phil Goodell (University of Texas at El Paso), and Curtis Monger (New Mexico State University).

### Geothermal Features and Processes

The Rio Grande rift has a high thermal gradient and high heat flux (Sass and Morgan 1988). This results in the presence of hydrothermal waters close to the surface that discharge as hot springs along the rift. During GRE scoping in 2007, participants mentioned that known geothermal activity in the northern Tularosa Basin is associated with the Malpais lava flow—part of the Carrizozo volcanic field north of White Sands National Monument, and not to be confused with the lava flows in El Malpais National Monument (KellerLynn 2012), which are part of the Zuni–Bandera volcanic field, farther north and west. Proximity of the Malpais lava flow suggests the possibility for geothermal activity at White Sands National Monument. Based on the presence of thermophilic bacteria strains and hydrothermal minerals in the soil, Schulze-Makuch (2002) and Schulze-Makuch et al. (2007) hypothesized the existence of active discharge of hydrothermal fluids into the playas near White Sands. However, investigators have yet to detect any hot-spring activity at White Sands or in the other basins that contain gypsum dunes (Szynkiewicz et al. 2009).

# Geologic History

*This section describes the rocks and unconsolidated deposits that appear on the digital geologic and geomorphic maps of White Sands National Monument, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.*

The geologic history of White Sands National Monument encompasses the formation and erosion of an ancient mountain or rift system during Precambrian time; repeated inundation by seas from the Cambrian through the Cretaceous periods; uplifted mountains and sediments shed into basins during the Pennsylvanian, Permian, and Cretaceous periods; crustal extension (pulling apart of Earth's crust), basin infilling/sedimentation, and volcanism during the Oligocene Period; the formation and evolution of a major fluvial system during the Pliocene and Pleistocene epochs; development of pluvial lakes during the Pleistocene Epoch; and formation of playas and dunes during the Holocene Epoch (figs. 35 and 36). Refer to figure 6 for a geologic time scale.

### Precambrian Time: Ancient Mountain or Rift System

The Precambrian rocks in the vicinity of White Sands National Monument represent deeply eroded roots of an ancient mountain or rift system that formed about 1.4 billion years ago (Condie and Budding 1979; Seager 1981). Seager (1981) interpreted the gneisses (geologic map unit symbol PCgn) and schists (PCs) as downward projections of country rock, called "roof pendants," into a Precambrian batholith (large body of igneous rock). The gneisses and schists probably originated as sedimentary rocks formed in an arc-related basin or rift, perhaps hundreds of millions of years before they were intruded and metamorphosed by granitic batholiths (PCg) as part of mountain-building processes (Seager 1981). Later, the arc system underwent extension in a southeast–northwest direction, and swarms of diorite-diabase dikes (PCmd) were intruded into the resulting northeast-trending fractures. During the last few tens or hundreds of millions of years of Precambrian time, the rifts or mountain ranges were eroded down to their roots, and a broad, low-relief erosion surface formed.

### Cambrian and Ordovician Periods: Advancing Seas

At the start of the Cambrian Period (approximately 542 million years ago), seas spread across the extensive Precambrian erosion surface and deposited the Bliss Sandstone and El Paso Group (limestone). These rocks were deposited near the paleoequator, on a passive continental margin along the western edge of the ancient North American continent, which is known as "Laurentia." Passive continental margins are far from an active plate boundary and, therefore, lack significant tectonic activity such as earthquakes, volcanic eruptions, and mountain building. They mark a transition between thick continental crust and thin oceanic crust (Lillie 2005). Seager et al. (1987)—the geologic map for White Sands National Monument—mapped the rocks of the Bliss Sandstone and El Paso Group as an undivided unit (OCeb). Together, these rocks record global sea level rise, inundating the continental margin from the west and south (Mack 2004). The transgression (advancing sea) represented by Bliss and El Paso strata occurred during the Cambrian and Ordovician periods; the Bliss Sandstone spans the Cambrian-Ordovician boundary (488 million years ago).

### Ordovician and Silurian Periods: Marine Waters

Following deposition of the undivided El Paso Group and Bliss Sandstone (OCeb), the Montoya Group and overlying Silurian Fusselman Dolomite were deposited within 30° of the equator on the passive margin of the North American continent. Seager et al. (1987) mapped these rocks as an undivided unit (SOfm). The Montoya Group records marine conditions, predominately subtidal deposition on a gently dipping carbonate platform (Pope 2004). Dolomitization of the Montoya Group suggests a warm, shallow, saline marine environment, perhaps in an arid climate (Seager 1981). The Fusselman Dolomite was deposited atop the Montoya beds in shallow marine waters. Like the Montoya Group, the Fusselman was dolomitized.

### Devonian and Mississippian Periods: Changing Marine Conditions

Seager et al. (1987) grouped the rocks of the Mississippian and Devonian periods as "Mississippian and Devonian rocks" (MDr). During the Middle and Upper Devonian Periods (398 million–359 million years ago), major changes in the character of sedimentation accompanied marine waters in south-central New Mexico. These sediments were silty or clayey, and appear to have formed in a confined basin, such as a lagoon or shallow-marine sea, with a muddy bottom and restricted circulation. As a result, strata such as the Percha Shale (part of MDr) are black and nonfossiliferous, and contain pyrite—the product of anaerobic bottom conditions where oxygen is depleted.

By the Lower Mississippian Period, the restricted seas of the previous Devonian Period were gradually replaced by open marine waters that teemed with life. In the vicinity of White Sands National Monument, Mississippian strata are part of the package of Mississippian and Devonian rocks (MDr) mapped by Seager et al. (1987) that includes the Caballero Formation, Lake Valley Limestone, Las Cruces Limestone, Rancheria Formation, and Helms Formation. These strata contain fossils such as crinoid debris, interpreted as banks, submarine dunes, or mounds.

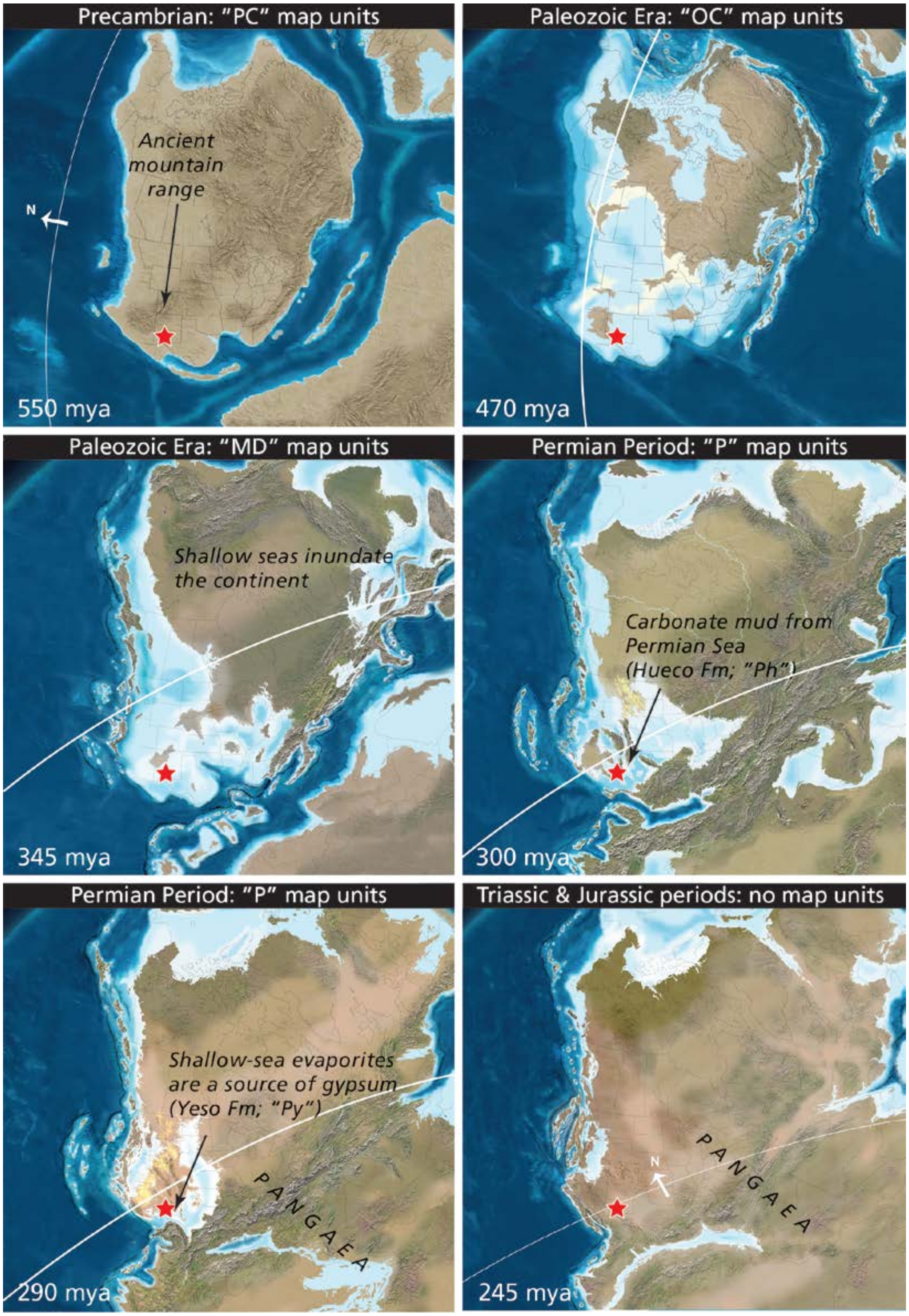

**Figure 35. Precambrian, Paleozoic, and Mesozoic paleogeographic maps for White Sands National Monument. The geologic history of White Sands National Monument includes the formation and erosion of an ancient mountain or rift system (PC), advancing seas (OC), marine conditions (MD), formation of the supercontinent Pangaea during the Pennsylvanian Period, more marine conditions (P), and a lack of Triassic and Jurassic rocks. The stars on the figure represent the approximate location of White Sands National Monument during various points in geologic time. The white lines across the graphics represent the approximate location of the equator. mya = million years ago. Map units refer to those on the geologic map for White Sands National Monument (Seager et al. 1987). Graphic complied by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 25 January 2012).**

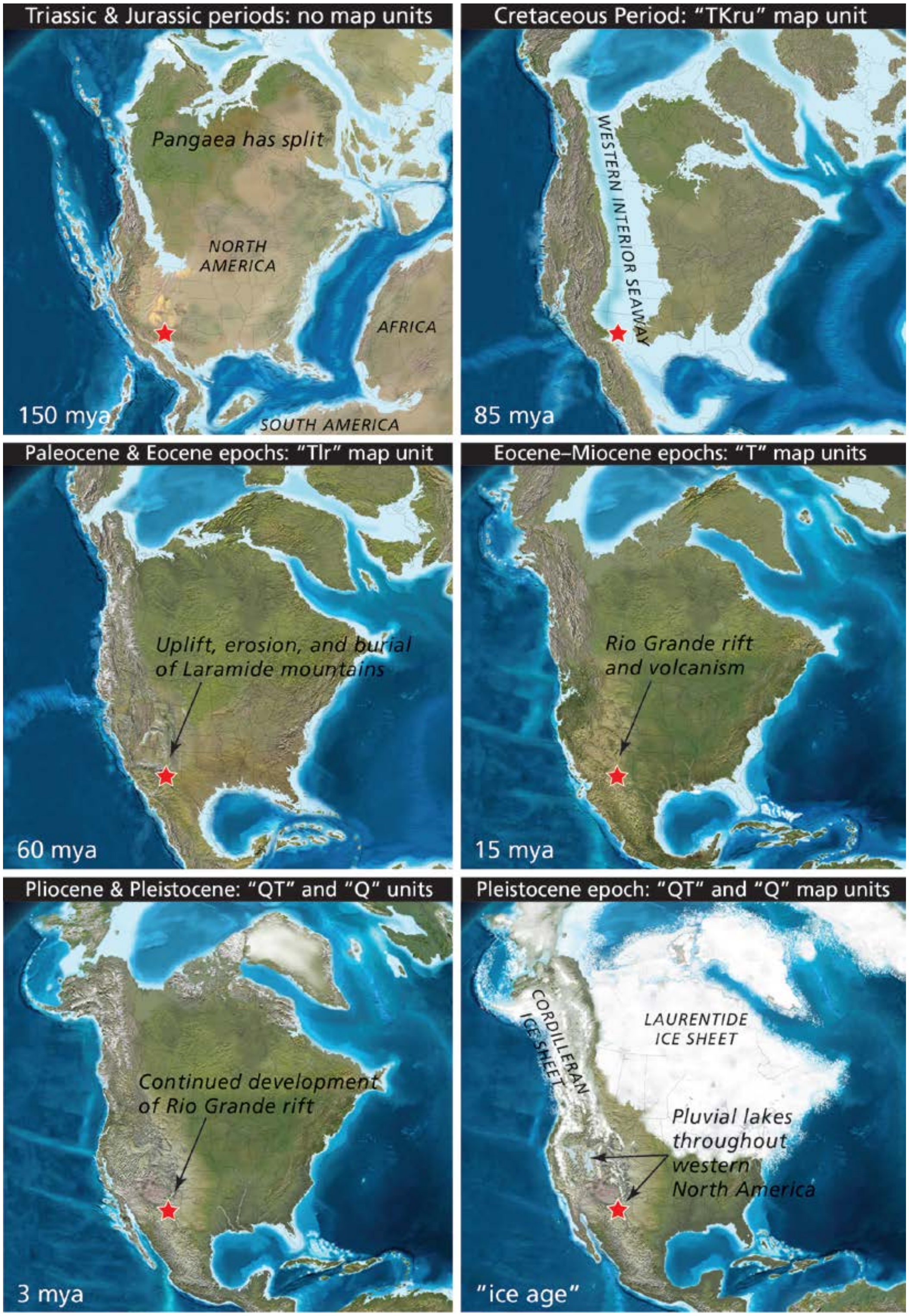

**Figure 36. Mesozoic and Cenozoic paleogeographic maps. During Tertiary time (T) and the Cretaceous Period (K), the Western Interior Seaway invaded New Mexico, and the Rocky Mountains began to rise. During the Oligocene Epoch, depicted by Tertiary (T) units on the figure, basin filling, volcanic eruptions, and crustal extension (pulling apart of Earth's crust) along the Rio Grande rift occurred. Rifting continued into the Quaternary Period (Q), and the ancestral Rio Grande developed at this time. Pluvial lakes, such as Lake Otero, covered the area during the Pleistocene ("ice age") Epoch. Regional aridity during the Holocene caused drying of pluvial lakes, and formation of playas and dunes. The stars on the figure represent the approximate location of White Sands National Monument during various points in geologic time. The white lines across the graphics represent the approximate location of the equator. mya = million years ago. Map units refer to those on the geologic map for White Sands National Monument (Seager et al. 1987). Graphic complied by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 25 January 2012).**

These mound-like features were separated by stretches of calcareous mud that was inhabited by brachiopods, bryozoans, corals, and other organisms. Black calcareous mud of the Las Cruces Limestone and Rancheria Formation collected in deep marine basins. The Helms Formation—composed of clastic rocks (derived from land) and oolitic limestone—records the gradual withdrawal of the seas southward during the Upper Mississippian Period (328 million–318 million years ago).

### Pennsylvanian Period: Pangaea and the Ancestral Rocky Mountains

During late Pennsylvanian and early Permian time, all the major continents, including North America, came together to form the supercontinent Pangaea. The final assembly of Pangaea involved the collusion of Laurentia (North America) and Gondwanaland (Africa and South America).

The formation of Pangaea was responsible for enormous upheavals. In what is now the eastern United States, colliding continents created the Appalachian Mountains. In the western United States, the Ancestral Rocky Mountains formed at this time (320 million–290 million years ago). In New Mexico, the Ancestral Rocky Mountains orogeny (mountain-building event) partitioned the former extensive low-relief, passive margin into narrow, deep basins separated by uplifts with cores of basement rocks. The basin near White Sands National Monument was the Orogrande Basin; uplifts in the vicinity were the Pedernal and Hueco (Kues and Giles 2004).

The Lead Camp Limestone (PNlc), which Seager et al. (1987) mapped near White Sands, documents the deposition of sediments into the Orogrande Basin under normal marine conditions on a stable continental shelf (Seager et al. 1987). These deposits grade up into thick, largely clastic beds of the Panther Seep Formation (PNps), which filled the Orogrande Basin in Upper Pennsylvanian time (Pray 1960). The Panther Seep Formation, which is primarily silt, sand, and gypsum, is lacking in fossils, indicating that at the time of deposition, waters in the basin were sediment laden and murky or restricted in circulation, and not particularly hospitable to marine life. Mud cracks, ripple marks, stromatolites (fossil algal mats), local caliche (hard, calcareous material or "hardpan") and gypsum beds, and dolomitized limestone suggest an intertidal to supertidal depositional setting for the Panther Seep Formation (Seager 1981).

### Permian Period: Marine and Marginal Marine Sediments

At the time of Pangaea, present-day New Mexico was submerged in a tropical sea just south of the equator. The limestone mountains of Carlsbad Caverns National Park in northern New Mexico (Graham 2007) and Guadalupe Mountains National Park in Texas (KellerLynn 2008b) represent the remains of a large barrier reef that developed on the edge of this supercontinent. In the vicinity of White Sands National Monument, Seager et al. (1987) mapped limestone composed of algae, gastropods, echinoids, brachiopods, and fusulinids—an indication of the abundance of marine life. A thick accumulation of marine sediments—as much as 690 m (2,250 ft) thick—developed, and later became lithified as the Hueco Formation (Ph). The Hueco Formation represents the return to stable shelf conditions during the early Permian Period (Seager 1981).

Although most of the Permian Period is characterized by marine conditions, uplift in northern New Mexico, southern Colorado, and southeastern Utah produced a huge apron of continental sand, gravel, silt, and mud early in this geologic period. Streams distributed these sediments southward across central New Mexico. The terrestrial Abo Formation (Pa) records this flood of clastic material. Lagoonal rocks of the Yeso Formation and the marine Yeso-San Andres limestone overlie the Abo Formation and record the gradual spread of seas across south-central New Mexico (Seager 1981). The intertonguing and overlying Yeso Formation, Pya and Py, respectively, are made up of several distinct beds of rocks that indicate a north to south transition from terrestrial to marine conditions. The deposits include sandstones of various origins, including eolian dunes and sand sheets, sabkhas and hypersaline lagoons, and coastal-plain and tidal settings. Also carbonate rocks from these units formed in coastal-sabkha, restricted-marine, and marine-shelf environments (Stanesco 1991).

On a smaller scale, vertical repetition of sediments within the Yeso Formation (Py) reflects cyclical changes in environmental conditions. These cycles generally occur over an interval of 1 m (3.3 ft) to 8 m (26 ft) (Stanesco 1991). The cycles are initiated by a layer of limestone with a sharp lower contact, which probably indicates rapid marine transgression (rise in sea level/retreat in shoreline) (Blakey and Middleton 1983). The cycles coarsen upward, indicating regression (fall in sea level/advance in shoreline) of a retreating sea, as well as representing the lateral migration of eolian sand-sheet and dune strata over supertidal mud-flat and coastal sabkha deposits (Stanesco 1991). At the end of the Permian Period, carbonate muds of the undivided San Andres Formation and Yeso Formation (Psy), which accumulated under normal marine conditions in shallow seas, buried the older Yeso Formation (Py) sediments.

The Permian sequences of rocks in the Tularosa Basin, in particular the Yeso Formation (Py), have great importance for the geologic history of White Sands National Monument because these formations contributed the bulk of the evaporite sediments, namely gypsum, to the basin (Fryberger 2001a). The gypsum deposits of the Yeso Formation (Py) exceed 1,280 m (4,200 ft) in thickness at the depositional center near the town of Carrizozo, New Mexico, to the north of White Sands. Much of the gypsum underlying the modern, active Holocene lake basin (geomorphic map unit symbol *ahlb*) may have been flushed from the north and east southward towards the low point at Lake Lucero. The widespread exposure of gypsum-bearing rocks, the great thickness of the gypsum, and a broad catchment area for surface runoff and subsurface flow facilitated this process (Fryberger 2001a).

### Triassic and Jurassic Periods: Erosion

Erosion as a result of uplift and exposure removed most of the evidence of the Triassic and Jurassic periods from the southern part of New Mexico. Thus, rocks from this time (251 million–145 million years ago) do not occur on the geologic map of White Sands National Monument (see "Geologic Map Data" section). However, exposures of these rocks in central and northern New Mexico reveal primarily nonmarine depositional settings, where sedimentation occurred in rivers, lakes, sand dunes, and tidal flats (Lucas 2004).

Some of the most famous rock formations of the western United States were deposited during the Triassic and Jurassic periods. The Triassic Chinle Formation is known for its petrified wood, and is particularly well-exposed at Petrified Forest National Park in Arizona (KellerLynn 2010b). The Jurassic Morrison Formation is known for its dinosaur remains and is the source of the spectacular fossil discoveries within Dinosaur National Monument in Utah and Colorado (Graham 2006b). These formations do not occur in the vicinity of White Sands National Monument.

### Tertiary Time and Cretaceous Period: Interior Seaway and Rise of the Rocky Mountains

Marine transgression (rise in sea level/shoreline retreat) followed erosion of Triassic and Jurassic strata in southern New Mexico. An extensive seaway, called the "Western Interior Seaway," characterizes the Cretaceous Period (145 million–65.5 million years ago) in the western United States. The Western Interior Seaway extended from the Arctic to the Tropics, covering the entire west-central part of the North American continent. Thick deposits of shale, siltstone, and sandstone were deposited in this marine basin. In the vicinity of White Sands National Monument, Seager et al. (1987) mapped a package of undifferentiated rocks, including Sarten and Dakota Sandstone (TKru), which represent beach and nearshore deposits associated with sea-level rise and shoreline retreat of the seaway.

By the end of the Cretaceous Period (about 70 million years ago), the western margin of the North American continent was tectonically active, as oceanic crust subducted under continental crust. Active tectonism provided the compressional forces that caused uplift of the Rocky Mountains during a period of mountain building called the "Laramide Orogeny." Although White Sands National Monument is about 320 km (200 mi) south of the Rockies, the same compressional forces that formed the Rocky Mountains also uplifted the rocks in southern New Mexico. Without the Laramide Orogeny, the elevation of southern New Mexico would be substantially lower (National Park Service 2005). Mountain building and uplift ultimately displaced the Western Interior Seaway (Smith and Siegel 2000).

### Oligocene Epoch: Basin Filling, Volcanism, and Crustal Extension

As a result of uplift and associated erosion, sediments were shed from uplands, including the Rio Grande uplift in southern New Mexico. Eroded sediments were deposited in adjacent basins. The Love Ranch Formation (Tlr) exemplifies this basin-filling process in the vicinity of White Sands National Monument. The sediments of the Love Ranch Formation, which were derived from Precambrian–Permian rocks, were deposited concurrently and following the uplift, erosion, and burial of Laramide mountains. The Love Ranch Formation occurs primarily as alluvial fans, but also fluvial and debris-flow deposits (Seager et al. 1997).

Following the Laramide Orogeny, volcanism was widespread, and in many areas of New Mexico, volcanic rocks cover Laramide sediments. This period of volcanic activity spanned the late Eocene (approximately 37 million years ago) through Miocene (5.3 million years ago) epochs, but peaked in the Oligocene Epoch (34 million–23 million years ago). Huge volcanic fields associated with this period cover southwestern New Mexico. These fields developed during the transition from Laramide subduction-related magmatism to rifting (Chapin et al. 2004). In the vicinity of White Sands National Monument, Seager et al. (1987) mapped silicic plutonic rocks (Tis), non-foliated rhyolite intrusive (Tri), and intermediate-composition plutonic rocks (Tii). Dikes and stocks of these units intrude older rocks, for example, the Pennsylvanian Lead Camp (PNlc) and Panther Seep (PNps) formations, and the Permian Hueco (Ph) and Abo (Pa) formations. These and other igneous rocks record a period of geologic time when volcanism rather than uplift, faulting, and folding shaped the landscape of south-central New Mexico. The Organ batholith and caldera were the source of most of these volcanic rocks (Seager 1981; Seager et al. 1987). The caldera encloses the Dona Ana and Organ mountains southwest of White Sands National Monument.

Volcanism was followed by, and in part coeval with, extension, leading to the development of the Rio Grande rift (Kelley and Chapin 1997). Extension is the process by which Earth's crust is pulled apart, resulting in rocks breaking along normal faults. The southern Rio Grande rift has been affected by four episodes of extension, beginning about 40 million years ago (Kelley and Chapin 1997). Crustal extension resulted in volcanism, normal fault-block uplifts, and deposition in terrestrial basins (Mack 2004). The segment of the rift in the vicinity of White Sands is called the "southern Rio Grande rift" (Mack 2004). The Tularosa Basin, which formed along the rift as a result of crustal extension, is one of the many basins that formed in this manner (see fig. 2).

### Pleistocene and Pliocene Epochs: Rio Grande and the Rio Grande Rift

The Camp Rice Formation (QTcc, QTcu, Qcl, Qcp, and Qpu) was deposited by the ancestral Rio Grande as the southern Rio Grande rift stretched apart. The Camp Rice Formation is composed of various sedimentary facies, which reflect conditions of origin. These facies are (1) fanglomerate (QTcc), (2) an undivided piedmont-slope and fanglomerate (QTcu), (3) sediments associated with the La Mesa surface (Qcl), (4) piedmont slopes (Qcp), and (5) undifferentiated older piedmont-slope deposits and Camp Rice Formation (Qpu) (Seager et al. 1987). A fanglomerate is an alluvial fan that has cemented into solid rock. Sediments associated with the La Mesa surface are fluvial, playa, and alluvial-fan deposits, which are commonly reworked by the wind, and represent the basin-floor sediments of the internally drained La Mesa Basin, which extended southward to Chihuahua, Mexico (Ruhe 1962).

All of the facies of the Camp Rice Formation were deposited by the Rio Grande, but before the river began to incise its modern channel. Thus, the Camp Rice Formation marks the initial development of the ancestral Rio Grande fluvial system in southern New Mexico (Seager 1981). The ancestral Rio Grande is interpreted as having been a braided stream (Mack and James 1993). Braided streams divide into interweaving channels separated by sediment bars. Deposition of the Camp Rice Formation ended when the ancestral Rio Grande and tributary arroyos began to entrench the basin, probably in response to capture of the upper Rio Grande by the lower Rio Grande (Hawley and Kottlowski 1969; Hawley 1981).

According to Leeder et al. (1996), the ancestral Rio Grande first entered the southern Rio Grande rift about 5 million years ago, and occupied numerous distinct basins along the rift, including the Tularosa and Hueco basins (Hawley 1975; Mack and Seager 1990; Mack et al. 1997). Passing through Fillmore Gap to the west, the river flowed into the Tularosa and Hueco basins and deposited a huge fan delta (fig. 37). The river flowed southward, perhaps emptying into lakes at the southern end of the Hueco Basin and adjacent parts of Chihuahua, Mexico (Hawley 1975). Eventually, the river abandoned its course through Fillmore Gap. Sediment probably filled to the level of the pass, shifting the location of the river channel eastward (Mack 2004). The large alluvial fan constructed by the ancestral Rio Grande may have been responsible for impounding Lake Otero (Seager 1981; Mack et al. 1997) (fig. 37). Subsequent uplift along faults located east of Fillmore Gap probably helped to force the river westward into the Mesilla Basin, where it flows today (Mack et al. 1997).

In the Rio Grande valley, volcanism was coeval with deposition of the Camp Rice Formation. Volcanic features near White Sands National Monument appear in the digital geologic map data for White Sands National Monument as point features within polygons of units Qcl and QTcu. In addition, Seager et al. (1987) mapped cinder cones and flows of olivine basalt (Qb) southeast of White Sands National Monument.

### Pleistocene Epoch: Basin Fill and Pluvial Lake Otero

Ongoing sedimentation is a characteristic of the last 65.5 million years at White Sands National Monument. Basin-fill sedimentation started with the Love Ranch Formation, followed by the various facies of the Camp Rice Formation, and continued with numerous Pleistocene and Holocene deposits, including piedmont slope, basin floor, gypsum dune, quartz dune, lacustrine, and playa materials.

After deposition of the Camp Rice Formation, the ancestral Rio Grande began to alternately incise and partially backfill basins. Initial incision, which occurred about 780,000 years ago, resulted from a change in base level, most likely driven by climate (Gile et al. 1981). In the Tularosa Basin, more-or-less continuous accumulation of sediments, with little or no incision, has occurred throughout the middle and late Quaternary Period (Mack 2004). In the vicinity of White Sands National Monument, Seager et al. (1987) mapped many deposits from this time, including piedmont-slope deposits (Qpo, Qpg, Qpa, and Qpy), basin-floor deposits (Qbfg, Qpg, and Qbf), inactive gypsum dunes (Qegi), and eolian quartz sand (Qes). In addition, Seager et al. (1987) mapped many deposits associated with “Tularosa Basin lakes,” including gypsiferous lake deposits (Qlg) and eolian deposits (Qegs). These particular eolian deposits are mostly inactive dunes. Fryberger (2001a) correlated these deposits with the timing of ancient Lake Otero, which covered much of the Tularosa Basin during pluvial (wet) periods.

At the height of the last ice age, when climate was wetter than it is today, many intermontane basins in the Southwest were occupied by large, pluvial lakes (Allen 1994, 2005). The Tularosa Basin has long been interpreted as the site of large pluvial Pleistocene lakes, of which the latest is known as Lake Otero. Herrick (1904) was the first to make this interpretation, but many investigations have followed: Allen and Anderson (1993, 2000), Anderson et al. (2002), Menking et al. (2004), Allen (2005), and Allen et al. (2009) (see “Climate Change” section).

At its greatest extent, Lake Otero filled the Tularosa Basin with a shoreline at approximately 1,204 m (3,950 ft) above sea level, covering roughly 2,000 km$^2$ (770 mi$^2$) (Allen 2005). Radiocarbon dates indicate that basal nearshore lake deposits started accumulating about 45,000 years ago, continuing until about 28,000 years ago (Allen et al. 2009). Between about 28,000 and 25,000 years ago, a widespread episode of erosion removed at least 2 m (7 ft) of lake-margin deposits. Overlying this erosion surface are lake beds that contain both siliciclastic sediments and aquatic fossil organisms, suggesting repeated episodes of increased precipitation, surface water runoff, and freshening of the lake system. These inferred episodes of increased precipitation and enhanced fluvial activity in the basin began about 24,500 years ago and lasted for 9,000 years (Allen et al. 2009).

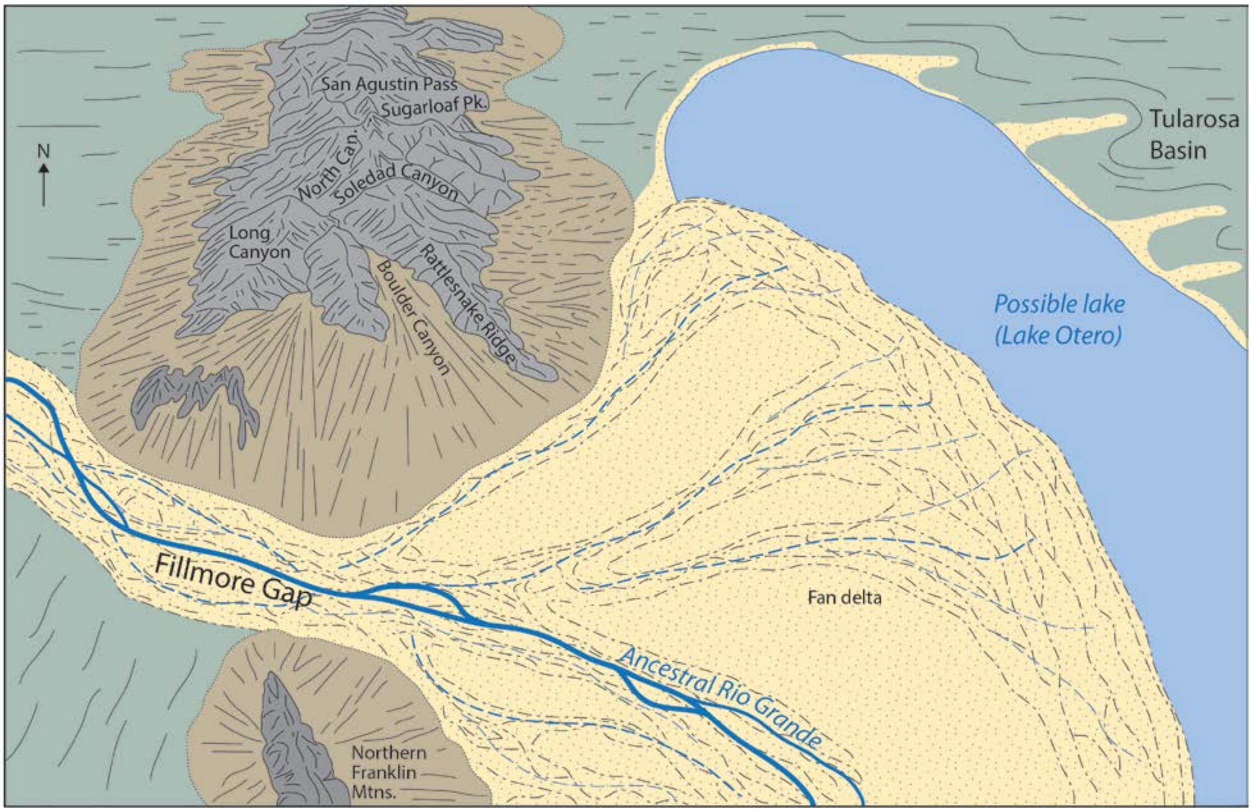

**Figure 37. Evolution of the Rio Grande. The ancestral Rio Grande first entered the southern Rio Grande rift about 5 million years ago. Passing through Fillmore Gap to the west of the Tularosa Basin, the river flowed into the basin and deposited a huge fan delta. Eventually, the river abandoned its course through Fillmore Gap. Sediment probably filled to the level of the pass. The large alluvial fan constructed by the ancestral Rio Grande may have been responsible for impounding Lake Otero. Subsequent uplift along faults located east of the gap probably helped to force the river westward into the Mesilla Basin, where it flows today. From Seager (1981), modified by Trista Thornberry-Ehrlich (Colorado State University).**

Details of the history of Lake Otero since about 15,500 years ago remain sketchy due to wind deflation of the basin floor and wholesale removal of lacustrine deposits during the Holocene Epoch (Allen et al. 2009). However, Lake Otero appears to have been present on the White Sands landscape in some form until about 7,300 years ago (Kocurek et al. 2007).

Because much lake-bed material has blown away or been covered by migrating dunes, it is difficult to know the original extent or thickness of the gypsum deposits within the Lake Otero basin. However, it is apparent from outcrops (*lo_outcrops*) that enormous amounts of gypsum were deposited on the floor of Lake Otero, and much of it was in the form of sand-sized gypsum crystals, which are perfectly suited for uptake and transport by the wind (Fryberger 2001a). On the digital geologic map of White Sands National Monument, map unit Qlg (gypsiferous lake deposits in the Tularosa Basin) approximates the extent of Lake Otero (see Overview of Digital Geologic Data).

### Holocene Epoch: Playa and Dune Formation

Following the last major glacial advance, regional aridity caused the water table to drop, which increased the availability of sediment for eolian transport (Langford 2003; Kocurek et al. 2007). Like today, the water table played an important role in dune formation and sand accumulation (see "Groundwater" section). A drying climate caused the contraction of Lake Otero, resulting in the formation of playas such as Lake Lucero. Aridity also caused deflation of Lake Otero strata, in particular from the scour platform, an area of extensive deflation of gypsum sand.

Thinking of modern Lake Lucero as a remnant of Pleistocene Lake Otero is tempting explanation. However, such an explanation implies depositional continuity between Lake Otero and Lake Lucero, but the hydrological frameworks and sedimentology of the two lakes are quite different and distinctive (Steve Fryberger, consultant, written communication, 29 March 2012). Most likely before climate change (or some other factor) caused the formation of Lake Lucero in the hollowed-out sediments of older Lake Otero, a long period of extreme deflation, with no lake occurred (Steve Fryberger, consultant, written communication, 29 March 2012).

Geomorphic evidence and age dating suggest that deflation of Lake Otero sediments occurred in a stepwise fashion on relict shorelines of Pleistocene Lake Otero. The shorelines mark playas that formed between stages of deflation, which eroded Lake Otero sediments to their present profile (Langford 2003). Deflated sediments were transported by the wind, from southwest to northeast across the basin. The first deflation episode began about 7,000 years ago and resulted in the "L1 shoreline" of Langford (2003), which is at an elevation of 1,200 m (3,937 ft) above sea level and approximately 14.5 m (48 ft) above Lake Lucero. A second deflation event started about 4,000 years ago, and resulted in the scour of Lake Otero beds by about 9 m (30 ft). This is the drop in elevation between the L1 and L2 shorelines of Langford (2003). The lower L2 shoreline is about 1,191 m (3,907 ft) above sea level and approximately 5.5 m (18 ft) above modern Lake Lucero (Langford 2003). A third period of deflation downcut to the Lake Lucero floor, resulting in removal of an additional 6 m (20 ft) of strata (Langford 2003; Kocurek et al. 2007).

Work by Szynkiewicz et al. (2009, 2010a), which analyzed sulfur isotopes, provides further evidence for this "stepwise deflation" hypothesis. According to these studies, the source of sand for the parabolic dunes was sediments at the top of the lake beds; while the source of sand for the barchan dunes was older lake beds. In other words, the area of parabolic dunes is older than the barchanoid dune field. The barchanoid dune field was emplaced during the second deflationary event, after the top layers of lake sediments had already been eroded and transported to the parabolic dunes. Dunes formed during each deflation event and then stabilized; the ancient, stabilized dunes now make up the areas of marginal parabolic dunes (Rip Langford, written communication, 9 April 2012). Furthermore, after each deflation event, the White Sands dune field was or became a wet eolian system, as interpreted by Kocurek et al. (2007), which prevented sand mixing within the dune field system (Szynkiewicz et al. 2009, 2010a).

Further evidence for the evolution of White Sands dune field via stepwise deflation comes from Langford et al. (2009). Using optically stimulated luminescence (OSL) and radiocarbon dates from various sources (i.e., Fryberger 2001a; Langford 2003), Langford et al. (2009) estimated that the eastern dune field across which the older parabolic dunes are now traveling was stabilized by 3,500 years ago, and the central, more westward dune field across which the younger barchan dunes are now traveling was stabilized by 2,100 years ago. Moreover, the preserved lacustrine landscape, which is covered with sand sheets east of the dunes, indicates that the location of the dune front has not changed substantially over the past 6,000 years (Langford et al. 2009).

# Geologic Map Data

*This section summarizes the geologic and geomorphic map data available for White Sands National Monument. The map overview graphics display the geologic and geomorphic map data draped over a shaded relief image of the national monument and surrounding area. The foldout map unit properties tables summarize this report's content for the each geologic and geomorphic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).*

### Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the Quaternary Period (past 2.6 million years). Surficial or geomorphic map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 6. Both geologic and surficial map data are provided for White Sands National Monument.

Geologic maps also may show geomorphic features (landforms), structural interpretations, and locations of past geologic hazards (e.g., landslide deposits) that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

### Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to produce the digital geologic data for White Sands National Monument. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Seager, W. R., J. W. Hawley, F. E. Kottlowski, and S. A. Kelley. 1987. Geology of east half of Las Cruces and northeast El Paso 1° x 2° sheets (scale 1:125,000). Geologic map 57. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico, USA.

Fryberger, S. G. 2001b. Reconnaissance geomorphic map of the active White Sands dune field, New Mexico (scale 1:50,000). Figure 2-17A *in* Geological overview of White Sands National Monument, chapter 2: a summary of the Quaternary geology of the White Sands area. Shell Exploration and Production, United Kingdom. http://www.nature.nps.gov/geology/parks/whsa/geows/index.htm (accessed 25 January 2012).

### Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for White Sands National Monument using data model version 2.1.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select White Sands National Monument from the unit list.

The following components and geologic data layers are part of the data set:

- Separate zip files for the geologic (Seager et al. 1987) and the geomorphic (Fryberger 2001b) maps
- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see table below)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A PDF document that contains all of the ancillary map information and graphics, including geologic unit correlation tables, map unit descriptions, legends, and other information captured from source maps
- An ESRI map document file (.mxd) that displays the digital geologic data.

**Table 1. Data layers on the White Sands National Monument geologic map (Seager et al. 1987)**

| Data Layer | Data Layer Code | On Overview Graphic? |
|---|---|---|
| Geologic Cross Sections Lines | SEC | No |
| Geologic Attitude Observation Localities | ATD | No |
| Volcanic Point Features | VPF | No |
| Mine Point Features | MIN | No |
| Map Symbology | SYM | Yes |
| Folds | FLD | Yes |
| Faults | FLT | Yes |
| Geologic Contacts | GLGA | Yes |
| Geologic Map Units | GLG | Yes |

**Table 2. Data layers on the White Sands National Monument geomorphic map (Fryberger 2001b)**

| Data Layer | Data Layer Code | On Overview Graphic? |
|---|---|---|
| Geologic Observation Localities | GOL | Yes |
| Mine Point Features | MIN | No |
| Observed Extent Lines | FLIN | Yes |
| Geologic Features Lines | GLF | Yes |
| Faults | FLT | Yes |
| Geomorphic Unit Boundaries | MRPHA | Yes |
| Geomorphic Units | MRPH | Yes |

### Geologic Map Overview Graphics

Map overview graphics (in pocket) display the GRI digital geologic and geomorphic data draped over a shaded relief image of White Sands National Monument and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overviews, as indicated in the above table. Cartographic elements and basic geographic information have been added to overviews. Digital elevation data and geographic information, which are part of the overview graphics, are not included with the GRI digital geologic GIS data for the national monument, but are available online from a variety of sources.

### Map Unit Properties Tables

The geologic and geomorphic units listed in the map unit properties tables (in pocket) correspond to the accompanying digital geologic data. One of the map unit properties tables shows the geologic data of Seager et al. (1987), and shows the geomorphic data of Fryberger (2001b). Following the structure of the report, the tables summarize the geologic issues, features and processes, and geologic history associated with each map unit. The tables also list the geologic time period, map unit symbol, and a simplified geologic description of the unit.

### Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphics. Based on U.S. National Map Accuracy Standards and the source map scales—1:125,000 for Seager et al. (1987) and 1:50,000 for Fryberger (2001b)—geologic features represented here are horizontally within 64 m (208 ft) at map scale 1:125,000 and 25 m (83 ft) at map scale 1:50,000 of their true location.

Please contact GRI with any questions.

# Glossary

*This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

**alluvial fan.** A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

**alluvium.** Stream-deposited sediment.

**aquifer.** A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

**arc.** See "volcanic arc."

**arroyo.** A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.

**ash (volcanic).** Fine material ejected from a volcano (also see "tuff").

**avulsion.** The sudden cutting off or separation of land by a flood or by an abrupt change in the course of a stream, as by a stream breaking through a meander or by sudden change in current whereby the stream deserts its old channel for a new one.

**bajada.** Geomorphic feature formed from the coalescence of alluvial fans along a basin margin.

**barchan dune.** A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.

**basalt.** A dark-colored, often low-viscosity, extrusive igneous rock.

**base level.** The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

**basement.** The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

**basin (structural).** A doubly plunging syncline in which rocks dip inward from all sides.

**basin (sedimentary).** Any depression, from continental to local scales, into which sediments are deposited.

**batholith.** A massive, discordant pluton, larger than 100 $km^2$ (40 $mi^2$), and often formed from multiple intrusions of magma.

**beach.** A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

**bed.** The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

**bedding.** Depositional layering or stratification of sediments.

**bedrock.** A general term for the rock that underlies soil or other unconsolidated, surficial material.

**bioturbation.** The reworking of sediment by organisms.

**braided stream.** A sediment-clogged stream that forms multiple channels which divide and rejoin.

**breccia.** A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

**calcrete.** A term for a pedogenic calcareous soil (e.g., limestone consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution and redeposited through the agency of infiltrating waters, or deposited by the escape of carbon dioxide from vadose water.

**caldera.** A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

**caliche.** Hard, calcium-carbonate cemented layer commonly found on or near the surface of arid and semiarid regions.

**capture.** Another word for "stream capture" or "piracy," which is the natural diversion of the headwaters of one stream into the channel of another stream having greater erosional activity.

**carbonate.** A mineral that has $CO_3^{-2}$ as its essential component (e.g., calcite and aragonite).

**carbonate rock.** A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

**cementation.** Chemical precipitation of material into pores between grains that bind the grains into rock.

**cinder cone.** A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

**clast.** An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

**clastic.** Describes rock or sediment made of fragments of pre-existing rocks (clasts).

**clay.** Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

**continental crust.** Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

**continental rifting.** Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

**continental rise.** Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

**continental shelf.** The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

**continental slope.** The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

**country rock**. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

**crinoid.** A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

**cross-bedding.** Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

**crust.** Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

**cryptogamic soil.** The brown crust on sandy, desert soils that is composed of an association of algae, lichen, mosses, and fungi. Helps stabilize the soil.

**crystalline**. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

**debris flow**. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

**deflation**. The removal of material from a beach, desert, or other land surface by wind action.

**delta.** A sediment wedge deposited where a stream flows into a lake or sea.

**depocenter.** An area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin.

**devitrification.** Conversion of glass to crystalline material.

**dike.** A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

**dip.** The angle between a bed or other geologic surface and horizontal.

**discharge.** The rate of flow of surface water or groundwater given at a given moment, expressed as volume per unit of time.

**dolomite.** A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

**dolomitic.** Describes a dolomite-bearing rock, or a rock containing dolomite.

**dolomitization.** The process by which limestone is wholly or partly converted to dolomite rock or dolomitic limestone through the replacement of the original calcium carbonate (calcite) by magnesium carbonate (mineral dolomite), usually through the action of magnesium-bearing water (seawater or percolating meteoric water). It can occur contemporaneously or shortly after deposition of the limestone, or during lithifaction at a later period.

**dome.** General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.

**downcutting.** Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

**dune.** A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

**eolian.** Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

**ephemeral stream.** A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

**escarpment.** A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

**evaporite.** A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

**extension.** A type of strain resulting from forces "pulling apart." Opposite of compression.

**extrusive.** Describes molten (igneous) material that has erupted onto Earth's surface.

**facies (sedimentary).** The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

**fanglomerate.** A sedimentary rock of heterogeneous materials that were originally deposited in an alluvial fan and have since been cemented into solid rock.

**fault.** A break in rock along which relative movement has occurred between the two sides.

**feldspar.** A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

**feldspathic.**

**formation.** Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

**fracture.** Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

**fulgurite.** An irregular glassy tube or crust produced by the fusion of loose sand by lightning, and found especially in dune areas.

**geology.** The study of Earth including its origin, history, physical processes, components, and morphology.

**gneiss.** A foliated rock formed by regional metamorphism with alternating bands of dark and light minerals.

**gully.** A small channel produced by running water in earth or unconsolidated material (e.g., soil or a bare slope).

**gypcrete.** A gypsum deposits that forms cemented desert pavements within the soil profiles developed in the Fayum Depression of Egypt and elsewhere. It is the gypsum equivalent of calcrete.

**gypsite**. An earthy variety of gypsum containing dirt and sand, found only in arid regions as an efflorescent deposit occurring over the ledge outcrop of gypsum or of a gypsum-bearing stratum.

**gypsum.** The most common sulfate mineral (calcium sulfate). Frequently associated with halite and anhydrite in evaporites.

**horst.** Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

**hypersaline.** Excessively saline; with salinity substantially greater than that of average seawater.

**igneous.** Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

**interdune.** Pertaining to the relatively flat surface, whether sand-free or sand-covered, between dunes.

**intertidal.** Pertaining to the benthic ocean environment or depth zone between high water and low water; also, pertaining to the organisms of that environment. Also referred to as "littoral."

**intertonguing.** The disappearance of sedimentary bodies in laterally adjacent masses owing to splitting into many tongues, each of which reaches an independent pinch-out termination; the integradation of markedly different rocks through vertical succession of thin interlocking or overlapping wedge-shaped layers.

**intrusion.** A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

**laccolith.** A mushroom- or arcuate-shaped pluton that has intruded sedimentary strata and domed up the overlying sedimentary layers. Common on the Colorado Plateau.

**lacustrine.** Pertaining to, produced by, or inhabiting a lake or lakes.

**lava.** Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

**light detection and ranging.** A method and instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses. The measured interval is converted to distance. Shortened forms: lidar, LiDAR. Abbrev: LIDAR.

**limestone.** A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

**limonite.** A field term for a group of brown amorphous hydrous ferric oxides. Limonite is a common secondary material, formed by weathering (oxidation) of iron-bearing minerals; it may also occur as a precipitate in bogs or lakes. It occurs as coatings, earthy masses, and in a variety of other forms, and is the coloring material of yellow clays and soils. Limonite is a minor ore of iron.

**loam.** A rich permeable soil composed of a mixture of clay, silt, sand, and organic matter.

**magma.** Molten rock beneath Earth's surface capable of intrusion and extrusion.

**magmatism.** The development and movement of magma, and its solidification to igneous rock.

**marl.** An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

**mass wasting.** A general term for the downslope movement of soil and rock material under the direct influence of gravity.

**meta–.** A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

**meteoric water.** Pertaining to water of recent atmospheric origin.

**micrite.** A descriptive term for the semiopaque crystalline matrix of limestones, consisting of chemically precipitated carbonate mud with crystals less than 4 microns in diameter, and interpreted as a lithified ooze. The term is now commonly used in a descriptive sense without genetic implication.

**monzodiorite.** A type of plutonic rock.

**mud cracks.** Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

**normal fault.** A dip-slip fault in which the hanging wall moves down relative to the footwall.

**olivine.** An olive-green mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.

**oolite.** A sedimentary rock, usually limestone, made of ooliths—round or oval grains formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain. These laminated grains can reach diameters of 2 mm (0.08 in), but 0.5–1 mm (0.02–0.04 in) is common.

**orogeny.** A mountain-building event.

**ostracode.** Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracodes are of microscopic size.

**outcrop.** Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

**Pangaea.** A theoretical, single supercontinent that existed during the Permian and Triassic periods.

**passive margin.** A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

**pebble.** Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

**pendant.** A solutional remnant hanging from the ceiling or wall of a cave.

**perched aquifer.** An aquifer containing unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

**permeability.** A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

**phreatic zone.** The zone of saturation. Phreatic water is groundwater.

**piedmont.** An area, plain, slope, glacier, or other feature at the base of a mountain.

**platform.** Any level or nearly-level surface, ranging in size from a terrace or bench to a plateau or peneplain.

**pluton (plutonic).** A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

**pluvial.** Describes geologic processes or features resulting from rain.

**progradation.** The seaward building of land area due to sedimentary deposition.

**recharge.** Infiltration processes that replenish groundwater.

**regression.** A long-term seaward retreat of the shoreline or relative fall of sea level.

**rhyolite.** A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

**rift.** A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

**rift valley.** A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

**rilles.** A trench-like or crack-like valley, commonly occurring on planetary surfaces subjected to plains volcanism; they may be irregular with meandering courses (sinuous rilles) or relatively straight (normal rilles).

**ripple marks.** The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

**rock.** A solid, cohesive aggregate of one or more minerals.

**rock fall.** Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

**sabkha.** A coastal environment in an arid climate just above high tide. Characterized by evaporate minerals, tidal-flood, and eolian deposits. Common in the Persian Gulf.

**sand.** A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

**sand sheet.** A large irregularly shaped plain of eolian sand, lacking the discernible slip faces that are common on dunes.

**sandstone.** Clastic sedimentary rock of predominantly sand-sized grains.

**schist.** A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

**sediment**. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

**sedimentary rock.** A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

**sequence.** A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.

**shale.** A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

**sheet flow.** An overland flow or downslope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

**sheetflood.** A broad expanse of moving, storm-borne water that spreads as a thin, continuous, relatively uniform film over a large area in an arid region and that is not concentrated into well-defined channels; its distance of flow is short and its duration is measured in minutes or hours. Sheetfloods usually occur before runoff is sufficient to promote channel flow, or after a period of sudden and heavy rainfall.

**siliceous.** Said of a rock or other substance containing abundant silica.

**sill.** An igneous intrusion that is of the same orientation as the surrounding rock.

**silt.** Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

**siltstone.** A variably lithified sedimentary rock composed of silt-sized grains.

**sinkhole.** A circular depression in a karst area with subterranean drainage and is commonly funnel-shaped.

**slip face**. The steeply sloping surface on the lee side of a dune, standing at or near the angle of repose of loose sand, and advancing downwind by a succession of slides wherever that angle is exceeded.

**solute**. A dissolved substance.

**slope.** The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

**soil.** Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

**spring.** A site where water issues from the surface due to the intersection of the water table with the ground surface.

**stock.** An igneous intrusion exposed at the surface; less than 100 km$^2$ (40 mi$^2$) in size. Compare to "pluton."

**strata.** Tabular or sheet-like masses or distinct layers of rock.

**stratification.** The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

**stratigraphy.** The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

**stream.** Any body of water moving under gravity flow in a clearly confined channel.

**stream channel.** A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

**stromatolite.** An organosedimentary structure produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes (blue-green algae). It has a variety of gross forms, form nearly horizontal to markedly columnar, domal, or subspherical.

**structure.** The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

**subsidence.** The gradual sinking or depression of part of Earth's surface.

**sulfate**. A mineral compound characterized by the sulfate radical $SO^{4-}$. Anhydrous sulfates, such as barite, $BaSO_4$, have divalent cations linked to the sulfate radical; hydrous and basic sulfates, such as gypsum, $CaSO_4 \cdot 2H_2O$, contains water molecules.

**sulfide**. A mineral compound characterized by the linkage of sulfur with a metal or semimetal, such as galena, PbS, or pyrite, $FeS_2$.

**supertidal.** Describes features or processes at elevations higher than normal tidal range on a give shoreface.

**syenite**. A group of plutonic rocks usually containing orthoclase, microcline, or perthite, a small amount of plagioclase, one or more mafic minerals (especially hornblende), and little or no quartz; also any rock in that group.

**tectonic.** Relating to large-scale movement and deformation of Earth's crust.

**tectonics.** The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

**terrace.** A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

**terrestrial.** Relating to land, Earth, or its inhabitants.

**terrigenous.** Derived from the land or a continent.

**tongue (stratigraphy).** A member of a formation that extends and wedges out away from the main body of a formation.

**topography.** The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

**trace fossil.** Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

**transgression.** Landward migration of the sea as a result of a relative rise in sea level.

**uplift.** A structurally high area in the crust, produced by movement that raises the rocks.

**vadose water.** Water of the unsaturated zone or zone of aeration.

**volcanic.** Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

**volcanic arc.** A commonly curved, linear, zone of volcanoes above a subduction zone.

**water table.** The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

**weathering.** The physical, chemical, and biological processes by which rock is broken down.

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# Additional References

*This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of September 2012.*

### Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

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NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views Program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/.

USGS Geology of National Parks (3D and photographic tours): http://3dparks.wr.usgs.gov/.

### NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual: Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://etic.nps.gov/

2009 Paleontological Resources Preservation Act: http://nature.nps.gov/geology/nationalfossilday/prpa.cfm

### Geological Surveys and Societies

New Mexico Bureau of Geology and Mineral Resources: http://geoinfo.nmt.edu/

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

### U.S. Geological Survey Reference Tools

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

U.S. Geological Survey Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

U.S. Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

# Appendix: Scoping Meeting Participants

*The following are lists of meeting participants for White Sands National Monument. Please consult the Geologic Resources Division for current contact information. The geoindicators report and Geologic Resource Evaluation scoping summary were used as the foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).*

**2003 Geoindicators Meeting Participants**

White Sands National Monument

Bill Conrod, Natural Resource Specialist
Kathy Denton, Education Specialist
Jessica Kusky, Interpreter
Julie Lockhard, Student Conservation Association Intern
Jim Mack, Superintendent
John Mangimeli, Chief of Interpretation
Diane White, Cultural Resource Specialist

Other National Park Service

Bob Higgins, Geologist, Geologic Resources Division
Greg McDonald, Paleontologist, Geologic Resources Division
Lisa Norby, Geologist, Geologic Resources Division
Pete Penoyer, Hydrologist, Water Resources Division
Andrew Valdez, Geologist, Great Sand Dunes National Park
Bill Reid, Network Coordinator, Chihuahuan Desert Network

New Mexico Bureau of Geology and Mineral Resources

Bruce Allen, Field Geologist
Dave Love, Principal Senior Environmental Geologist
Greer Price, Senior Geologist/Chief Editor
Peter Scholle, Director/State Geologist

U.S. Geological Survey

Rick Huff, Hydrogeologist, Las Cruces
Anne-Marie Matherne, Hydrologist, Albuquerque

Holloman Air Force Base

Andrew "JR" Gomolak, Geologist/Archeologist
Rich Wareing, Chief of Environmental Analysis

Other Participants

Phil Goodell, Associate Professor, University of Texas at El Paso
Adrian Hunt, Director, New Mexico Museum of Natural History and Science
Katie KellerLynn, Geologist/NPS Contractor
Rip Langford, Professor, University of Texas at El Paso
Curtis Monger, Professor, New Mexico State University
Robert Myers, Geologist, White Sands Missile Range

**2007 Scoping Cooperators**

White Sands National Monument

David Bustos, Biologist

Other National Park Service

Bruce Heise, Geologist, Geologic Resources Division
Hildy Reiser, Science Advisor, Chihuahuan Desert Network
Scott Schrader, GIS/Remote Sensing Analyst, Chihuahuan Desert Network

Other Participants

Steve Fryberger, Consultant
Katie KellerLynn, Research Associate, Colorado State University
Gary Kocurek, Professor, University of Texas at Austin
Rip Langford, Professor, University of Texas at El Paso
Dave Love, Geologist, New Mexico Bureau of Geology and Mineral Resources
Gordon Michaud, Soil Scientist, Natural Resource Conservation Service
Anna Szynkiewicz, Researcher, Indiana University

NPS 142/117235, October 2012

**National Park Service**
**U.S. Department of the Interior**

**Natural Resource Stewardship and Science**
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

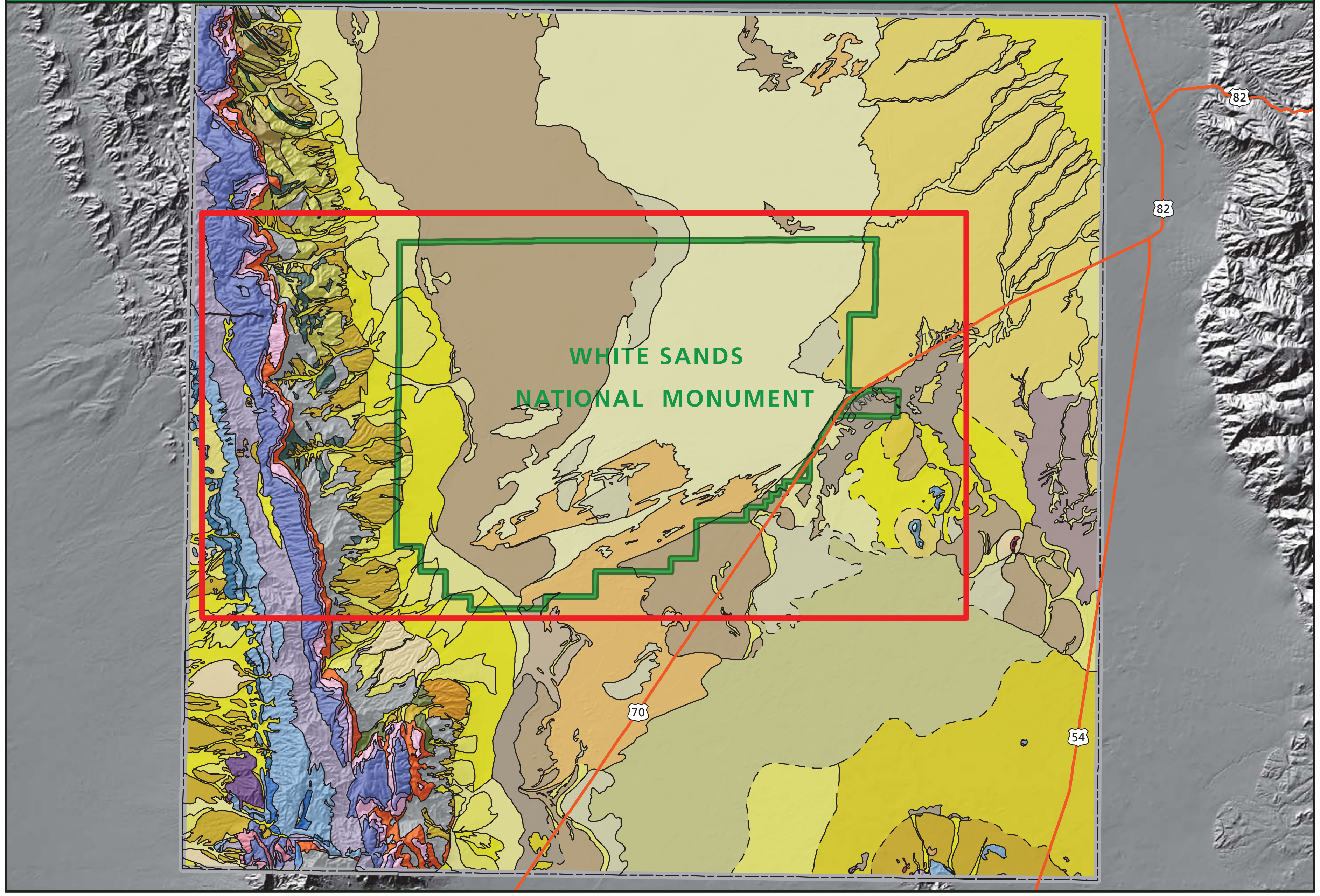
www.nature.nps.gov

**White Sands National Monument**
**New Mexico**

**National Park Service**
**U.S. Department of the Interior**

# Overview of Digital Geologic Data for White Sands NM

**Full Extent of Digital Geologic Data, Area of Detail in Red**



**Geologic Units**

- 🟨 Qpy - Younger piedmont-slope deposits
- 🟨 Qpa - Qpy amnd Qpo, undifferentiated
- 🟨 Qpa + Qegs - Qpy and Qegs, undifferentiated
- 🟨 Qpa/Qpu - Qpa units overlying Qpu units, undifferentiated
- 🟫 Qbf - Basin-floor sediments
- 🟫 Qbf/Qlg - Qbf overlying Qlg
- 🟫 Qbf/Qpg - Qbf overlying Qpg
- 🟫 Ql - Deposits of small, non-alkaline playa lakes and depressions
- 🟫 Qlg - Gypsiferous lake deposits in the Tularosa Basin
- 🟨 Qegs - Eolian deposits associated with Tularosa Basin lakes
- 🟨 Qegs/Qpg - Qegs overlying Qpg
- 🟨 Qegs + Qbfg - Qegs and Qbfg, undifferentiated
- 🟨 Qegs/Ph? - Qegs overlying Ph?
- 🟨 Qega - Active gypsum dunes
- 🟧 Qes - Eolian quartz sand
- 🟨 Qes/Qpu - Qes overlying Qpu units
- 🟨 Qes/Qbfg - Qes overlying Qbfg
- 🟨 Qes/Qcl - Qes overlying Qcl
- 🟨 Qpo - Older piedmont-slope deposits
- 🟨 Qpu - Qpo and Qcp, undifferentiated
- 🟨 Qpg - Older gypsiferous basin-floor and distal piedmont slope deposits
- 🟨 Qbfg - Older gypsiferous basin-floor deposits and lake beds
- 🟧 Qegi - Inactive gypsum dunes
- 🟧 Qb - Olivine basalt
- 🟧 Qcp - Camp Rice Formation, piedmont-slope facies
- 🟨 QTcu - Qcp and QTcc, undifferentiated
- 🟨 Qcl - Camp Rice Formation, sediments associated with La Mesa surface
- 🟧 QTcc - Camp Rice Formation, fanglomerate facies
- 🟥 Tii - Intermediate-composition plutonic rocks
- 🟥 Tri - Non-foliated rhyolite intrusives
- 🟪 Tis - Silicic plutonic rocks
- 🟪 Tlr - Love Ranch Formation
- 🟨 TKru - Sarten and Dakota Sandstone with unknown rocks, undifferentiated
- 🟦 PZu - Paleozoic rocks, undifferentiated
- 🟦 Ps - San Andres Formation
- 🟦 Psy - San Andres Formation and Yeso Formation, undivided
- 🟦 Py - Yeso Formation
- 🟦 Pya - Yeso (?) beds and Abo Formation
- 🟦 Pa - Abo Formation
- 🟦 Ph - Hueco Formation
- 🟪 PNps - Panther Seep Formation
- 🟦 PNlc - Lead Camp Limestone
- 🟦 PNls/ls? - Lead Camp Limestone overlying ls?
- 🟪 MDr - Mississippian and Devonian Rocks, undifferentiated
- 🟪 SOfm - Fusselman Dolomite and Montoya Group, undivided
- 🟥 OCeb - El Paso Group and Bliss Sandstone, undivided
- ⬜ PCg - Precambrian rocks, granite
- 🟨 PCq - Precambrian rocks, quartzite
- 🟫 PCs - Precambrian rocks, schist and phyllite
- 🟩 PCa - Precambrian rocks, amphibolite
- 🟩 PCmd - Precambrian rocks, metadiabase
- 🟩 PCgn - Precambrian rocks, gneiss

**NPS Boundary**

🟩

**Folds**

- anticline, known or certain, dashed where approximate or inferred
- syncline, known or certain, dashed where approximate
- overturned syncline, known or certain
- monocline, known or certain

**Faults**

- thrust fault, known or certain, dashed where approximate, teeth on upthrown side
- normal fault, known or certain, dashed where approximate or inferred, dotted where concealed bar and ball on downthrown side
- unknown offset/displacement, known or certain, dashed where approximate or inferred

**Geologic Contacts**

- known or certain, dashed where approximate or inferred
- quadrangle boundary

These figures are an overview of compiled digital geologic and geomorphic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:125,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 63 meters / 203 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Seager, W.R., J.W. Hawley, F.E. Kottlowski, and S.A. Kelley. 1987. Geology of East Half of Las Cruces and Northeast El Paso 1° x 2° Sheets, New Mexico (scale 1:125,000). Geologic Map 57. New Mexico Bureau of Mines and Mineral Resources.

Digital geologic data and cross sections for White Sands National Monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. (Enter "GRI" as the search text and select White Sands National Monument from the unit list.)

**Produced by the Geologic Resources Inventory**

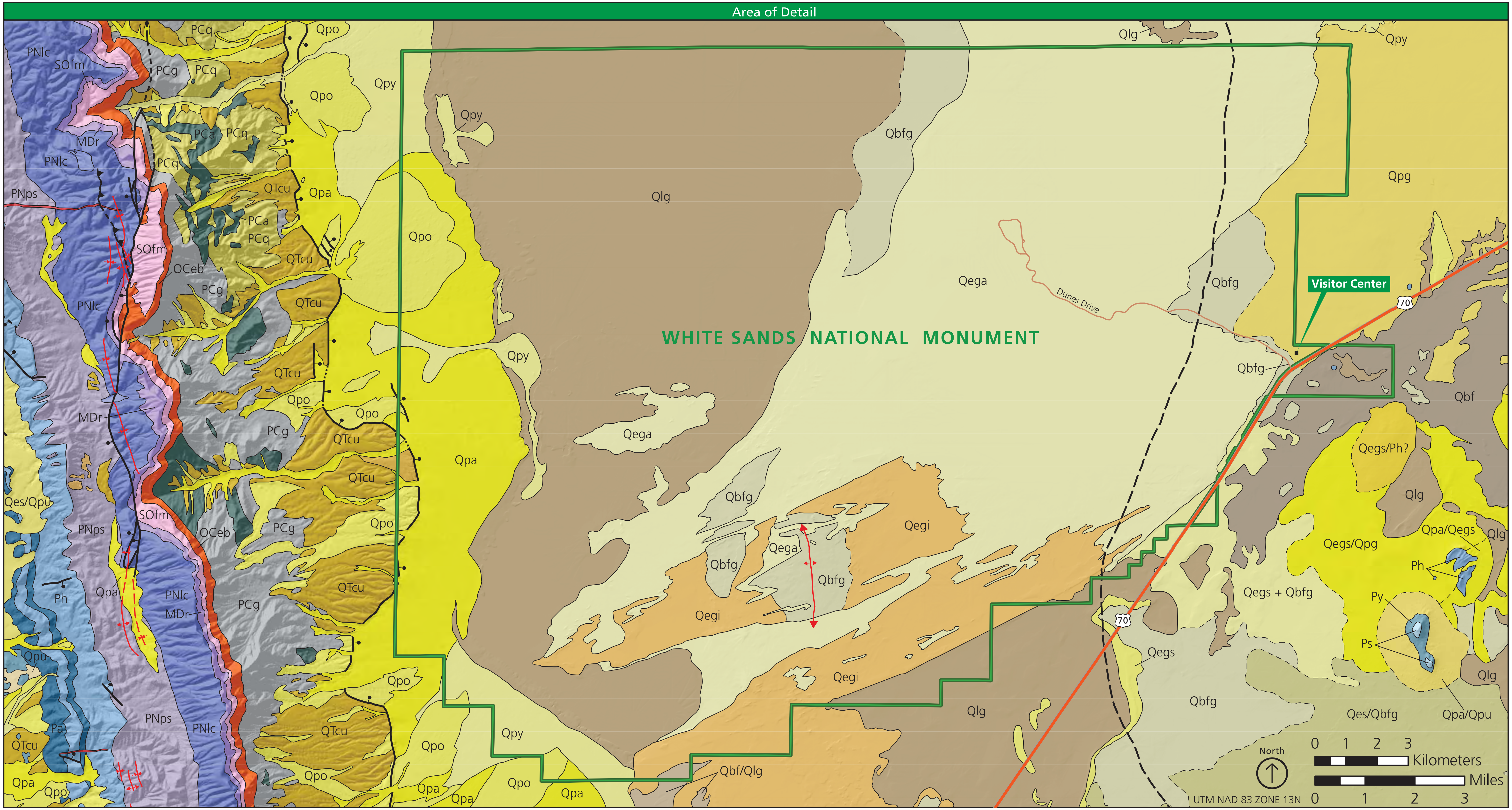
**October 2012**

White Sand National Monument
New Mexico

National Park Service
U.S. Department of the Interior

# Overview of Digital Geologic Data for White Sands NM

Area of Detail



Produced by the Geologic Resources Inventory

October 2012

# Geologic Map Unit Properties Table: White Sands National Monument

**Gray-shaded rows indicate units not mapped within White Sands National Monument by Seager et al. (1987). "*" Indicates additional information on Geomorphic Map Unit Properties Table. "?" Indicates uncertain occurrences as noted on the source map.**

| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| HOLOCENE AND PLEISTOCENE | Younger piedmont-slope deposits (Qpy) | Unconsolidated sand, gravel, and loamy sediments, of drainageways that cross and are inset below or bury older piedmont slopes, and of fans constructed on distal piedmont slopes at the lower end of such drainageways. Up to 5 m (15 ft) thick. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Corresponds in time with ancient Lake Otero and modern Lake Lucero. |
|  | Undifferentiated piedmont-slope deposits (Qpa) | Qpa consists of the following units:<br>Younger piedmont-slope deposits (**Qpy**): See description above.<br>Older piedmont-slope deposits (**Qpo**): See description below. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Postdates river valley incision by Rio Grande. |
|  | Undifferentiated piedmont-slope deposits (Qpa) and eolian deposits associated with Tularosa Basin lakes (Qegs), undifferentiated<br>(Qpa + Qegs) | Qpa + Qegs consists of the following units:<br>Undifferentiated piedmont-slope deposits (**Qpa**): See description above.<br>Eolian deposits associated with Tularosa Basin lakes (**Qegs**): See description below. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—east of the White Sands dune field. Surface water intercepted by dune field.<br>*Climate Change*—increased eolian activity as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* and active sand (**active_sand?**).*<br>*Alluvial Deposits*—occurs east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |
| HOLOCENE OVER PLIOCENE | Undifferentiated piedmont-slope deposits (Qpa) overlying Qpu (older sediment deposits [Qpo] and Camp Rice Formation [Qcp])<br>(Qpa/Qpu) | Qpa/Qpu consists of Qpa (Qpy and Qpo units) overlying Qpu (Qpo and Qcp units):<br>Younger piedmont-slope deposits (**Qpy**): See description above.<br>Older piedmont-slope deposits (**Qpo**): See description below.<br>Camp Rice Formation (**Qcp**): See description below. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—east of the White Sands dune field. Surface water intercepted by dune field. | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* and active sand (**active_sand?**)* east of White Sands dune field.<br>*Alluvial Deposits*—occurs east of White Sands dune field. | Deposited after incision by ancestral Rio Grande. |
| HOLOCENE AND/OVER PLEISTOCENE | Basin-floor sediments (Qbf) | Mostly loam, silt, or clay. Some locations have thin zones of pebbly gravel. Deposits in eastern Tularosa Basin are commonly gypsiferous and up to 5 m (15 ft) thick. | *Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* and active sand (**active_sand?**)* east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |

**Gray-shaded rows indicate units not mapped within White Sands National Monument by Seager et al. (1987). "*" Indicates additional information on Geomorphic Map Unit Properties Table. "?" Indicates uncertain occurrences as noted on the source map.**

| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| HOLOCENE AND/OVER PLEISTOCENE | Basin-floor sediments (Qbf) overlying gypsiferous lake deposits in the Tularosa Basin (Qlg)<br>(Qbf/Qlg) | Unit consists of Qbf overlying Qlg:<br>Basin-floor sediments (**Qbf**): See description above.<br>Gypsiferous lake deposits in the Tularosa Basin (**Qlg**): See description below. | *Erosion*—erosion of beds may reveal fossils or other paleontological information about ancient Lake Otero.<br>*Paleontological Resources*—potential for fossil trackways.<br>*Climate Change*—greater potential for deflation as a result of longer and more severe droughts.<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* and shoreline dunes (**shrln_dune**)* south of White Sands dune field. Also correlated with with **sp_los*** and **lo_outcrops*** (see "Lake Otero Strata" section in report).<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |
| | Basin-floor sediments (Qbf) overlying older gypsiferous basin-floor and distal piedmont slope deposits (Qpg)<br>(Qbf/Qpg) | Qbf/Qpg consists of Qbf overlying Qpg:<br>Basin-floor sediments (**Qbf**): See description above.<br>Older gypsiferous basin-floor and distal piedmont slope deposits (**Qpg**): See description below. | *Surface Water*—east of White Sands dune field. Surface water flow intercepted by dune field.<br>*Climate Change*—greater potential for deflation as a result of longer and more severe droughts. | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**).*<br>*Alluvial Deposits*—not part of bajada. Occurs on east side of national monument.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |
| | Deposits of small, non-alkaline playa lakes and depressions (Ql) | Mostly clay and silt. Up to 5 m (15 ft) thick. | *Groundwater*—relationship to groundwater system unknown.<br>*Surface Water*—less saline source of water. Occur outside of the active Holocene lake basin (**ahlb**).* | *Miscellaneous Geomorphic Features*—active lake (**active_lake**).* | Corresponds to onset of regional aridity during Holocene Epoch. |
| | Gypsiferous lake deposits in the Tularosa Basin (Qlg) | Mostly gypsite, gypsiferous red and green clay, and gypsiferous silt, locally covered by thin, loamy to silty, eolian deposits of alluvium. Includes ancient Lake Otero with highest shoreline near 1,204 m (3,950 ft) above sea level and several smaller lake beds in the eastern Tularosa Basin. At least 8 m (25 ft) thick. | *Erosion*—erosion of beds may reveal fossils or other paleontological information about ancient Lake Otero.<br>*Paleontological Resources*—lake beds host fossil trackways.<br>*Climate Change*—more sediment available for eolian transport as a result of longer and more severe droughts.<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes).<br>*Tamarisk*—invaded around Lake Lucero (**ahlb_nll** and **ahlb_nll**)* and between widespread area of **Qlg** and **Qega** in White Sands National Monument. | *Active Holocene Lake Basin*—corresponds to active Holocene lake basin (**ahlb**).*<br>*Scour Platform* and *Miscellaneous Geomorphic Features*—correlated with **sp_los*** and **lo_outcrops*** (see "Lake Otero Strata" section in report) and shoreline lunette dunes (**shrln_l_dune**)* and subdued eolian topography (**sbdd_eln_top**)* south of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated with ancient Lake Otero. |
| | Eolian deposits associated with Tularosa Basin lakes (Qegs) | Mostly inactive, ridge-like dunes of yellowish to tan, gypsiferous quartzose silt and fine quartzose sand with gypsite layers. Located on the lee (eastern) side of lake (**Qlg**) beds. Many have 0.3 m (1 ft) to 0.6 m (2 ft) of pedogenic gypsite (gypcrete) capping the deposits. Up to 23 m (75 ft) thick. | *Climate Change*—increased eolian activity as a result longer and more severe droughts.<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Miscellaneous Geomorphic Features*—correlated with Lake Otero outcrops (**lo_outcrops**).* Similar to lunettes (**shrln_l_dune**).* The larger patch at NW 30 includes non-lunette stabilized dunes, probably older than the other lunette dunes (Rip Langford, University of Texas at El Paso, professor, written communication, 8 April 2012).<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |

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| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| HOLOCENE AND/OVER PLEISTOCENE | Eolian deposits associated with Tularosa Basin lakes (Qegs) overlying older gypsiferous basin-floor and distal piedmont slope deposits (Qpg)<br>(Qegs/Qpg) | Qegs/Qpg consists of Qegs overlying Qpg:<br>Eolian deposits associated with Tularosa Basin lakes (**Qegs**): See description above.<br>Older gypsiferous basin-floor and distal piedmont slope deposits (**Qpg**): See description below. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—east of White Sands dune field. Surface water flow intercepted by dune field.<br>*Climate Change*—greater potential for deflation as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* east of White Sands dune field.<br>*Alluvial Deposits*—not part of bajada. Occurs east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |
| | Eolian deposits associated with Tularosa Basin lakes (Qegs) and older gypsiferous basin-floor deposits and lake beds (Qbfg), undifferentiated<br>(Qegs + Qbfg) | Qegs + Qbfg consists of the following units that have not been differentiated:<br>Eolian deposits associated with Tularosa Basin lakes (**Qegs**): See description above.<br>Older gypsiferous basin-floor deposits and lake beds (**Qbfg**): See description below. | *Climate Change*—greater potential for deflation as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |
| HOLOCENE AND PLEISTOCENE OVER PERMIAN | Eolian deposits associated with Tularosa Basin lakes (Qegs) overlying Hueco Formation? (Ph?)<br>(Qegs/Ph?) | Qegs/Ph? consists of Qegs overlying Ph?:<br>Eolian deposits associated with Tularosa Basin lakes (**Qegs**): See description above.<br>Hueco Formation (**Ph?**): See description below. | *Climate Change*—greater potential for deflation as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero. |
| HOLOCENE AND PLEISTOCENE | Active gypsum dunes<br>(Qega) | White dunes of pure gypsum sand located east of and derived from modern (see note) and ancestral Lake Lucero. Up to 18 m (60 ft) thick.<br>*Note: Fryberger (2001a) concluded that very little gypsum sand is supplied by modern Lake Lucero, as suggested here by Seager et al. (1987).* | *Groundwater*—associated with dune-field groundwater system.<br>*Climate Change*—dunes may become more active as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sand*—potential for blowing sand, corrosion, and gypsum "glue."<br>*Tamarisk*—invaded dune field, particularly interdune areas. | *Active Holocene Lake Basin*—**Qega** deposits cover a small portion of the active Holocene lake basin (**ahlb**).*<br>*Barchanoid Dune Field* and *Marginal Parabolic Dunes*—represent the modern, active White Sands dune field. Part of barchanoid dune field (**bdf**) and marginal parabolic dunes (**mpd**).<br>*Miscellaneous Geomorphic Features*—cover yardang (**yrdng**) east of South Lake Lucero.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Started forming about 7,000 years ago during deflation event. Marginal parabolic dunes (**mpd**) formed first, followed by barchanoid dune field (**bdf**). |
| | Eolian quartz sand<br>(Qes) | Dunes and irregular hummocks of quartz sand, especially extensive on western piedmont slopes of San Andres Mountains, on the La Mesa surface southwest of Las Cruces, east of San Diego Mountain, and in the southern Tularosa Basin. The sand is derived largely from the Camp Rice Formation **(Qcp)** (see description below). | *Climate Change*—greater potential for eolian activity as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure*—potential for blowing sand. | *Alluvial Deposits*—occurs on western piedmont slopes of San Andres Mountains. Commonly found along course of Rio Grande. Comprises scattered coppice dunes on a stabilized surface of piedmont alluvium and Camp Rice Formation (**Qcp**) sand (Rip Langford, University of Texas at El Paso, professor, written communication, 8 April 2012). | Formation of coppice dunes during Holocene Epoch. |

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| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| HOLOCENE OVER PLEISTOCENE AND PLIOCENE | Eolian quartz sand (Qes) overlying older piedmont-slope deposits (Qpo) and Camp Rice Formation (Qcp), undifferentiated<br>(Qes/Qpu) | Qes/Qpu consists of Qes overlying Qpu:<br>Eolian quartz sand (**Qes**): See description above.<br>Older piedmont-slope deposits (Qpo) and Camp Rice Formation (Qcp), undifferentiated (**Qpu**): See description below. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009). | *Alluvial Deposits*—occurs on western piedmont slopes of San Andres Mountains. Commonly found along course of Rio Grande. Comprises scattered coppice dunes on a stabilized surface of piedmont alluvium and Camp Rice Formation (**Qcp**) sand (Rip Langford, University of Texas at El Paso, professor, written communication, 8 April 2012). | Postdates Rio Grande incision. |
| HOLOCENE OVER PLEISTOCENE | Eolian quartz sand (Qes) overlying older gypsiferous basin-floor deposits and lake beds (Qbfg)<br>(Qes/Qbfg) | Qes/Qbfg consists of Qes overlying Qbfg:<br>Eolian quartz sand (**Qes**): See description above.<br>Older gypsiferous basin-floor deposits and lake beds (**Qbfg**): See description below. | *Surface Water*—east of White Sands dune field. Surface water intercepted by dune field.<br>*Climate Change*—dune shrublands have expanded historically at the expense of grasslands (Rip Langford, written communication, 8 April 2012).<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Pre-Lake Otero deposits. |
| | Eolian quartz sand (Qes) overlying Camp Rice Formation, sediments associated with La Mesa surface (Qcl)<br>(Qes/Qcl) | Qes/Qcl consists of Qes overlying Qcl:<br>Eolian quartz sand (**Qes**): See description above.<br>Camp Rice Formation, sediments associated with La Mesa surface (**Qcl**): See description below. | *Climate Change*—greater potential for eolian activity as a result of longer and more severe droughts. Dune shrublands have expanded historically at the expense of grasslands (Rip Langford, written communication, 8 April 2012).<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009). | *Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* east of White Sands dune field. | Deposited after incision by ancestral Rio Grande. |
| PLEISTOCENE | Older piedmont-slope deposits (Qpo) | Fan and terrace deposits and erosion-surface veneers on piedmont slopes graded to closed-basin floors. Mostly weakly consolidated gravel and sandy gravel, grading downslope to gravelly loam, with thin horizons (surficial and buried) of soil-carbonate and clay accumulation. Gravelly carbonate horizons are commonly indurated and form thin pedogenic calcretes. At least two generations of fans are present at most places along the San Andres–Organ-Franklin Mountains front. Up to 15 m (50 ft) thick. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Ancient Lake Otero and pre-Lake Otero deposits.<br>Postdates river-valley incision by Rio Grande. |
| PLEISTOCENE AND PLIOCENE | Older piedmont-slope deposits (Qpo) and Camp Rice Formation (Qcp),<br>undifferentiated (Qpu) | Qpu consists of Qpo and Qcp, undifferentiated:<br>Older piedmont-slope deposits (**Qpo**): See description above.<br>Camp Rice Formation (**Qcp**): See description below. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. Deposits also occur east of the dune field. | Deposited by ancestral Rio Grande and associated with extension of Rio Grande rift. |

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| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| PLEISTOCENE | Older gypsiferous basin-floor and distal piedmont slope deposits (Qpg) | Primarily distal piedmont deposits in east-central Tularosa Basin. Mostly gypsiferous red clay and silt, tan, eolian gypsum sand, yellow, limonitic quartzose sand, tan, clayey siltstone (adobe), all moderately hardened, and gypsite. Capped everywhere by 0.3 m ( 1 ft) to 0.6 m (3 ft) of gypsite, which probably developed in conjunction with soil formation. Up to 8 m (25 ft) thick. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—east of White Sands dune field. Surface water intercepted by dune field.<br>*Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Alluvial Deposits*—not part of bajada. Occurs on eastern side of White Sands National Monument.<br>*Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**).*<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Age is uncertain but probably late Pleistocene, younger than 400,000 years old.<br>Ancient Lake Otero and pre-Lake Otero deposits (?). |
|  | Older gypsiferous basin-floor deposits and lake beds (Qbfg) | Mostly red and green gypsiferous clay and silt interbedded with gypsite. Upper 0.3 m (1 ft) to 0.9 m (3 ft) is gypsite of probable pedogenic origin. Crops out as high as 1,218 m (3,995 ft) above sea level and underlies much of the central Tularosa Basin north of the Jarilla Mountains. Grades to **Qpg** above 1,219 m (4,000 ft) above sea level. At least 8 m (25 ft) thick. | *Infrastructure and Gypsum Sand*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | *Scour Platform*—part of the scour platform (**sp**).<br>*Miscellaneous Geomorphic Features*—corresponds to subdued eolian topography (**sbdd_eln_top**)* south and east of White Sands dune field.<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Pre-Lake Otero deposits. Age of exposed beds is uncertain, probably late Pleistocene, younger than 400,000 years old. |
|  | Inactive gypsum dunes (Qegi) | Dunes of gypsite with well-developed gypcrete crusts. May be sandy or silty (quartz) locally, grading into **Qegs** (see description above). Up to 15 m (50 ft) thick. | *Climate Change*—dunes may become active as a result of longer and more severe droughts.<br>*Monitoring Eolian Processes*—mostly inactive dunes at present. Potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sand*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Marginal Parabolic Dunes*—mostly marginal parabolic dunes (**mpd**).*<br>*Miscellaneous Geomorphic Features*—includes stabilized shoreline lunette dunes (**shrln_l_dune**)* and shoreline dunes (**shrln_dune**).*<br>*Source of Gypsum Sand*—composed of gypsum from Yeso Formation (**Py**) and other Permian rocks recycled in ancient Lake Otero beds. | Correlated in time with ancient Lake Otero and younger playa deposits. |
| PLEISTOCENE AND PLIOCENE | Olivine basalt (Qb) | Mostly, if not entirely, alkali-olivine basalt. Forms cinder cones and flows. | *Infrastructure*—areas around lava flows are prone to dissolution. | *Geothermal Features and Processes*—volcanic features are associated with elevated groundwater temperatures. | Coeval with Camp Rice Formation (**Qcp**) before incision by ancestral Rio Grande. Flows range in age from 1.23 million to 25,000 years old. |
|  | Camp Rice Formation, piedmont-slope facies (Qcp) | Deposits associated with piedmont slopes graded to basin floors predating river-valley incision. Weakly to moderately cemented, boulder to cobble fan deposits and erosion-surface veneers near mountain fronts, grading to gravelly silt, loam, or clay on distal piedmont slopes. Surficial layers, up to 3 m (10 ft) thick, usually with prominent horizons of soil-carbonate accumulation and, locally, reddish-brown horizons of clay accumulation. Gravelly carbonate horizons are commonly indurated forming pedogenic calcrete zones up to 1.5 m (5 ft) thick. Multiple buried soils are present in thicker deposits; generally less than 24 m (80 ft) thick. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Deposited by ancestral Rio Grande and associated with extension of Rio Grande rift.<br>Discontinuous lenses of volcanic ash (600,000 to 700,000 years old) are locally present. |
|  | Camp Rice Formation (Qcp) and Camp Rice Formation, fanglomerate facies (QTcc), undivided<br>(QTcu) | QTcu consists of Qcp and QTcc, undivided:<br>Camp Rice Formation, piedmont-slope facies (**Qcp**): See description above.<br>Camp Rice Formation, fanglomerate facies (**QTcc**): See description below. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Deposited by ancestral Rio Grande and associated with extension of Rio Grande rift. |

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|---|---|---|---|---|---|
| PLEISTOCENE AND PLIOCENE | Camp Rice Formation, sediments associated with La Mesa surface (Qcl) | Basin-floor sediments, the constructional top of which is the La Mesa geomorphic surface (shown on geologic map with horizontal-line pattern). Generally consists of sand, silt, loam, or clay. Surficial layers, up to 3 m (10 ft) thick, have prominent horizons of soil-carbonate accumulation and, locally, reddish-brown horizons of clay accumulation. Carbonate horizons are commonly indurated (hardened), forming pedogenic calcrete zones up to 1.5 m (5 ft) thick. Overlain by discontinuous veneer of Holocene eolian sand or, locally, by upper Quaternary playa or alluvial-flat deposits. Up to 15 m (50 ft) exposed, may be locally thicker in subsurface. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Deposited by ancestral Rio Grande and associated with extension of Rio Grande rift.<br>Includes fluvial, playa, and alluvial-flat deposits that are commonly reworked by the wind. |
| | Camp Rice Formation, fanglomerate facies (QTcc) | Calcite-cemented, reddish-brown to tan fanglomerate and conglomerate underlying **Qcp**, **Qct**, or **Qcf**. Locally intertongues with **Qcf**. As thick as 90 m (300 ft) where it filled late Pliocene valleys cut into uplifts, probably much thicker in grabens below range-boundary faults. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Surface Water*—location of intermittent streams on western side of White Sands National Monument.<br>*Debris Flows and Rockfall*—site of mass wasting. | *Alluvial Deposits*—serve as pathway for surface water runoff and sediment input to the active Holocene lake basin (**ahlb**).* Part of bajada. | Deposited by ancestral Rio Grande and associated with extension of Rio Grande rift.<br>Locally contains basalt flows. |
| OLIGOCENE | Intermediate-composition plutonic rocks (Tii) | Medium- to dark-gray, equigranular monzodiorite stock in the Organ Mountains. | *Mining and Energy Development*—related to mineralization in the Organ mining district. | None reported. | Batholith and volcanism.<br>Exposed in San Andres Mountains.<br>33 million years old. |
| | Nonfoliated rhyolite intrusives (Tri) | Nonporphyritic to slightly porphyritic siliceous dikes, sills, and small plugs in the Robledo Mountains–Selden Canyon area and northwest Organ Mountains. Yellow-brown intrusive rhyolite and breccia, devitrified (converted from glass to crystalline material) and chaotic (with randomly oriented crystals), in the western Dona Ana Mountains. | *Mining and Energy Development*—related to mineralization in the Organ mining district. | None reported. | Batholith and volcanism.<br>Exposed in San Andres Mountains.<br>35 million years old. |
| | Silicic plutonic rocks (Tis) | Quartz-monzonite porphyry, granite, quartz syenite, and syenite of the Organ batholiths. Monzonite-porphyry dikes, small stocks, and a laccolith of the Dona Ana Mountains. Monzonite-porphyry dikes, sills, and stocks of the Jarilla Mountains. Syenitic sills and associated stocks (?) or laccoliths (?) in the Hueco Mountains. | *Mining and Energy Development*—Organ intrusives are related to mineralization in the Organ mining district. Jarilla intrusives (late Eocene? or Oligocene?) are related to mineralization in the Orogrande district. | None reported. | Batholith and volcanism.<br>Exposed in San Andres Mountains.<br>Organ and Dona Ana intrusives are 32.8 million years old and 33.7 million years old, respectively, and associated with thick cauldron-fill, ash-flow tuffs. |
| | Love Ranch Formation (Tlr) | Pebble to boulder conglomerate, red mudstone, and sandstone derived from Paleozoic rocks and (locally) Precambrian granite. As thick as 610 m (2,000 ft) in southern San Andres Mountains. | *Groundwater*—part of basin-fill groundwater aquifer.<br>*Debris Flows and Rockfall*—contributes material to debris-flow deposits. | *Alluvial Deposits*—exemplifies valley-filling process of Tularosa Basin. | Alluvial-fan and fluvial deposits formed as a result of erosion during Laramide uplift. |

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|---|---|---|---|---|---|
| TERTIARY AND CRETACEOUS | Sarten and Dakota Sandstone, undivided and rocks correlative with Mancos Shale and Gallup Sandstone (TKru) | Yellow-, tan-, and gray-weathering, soft sandstone, shale, and siltstone and massive, cross-bedded, gray quartzite. | *Paleontological Resources*—pelecypods and pelecypod coquina (deposit of fossil-shell debris) in Sarten and Dakota Sandstone. Mancos Shale has petrified wood, pelecypods, and ammonites. | None reported. | Marine and fluvial settings. |
| PALEOZOIC ERA | Paleozoic rocks, undifferentiated (PZu) | No description provided by Seager et al. (1987). | Unknown. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | Open marine setting. |
| PERMIAN | San Andres Formation (Ps) | Gray to dark-gray, medium-bedded to massive, fetid limestone with a basal (Glorieta) sandstone. Basal sandstone is yellowish and cross-laminated. 60 m (200 ft) to 180 m (600 ft) thick. | *Paleontological Resources*—fossiliferous limestone. | None reported. | Marine setting. |
| | Yeso Formation–San Andres Formation, undivided (Psy) | Thick- to medium-bedded, light- and dark-gray, fine-grained limestone. Minor beds of soft, yellow, fine-grained sandstone. Approximately 170 m (550 ft) thick. | *Groundwater*—significant for groundwater-flow model and deposition of gypsum in Tularosa Basin. | *Gypsum*—source of gypsum in the Tularosa Basin. | Marine setting. |
| | Yeso Formation (Py) | Light-brown to light-red sandstone, light-gray to white gypsum, and sandy, medium- to dark-gray, fetid limestone. 200 m (660 ft) to 274 m (900 ft) thick. | *Groundwater*—significant for groundwater-flow model and deposition of gypsum in Tularosa Basin.<br>*Paleontological Resources*—limestones are moderately to sparsely fossiliferous; contain brachiopods, gastropods, and algae. | *Source of Gypsum Sand*—source of the bulk of gypsum in the Tularosa Basin. Ultimate source of gypsum sand for dunes. | Cyclic deposition within marine and eolian environments. |
| | Yeso (?) beds and Abo Formation (Pya) | Consists of beds of Yeso Formation (**Py**)? (see description above) and Abo Formation (**Pa**) (see description below). | *Groundwater*—significant for groundwater-flow model and deposition of gypsum in Tularosa Basin. | *Source of Gypsum Sand*—source of gypsum in the Tularosa Basin. | Marine setting. |
| | Abo Formation (Pa) | Reddish-brown siltstone, fine sandstone, and arkosic sandstone, with red, green, and gray shale. 130 m (425 ft) to 194 m (615 ft) thick. | *Debris Flows and Rockfall*—forms valley and ridge topography.<br>*Paleontological Resources*—vertebrate tracks and plant impressions (elsewhere). | None reported. | Continental setting. In places, the Abo and Hueco formations intertongue, suggesting shifting shorelines of terrestrial (Abo) and marine (Hueco) settings. |

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| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| PERMIAN | Hueco Formation (Ph) | Algal limestone, gastropod-echinoid-brachiopod limestone, fusulinid limestone, chert-pebble conglomerate, sandy limestone, gray shale, shaly limestone, siltstone, massive cherty limestone. As much as 690 m (2,250 ft) thick. | *Groundwater*—significant for groundwater-flow model.<br>*Paleontological Resources*—fusulinids, gastropods, and ostracodes. | None reported. | Only bedrock unit mapped within White Sands National Monument.<br>Later intruded by stocks and dikes of plutonic rocks (**Tis**, **Tri**, and **Tii**).<br>Marine setting. In places, the Abo and Hueco formations intertongue, suggesting shifting shorelines of terrestrial (Abo) and marine (Hueco) settings. |
| PENNSYLVANIAN | Panther Seep Formation (PNps) | Brown to gray shale, sandstone, siltstone, gypsum, and fine-grained, laminated limestone. Mostly of Late Pennsylvanian age. Grades downward into Middle Pennsylvanian beds and upward into Hueco Formation. As much as 690 m (2,500 ft thick). | *Groundwater*—significant for groundwater-flow model and deposition of gypsum in Tularosa Basin.<br>*Debris Flows and Rockfall*—soft and easily eroded.<br>*Paleontological Resources*—stromatolitic algae and fusulinids. | *Source of Gypsum Sand*—source of gypsum in Tularosa Basin. | Later intruded by stocks and dikes of plutonic rocks (**Tis**, **Tri**, and **Tii**).<br>Restricted marine or sediment-laden setting. |
| | Lead Camp Limestone (PNlc) | Massive, thick- to medium-bedded, fossiliferous, cherty, gray limestone and dolomite cyclically interbedded with shale; sandstone, conglomerate, and quartzite form local pods lower third of the unit. Becomes very dolomitic, shaly, and gypsiferous at top where it weathers orange, yellow, or olive and grades into Panther Sheep Formation (**PNps**). As much as 370 m (1,200 ft) thick. | *Paleontological Resources*—fusulinids. | None reported. | Later intruded by stocks and dikes of plutonic rocks (**Tis**, **Tri**, and **Tii**).<br>Open marine setting. |
| | Lead Camp Limestone overlying limestone (PNlc/ls) | PNlc/ls consists of PNlc overlying ls:<br>Lead Camp Limestone (**PNlc**): See description above.<br>Limestone (**ls**): Seager et al. (1987) provided no information. | *Paleontological Resources*—fusulinids. | None reported. | Later intruded by stocks and dikes of plutonic rocks (**Tis**, **Tri**, and **Tii**).<br>Open marine setting. |
| MISSISSIPPIAN AND DEVONIAN | Mississippian and Devonian rocks (MDr) | Undifferentiated unit of Mississippian and Devonian rocks, including the following:<br>Mississippian—Helms Formation (limestone), Rancheria Formation (micrite), Las Cruces Limestone, Lake Valley Limestone, and Caballero Formation (siltstone and limestone).<br>Devonian—Percha Shale and Canutillo Formation (limestone). | *Debris Flows and Rockfall*—Lake Valley Limestone is cliff forming. Percha Shale is exceptionally soft and fissile, forming erosional slopes.<br>*Paleontological Resources*—Mississippian rocks have conodonts, crinoids, corals, brachiopods, bryozoans, snails, and other mollusks. Devonian rocks have primarily brachiopods. | None reported. | Mississippian—open marine setting.<br>Devonian—restricted marine setting. |
| SILURIAN AND ORDOVICIAN | Fusselman Dolomite and Montoya Group, undivided (SOfm) | Fusselman Dolomite: Massive, dark-gray, cherty dolomite in northern part of map area; pale-tan-weathering, light-gray, massive dolomite in southern areas. Up to 195 m (640 ft) thick.<br>Montoya Group: Basal, tan, coarse-grained Cable Canyon Sandstone overlain by massive, dark-gray Upham Dolomite, followed upward by cherty, light- and dark-gray Aleman Dolomite. Capped by light-gray, fine-grained, thin-to medium-bedded Cutter Dolomite. Up to 140 m (470 ft) thick. | *Debris Flows and Rockfall*—Cutter Dolomite forms ledges and cliffs. Fusselman Dolomite forms cliffs and ridge crests.<br>*Mining and Energy Development*—Fusselman Dolomite has barite-fluorite and base-metal deposits. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | Open marine setting. |

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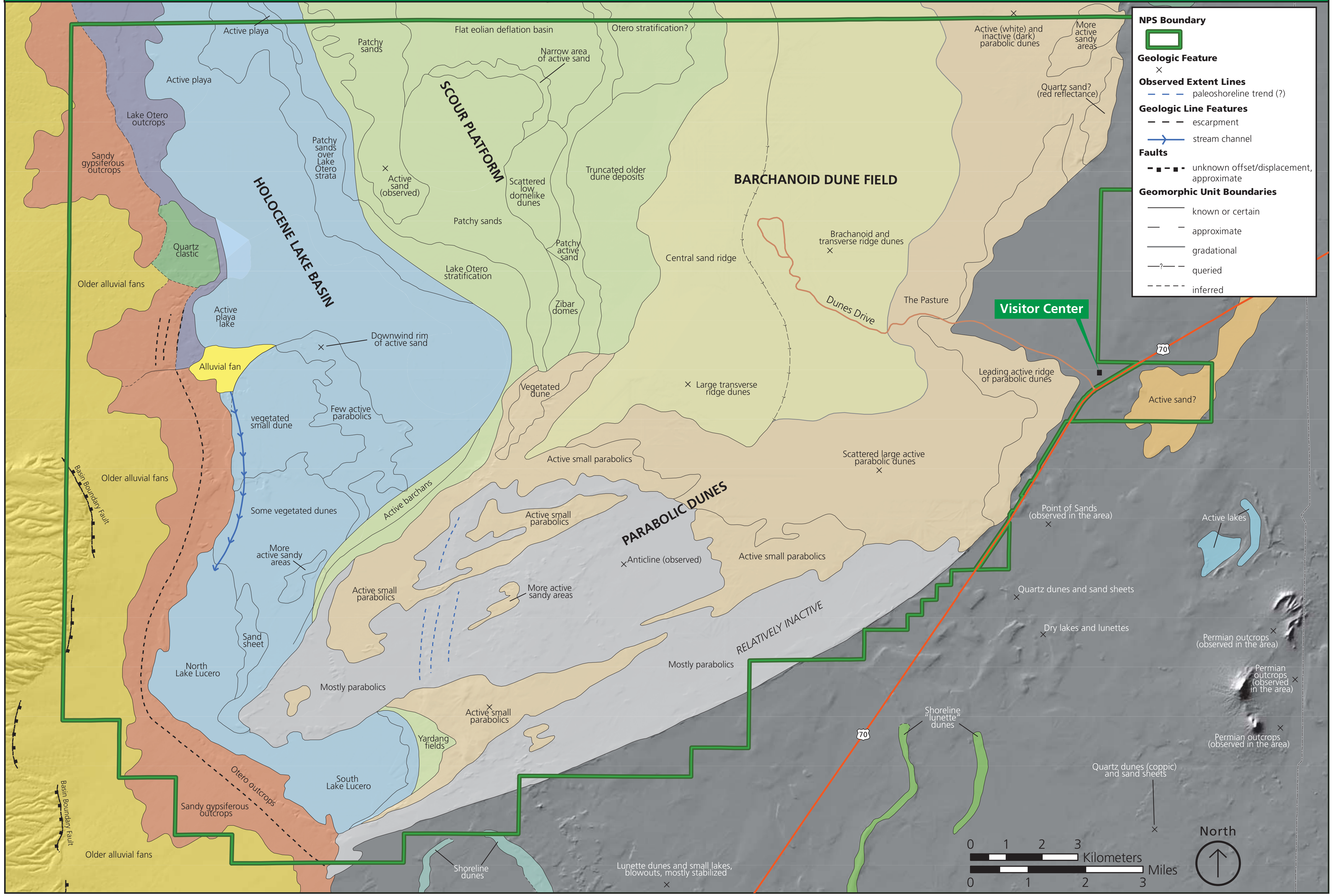
| Age | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|
| ORDOVICIAN AND CAMBRIAN | El Paso Group and Bliss Sandstone, undivided (OCeb) | El Paso Group: Thin-bedded, siliceous, sandy, orange- to brown-weathering limestone in lower third, thick- to medium-bedded gray dolomite or limestone in upper two-thirds. Up to 410 m (1,340 ft) thick.<br>Bliss Sandstone: Brown, gray, or black hematitic sandstone, shale, siltstone, and quartzite. Up to 60 m (200 ft) thick. | *Paleontological Resources*—El Paso Group has burrows. Fossils are sparse in Bliss Sandstone. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | Open marine setting. |
| PRECAMBRIAN | Precambrian rocks, granite (PCg) | Pink to brown, coarse-grained granite cut by systems of northeast- or east-trending diabase-amphibolite dikes. | Unknown. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | Arc or rift setting.<br>Batholith is 1.4 billion to 1.3 billion years old.<br>Forms core of Laramide uplift.<br>Exposed in San Andres Mountains |
| | Precambrian rocks, quartzite (PCq) | Variable-colored, fine- to medium-grained quartzite, feldspathic quartzite, and arkose interbedded with lenses and beds of phyllite and mica schist. | Unknown. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | |
| | Precambrian rocks, schist and phyllite (PCs) | Medium- to fine-grained, quartz-mica schist and phyllite with interbeds of quartzite, talc, and minor bodies of amphibolite. | Unknown. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | |
| | Precambrian rocks, amphibolite (PCa) | Black to greenish-black dikes, sills, and irregular bodies of hornblende-plagioclase amphibolite; includes gneissic bodies locally, mixed with amphibolite. | *Mining and Energy Development*—gold-copper-quartz mineralization. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | |
| | Precambrian rocks, metadiabase (PCmd) | Black to greenish-black metadiabase sills and dikes. | Unknown. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | |
| | Precambrian rocks, gneiss (PCgn) | Quartz-feldspar-mica gneiss with granite pods; locally migmatic. | Unknown. | *Alluvial Deposits*—supplies material to alluvial fans and bajada. | |

**White Sands National Monument**
**New Mexico**

**National Park Service**
**U.S. Department of the Interior**

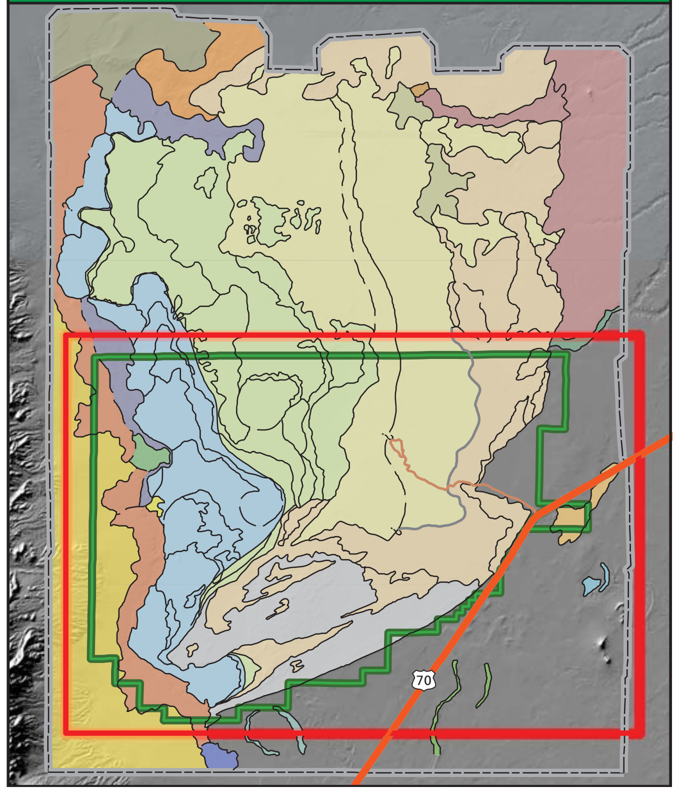
# Overview of Digital Geomorphic Data for White Sands NM

## Area of Detail



UTM NAD83 ZONE 13N

## Full Extent of Digital Geomorphic Data, Area of Detail in Red



- Active Holocene Lake Basins
- Scour Platform
- Barchanoid Dune Field
- Marginal Parabolic Dunes

**Miscellaneous Geomorphic Features**

- Active lake
- Active sand?
- Alluvial fan
- Inactive dunes (grey)
- Lake Otero outcrops
- More active sandy areas
- Older alluvial fans
- Older basin floor
- Plateau
- Quartz clastic
- Quartzose dunes
- Sabkha
- Sandy gypsiferous outcrops
- Shoreline "lunette" dunes
- Shoreline dune
- Subdued eolian topography

These figures are an overview of compiled digital geologic and geomorphic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:50,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 25 meters/83 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Fryberger, S.G. 2001b. Reconnaissance Geomorphic Map of the White Sands Dune Field, New Mexico (scale 1:50,000). Figure 2-17A, in Geological Overview of White Sands National Monument, Chapter 2: Quaternary Geology.

Digital geologic data and cross sections for the monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. (Enter "GRI" as the search text and select WHSA from the unit list.)

Produced by the Geologic Resources Inventory

October 2012

# Geomorphic Map Unit Properties Table: White Sands National Monument

**Gray-shaded rows indicate units not mapped within White Sands National Monument by Fryberger (2001b). "*" Indicates additional information on Geologic Map Unit Properties Table. "?" Indicates uncertain occurrences as noted on the source map.**

| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE AND PLEISTOCENE | **Active Holocene lake basin (ahlb)** | Active Holocene lake basin (ahlb and ahlb?) | Region west of the scour platform (**sp**) where there is evidence (on the ground and in air photographs) that flooding has occurred in the modern depositional system. Over most of the area, "lakes" that form are very temporary. | *Groundwater*—area of groundwater discharge. Wet or damp areas hold sand in place.<br>*Surface Water*—ephemeral lakes, filled with water after storms. Sediment input by intermittent surface water flow.<br>*Infrastructure and Gypsum Sands*—potential for corrosion, gypsum "glue," and dissolution (sinkholes).<br>*Paleontological Resources*—wave activity along shorelines may expose fossil tracks in Lake Otero sediments (**sp_los**).<br>*Climate Change*—lower water table and greater potential for deflation as a result of more severe and longer droughts.<br>*Tamarisk*—invaded areas of the active Holocene lake basin.<br>*White Sands Missile Range*—potential for contaminated runoff from rocket test site. | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Source of Gypsum Sand*—composed of evaporite material, primarily from ancient Lake Otero, but also recent evaporation from modern Lake Lucero.<br>*Alluvial Deposits*—coarsest sand on the western side of the active Holocene lake basin reflects input by intermittent channel flow and sheet flow. Active Holocene lake basin is east of the alluvial deposits (bajada) at the base of the San Andres Mountains. | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin. |
| HOLOCENE | | Active playa (ahlb_ap) | Small, unnamed playas that occupy the low parts of the active Holocene lake basin. | *Groundwater*—may receive groundwater discharge. Wet or damp areas hold sand in place.<br>*Surface Water*—existence of water is related to the frequency of flooding and elevation. Higher lakes to the east flood less frequently.<br>*Paleontological Resources*—wave activity along shorelines may expose fossil tracks in Lake Otero sediments (**sp_los**).<br>*Tamarisk*—invaded areas of the active Holocene lake basin. | *Source of Gypsum Sand*—playas form in gypsiferous beds of ancient Lake Otero. | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin.<br>Today, active playas include many small unnamed low areas or depressions in the active Holocene lake basin. |
| | | Quartz clastic wedge (ahlb_qcw) | Composed of quartz. Deposits of channelized flow and sheetflood deposits at the break of slope where alluvial fans meet the playa surface. | *Surface Water*—clastic material deposited by intermittent surface water flow. Wedges represent progradation of quartz clastic materials, mainly delivered by unconfined flows, onto the surface of the playa. | *Active Holocene Lake Basin*—**ahlb_qcw** found along the western margin of the active Holocene lake basin.<br>*Alluvial Deposits*—mapped as younger piedmont-slope deposits (**Qpy**)* by Seager et al. (1987). Contains coarse clastic material transported through bajada by intermittent channelized flow and sheet flow. | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin. |
| | | Few active parabolic dunes (ahlb_fap) | Parabolic dunes are considered active if the slip face and arms are composed of bare, moveable sand, which is shown as white on air photographs. Less active dunes have the arms mostly stabilized by vegetation with only the slip faces still active. | *Climate Change*—dunes may become more active as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Marginal Parabolic Dunes*—parabolic dunes that have formed within the active Holocene Lake basin. Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin. |

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| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE | **Active Holocene lake basin (ahlb)** | More active sandy areas (ahlb_masa) | Areas interpreted to have active dunes and unvegetated interdunes within the active Holocene lake basin. Show sharp slip faces and clean, unvegetated sand between dunes. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring location for 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for corrosion, gypsum "glue," and dissolution (sinkholes). | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—unvegetated areas between dunes. | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin. |
| HOLOCENE AND PLEISTOCENE | | North Lake Lucero (ahlb_nll) and South Lake Lucero (ahlb_sll), active playa | Named portions of active Holocene lake basin. Occupy deepest part of the basin. Playa is composed of silt, clay, sand, gravel, and evaporite material. | *Groundwater*—local area of groundwater discharge. Represents basinwide groundwater system within White Sands National Monument. Holds local groundwater discharge and surface water runoff; proportion of surface water vs. groundwater is unknown.<br>*Surface Water*—existence of water related to frequency of flooding.<br>*Paleontological Resources*—wave activity along shoreline may expose fossil tracks.<br>*Tamarisk*—invaded areas around North Lake Lucero and South Lake Lucero.<br>*White Sands Missile Range*—potential for contaminated runoff from rocket test site. | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Source of Gypsum Sand*—**Qlg**/Lake Otero strata are primary contributor of fresh gypsum sand to dune field. Wave activity breaks down Lake Otero beds, making gypsum available for eolian transport. | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin.<br>Today, active playas include North Lake Lucero and South Lake Lucero in the active Holocene lake basin. |
| | | Patchy sand (ahlb_ps) | Scattered areas of loose, mobile sand appear surrounded by less active eolian or non-eolian terrains. Thin active sand sheets with a few dunes. Found either atop sabkha-like areas with little obvious active sand, or in vegetated areas that may have become destabilized. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Source of Gypsum Sand*—**Qlg**/Lake Otero strata are primary contributor of fresh gypsum sand to dune field. | The onset of regional aridity during the Holocene Epoch caused the contraction of ancient Lake Otero and the development of Lake Lucero and other smaller playas of the active Holocene lake basin. |
| | | Sand sheet (ahlb_ss) | One of the four major eolian facies groups—dune, interdune, sand sheet, and sabkha. See Fryberger et al. (1979) for a comprehensive discussion of eolian sand sheets. Sand sheets, with more or less vegetation, are a common linking facies between active dunes and older dune terrains at White Sands National Monument. Commonly rippled on surface. | *Paleontological Resources*—trace fossils; commonly bioturbated.<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Barchanoid Dune Field* and *Marginal Parabolic Dunes*—widespread, flat-bedded or low-angle deposits found on the margins of dune fields or between belts of dunes such as active parabolic dunes.<br>*Source of Gypsum Sand*—**Qlg**/Lake Otero strata are primary contributor of fresh gypsum sand to dune field. However, sand sheets have coarser sand grains or lack of sand supply. | |

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| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE AND PLEISTOCENE | **Scour platform (sp)** | Scour platform (sp and sp?) | An extensive region upwind of the main dune field where wind scour of older sediments is the dominant process. This scour may include Lake Otero sediments; older, usually cemented dune strata; or recent material deposited during floods or by the wind. Area of net sediment loss. | *Paleontological Resources*—fossil trackways.<br>*Climate Change*—greater scour/deflation as a result of more severe and longer droughts, with more dunes moving out of scour platform. Historically the scour platform has expanded and contacted with climate change.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes).<br>*Tamarisk*—invaded eastern edge of scour platform, immediately west of the central sands ridge of the barchanoid dune field. | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Scour Platform*—Alkali Flat is representative feature of the scour platform.<br>*Source of Gypsum Sand*—**Qlg**/Lake Otero strata are primary contributor of fresh gypsum sand to dune field. | Scour platform formed via stepwise deflation of ancient Lake Otero basin. |
| | | Quartz clastic wedge (sp_qcw) | Composed of quartz. Mainly channelized and unchannelized sheetflood deposits at the break of slope where the alluvial fans meet the playa. They represent progradation of quartz clastic materials, mainly delivered by unconfined flows, onto the playa surface. | *Surface Water*—evidence of intermittent channelized flow and surface water runoff. | *Alluvial Deposits*—mapped as younger piedmont-slope deposits (**Qpy**)* by Seager et al. (1987). Contains coarse clastic material transported through bajada by intermittent flow. | |
| PLEISTOCENE | | Deflation surface? (sp_d?) | Refers to local areas where deflation is occurring. Large area of possible deflation north of White Sands National Monument. | *Climate Change*—greater scour/deflation as a result of more severe and longer droughts. | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Source of Gypsum Sand*—**Qlg** is primary contributor of fresh gypsum sand to dune field. | |
| HOLOCENE | | Few active parabolic dunes (sp_fap) | Parabolic dunes were mapped as "active" if the slip face and arms had bare, moveable sand, which is shown as white on air photographs. Less active dunes had the arms mostly stabilized by vegetation with only the slip faces still active. | *Climate Change*—greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Marginal Parabolic Dunes*—parabolic dunes within the scour platform. Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | Scour platform formed via stepwise deflation of ancient Lake Otero basin. |
| PLEISTOCENE | | Flat eolian deflation surface (sp_fe_ds) | Refers to an area where wind has scoured underlying deposits to a flat surface, rather than, for example, to yardangs (**yrdng**). | *Groundwater*—underlying water table may control the deflation surface (see Fryberger et al. 1988).<br>*Climate Change*—greater area of wind scour as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Source of Gypsum Sand*—**Qlg** is primary contributor of fresh gypsum sand to dune field. | |

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|---|---|---|---|---|---|---|
| PLEISTOCENE | **Scour platform (sp)** | Lake Otero stratification (sp_los) | Sediments of ancient Lake Otero exposed at the surface. Consist of laminated clays and silts, as well as gypsiferous marls, limestone, and massive silts containing large gypsum crystals; also greenish lacustrine shales. A few horizons of coarse-grained gypsum crystals. Outcrops on western shore of Lake Otero are coarser grained than on eastern side. Some cemented horizons hold up in outcrop. | *Erosion*—gully erosion produces fresh exposures along the trail to Lake Lucero.<br>*Paleontological Resources*—fossil tracks. Source of paleoenvironmental material.<br>*Climate Change*—more sediment available for eolian transport as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Active Holocene Lake Basin, Lake Otero Strata*—mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987). **Qlg** is equivalent to Lake Otero strata.<br>*Source of Gypsum Sand*—primary contributor of gypsum sand to dune field. | Deposited in pluvial Lake Otero during the Pleistocene Epoch.<br>Scour platform formed via stepwise deflation of ancient Lake Otero basin. |
| HOLOCENE | | Narrow area of active sand (sp_naas) | Refers to a narrow area of active sand (as seen on air photographs), downwind from deflation areas, which are often circular in appearance. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring location for 10 vital signs (see Lancaster 2009). | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | Scour platform formed via stepwise deflation of ancient Lake Otero basin. |
| | | Patchy active sand (sp_pas) | Areas of loose, mobile sand that form thin active sand sheets with a few dunes. Found either atop sabkha-like areas with little obvious active sand, or in vegetated areas that may have become destabilized. Mobile sand surrounded by less active eolian or non-eolian terrains. Appear as distinctively light-colored areas on air photographs. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | | |
| | | Scattered low domelike dunes (sp_sldd) | Referred to as "low" because these features are only about 0.3 m (1 ft) in height. Their low domelike forms in cross section dominate their character "in the field," though they may occur in a variety of shapes (barchanoid or transverse) in plan view. When trenched, some of these dune forms have cross-bedding, suggesting that from time to time, small slip faces formed. | *Climate Change*—observed decline in the number of dome dunes, possibly as a result of drier conditions.<br>*Monitoring Eolian Processes*—potential monitoring location for 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Barchanoid Dune Field*—may be "embryonic" dune forms; evolve downwind into barchan dunes. Occur mostly along the upwind margins or sand-starved areas of the dune field. Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | |
| | | Truncated older dune deposits (sp_todd_d) | A major deposit/unit along the upwind margins of the barchanoid dune field. Occur as an extensive (mappable) surface. Characterized by some deflation. | *Climate Change*—more sediment available for eolian transport as a result of more severe and longer droughts. | *Barchanoid Dune Field* and *Interdunes*—mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—**sp_todd_d** are very common in the flat interdunes.<br>Miscellaneous Geomorphic Features, *Sabkhas*—distinguished from flat sabkha-like terrains that are dominated by salt ridges or muds. | |
| | | Zibar dunes (sp_zd) | Low ridges of sand with dune-like form but no discernable slip face. Their morphologic evolution is uncertain: Some workers think they are true proto-dunes, while others think they are basically an independent form that does not evolve into anything else. Generally composed of rather coarse sand. | Unknown. | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | |

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| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE | **Barchanoid dune field (bdf)** | Barchanoid dune field (bdf) | Geomorphic area east of the scour platform (**sp**). Divided into a central sand ridge (**bdf_csr**), scattered parabolic dunes (**bdf_spd**), barchan dune-outliers (**bdf_bd_o**), barchanoid dunes-active (**bdf_bd_a**), and possible barcan? (**bdf_b?**). | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of the groundwater table. Groundwater salinity influences morphology of dunes (barchan dunes form under more saline conditions than parabolic dunes).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue."<br>*Tamarisk*—invaded some interdune areas of barchanoid dune field (**bdf**). | *Barchanoid Dune Field*—area represents the active, modern dune field. Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—occur everywhere there are dunes.<br>*Source of Gypsum Sand*—source of sand is lower/older Lake Otero sediments. | Formed with sand from scour platform (Lake Otero sediments) after formation of the marginal parabolic dunes.<br>Dune field established by 2,100 years ago. |
| | | Barchan dunes (bdf_b?) | Freely moving sand developed into crescent-shaped dunes with short arms that extend downwind. As interpreted from air photographs, some have questionable occurrence (**bdf_b?**). | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (barchans form under more saline conditions than parabolics).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—occur everywhere there are dunes.<br>*Source of Gypsum Sand*—source of sand is lower/older Lake Otero sediments. | Formed with sand from scour platform (Lake Otero sediments) after formation of the marginal parabolic dunes.<br>Dune field established by 2,100 years ago. |
| | | Barchan dunes - outliers (bdf_bd_o) | Freely moving sand developed into crescent-shaped dunes with short arms that extend downwind. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (barchans dunes form under more saline conditions than parabolic dunes).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Marginal Parabolic Dunes*—occur east of the main barchanoid dune field as an active outlier, spreading into an area of marginal parabolic dunes.<br>*Interdunes*—the boundary between the barchanoid dune field and the marginal parabolic dunes is marked by damp interdunes.<br>*Source of Gypsum Sand*—source of sand is lower/older Lake Otero sediments. | |

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| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE | **Barchanoid dune field (bdf)** | Barchan dunes - active (bdf_bd_a) | Freely moving sand developed into crescent-shaped dunes with short arms that extend downwind. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (barchans form under more saline conditions than parabolics).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). Make up the main, central part of the White Sands dune field.<br>*Interdunes*—occur everywhere there are dunes.<br>*Source of Gypsum Sand*—source of sand is lower/older Lake Otero sediments. | Formed with sand from scour platform (Lake Otero sediments) after formation of the marginal parabolic dunes.<br>Dune field established by 2,100 years ago. |
| | | Central sand ridge (bdf_csr) | A buildup of sand dunes forming a topographic ridge along the upwind margin of the barchanoid dune field (**bdf**). The ridge feature is more prominent north of White Sands National Monument. Origin unknown. Clearly visible on air photographs. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (barchans form under more saline conditions than parabolics).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue."<br>*Tamarisk*—invaded eastern edge of scour platform, immediately west of the central sand ridge. | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—dunes appear tightly spaced, with very small interdunes.<br>*Source of Gypsum Sand*—source of sand is lower/older Lake Otero sediments. | |

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|---|---|---|---|---|---|---|
| HOLOCENE | **Marginal parabolic dunes (mpd)** | Marginal parabolic dunes (mpd) | Parabolic dunes fringe the southern and eastern margins of the barchanoid dune field at White Sands National Monument.<br>Dunes consist of central mass of sand with arms that extend upwind. Arms often anchored by vegetation. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (parabolics form under fresher conditions than barchan).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | *Marginal Parabolic Dunes*—representative features are active and inactive parabolic dunes. Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—the boundary between the barchanoid dune field and the marginal parabolic dunes is marked by damp interdunes. | Formed before barchanoid dune field.<br>Dune field established by 3,500 years ago. |

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| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE | **Marginal parabolic dunes (mpd)** | Abundant active parabolic dunes (mpd_aap) | Actively migrating central mass of sand with long arms extending upwind. Considered "active" during mapping if slip faces and arms had bare, moveable sand, shown as white on air photographs. Less active dunes had arms mostly stabilized by vegetation, with only slip faces active. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (parabolics form under fresher conditions than barchan).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—occur everywhere there are dunes. | Formed before barchanoid dune field.<br>Dune field established by 3,500 years ago. |
|  |  | Active parabolic dunes (mpd_ap) | Actively migrating central mass of sand with long arms extending upwind. Considered "active" during mapping if slip faces and arms had bare, moveable sand, shown as white on air photographs. Less active dunes had arms mostly stabilized by vegetation, with only slip faces active. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (parabolics form under fresher conditions than barchan).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." |  |  |
|  |  | Active small parabolic dunes (mpd_asp) | Actively migrating central mass of sand with long arms extending upwind. Considered "active" during mapping if slip faces and arms had bare, moveable sand, shown as white on air photographs. Less active dunes had arms mostly stabilized by vegetation, with only slip faces active. Appears as "choppy terrain" on air photographs. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (parabolics form under fresher conditions than barchan).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—occur everywhere there are dunes. | Formed before barchanoid dune field.<br>Dune field established by 3,500 years ago. |
|  |  | Leading active ridge (mpd_lar) | Eastern edge of parabolic dune field. Very near visitor center. | *Climate Change*—may have greater area of eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). |  |

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| Age | Geomorphic Area (Symbol) | Map Unit (Symbol) | Geologic Description | Geologic Issues | Geologic Features and Processes | Geologic History |
|---|---|---|---|---|---|---|
| HOLOCENE | **Marginal parabolic dunes (mpd)** | More active sandy areas (mpd_masa) | Areas interpreted from air photographs to have active dunes and unvegetated interdunes, based on sharp slip faces and clean, unvegetated sand between dunes. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—unvegetated areas between dunes. | Formed before barchanoid dune field.<br>Dune field established by 3,500 years ago. |
| | | Parabolic dunes (mpd_pd) | Parabolic-shaped dunes composed of an actively migrating central mass of sand with long arms extending upwind. Parabolic dunes are considered active if the slip face and arms have bare, moveable sand, shown as white on the air photographs. Less active dunes have the arms mostly stabilized by vegetation, with only the slip faces still active. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (parabolics form under fresher conditions than barchan).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—occur everywhere there are dunes. | Formed before barchanoid dune field.<br>Dune field established by 3,500 years ago. |
| HOLOCENE AND PLEISTOCENE | | Quartz dunes? (mpd_qd?) | Questioned occurrence of dunes composed of quartz. Appear as red reflectance on air photographs. Occur north of White Sands National Monument within an area of marginal parabolic dunes. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand. | Mapped as eolian quartz sand (**Qes**)* by Seager et al. (1987). | The sand is derived largely from the Camp Rice Formation (**Qcp**). |
| | | Quartz sand? (mpd_qs?) | Questioned occurrence of quartz sand on the eastern edge of the marginal parabolic dunes within White Sands National Monument. Appear as red reflectance on air photographs. | *Surface Water*—material contributed through fluvial activity.<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts. | Mapped as eolian quartz sand (**Qes**)* by Seager et al. (1987). | The sand is derived largely from the Camp Rice Formation (**Qcp**). |
| HOLOCENE | | Scattered parabolic dunes (mpd_spd) | Actively moving sand in the form of parabolic dunes, though not contiguous with the main parabolic dune area. Occur north of White Sands National Monument. | *Groundwater*—influenced by dune-field groundwater system. Relationship to basinwide groundwater system unknown. Very sensitive to changes in the level of groundwater table. Groundwater salinity influences morphology of dunes (parabolics form under fresher conditions than barchan).<br>*Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum "glue." | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Interdunes*—occur everywhere there are dunes. | Formed before barchanoid dune field.<br>Dune field established by 3,500 years ago. |

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|---|---|---|---|---|---|---|
| HOLOCENE | **Marginal parabolic dunes (mpd)** | Sand sheet or small dunes (mpd_ss_sd) | Marks a place where both a sand sheet and small dunes are found. In many places, sand sheets commonly have scattered, small dunes on their surfaces (see Fryberger et al. 1979). | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, and gypsum “glue.” | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | An area of active sand within the marginal parabolic dunes.<br>Dune field established by 3,500 years ago. |
| | | The Pasture (mpd_tp) | A grassy area on the eastern margin of the marginal parabolic dunes. | *Climate Change*—loss of vegetation as a result of more severe and longer droughts would increase eolian activity. | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | Part of the marginal parabolic dunes, which formed before the barchanoid dune field; otherwise, origin is unknown. |
| HOLOCENE | **Miscellaneous Geomorphic Features** | Active lake (active_lake) | Non-alkaline lakes within the dune field or area of subdued eolian topography (**sbdd_eln_top**) east of the dune field. | *Groundwater*—relationship to basinwide groundwater system unknown.<br>*Surface Water*—existence of water related to frequency of flooding. | Mapped as deposits of small, non-alkaline playa lakes and depressions (**Ql**)* by Seager et al. (1987). | Correspond to the onset of regional aridity during the Holocene Epoch. |
| HOLOCENE AND PLEISTOCENE | | Active sand? (active_sand?) | Usually applied to areas that were not field checked by Fryberger (2001b). Gypsum sand, possibly active and probably not vegetated, east of the visitor center. Dunes are too small to be seen on air photographs. Whether these are areas of scour rather than deposition is unknown. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum “glue,” and dissolution (sinkholes). | Mapped as basin-floor sediments (**Qbf**)* by Seager et al. (1987). | Correlated in time with ancient Lake Otero. |
| HOLOCENE AND PLEISTOCENE | | Alluvial fan (allvl_fan) | Quartz clastic, low angle, sheetflood fan in the playa. Smaller quartz clastic alluvial and sheetflood fans, in places overlapping or “coalesced,” that have formed where outwash from the alluvial fans of the mountain front reach the flat active lake basin. Mapped separately from **o_allvl_fan** by Fryberger (2001b). | *Groundwater*—part of basin-fill aquifer.<br>*Surface Water*—runoff during storms adds material to basin as fans. Pathway for surface water to active Holocene lake basin.<br>*Debris Flows and Rockfall*—part of bajada, where mass-wasting deposits originate. | Mapped as basin-floor sediments (**Qpy**)* by Seager et al. (1987). | Corresponds in time with the active Holocene lake basin |
| PLEISTOCENE | | Inactive dunes, mostly parabolic dunes (i_dune_p) | Inactive sand dunes. Partly lithified internally. The older parabolic dunes are usually inactive in this region due to early cementation (of gypsum crusts) and vegetation. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—prone to form blowouts or slowly migrating parabolic dunes. Potential for corrosion and gypsum “glue.” | *Marginal Parabolic Dunes*—occur along the southern edge of White Sands National Monument in an area of both active and inactive marginal parabolic dunes. Mapped as inactive gypsum dunes (**Qegi**)* by Seager et al. (1987). | Correlated in time with ancient Lake Otero and younger playa deposits. |

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|---|---|---|---|---|---|---|
| PLEISTOCENE | **Miscellaneous Geomorphic Features** | Lake Otero outcrops (lo_outcrops) | Outcrops of sediments deposited by Lake Otero. 3 m (10 ft) to 8 m (25 ft) thick. Selenite crystal horizons common. | *Surface Water*—gullying common.<br>*Paleontological Resources*—fossil tracks.<br>*Climate Change*—more sediment available for eolian transport as a result of more severe and longer droughts. | *Active Holocene Lake Basin* and *Scour Platform*—**lo_outcrops** occur as cliffs—1 m (3 ft) to 2 m (7 ft) high—along the west side of Lake Lucero and the active Holocene lake basin, and as low ridges and planed-off, gypsiferous-sand strata on the scour platform. Mapped as gypsiferous lake deposits (**Qlg**)* by Seager et al. (1987).<br>*Source of Gypsum Sand*—primary contributor of fresh sand to dune field. | Represents previous pluvial (wetter) conditions during the Pleistocene Epoch. |
| HOLOCENE | | More active sandy areas (masa) | Areas interpreted on air photographs to have active dunes and un-vegetated interdunes, based on sharp slip faces, and clean, unvegetated sand between dunes. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Active Holocene Lake Basin* and *Marginal Parabolic Dunes*—mapped primarily in the active Holocene lake basin (**ahlb_masa**) and marginal parabolic dunes (**mpd_masa**), but also mapped north of White Sands National Monument near sabkha (**sabkha**) and subdued eolian topography (**sbdd_eln_top**). Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | Corresponds to the onset of regional aridity during the Holocene Epoch. |
| PLEISTOCENE | | Older alluvial fans (o_allvl_fan) | The term "alluvial fan" refers to the conventional coarse fan deposits of sand and gravel with some mud that form large fans between the mountains and the active Holocene lake basin. | *Groundwater*—part of basin-fill aquifer.<br>*Surface Water*—runoff during storms adds material to basin as fans. Pathway for surface water to active Holocene lake basin.<br>*Debris Flows and Rockfall*—part of bajada, where mass-wasting deposits originate. | Mapped as older piedmont-slope deposits (**Qpo**)* by Seager et al. (1987).<br>*Alluvial Deposits*—alluvial fans, mostly weakly consolidated gravel and sandy gravel, grading downslope to gravelly loam, with thin horizons (surficial and buried) of soil-carbonate and clay accumulation | Ancient Lake Otero and pre-Lake Otero deposits. |
| | | Older basin floor (o_bas_floor) | Mostly red and green gypsiferous clay and silt interbedded with gypsite. | Unknown. | Mapped as older gypsiferous basin-floor deposits and lake beds (**Qbfg**)* by Seager et al. (1987). | Pre-Lake Otero deposits. |
| unknown | | Plateau (plateau) | Labeled on map but not defined by Fryberger (2001a). North of White Sands National Monument. | Unknown. | Unknown. | Unknown. |
| HOLOCENE AND PLEISTOCENE | | Quartz clastic input to dune system (qci_ds) | Represents progradation of quartz clastic materials, mainly delivered by unconfined flows, onto the surface of the playa. Found along the western margin of the Holocene lake basin. | *Surface Water*—runoff during storms adds material to basin as fans. Pathway for surface water to the active Holocene lake basin. | Mapped as undifferentiated piedmont-slope deposits (**Qpa**)* by Seager et al. (1987).<br>*Alluvial Deposits*—associated with alluvial fan (**o_allvl_fan**) on western edge of active Holocene lake basin. | Postdates river valley incision by Rio Grande. |
| | | Quartzose dunes (quartzose_d) | Includes quartzose dunes north of White Sands National Monument. Commonly found along course of Rio Grande. Appear as red reflectance on air photographs. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Monitoring Eolian Processes*—potential monitoring of 10 vital signs (see Lancaster 2009).<br>*Infrastructure and Gypsum Sands*—potential for blowing sand. | Mapped as eolian quartz sand (**Qes**)* by Seager et al. (1987). The sand is derived largely from Camp Rice Formation (**Qcp**). | Postdates river valley incision by Rio Grande. |

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|---|---|---|---|---|---|---|
| HOLOCENE | **Miscellaneous Geomorphic Features** | Sabkha (sabkha) | Refers to flat salty areas, often partly flooded by tides, along the coast of the Arabian Gulf. Used as a means for describing subsurface sediment packages at White Sands National Monument. Common (though too small for map scale) on Alkali Flat and margins of Lake Lucero. | *Groundwater*—research on sabkhas at White Sands indicates lowering of water table.<br>*Climate Change*—low water table may result from more severe and longer droughts. | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987).<br>*Miscellaneous Geomorphic Features, Sabkhas*—prominent mapped sabkhas north of White Sands National Monument between the barchanoid dune field and marginal parabolic dunes. | Part of the Holocene dune system. |
| PLEISTOCENE | | Subdued eolian topography (sbdd_eln_top) | Occurs beyond/east of the marginal parabolic dunes within White Sands National Monument. Topography as a whole suggests eolian dunes by its gentle rise and fall and systematic organization. Interpreted as "subdued" because dunes are not particularly obvious or active. | *Climate Change*—may have greater eolian activity as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | Mapped as older gypsiferous basin-floor and distal piedmont-slope deposits (**Qpg**)* by Seager et al. (1987). | Ancient Lake Otero and pre-Lake Otero deposits (?). |
| HOLOCENE AND PLEISTOCENE | | Sandy gypsiferous outcrops (sg_outcrops) | Outcrops composed of a mixture of quartz and gypsum sand, apparently wind-scoured and of eolian origin. Occur along the western side of White Sands National Monument. | *Groundwater*—recharge area for basinwide groundwater system.<br>*Surface Water*—runoff during storms adds material to basin as fans. Pathway for surface water to active Holocene lake basin.<br>*Debris Flows and Rockfall*—part of bajadas, where mass-wasting deposits originate. | Mapped as undifferentiated piedmont-slope deposits **(Qpa)*** by Seager et al. (1987). | Postdates river valley incision by Rio Grande. |
| | | Shoreline dune (shrln_dune) | A dune that has developed along a lake shoreline, commonly non-migratory, held in place by vegetation or early cementation. | Unknown. | Mapped as eolian deposits associated with Tularosa Basin lakes (**Qegs**)* by Seager et al. (1987). | Correlated in time with ancient Lake Otero. |
| | | Shoreline "lunette" dunes (shrln_l_dune) | A type of shoreline dune (**shrln_dune**) but formed on the downwind side of a standing lake in the shape of a quarter moon, thus the term "lunette." The curve of the lake determines the shape of the dune. Composed of material blown off the beach (or lake bottom when dry). Lunette dunes are commonly anchored in place by early cementation or vegetation. | Unknown. | Mapped as eolian deposits associated with Tularosa Basin lakes (**Qegs**)* by Seager et al. (1987). | Correlated in time with ancient Lake Otero. |
| HOLOCENE | | Vegetated dunes (veg_d) | Stabilized areas of gypsum sand dunes held in place by vegetation. | *Climate Change*—loss of vegetation as a result of more severe and longer droughts would increase eolian activity. | Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). | Associated with deflation of Lake Otero sediments. |
| | | Yardangs (yrdng) | Long, sharp-crested ridge of coherent gypsum sand. Typically have the shape of an inverted boat hull. Form in the direction of dominant wind. In some places at White Sands National Monument, yardangs have formed in groups (or fields), for example downwind of South Lake Lucero. | *Climate Change*—may have greater wind scour as a result of more severe and longer droughts.<br>*Infrastructure and Gypsum Sands*—potential for blowing sand, corrosion, gypsum "glue," and dissolution (sinkholes). | *Scour Platform* and *Marginal Parabolic Dunes*—Mapped as active gypsum dunes (**Qega**)* by Seager et al. (1987). Yardangs occur in the scour platform (sp) and within the marginal parabolic dunes (mpd) geomorphic areas. | Part of the Holocene dune system. |