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Great Sand Dunes National Park & Preserve

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/011

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Geologic Resources Division
Natural Resource Program Center
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Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Great Sand Dunes National Park and Preserve in Colorado. It contains information relevant to resource management and scientific research.

Great Sand Dunes National Park and Preserve is home to the tallest sand dunes in North America with some dunes rising 750 feet (230 m) above the San Luis Valley floor. Unique to the Rocky Mountain physiographic province, the high- altitude desert dunes of the park and preserve represent one of the most complex dune systems in the world. The 30 square miles (78 sq km) of Great Sand Dunes are part of a larger dune field that includes a relatively flat sand sheet and sabkha and covers 150 square miles (389 sq km). High velocity, bi- directional winds shape the dunes, which offer the visitor an exceptional experience of dynamic eolian processes and sand dune morphology.

The dunes of Great Sand Dunes lie on the eastern edge of the San Luis Valley at the base of the Sangre de Cristo Mountains. The dune field is part of the 84,000 total acres of the park and preserve that also protect alpine lakes, tundra, six peaks over 13,000 feet (3,962 m), ancient spruce and pine forests, large stands of aspen and cottonwood, grasslands, and wetlands. Rocks representing all of the geologic eras are exposed in the Sangre de Cristo Mountains and Great Sand Dunes National Park and Preserve.

Precipitation in the Sangre de Cristo Mountains provides surface runoff throughout the year and maintains the Medano and Sand Creeks which define the borders of the sand dunes. Water flowing in these shallow, braided streams seeps through the porous sand feeding underground aquifers that provide water for both agriculture and domestic use in the arid San Luis Valley, the largest intermontane basin in Colorado. Archeological evidence suggests that the San Luis Valley has been inhabited for thousands of years.

The large dunes are the reason that Great Sand Dunes was established as a national monument in 1932. Geologic issues that affect the resource management of the dunes, as well as other features in the park and preserve, fall into four broad categories:

- Water issues that affect dune preservation
- Earthquake potential along the Sangre de Cristo mountain front
- Oil and gas development in the Baca grant, north and west of Great Sand Dunes
- Past mining activities

Located in an arid climate, Great Sand Dunes is dependent on limited water resources. Both surface water and groundwater are critical for the preservation of the dunes and dune ecosystem. The delicate balance among precipitation, surface flow, and groundwater sustains the dune morphology, surge flow and surface flow conditions in Medano and Sand Creeks, and interdunal ponds and wetlands. If the groundwater table is lowered, surface water is lost to the subsurface, sand isn't recycled, and the dunes are negatively impacted. Surface water and groundwater also are precious resources for agriculture and potable water supplies. As population within Colorado and in neighboring states continues to grow, demands on the water resources in San Luis Valley will continue to generate management issues for Great Sand Dunes.

The Sangre de Cristo fault zone passes beneath the park and defines the east boundary of the San Luis basin. Only one seismic event has been recorded in the last 120 years, however, paleoearthquakes mark the Sangre de Cristo as one of Colorado's few active fault zones. Surface shaking from earthquakes may impact water tanks, pipelines, and most of the other facilities at Great Sand Dunes that lie in the vicinity of faults. The Great Sand Dunes Visitor's Center was built on a fault scarp and the campground is located on a landslide and/or debris flow that may be reactivated during a seismic event.

The approximately 1,800- acre Baca land grant lies north and west of the park and preserve. Exploration for gold in the area led to the accidental discovery of oil on the Baca grant. However, economic deposits of gold or oil have not been found, and no new exploratory wells have been drilled since the mid- 1990s. Nevertheless, previous exploration targets may become more economically attractive in the future. Increased exploration on the Baca grant may lead to an increase in groundwater withdrawal and negative impacts on ground water and surface water quality and the dune ecosystem at Great Sand Dunes.

Past mining operations in the Sangre de Cristo watershed may affect water quality in the park. While some prospect excavations in the main Cold Creek drainage channel can generate acids when exposed to water, many of the past mining sites are small, without concentrated mineralization, and are located some distance from stream channels so that they pose little threat to surface water quality. Past placer gold mining activity in the dunes does not present a water quality issue for Great Sand Dunes.

Research projects proposed in a workshop, held at the park in 1998, may help define these geologic issues for the resource manager. Potential areas of research are identified in the Geologic Issues section of this report.

The dunes of Great Sand Dunes form one large dune feature called a draa that is constantly being shaped and reshaped by a complex wind regime. Bimodal and complex wind patterns form reversing and star dunes on the draa. Unimodal winds form parabolic, barchan, and transverse dune forms. Surge flow in Medano Creek and Sand Creek is a rare hydrologic process and plays a significant role in recycling sand back onto the dunes. Features on the sand sheet and sabkha are more subdued than on the sand dunes, yet both environments are critical for the maintenance of dune features.

Both riverine and palustrine wetlands are recognized in Great Sand Dunes. Riverine wetlands form along creek channels while palustrine wetlands are associated with interdunal ponds and depressions that nearly intersect the water table. Important habitat for a variety of species, palustrine wetlands have decreased markedly in recent years.

With the passage of the Great Sand Dunes National Park and Preserve Act in 2000, thousands of acres of diverse mountain and valley landscapes were added to the park. Alpine glacial features are common in the Sangre de Cristo Mountains and structural features, generated during the Laramide Orogeny, are also found in the strata exposed in the mountain range. Rock units of Precambrian, Paleozoic, and Mesozoic age are exposed in the Sangre de Cristo Range. A wide variety of marine and terrestrial depositional environments are represented by these strata. Each mappable rock unit has characteristics which may be important to the resource manager regarding resistance to erosion, fossil contents, mineral and cultural resources, and suitability for development. Great Sand Dunes National Park and Preserve now preserves and protects not only the tallest dunes in North America, but also pieces of the geologic record that extend back in time approximately 1,700 million years in the Great Sand Dunes region.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resource Evaluation Program.

Purpose of the Geologic Resource Evaluation Program

Geologic resources serve as the foundation of park ecosystems and yield important information for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resources Division. The goal of the GRE Program is to provide each of the identified 270 "Natural Area" parks with a digital geologic map, a geologic report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and each is designed to be user friendly to non- geoscientists. In preparing products the GRE team works closely with park staff and partners (e.g., USGS, state geologic surveys, and academics).

The GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss the geologic issues in the park. Park staff are afforded the opportunity to meet with the experts on the geology of their park. Scoping meetings are usually held in each park individually, although, to expedite the process, some scoping meetings are multipark meetings held for an entire Vital Signs Monitoring Network.

For additional information regarding the content of this report, refer to the Geologic Resources Division of the National Park service, located in Denver, Colorado, with up to date contact information at the following Website http://www.nature.nps.gov/geology.

Geologic Setting

Great Sand Dunes National Park and Preserve is located in the San Luis Valley of Colorado, where the Sangre de Cristo Range bends to form a topographic pocket, or reentrant (figure 1). Near Blanca Peak and partially encompassing the great Sangre de Cristo Mountains that rise 6,000 feeı (825 m) above the San Luis Valley floor, Great Sand Dunes protects 84,000 acres of sand dunes, alpine lakes and tundra, six peaks over 13,000 feet (3,962 m), ancient spruce and pine forests, large stands of aspen and cottonwood, grasslands, and wetlands. Much of this diverse landscape was added to Great Sand Dunes National Monument in 2000 with the passage of the Great Sand Dunes National Park and Preserve Act. The original monument that was designated in 1932 was created in order to preserve the 19,200 acres (7,700 hectares of dunes) (figure 2).

The high- altitude desert dunes of Great Sand Dunes are unique in the Rocky Mountain physiographic province and represent one of the most complex dune systems in the world. The dune field, of which Great Sand Dunes is a part, covers 150 sq miles (389 sq km). Eolian (wind) processes constantly shape and reshape the dunes, forming dune features that appear and disappear on a regular basis. Classic examples of reversing and star dune types populate the dune field. High velocity, bidirectional winds that shape the dunes are funneled in and out of the valley through three relatively low passes in the Sangre de Cristo Range – Mosca, Medano, and Music passes. Medano Pass also is the source area for Medano Creek.

Precambrian igneous and metamorphic rocks, Paleozoic and Mesozoic sedimentary rocks, Tertiary igneous and sedimentary rocks, and unconsolidated Quaternary sediments are exposed in the Sangre de Cristo Mountains and Great Sand Dunes National Park and Preserve (Map Unit Properties Table) (Bruce and Johnson 1991; Johnson et al. 1989; Lindsey et al. 1986). Gaps in the geologic record are represented by unconformities, which reflect periods of either erosion or nondeposition. The Precambrian rocks span the Early Proterozoic from 1.6 to 2.5 billion years ago and consist of quartz monzonite, diorite, and gneiss.

The Paleozoic and Mesozoic exposures are primarily sedimentary rocks of the Pennsylvanian Minturn Formation (285 to 320 million years ago (Ma)) and the Pennsylvanian- Permian Sangre de Cristo Formation (250 to 300 Ma). Both formations consist mostly of shale, sandstone, and conglomerate. Mississippian, Devonian, and Ordovician strata are mapped as one unit, but include the Lower Mississippian Leadville Limestone, the Mississippian(?) to Lower Devonian Chaffee Group, the Upper Ordovician Fremont Dolomite, the Middle Ordovician Harding Sandstone, and the Lower Ordovician Manitou Limestone (Johnson et al. 1989). Rocks of Silurian age are missing in the region while only sporadic exposures of the Cambrian Sawatch Quartzite are present. In most of the region, the Ordovician Manitou Limestone rests on eroded Precambrian basement. In the Sangre de Cristo Mountains, the Middle Jurassic Entrada Sandstone and Upper Jurassic Morrison Formation represent the Mesozoic Era.

Tertiary rocks in the Sangre de Cristo Mountains consist of Miocene and Oligocene igneous rocks and stratified sediments of the Santa Fe Formation that were deposited in the Pliocene and Miocene epochs. A variety of unconsolidated Quaternary- age deposits has been mapped in the Sangre de Cristo Mountains and the eastern part of Great Sand Dunes (Lindsey et al. 1986).

The San Luis Valley is the result of extensional, tectonic forces rather than erosional processes. Crustal extension began about 30 Ma and initiated the extensive volcanic activity that built the San Juan Mountains which border the San Luis Valley to the west (figure 3). Since extension began, displacement along normal faults in the basin-bounding fault zone adjacent to the Sangre de Cristo Mountains has amounted to over 30,000 vertical feet (9,200 m) (Kluth and Schaftenaar 1994). Great Sand Dunes lies within this fault zone. The dip of this fault zone ranges from 45 degrees to 60 degrees (Kluth and Schaftenaar 1994).

As much as 21,000 feet (6,400 m) of Tertiary and Quaternary age sediments underlie the asymmetric San Luis Valley as a result of fault movement (Kluth and Schaftenaar 1994). Aquifers in these sediments are critical to the survival of the dunes and agriculture in the valley. The northern part of the San Luis Valley, north of the San Luis Hills, has been termed the Alamosa Basin (Brister and Gries 1994). The Alamosa Basin, in turn, has been subdivided into two smaller basins: a western graben (the Monte Vista graben) and a deeper, narrower, eastern graben (the Baca graben) (figure 3) (Brister and Gries 1994). Separating the two sub- basins is a basement high called the Alamosa horst. The Baca graben has a greater degree of tilting than the Monte Vista graben (Brister and Gries 1994).

The Baca graben also contains a thicker sequence of sediments than the Monte Vista graben. Up to 9,930 feet (3,027 m) of post- Eocene sediments were deposited in the Monte Vista graben compared to almost 16,000 feet (4,900 m) of sediments in the Baca graben. The basin fill thins to 5,400 feet (1650 m) on the Alamosa horst (McCalpin 1994). The degree of tilting and amount of sedimentary fill is due to the Baca graben's proximity to the Sangre de Cristo fault zone (Brister and Gries 1994).

The San Luis Valley is the largest intermontane basin in Colorado, stretching almost 135 miles (217 km) from north to south and 56 miles (90 km) from east to west (figure 4). At the latitude of the dunes, the valley is 40 miles (64 km) wide. The northern terminus of the San Luis Valley is Poncha Pass, which separates the Rio Grande drainage from the Arkansas River drainage system (Johnson 1967). Except for the San Luis Hills, the surface of the San Luis Valley is remarkably flat. Elevations range from 7,546 feet (2,300 m) in the center of the valley to 7,874 feet (2,400 m) on the alluvial fans along the mountain front (Wurster and Cooper 2000).

The San Luis Valley also can be subdivided into a 2,900 square mile (7,600 sq km) closed basin to the north and an open basin through which the Rio Grande flows to the south (figure 4). Streams flowing into the closed basin form a system of wet meadows and ephemeral lakes (San Luis Lakes on figure 4). Evapotranspiration is the only outlet for water in the closed basin (Wurster and Cooper 2000).

The headwaters of the Rio Grande River drain part of the glacially carved peaks of the San Juan Mountains. The Rio Grande is the major drainage in the valley and its watershed covers 4,633 sq miles (12,000 sq km) (Wurster and Cooper 2000). Eroded debris is carried into the San Luis Valley where, as the river's gradient decreases at the foot of the mountains, sediment is deposited in an alluvial fan. The Rio Grande then meanders slowly in a southeasterly direction past Alamosa, Colorado and across a broad, flat flood plain (Johnson 1967).

The San Luis Valley is an arid environment with an average annual precipitation of only 8 inches per year (200 mm/yr) (Wurster and Cooper 2000). The rain shadow effect created by the San Juan Mountains that form the western border of the valley contributes to this arid climate by creating a barrier to moisture swept into the area from the southwest and west. Located on the eastern border of the San Luis Valley, Great Sand Dunes receives only a bit more precipitation than the center of the valley. Thunderstorms between June and September contribute 60 percent of the annual precipitation. Snowfall in the mountains during the winter months is typically 12 times greater than in the center of the valley.

Only a few days pass each year during which the sun does not shine in the San Luis Valley. High temperatures range from 50 degrees Fahrenheit (10 degrees Centigrade) during January to 90 degrees Fahrenheit (32 degrees Centigrade) in July (Wurster and Cooper 2000). When the clouds are pushed against the Sangre de Cristo Mountains, thunderheads build and may drop over an inch (2.5 cm) of water in less than an hour on the dry, rocky foothills above the dunes. The rocky slopes are unable to absorb such intensive downpours, and the water runs swiftly downhill along any trail, arroyo, tire track, or other available path, forming gullies several feet deep in only a few minutes. These flash floods typically last only a few minutes before fading to a trickle.

In the northwest corner of Great Sand Dunes, a wetland complex has developed on part of the sand sheet that surrounds 4,000 acres (10,000 hectares) of the tallest dunes in the park. In this area, dunes seldom exceed 33 feet (10 m) in height and most of the dunes have been stabilized by vegetation (Wurster and Cooper 2000). Here, interdunal wetlands occur in depressions between the dunes. Most wetlands are less than 0.2 acres (0.40 hectare) in size. Sand Creek, drains 15 sq miles (39 square km) of the Sangre de Cristo Mountains, and flows northwest of the interdunal wetland area, this is the largest stream entering Great Sand Dunes. Flow in the stream is seasonal, occurring between April and October.

Park History

Humans have inhabited the San Luis Valley for thousands of years. (Trimble 1972; Kiver and Harris 1999). Projectile points made 15,000 years B.C. have been found in the dunes and other locations in the valley (Trimble 1972). Hunters belonging to the Folsom and Clovis cultures hunted mammoth, bison, giant sloth, and other game in the valley about 10,000- 11,000 years ago

(Kiver and Harris 1999). Bones of a now- extinct bison along with the fluted spear points that killed the animal were found west of the park near remains of a campfire used to roast the kill 10,000 years ago.

Pueblo Indians were the only hunters in the valley for centuries until 1300 A.D. when Apaches and Navajos arrived from the north and the Utes entered Colorado from the west. The Utes soon established their dominance in the mountains, and they were the most recent Native Americans to hunt in the grasslands adjacent to the dunes. They were in the valley when Don Diego de Vargas and his exploration party, the first Europeans, arrived in 1694 and also when Zebulon Pike, of the United States Army, stumbled down Medano Pass with ten hungry, freezing men in 1807, looking for the source of the Red River. Upon seeing the dunes, Pike recorded "sandy hills…[whose] appearance was exactly that of the sea in a storm, except as to color, not the least sign of vegetation existing on them." (Trimble 1972). Pike's journal gave the world the first written description of the dunes.

Eventually, through a series of broken treaties beginning in 1855, the Utes were pushed from the San Luis Valley to a small reservation in the dry, southwestern corner of Colorado. Farmers and ranchers moved into the valley beginning in the 1850s, although the dry climate and harsh winters limited development. Miners scoured the Sangre de Cristo Mountains looking for gold and other precious minerals and by the 1890s, a "fair- sized" camp sprang up in North Arrastre Canyon, southeast of Great Sand Dunes (Trimble 1972). The canyon's name derives from the arrastra, or ore- grinding stone, that the prospectors found and which was probably left by the Spanish in the 1600's. No significant ore deposits were discovered and the camp was abandoned about as quickly as it had been built.

A richer strike was discovered north of the dunes in 1876. Duncan, Colorado, became the new boomtown until 1900, when the owners of the Baca land grant, upon which the town sprawled, decided to enforce their property rights and evicted the entire town. Residents moved across the fence, taking their town with them, and renamed it Liberty. The ore eventually ran out and the miners vanished. Today, only a few disintegrating buildings remain to mark the boom times at Liberty.

While prospectors' picks rang in every nook and cranny of the mountains, Ulysses Herard began raising cattle up the Medano Pass trail in 1878. To many, Herard is the official character of Great Sand Dunes (Trimble 1972). Stories of Herard feeding full- curl bighorn rams lumps of salt by hand and killing bears with a hatchet are as colorful as the land itself. Herard single- handedly raised 6,000 head of cattle, was quite well read, and lived in his meadow until the 1930's. The mountain above Medano Pass is still referred to by some as Herard Peak.

All of this human activity surrounded the sand dunes but rarely penetrated them. Sand won't support grain production or cattle and makes a poor foundation for cabins. The dune sand does contain a trace of gold, however, and the fever briefly lured miners into the area in the 1930s. The Volcanic Mining Company once built a mill along Medano Creek near today's picnic area, but the operation was not profitable and the buildings were torn down.

In order to preserve the dunes, some visionary women of the valley got together in 1930, led by Mrs. Elizabeth Spencer of Monte Vista and Mrs. Millicent Velhagen of Alamosa, and encouraged the creation of a Great Sand Dunes National Monument (Trimble 1972). Supported by valley residents, the state of Colorado, and Washington, D.C., their dreams became reality in 1932 when President Herbert Hoover proclaimed the area a National Monument.

National designation, however, does not necessarily discourage modern developers. Developers, spurred by the abundant groundwater beneath the monument, designed 13,000 houses to be built along or near the monument's edge (Kiver and Harris 1999). Because of concern that a lowering of the water table would threaten the preservation of the dunes as well as park plants and wildlife, the Great Sand Dunes National Park and Preserve Act was passed in 2000, derailing these developments. Groundwater in the San Luis Valley, however, remains a precious commodity especially for thirsty Front Range cities, primarily metropolitan Denver.

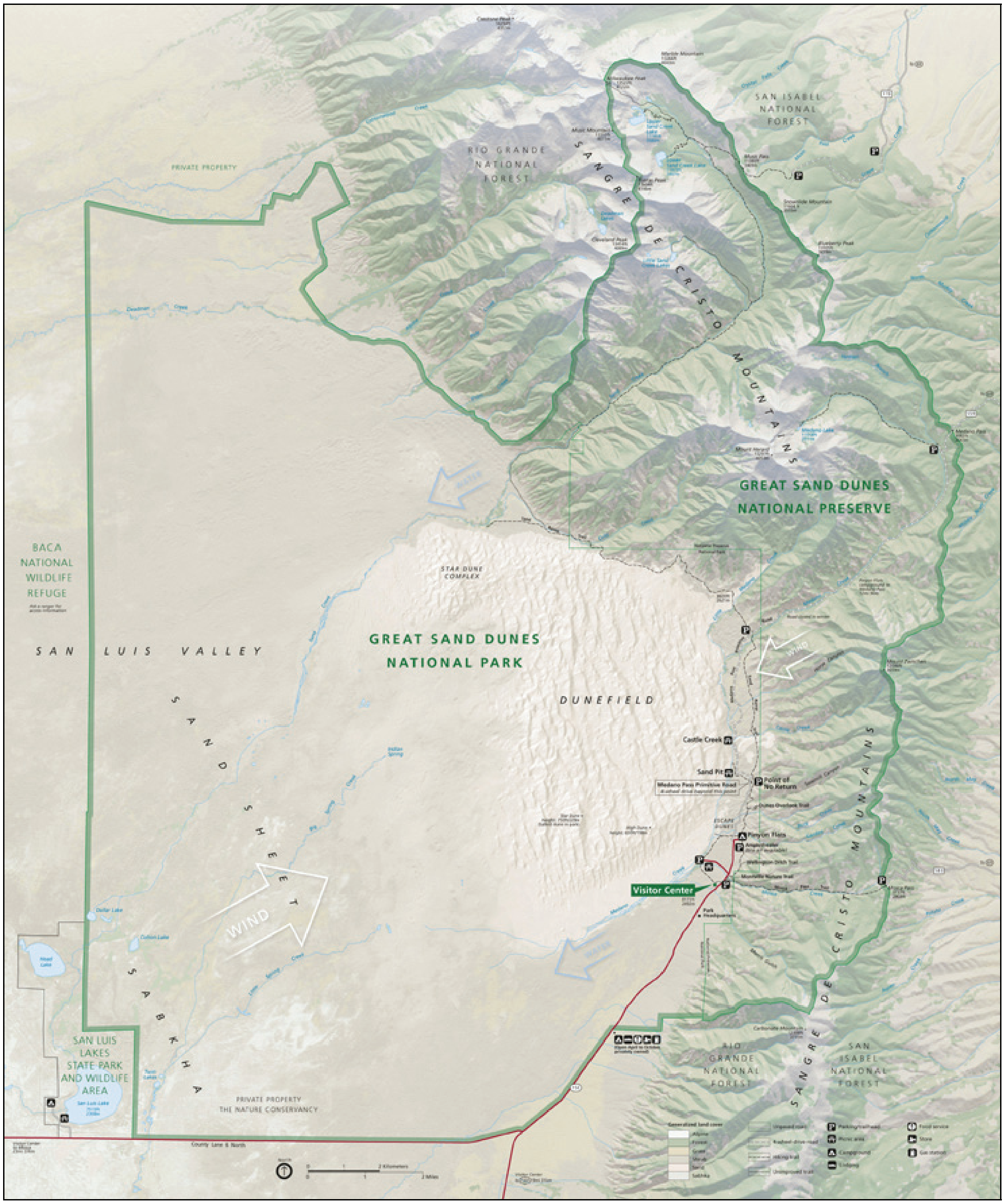


Figure 1. Map of Great Sand Dunes National Park and Preserve. Map courtesy of the National Park Service.

Figure 2. Great Sand Dunes and Sangre de Cristo Mountains. Photo courtesy of the National Park Service.

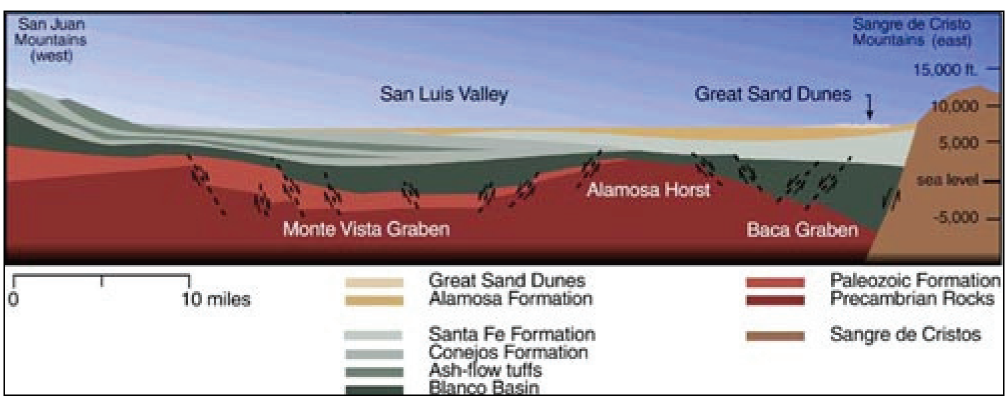


Figure 3. West to east geologic cross-section across the San Luis Valley. The structural valley is deeper on the eastern edge where movement is on the Sangre de Cristo Mountain-front fault. From NPS, http://www.nps.gov/grsa/resources/wind_regime.htm (access December 10, 2005).

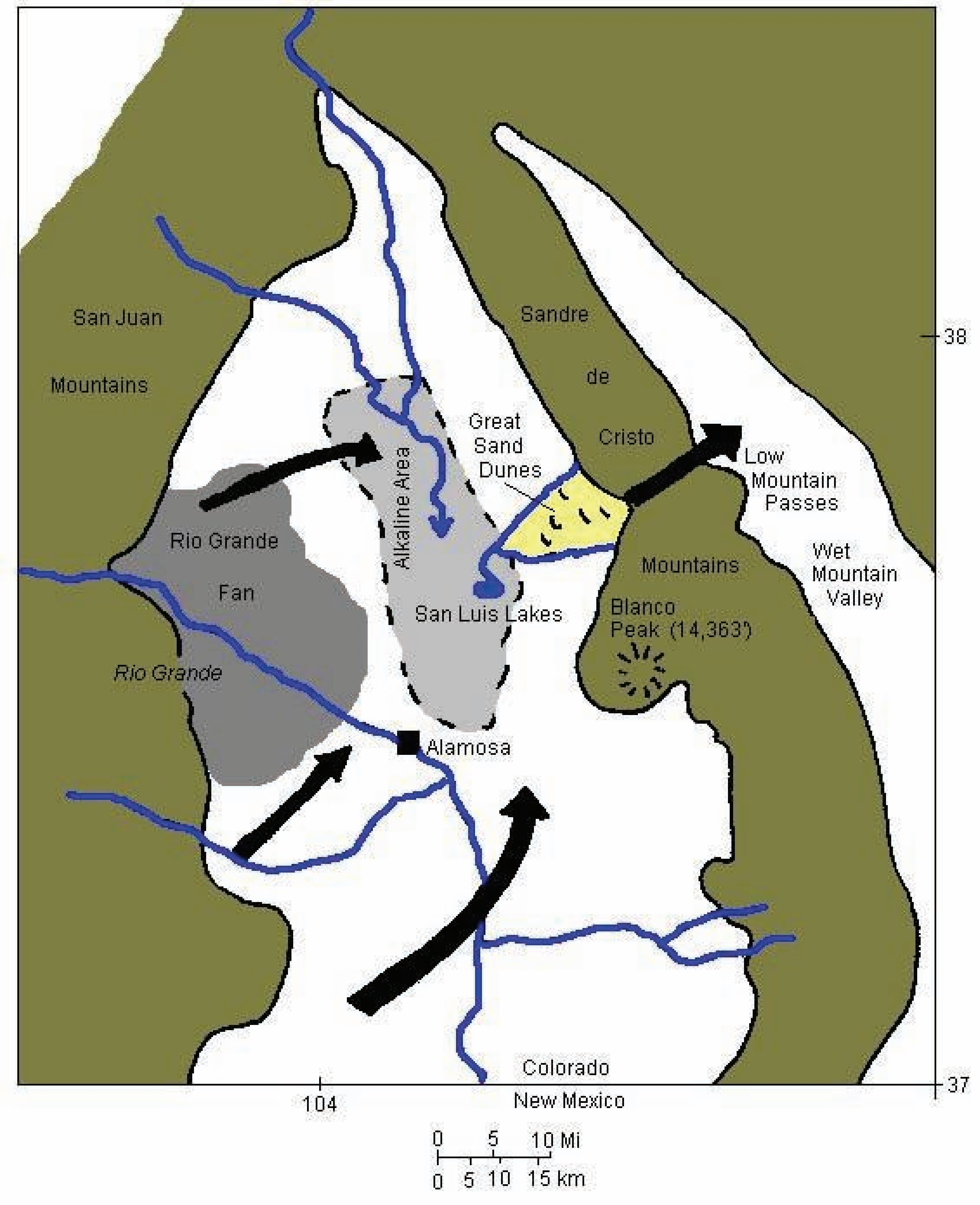


Figure 4. Geographic setting of Great Sand Dunes National Park and Preserve in southern Colorado. Black arrows indicate wind direction. Blue lines indicate fluvial systems. Brown areas indicate mountain ranges. Modified from Kiver and Harris, 1999.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Great Sand Dunes National Park and Preserve on August 21, 1998, to discuss geologic resources, to address the status of geologic mapping, and to assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

The sand dunes are the key to the dune field ecosystem of Great Sand Dunes National Park and Preserve (Resource Management Strategy 1994). They are the common thread binding the physical, biologic, and cultural subsystems in the Great Sand Dunes area. In order to understand and manage this ecosystem as a whole, resource managers must understand the eolian processes that shaped the dunes, the present status of the dunes, and their range of dynamic variations (Resource Management Strategy 1994). These dynamic variations, or fluctuations, not only need to be identified but also the causes of these fluctuations need to be determined.

This section addresses the following geologic issues important to Great Sand Dunes:

- Water issues and dune preservation
- Earthquake potential
- Oil and gas development
- Mining issues

The section also lists potential research projects discussed during the 1998 scoping workshop (Appendix B).

Water Issues

Water is the lifeblood of the Great Sand Dunes. Without water, creeks would no longer flow across the sand, the dunes and the sand deposits around them would change, and wetlands and ponds that support a rich diversity of life would dry up. Because of this integral relationship between water and sand, Congress passed the Great Sand Dunes National Park and Preserve Act, which authorized the creation of a national park (the former Great Sand Dunes National Monument) and a national preserve that includes the entire hydrological system of the dunes, from tundra to wetlands (figure 1).

Preservation of the sand sheet that lies west of the dune field, a major supplier of sand, is critical to the preservation of the dune field (figure 1). Groundwater withdrawal may adversely impact the sand sheet. In addition, water withdrawal may impact the health of the environment in Great Sand Dunes. The amount of water available for ecosystem management and drinking water supplies, is a major concern for the park and preserve.

All of the dune features, including the unique morphology of the dunes, surge flow in Medano and Sand Creeks, and interdunal ponds and wetlands are closely tied to the delicate balance among precipitation, surface flow, and groundwater. Slightly more precipitation falls at Great Sand Dunes than in the center of the valley due to its location at the base of the mountains (Chatman et al. 1997). The monsoons of July, August, and September bring in the greatest amount of precipitation. Although, the month- by- month precipitation is less during the winter than summer, snowfall is sufficient to produce a substantial snow pack in the mountains.

Water in the San Luis Valley is a precious resource. In 1991 an application by American Water Development Incorporated to pump 200,000 acre- ft of water per year from San Luis Valley aquifers and to transport it via pipeline to the Denver vicinity was denied. The proposed project would have lowered the water table 150 feet (46 m) along the park's boundary. Water resources of the San Luis Valley will continue to be sought by entities outside the valley – both within Colorado and from other states (Emery 2005). Management and monitoring of surface water and groundwater in the San Luis Valley and at Great Sand Dunes are critical to dune maintenance and sustainability.

Surface Hydrogeology: Most of the streams flowing out of the Sangre de Cristo Mountains are small and end within a few miles of the mountain front (Andrew Valdez, NPS geologist, personal communication, November, 2005). Two streams flow along segments of the dune field perimeter (figure 5). Sand Creek, the larger of the two, flows along the northwestern side and Medano Creek flows along the east and southeastern sides of the dune field. While Sand Creek occasionally reaches some playa lakes located 10 miles (16 km) from the mountain front, both streams infiltrate the groundwater system.

Since 1992, discharge has been measured on each stream with Parshall flumes placed near the location where the streams enter park service land. Peak flow on Sand Creek ranges from 54 to 225 cubic feet per second (cfs) and occurs in May and June. Base flow for Sand Creek varies from 0 to 1 cfs. Peak flow for Medano Creek fluctuates from 9 to 65 cfs with a base flow of 2- 3 cfs (Valdez 1996).

These two creeks erode sand from some parts of the dune field and deposit it in others. Both streams and their tributaries begin in the high, glaciated valleys of the Sangre de Cristo Range as typical mountain streams with steep gradients and rocky channels. However, once their gradient lessens, they become braided streams choked with a large sand load. Surge flows occur in the braided streams at regular intervals and are critical for the maintenance and sustainability of the dunes. A surge flow is a pulse of water that can flush more sand down the stream than steady flow. Surge flow is dependent on stream discharge levels, water depths, and flow velocities. A decrease in surface flow would lead to a lower mean velocity in the creeks resulting in a lower sediment transport rate (Wiegand 1977).

Two of three distinct regions of dune development are influenced by the action of Sand and Medano Creeks (figure 5). The thick sand deposits and closely spaced reversing dunes of Medano Creek ridge are a direct response to the availability of sand supplied by Medano Creek (Valdez 1996). Sand availability and a complex wind regime result in the Sand Creek star dunes.

Prevailing winds from the southwest blow sand back into the dunes. The great thickness of dunes in the park comes from vertical dune growth that is facilitated by excess sand and multiple wind directions (Valdez 1996). If surge flow is eliminated, steady flow will become the dominant process and less sand will be transported downstream becoming available for recycling into the dunes.

Groundwater Hydrogeology: Except for water lost to evapotranspiration, all the water in Sand and Medano Creeks normally infiltrates a shallow unconfined aquifer (Chatman et al. 1997; Rupert and Plummer 2004). The existence and natural maintenance of the dune field are dependent on maintaining historic groundwater levels in this aquifer. The unconfined aquifer and a deeper confined aquifer are the two principal aquifers at Great Sand Dunes.

The unconfined aquifer is located in the Alamosa Formation, which consists of unconsolidated gravels, sands, clays, and conglomerates. In most locations, the water table is within 10 feet (3 m) of the surface and is generally less than 100 feet (30 m) thick. A clay layer about 8 feet (2.4 m) thick and about 300 feet (91 m) deep separates the unconfined aquifer from the confined aquifer, also located within the Alamosa Formation. The eastward extent of the clay layer extends toward the base of the Sangre de Cristo Mountains is not known (Rupert and Plummer 2004).

The confined aquifer ranges from 500 feet (152 m) to 5,000 feet (1,524 m) thick. On the east side of the valley, an unconformity marks the base of the active confined aquifer while on the west side, the base of the aquifer lies above ash- flow tuffs. Artesian water from this confined aquifer was discovered in about 1887 and within four years, about 2,000 flowing wells had been developed (Emery 2005). The confined aquifer continues to be a primary water source in the valley.

Radiocarbon dating of groundwater in the confined aquifer indicates it is about 30,000 years old (plus or minus 3,000 years) (Rupert and Plummer 2004). For comparison, the last major ice advance (Wisconsin) during the ice age occurred about 20,000 years before present. Studies have shown that fluctuations in the interdunal ponds are not tied to the confined aquifer.

A third aquifer, called the "passive confined aquifer," has also been identified in the San Luis Valley (Chatman et al. 1997). This is the deepest aquifer. Water within the aquifer is "passive" and does not move. The passive confined aquifer is based in the Precambrian basement rocks, the San Juan volcanic units, and the underlying Blanco Basin/Vallejo Formations. Little is known about this aquifer but hydrologists believe the aquifer has low hydraulic conductivity and poor water quality.

Although less than 10 inches (25 cm) of precipitation falls in the area each year, a large aquifer system exists in the subsurface. Estimates of over 2 billion acre- feet of water stored in aquifers above 6,000 feet (1,829 m) have been made. The San Juan Mountains provide much more recharge to the aquifers than the Sangre de Cristo Mountains, yet the Sangre de Cristo Range is locally important to the aquifers in Great Sand Dunes.

Aquifers in the vicinity of Great Sand Dunes National Park and Preserve are important for four reasons (Chatman and others 1997):

- they are sources of agricultural and potable water
- they influence streamflow
- they create interdunal ponds where the dune surface intersects groundwater
- they influence wetlands

The proposal by American Water Development Incorporated to extract 200,000 acre- feet each year from the San Luis Valley led the NPS and other agencies to conduct research into the hydrologic system of the park and preserve. Studies using 21 groundwater monitoring wells, the Parshall flumes on Medano and Sand Creeks, and Schlumberger soundings and resistivity testing to map the water table near the creeks showed seasonal fluctuations in the water table. These studies showed fluctuations of up to 10 feet (3 m) in shallow wells (20 ft; 6 m) near the creeks and fluctuations of less than 1 foot (0.3 m) in deeper creek wells (100 ft; 30 m) and wells away from the streams (Valdez 1996). Results from the research predicted that any significant lowering of the water table would increase the gradient between the streams and groundwater and decrease the extent and volume of flow, the ability for surge flow to develop, and the ability of these streams to transport sand. If the creeks cannot transport sand back to the upwind side of the dune field, the long- term viability of the dune field will be jeopardized (Rupert and Plummer 2004).

Wetlands associated with interdunal ponds and depressions along the western edge of the dune field are also affected by changes in the shallow unconfined aquifer. The number of ponds decreased from 36 in 1936 to zero in 1966, and then gradually increased to 9 in 1995 (Chatman et al. 1997; Ruppert and Plummer 2004).

Interdunal ponds intersect the water table of the unconfined aquifer. Thus, their occurrence is directly affected by fluctuations in the water table of the unconfined aquifer. Lowering the water table of the shallow unconfined aquifer, results in an immediate decrease in the water levels of the interdunal ponds (Rupert and Plummer 2004). The water table may be lowered due to periods of drought, during periods of over pumping of the unconfined aquifer, or through lowering of local base level by downcutting of Big or Little Spring Creeks, both of which originate in the park and flow to the southwest (figure 1).

To better understand the hydrologic cycle at Great Sand Dunes, NPS staff are studying how snow pack, storm runoff, and the position of the water table relate to stream flow rates and duration (Valdez 1996). While the cycle is relatively simple – snow melts, flows down hill in streams, and soaks into the ground – predicting what changes in any part of the cycle would do to the other parts of the cycle is more complex. Data regarding the monitoring system, rates of discharge, water quality, groundwater flow direction, and gauge data are available in Chatman and others, 1997, and Rupert and Plummer, 2004.

The predominant feature in Great Sand Dunes is the 39 square- mile (100 sq km) dune field. Some of the dunes are as much as 750 feet (230 m) high. If the water table lowers, the process of sand recycling will be significantly reduced. Over time, if the dune field were unbounded by Sand Creek and Medano Creeks scientists expect that the dunes would spread out over a larger area at a lower height.

Earthquake Potential

Earthquakes present a potential problem due to surface shaking that might affect water tanks, pipelines, and most of the other facilities that lie in the vicinity of fault lines. The faults associated with Great Sand Dunes may act as barriers to groundwater flow thus causing additional pressure buildup along the faults that may lead to eventual failure. The Visitor's Center is currently located on a fault scarp and the campground is located on unstable ground (landslide or debris flow) that may be reactivated during a seismic event.

The Sangre de Cristo Range was rapidly uplifted about 19 Ma in the Miocene and uplift has continued into recent time. The approximately 1.2 miles (2 km) of relief on the range occurred primarily in the Late Miocene (Lindsey et al. 1986). Fault scarps, from multiple earthquakes, offset Quaternary deposits and landforms are evidence of continued uplift. The average vertical displacement on recent faults is 2.9 to 9.5 feet (1.2- 2.9 m) (McCalpin 1994). Magnitude 7 and greater earthquakes that accompany displacement have a return interval of 10- 47 thousand years. The last two earthquakes along the Sangre de Cristo mountain front fault with a magnitude greater than 7 occurred about 10- 13 thousand years ago and 7.6 thousand years ago, respectively. Holocene displacement of the Sangre de Cristo fault marks it as one of Colorado's few active faults (McCalpin 1994).

The Holocene and Quaternary faults in the San Luis Valley are not associated with any historical seismic event. In the last 120 years only one earthquake has been recorded, in 1952 (Stover 1988; McCalpin 1994).

Oil and Gas Development

Hydrocarbon exploration and development may negatively impact groundwater quality, scenic views, dark night sky, ambient sound levels, and plant and animal communities.

Interest in oil and gas development in the vicinity of Great Sand Dunes began in 1992 when Challenger Gold Inc. accidentally discovered oil while they were exploring for gold on the Baca land grant. The oil was discovered in 28 shallow exploratory drill holes. The discovery prompted Challenger (now doing business as Lexam Explorations) to redirect its gold exploration in favor of concentrating on developing the petroleum potential on the Baca lands. In 1995 two exploratory oil and gas wells (Baca #1 and Baca #2) were drilled by Lexam along the eastern edge of the valley near Crestone. The oil and gas operator stated that unrefined oil and gas was found in shallow cores in these wells, but the data are not available to the public. Neither of the wells was completed as a producing well (Lisa Norby, Geologic Resources Division, 2/06). Two additional exploratory drilling permits were obtained to test the hydrocarbon potential on the Baca lands but the permits expired in 2003 and the wells were never drilled.

The oil and gas drilling target in the park called the Crestone Prospect is a structural anticline in the Crestone sub- basin of the Baca Graben. The Baca Graben is part of the Tertiary aged rift system extending from south- central Colorado to Mexico. An additional prospect called the Pole Creek Prospect is a shallow oil target in a fault block near the margin of the basin (http://www.lexamexplorations.com). Both drilling targets were identified on seismic and gravity data. The geologic plays are interpreted by Lexam to contain Mesozoic- aged source (Mancos shale) and reservoir rocks (Dakota sandstone), but there are no publicly available geologic data to confirm or deny the presence of the Mesozoic strata in the basin. The most commonly held geologic interpretation is that the Mesozoic oil and gas source and reservoir rocks were eroded and are no longer present in the eastern portion of the San Luis Valley. However, recently Bob Kirkham of the Colorado Geological Survey and Andrew Valdez of Great Sand Dunes National Park located some outcrops that appear to be Dakota sandstone and Morrison Formation in a part of the Baca Ranch that is now managed by the US Forest Service (written communication Andrew Valdez, Great Sand Dunes National Park and Preserve 3/2/2006).

In 2004 Petro Hunt, an oil and gas company based in Dallas Texas leased all of oil and gas interests on the Baca Ranch from Lexam Exploration and Conoco/Phillips.

They conducted a 60 mile seismic survey to confirm the subsurface Crestone oil and gas prospect. The results of the seismic survey were discouraging and Petro Hunt elected to not drill the Crestone Prospect and released the leases to Lexam (pers. communication Steve Bressler, Petro Hunt 2/24/2006). Based on the Geologic Resources Division analysis of the limited available data, the lack of oil and gas production in the San Luis Basin, and minimal interest by oil and gas companies in drilling the Crestone Prospect, the division has concluded that the possibility of a commercial oil and gas discovery in the park is unlikely and highly speculative. Any future oil and gas development in the park would be regulated by the National Park Service's Nonfederal Oil and Gas Rights regulations art 36 CFR Part 9 Subpart B regulations.

Mining Issues

Lexam Explorations, Inc., originally prospected the Baca grant for gold in 1990. They patterned their program after the Battle Mountain Gold Company's San Luis Mine, located near the town of San Luis, CO. The San Luis Mine hosts disseminated gold of hydrothermal origin in a 24 to 27 million- year- old low- angle, detachment- style fault zone associated with the Rio Grande rift. Upward- migrating gold- bearing hydrothermal fluids at the San Luis Mine were trapped by a clay layer similar to the one that acts as the petroleum trap on the Baca grant oil shows. The hydrothermal fluids tended to pool below the clay zone. Minor quantities of sphalerite and galena are also present in the San Luis Mine which was prospected for lead and zinc decades ago. Copper is also present at the San Luis Mine. (http://www.nature.nps.gov/geology/parks/grsa/geology, access December 16, 2005).

Lexam drilled 42 exploratory drill holes around Deadman Creek in and near the foothills on the Baca grant, but a reserve estimate could not be substantiated. While gold exploration has currently been suspended, an increase in gold prices could issue a return of the exploration program. The structural zone that is thought to host the gold may extend beneath the park and preserve (http://www.nature.nps.gov/geology/parks/grsa/geology, access December 16, 2005). Although private companies do not have to submit exploration reports to the state, the Colorado Geological Survey knows of no new gold exploration on the Baca grant (James Cappa, Chief, Mineral and Mineral Fuels Section, Colorado Geological Survey, personal communication, December 21, 2005). Any company seeking to develop hard rock minerals in the park and preserve would need to obtain a National Park Service special use permit prior to undertaking any activity.

Lode Mining: A lode is a mineral deposit in consolidated rocks such as a vein, as opposed to a placer deposit found in loose gravels. Small mining operations and prospects were active in Great Sand Dunes in the past prior to the inclusion of the area in the National Park System. The park and preserve is closed to the location of new mining claims under the Mining Law of 1872. Numerous abandoned mine and prospect excavations exist upstream of and in the watershed that drains into the park. Mineral- development activities potentially could affect water quality of the park by introducing heavy metals and increasing acidity.

Most of the past lode mining activity within Great Sand Dunes occurred in the Cold Creek watershed on a small, unnamed tributary of Cold Creek in the Sangre de Christo Mountains in the northern part of the Preserve (figure 1). There is a 2,300 cubic yard dump at the main site, but little metallized or sulfidized rock is present, therefore acid mine drainage and heavy metal loading from this site are unlikely to impact water quality (http://www.nature.nps.gov/geology/parks/grsa/geology, access December 16, 2005).

Three other groups of prospect excavations are located north of the main Cold Creek drainage channel and all are thought to be sources of at least some of the iron-oxide cementation that occasionally occurs in Sand Creek. If iron and heavy metal sulfides are present, the cations can dissolve in the water creating sulfuric acid commonly know as acid mine drainage. These sites may require further investigation (http://www.nature.nps.gov/geology/parks/grsa/geology, access December 16, 2005).

Other excavations of lode deposits in Great Sand Dunes are not thought to be detrimental to water quality because the sites are small, lack concentrated mineralization and occur some distance from drainages. This is confirmed by water quality measurements. These sites include excavations in Sawmill Canyon, on the Wellington tract, and at Denton Spring. A detailed description of these sites was prepared by Chatman in 1995 and should be on file at the park headquarters (Chatman 1995; http://www.nature.nps.gov/geology/parks/grsa/geology, access December 16, 2005).

The Myrtle K Mine and mill site are upstream of the dunes on Sand Creek on a narrow fault zone that contains iron and copper sulfide mineralization. There is a 2,100 cubic yard dump, a boiler, and a five- stamp mill, all immediately adjacent to the creek. Slightly elevated levels of arsenic, boron, copper, manganese, and zinc have been found in samples taken from the fault and a shear zone in the site.

Workings on Medano Creek, Buck Creek, Morris Gulch, Evans Gulch, and South Arrastre Creek in the Sangre de Christo Mountains, and a working in the Sand Creek watershed about 0.5 miles (0.8 km) downstream from the Myrtle K Mine have very little impact on water quality. This is because the workings are small, they lack sulfide mineralization, the bedrock tends to neutralize any acid produced, and they are not close to any drainage channels, or some combination of these factors (http://www.nature.nps.gov/geology/parks/grsa/geology, accessed December 16, 2005). Historical information suggests that some copper may be present in Mosca Creek, but limited water quality testing has been negative for copper. If a decline in the water quality is detected in the future, the source of mineralization should be investigated.

Placer Mining: An unsuccessful gold rush was sparked in 1928 when gold was found to be associated with magnetite grains in dune field sand. Claims were located on lands in the dune field as well as on Medano Creek. Mining ended by 1938 due to low gold concentrations, although some prospecting continued to 1941. In 1980 another attempt to recover placer gold occurred at some unknown site on Medano Creek, probably inside the Rio Grande National Forest. The operation was terminated due to lack of access routes (http://www2.nature.nps.gov/geology/parks/grsa/geology, access December 16, 2005).

The abandoned placer claims do not pose a water quality issue for Great Sand Dunes. All equipment and materials have been removed. No mercury anomalies have been found in the water quality testing done since 1990.

Potential Research Projects

Coupled with these geologic issues are potential research projects that might help to better define them for the resource manager. At the workshop (Appendix B), the following projects were proposed:

- Date the dunes in order to get a better idea of dune history.
- Map the existing fault lines.
- Map groundwater flow patterns.
- Differentiate paleo- fluvial channels within the park and link this research with global warming studies, human history, and hydrologic history.
- Find the depth to bedrock, especially in the basin located west of the major dune field. Interest was expressed at the workshop in drilling below the confining layers. Projected drilling depth was estimated to be about 300 feet (91 m).
- Study the impact of groundwater withdrawal on sabkha environments.
- Study the rate of infiltration of moisture into the soil. Questions were raised concerning meteoric water, groundwater, and the origin of the vapor phase.
- Define the relationship between soil moisture and vegetation on dunes.
- Research why light colored ripples are coarser grained than dark colored ripples on the dunes, the different mineralogy of the dunes, and the provenance of the sands. Workshop participants were interested in why the light colored and dark colored sands didn't mix and questioned if they were the products of different wind regimes or some other factor.
- Study the impact of livestock grazing of vegetation on the sand sheet and its impact on the dunes. Dune preservation, vegetation, groundwater, and grazing are all interrelated, and a better understanding of this interrelationship might be beneficial to the resource manager.

The dune system at Great Sand Dunes National Park and Preserve is one of the most complex in the world. Great Sand Dunes offers scientists an unparalled opportunity to study high- altitude, cold climate dune ecosystems in detail.

Figure 5. Physiographic map of the dune field, Great Sand Dunes National Park and Preserve. From http://www.nps.gov/grsa/resources /maps/dune_field_relief.jpg.

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Great Sand Dunes National Park and Preserve.

Dune Features and Processes

Great Sand Dunes National Park and Preserve contains the tallest dunes in North America. Standing 750 feet (230 m) above the San Luis Valley floor, these dunes are internationally significant as a high- altitude, seasonally cold climate eolian system. The Great Sand Dunes are actually one giant dune with many smaller dunes superimposed on its surface. This type of large dune feature is called a *draa*, or giant dune field (Andrew Valdez, http://sangres.com/np/sanddunes/faq.htm, access December 12, 2005).

Main dune field: Roughly 39 square miles (100 sq km) of dunes between Sand Creek and Medano Creek are constantly being shaped and reshaped by wind (figure 6). Prevailing southwesterly winds carry sand that has been deposited on the floor of the San Luis Valley to the Sangre de Cristo Mountain front. Medano Pass, at about 9700 feet (2960 m) elevation, is the lowest of the three passes east of Great Sand Dunes. Although far removed from the preserve, the pass plays a major role in dune formation by funneling northeasterly winds across the dune field (Valdez 1996; Rupert and Plummer 2004). The resulting bimodal wind regime changes dune behavior from migratory to vertically growing.

Sand dunes grow to enormous heights not only because of a complex wind regime, but also due to a sand recycling process. Medano and Sand Creeks seasonally carry sand from the east and north side of the dune field and redeposit it where southwesterly winds can transport it back to the dune field.

Surge flow in the braided channel sections of the two streams plays a significant role in transporting sand beyond the western edge of the dune field so that it can be recycled onto the dunes. Surge flow is a rare hydrologic phenomena in nature because the process requires a high flow regime and a smooth, mobile channel (Chatman et al. 1997). Each surge is a pulse, or wave, of water released at regular intervals from bedforms called antidunes. Antidunes are relatively large, sinuous ripples that form in the fast flowing, smooth channel. When the unstable antidunes collapse, they release their stored water. Because the channel is sandy and creates little turbulence, the pulse of water continues downstream in a discrete packet and picks up more water from other antidunes (Schumm et al. 1982; Valdez 1996).

The magnitude of the surge wave depends on water depth. Surging usually occurs at 15 to 20- second intervals in depths of only a few inches. During spring runoff, surge waves may reach 8 to 10 inches (20 to 25 cm) high with 40 to 60- second cycles. As antidunes break, they carry a large sand load downstream. The sediment is deposited westward of the main dunes and southwesterly winds blow it back into the dune field.

Sand Creek and Medano Creek also contribute to two of three distinct regions of dune development shown on figure 6 (Valdez 1996). First, sand supplied by Medano Creek forms the thick sand deposits and closely spaced reversing dunes in the area known as the Medano Creek ridge. The north trending dunes cannot hold all of the sand supplied to them so sand fills their troughs, forming a second northeast trending ridge that becomes the horizon of the ridge. Secondly, the Sand Creek star dunes are the result of a complex wind regime that buffets sand from Sand Creek. The third area, the central dune field, isn't affected by the streams and so displays the simplest dune formation. Found in the central dune field are large north- trending reversing dunes, with an occasional star dune, that are separated by vegetated troughs.

Individual sand grains move in three ways: saltation, creep, and suspension. Saltation results when grains bounce slightly above the surface when blown by the wind. Wind velocities must be greater than 13 mph (21 km/h) to transport sand. Bouncing sand grains reach heights of less than 2 inches (5 cm) and move horizontally 2 to 4 inches (5 to 10 cm). When a sand grain collides with other grains, it "creeps" by rolling or making small jumps. When blown high in the air, a sand grain moves by suspension. Saltation accounts for 95 percent of sand grain movement; creep accounts for about 4 percent; and suspension accounts for 1 percent of sand grain movement.

The active main dune field extends as much as 5 miles (8 km) westward from the Sangre de Cristo Mountain front. The sand dunes contain approximately 170 billion cubic feet (4.8 billion cu m) of sand. Still, the main dune field covers the least area of three sand deposits in the Great Sand Dunes system (figure 6).

Sand sheet: Extending as much as 20 miles (32 km) westward from the Sangre de Cristo Mountain front is the more aerially extensive sand sheet deposit (figure 6). The sand sheet covers 180 square miles (466 sq km) and primarily is composed of low- relief, vegetation-stabilized sand dunes (figure 7B) (Rupert and Plummer, 2004). The thickness of the eolian sand sheet is about 140 feet (43 m).

Vegetation in the sand sheet helps to stabilize the sand and prevent it from moving. However, active parabolic and barchan dunes are located on the south and west areas, respectively, of the sand sheet. Over a 63- year time span, total net movement of the parabolic dunes was 0.2 to 0.4 miles (0.4 to 0.6 km). The barchan dunes moved less, averaging net movement of 0.1 to 0.2 miles (0.2 to 0.3 km) (Marin and Forman 2004). The dunes move farther during drought years when vegetation and surface water resources are reduced. During the most recent drought in the late 20th to early 21st centuries, there was an 8 percent increase in the rate of parabolic dune movement between 1998 and 1999 compared to prior wet years (Marin and Forman 2004).

Sabkha: Like the sand sheet, the sabkha is a subtle feature at Great Sand Dunes (figure 7C). The third major sand deposit, the Sabkha lies farther west in the valley, near the San Luis Lakes (figure 6). The sabkha covers 120 square miles (311 sq km) and is characterized by sand grains held together by evaporite minerals (salts). Because the sand in the sabkha is hardened by minerals, the wind cannot shape it into dunes. Seasonal ponds form on the sabkha and these ponds, along with other wetlands, are an important part of the greater Great Sand Dunes ecosystem, supporting rare shorebirds, mammals, amphibians, and the endangered Slender spiderflower. The sabkha would slowly disintegrate without regular saturation and evaporation.

Dune types: Bimodal and complex wind patterns form reversing and star dunes in the dune field, while areas with unimodal winds, such as the sand sheet and mountain flanks, develop parabolic, barchan, and transverse dunes (figure 8). Special dune features such as climbing dunes, coppice dunes, large blowouts, and sand ramps are also present.

Parabolic dunes and barchan dunes are crescent- shaped dunes (figure 8). Where the tails of parabolic dunes point upwind, however, the tails of barchan dunes point downwind. Parabolic dunes have a relatively limited sand supply compared to transverse dunes, and vegetation often anchors the tails of the dunes. Consequently, winds remove, or blow out, the sand from the center of the dune and form a nose pointing downwind. Parabolic dunes, therefore, are also called *blowout* dunes.

At Great Sand Dunes, parabolic dunes have been divided into parabolic dunes of accumulation and parabolic dunes of deflation (Johnson 1967). Parabolic dunes of deflation cover a large area southwest of all other dune types. Low mounds of loose sand, covered by grass and shrubs, form the parabolic dunes of deflation. Blowouts measure from a few feet to several thousands of feet across, and may have been the reason for the lakes and playas that now characterize this area of the dunes.

Parabolic dunes of accumulation are both active and fixed, but both form downwind of the parabolic dunes of deflation (Johnson 1967). The fixed parabolic dunes of accumulation are upwind from the active parabolic dunes of accumulation. The fixed dunes are only a few feet higher than the parabolic dunes of deflation, but the active dunes rise for 100 to 200 feet (30- 60 m) on a relatively steep slope from the fixed dunes to the transverse dunes. Sparse vegetation covers both parabolic types. Only small amounts of sand collect on the leeward side of the fixed parabolic dunes of accumulation. The sand from the blowouts seems to bypass the fixed parabolic dunes of accumulation and settle onto the active parabolic dunes of accumulation (Johnson 1967).

In contrast to parabolic dunes, the tails of the crescent-shaped barchan dune point downwind because there is little vegetation available to stabilize the limited sand supply (figure 8). Barchan dunes are not as aerially extensive as are reversing dunes (Johnson 1967). A grove of ponderosa pine is presently being inundated by advancing barchan dunes. In addition to the sand supply from the southwest, sand is being added to the barchan dunes from sand sheet material already in place.

Reverse dunes and star dunes are the result of highly variable wind directions and may constitute the majority of dune forms at Great Sand Dunes (Kiver and Harris 1999). Although the prevailing wind direction is from the southwest, especially during the spring, variable winds occur throughout the rest of the year. With variable winds, the sand tends to blow back westward and stack itself into higher levels rather than migrating horizontally. Star patterns form when the wind changes to several directions (figure 8). Great Sand Dunes has some of the world's most impressive reversing dunes.

Sand that accumulates on the far edges of the dune field piles against the steep flanks of the Sangre de Cristo mountains in climbing dunes and sand ramps. The climbing dunes at Great Sand Dunes are between Medano and Cold Creeks. The dunes rise from about 8,800 to 9,500 feet (2,680 to 2,896 m) in about one mile (1.6 km) (Johnson 1967). The climbing dunes have no regular dune like surface features. They seem to form in irregular mounds and swales and are practically devoid of vegetation.

Sedimentary structures that form on the dunes include animal tracks, avalanching foreset beds, and eolian ripple marks (figure 9). Mudcracks may also form between the dunes.

Wetlands

As part of the National Wetland Inventory, the U.S. Fish and Wildlife Service mapped and classified the wetlands in the park and preserve in 1992 (figure 10). These wetlands are defined in Chatman and others (1997). Briefly, seven different types of riverine wetland systems and five palustrine wetlands are the responsibility of Great Sand Dunes resource management.

Riverine wetlands occur along the channels of Medano and Sand Creeks and their tributaries. A palustrine wetland is one comprised of perennial and intermittent ponds and depressions that nearly intersect the water table and that support hydrophytes. In Great Sand

Dunes, they occur along the banks of creeks, in abandoned stream channels, in the sand sheet, and the interdunal areas of the active sand dune field.

Of particular interest to Great Sand Dunes resource managers, are the palustrine wetlands associated with interdunal ponds and depressions that nearly intersect the water table near the western edge of the dune field (Chatman et al. 1997; Wurster and Cooper 2000; Rupert and Plummer 2004). The interdunal ponds and depressions provide important habitat for a variety of species and have decreased markedly in recent years. Lowering of the water table may lead to continued disappearance of the interdunal ponds and wetlands.

Features in the Sangre de Cristo Range

Glacial features: The Sangre de Cristo Mountains contain alpine glacial features common to many mountain ranges in the Rocky Mountains of Colorado (figure 11). Cirques, arêtes, horns, and U- shaped valleys are among the more common glacial features. Tiejeras Peak, the highest point in Great Sand Dunes at 13,604 feet (4,146 m), is a glacial horn.

Structural features: The glacially sculpted Sangre de Cristo Mountains are fault- block mountains that form a lofty backdrop to the sand dunes at Great Sand Dunes. Major west- dipping reverse faults exposed in the Sangre de Cristo Range include (from west to east) the Crestone, Sand Creek, Deadman, and Spread Eagle thrusts. These faults date from the Late Cretaceous- middle Eocene Laramide Orogeny (about 65- 55 Ma) (McCalpin 1994).

In Great Sand Dunes the Crestone Thrust is a complex fault zone at least 2,600 feet (800 m) wide. It contains numerous fault slivers of pre- Pennsylvanian sedimentary rocks. Mylonite, slatey cleavage, and chloritoid phyllite mark the footwall of the thrust. Like the Crestone Thrust, the Sand Creek Thrust moved Precambrian basement rocks up and eastward over late Paleozoic rocks, such as the Sangre de Cristo Formation.

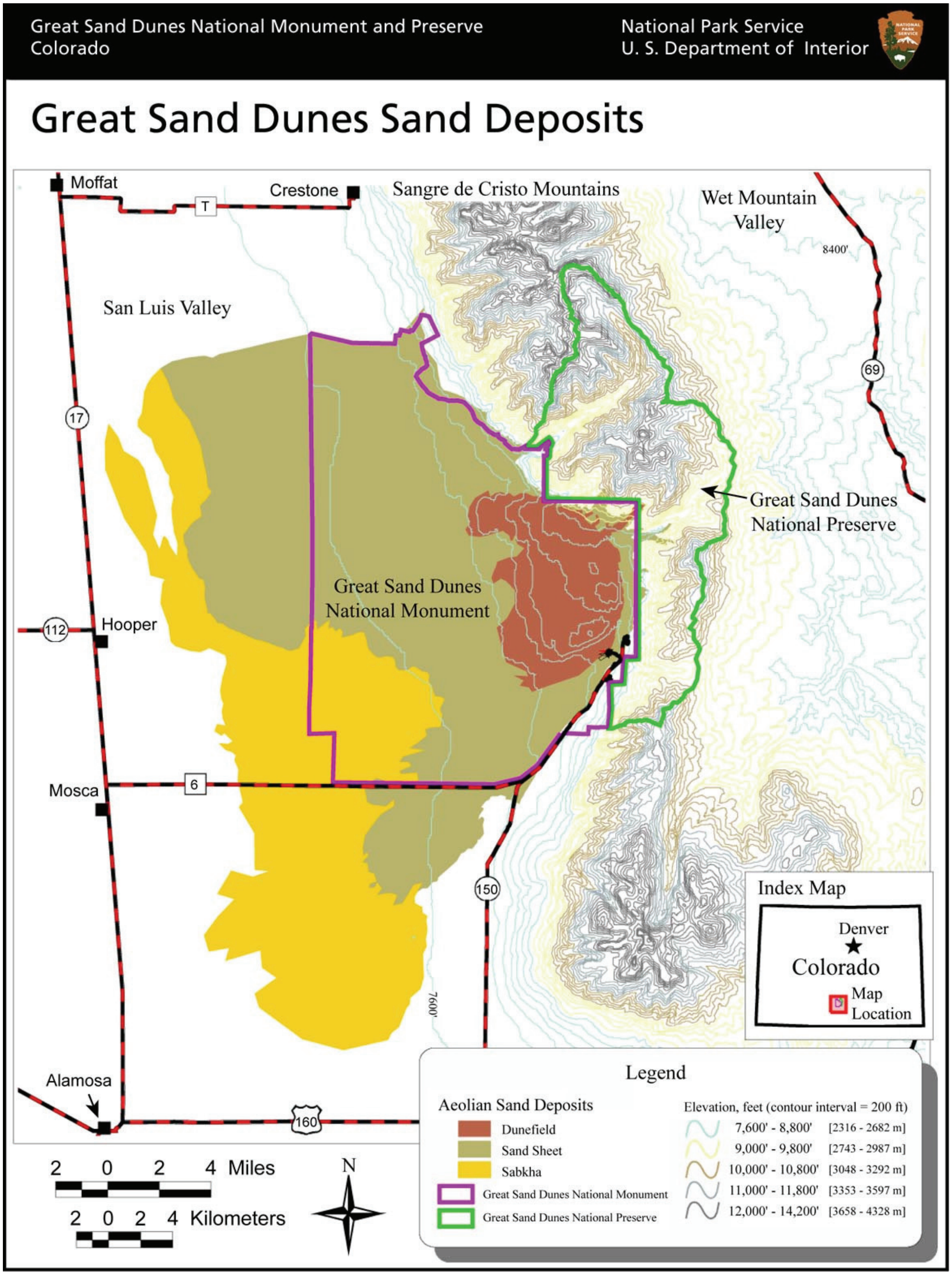


Figure 6. Eolian sand deposits in Great Sand Dunes National Park and Preserve. From http://www.nps.gov/grsa/resources/maps/GRSA_Sand_Deposits.jpg.

7 A. Active dune field

7 B. Sand sheet

7 C. Sabkha

Figure 7. The three major eolian sand deposits at Great Sand Dunes National Park and Preserve. A) the active dune field; B) the sand sheet, and C) the sabkha (aerial view). From Andrew Valdez, http://www.nps.gov/grsa/resources/wind_regime.htm (access December 10, 2005.)

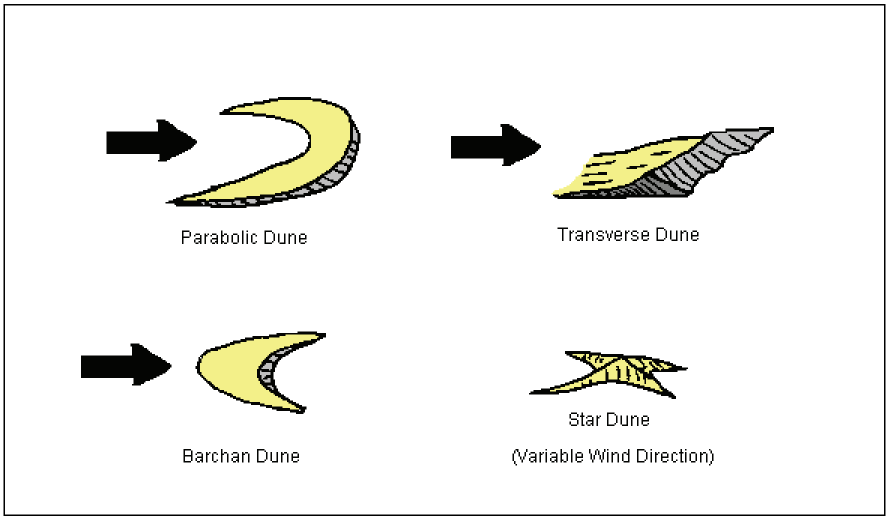


Figure 8. Common dune types. Arrows indicate wind direction.

Figure 9. Sand ripples on sand dunes caused by wind, Great Sand Dunes National Park and Preserve. Photo courtesy of http://www.nps.gov/grsa/resources/photos_dunes.htm (access December, 2005).

Figure 10. Great Sand Dunes wetland. Photograph courtesy of the National Park Service.

Figure 11. Music Pass, Sangre de Cristo Mountains. Glacial features in this photograph include a horn, an arête, a cirque basin, and a U-shaped valley. Photograph courtesy of the National Park Service.

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Great Sand Dunes National Park and Preserve. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

The following Map Unit Properties Table (MUPT) serves as a stratigraphic column for Great Sand Dunes National Park and Preserve and identifies specific properties of the different formations on the digital geologic map. The darker black horizontal lines in the MUPT represent major regional unconformities in the stratigraphic record. Geologic features and processes often occur in or can be restricted to a particular stratigraphic unit (group, formation, or member). This section ties together the geologic features with the formation properties, and also with the accompanying digitized geologic map.

The MUPT includes several properties specific to each unit in the stratigraphic column including a description of the lithology, the map symbol, erosion resistance, paleontologic and cultural resources, hazards, mineral resources, suitability for development, and a miscellaneous "other" column.

Map Unit Properties Table

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Paleontological Resources	Cultural Resources	Hazards	Mineral Resources	Suitability for Development	Other
QUATERNARY (Holocene)	Alluvium (Qal)	Unconsolidated sand, gravel and clay deposited by streams; includes Holocene stream deposits, Pleistocene glacial outwash, & locally, colluvium; up to several tens of feet thick.	Low	None	As part of the Great Sand Dunes eolian system archaeological program research, 67 prehistoric and historic sites were documented on the eastern side of GRSA	Flash flooding	None	Floodplain deposits	Recreation in Medano Creek
	Alluvial fan deposits (Qaf)	Poorly sorted, coarse sand & gravel deposited by distributary stream systems	Low	None		None	None	Cut by mountain front fault	
	Eolian sand (Qes)	Surficial deposits of well- sorted sand covered by sparse vegetation; thin and discontinuous, interspersed with alluvial sand & clay N of Deadman Creek.	Low	None		None	Placer gold, sand, magnetite	Unstable	Recreation popular on sand dunes
	Dune field (Qdf)	Wind- blown sand piled in various dune types.	Low	None		Burial	Placer gold, sand, magnetite	Unstable	
	Sandsheet (Qssh)	Unconsolidated sand	Low	None		None	None	Unstable	Hiking is a popular activity along mountain front
	Sabhka (Qsbk)	Clay and salt	Low	None		None	None	Wetland	
	Landslide deposits (Ql & Qls)	Angular rock debris of all sizes; forms hummocky topography; up to 100 ft (30 m) thick.	Low if disturbed by seismic activity or by construction	None		None	None	Low	
	Rockfall deposits (Qrf)	Accumulations of talus below large outcrops.	High	None		None	None	Low	
	Rock- glacier deposits (Qrg)	Angular blocks at base of steep slopes & valley floors; lobate & tongue- shaped; 32- 100 ft (10- 30 m) thick.	High	None		None	None	Low	
QUATERNARY (Pleistocene)	Pinedale glacial deposits, undiff. (Qpu)	Gray stratified alluvium of boulders, cobbles, pebbles & sand; forms mostly undissected & coalescing fans; locally covered by thin deposits of eolian sand; thickness unknown, may be as much as 330 ft (100 m) thick.	High	Mammoth femur & bison phalange (Pinedale/Bull Lake?)	None documented	None	Sand & gravel	Limited aerial extent	
	Pinedale alluvial fan deposits (Qpf)	Boulders, cobbles, pebbles, sand; some boulders as much as 10 ft (3 m) in diameter.	High		None documented	None	Sand & gravel	Limited aerial extent	
	Pinedale lacustrine clay (Qpl)	Glacial lake clay above terminal moraine on Willow Creek; thickness unknown.	Low if disturbed		None documented	None	Clay	Low (clay)	
	Pinedale outwash deposits (Qpo)	Gray, well- washed, stratified alluvium of boulders, cobbles, pebbles, sand; below terminal moraines on South Colony Creek; about 26 ft (8 m) thick.	Sand will erode more quickly than boulders		None documented	None	Sand & gravel	Limited aerial extent	
	Pinedale till (Qpt)	Gray, unsorted, unstratified deposit of boulders, cobbles, pebbles, sand & clay; 50- 100 ft (15- 30 m) thick.	Sand & clay will erode more quickly than boulders		None documented	None	Sand & gravel	Limited aerial extent	
	Pinedale & Bull Lake deposits, undiff. (Qpbu)	Boulders, cobbles, pebbles, sand	Variable		None documented	None	Sand & gravel	Limited aerial extent	
	Bull Lake alluvial fan deposits (Qbf)	Sorted, stratified alluvium of boulders, cobbles, pebbles, sand; forms dissected fans.	High except at times of intense runoff		None documented	None	Sand & gravel	Limited aerial extent	
	Bull Lake outwash deposits (Qbo)	Gray, sorted, stratified alluvium of boulders, cobbles, pebbles, sand; located in valleys below terminal moraines; thickness about 32 ft (10 m).	High except at times of intense runoff		None documented	None	Sand & gravel	Limited aerial extent	
	Bull Lake till (Qbt)	Yellow- gray, unsorted, unstratified compact deposit of boulders, cobbles, pebbles, sand & clay; 160 ft (50 m) thick on South Colony and Willow Creeks.	High		None documented	None	Sand & gravel	Limited aerial extent	
Unconformity									
TERTIARY (Oligocene/ Eocene)	Santa Fe Formation (Ts)	Tan, pink, buff, orange, brick red, light olive, and light gray to black stratified sand & gravel mostly from Precambrian and upper Paleozoic rocks; 1,300 ft (400 m) thick in subsurface.	High	None documented in GRSA	None documented	None	Methane in the (basin) overlying Alamosa Fm.	Limited aerial extent; wilderness	
	Granite & granodiorite (Tgr)	Small irregularly shaped intrusions; tan to light- gray; leucocratic, medium- to coarse- grained; seriate; nonfoliated; plagioclase, microcline, & quartz in subequal amounts with 1%- 5% biotite; accessory minerals include magnetite & apatite.	High	None	None documented	None	None	None - in Preserve & wilderness	
	Andesite (Ta)	Andesitic lahar, biotite latite, & dense hornblende- pyroxene andesite.	High	None	None	None	Hornblende, pyroxene, biotite	None - in Preserve & wilderness	
	Mafic volcanic rocks (Tmv)	Black, vesicular, porphyritic olivine basalt; composed of several flows; rests unconformably on Sangre de Cristo Formation; 250 ft (75 m) thick	High	None	None documented	None	None	None - in Preserve & wilderness	
	Felsic dikes (Tf)	Light- gray to white, fine- grained, felsic dike as much as 10 ft (3 m) wide; composed of microphenocrysts of quartz, feldspar & sparse biotite in groundmass of same minerals.	Phenocrysts will weather more quickly than groundmass	None	None documented	None	Feldspar, quartz	None - in Preserve & wilderness	
	Mafic dikes (Tm)	Dark gray- green to black, aphanitic to medium- grained; generally massive, locally porphyritic; nonfoliated; as much as 10 ft (3 m) wide.	High	None	None documented	None	None	None - in Preserve & wilderness	
Unconformity									

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Paleontological Resources	Cultural Resources	Hazards	Mineral Resources	Suitability for Development	Other
UPPER JURASSIC	Morrison Formation (Jm)	Interbedded gray to brown shale, gray to brown sandstone, & minor gray, fine-grained limestone. 250 ft (75 m) thick.	Shale has low resistance	None documented in GRSA	None documented	None	None documented	None - in Preserve & wilderness	Known for dinosaur fossils & uranium
MIDDLE JURASSIC	Entrada Sandstone (Je)	Thin- bedded, white to tan, friable quartz sandstone, fine- to medium- grained, well- sorted, well- rounded & frosted. 39 ft (12 m) thick.	Friable surface grains, otherwise high	None documented in GRSA	None documented	None	None documented	None - in Preserve & wilderness	Most widespread preserved eolianite in western US
		Unconformity							
UPPER PENNSYLVANIAN/PERMIAN	Sangre de Cristo Formation Undivided (PPNsu)	Red arkosic sandstone, conglomeratic sandstone, siltstone, shale, minor limestone; cross- bedding in sandstone; ripple marks, cross- laminations, mudcracks, raindrop impressions, burrows in siltstone & shale; thin limestone is unfossiliferous, marine limestone contains bryozoan fossils; max exposed thickness of about 4,600 ft (1,400 m) at Horn Peak.	Feldspars and limestone will erode more quickly than quartz sandstone	Bryozoan fossils in marine limestone beds on Music Creek	None documented	Rockfall?	None documented	None - in Preserve & wilderness	
UPPER PENNSYLVANIAN/PERMIAN	Sangre de Cristo Formation Crestone Member (PPNsc)	Red conglomerate, conglomeratic sandstone, & minor siltstone & shale; boulders & cobbles of Early Proterozoic gneiss, syenite & quartz. monzonite; sandstone is horizontally laminated & cross- bedded; exposed between Sand Creek Thrust and Little Sand Creek Thrust; 6,500 ft (2,000 m) thick.	Variable	Crinoid columns, brachiopods, sponge spicules, bryozoans; *Eomarginifera* sp & fusulinids found in biohermal units; trunks of *Calamites* in clastic beds	None documented	Rockfall?	None documented	None - in Preserve & wilderness	Mountain biking, rock climbing, caving at higher elevations
UPPER PENNSYLVANIAN/PERMIAN	Sangre de Cristo Formation Lower Member (PPNsl)	Red arkosic sandstone, conglomeratic sandstone, siltstone, & shale; sandstone cross- bedded; siltstone & shale contain ripple marks, cross- lamination & sparse mudcracks; conformably overlies Minturn Fm.; interfingers with overlying Crestone Conglomerate Member; thickens northward; thickness about 2,000 ft (600 m) west of Rito Alto Peak.	High	None documented	None documented	Rockfall?	None documented	None - in Preserve & wilderness	
MIDDLE PENNSYLVANIAN	Minturn Formation (PNm)	Gray & red arkosic sandstone, conglomerate, siltstone, shale, and minor marine limestone; occurs in thrust plates west of Mosca Pass; max thickness about 6,500 ft (2,000 m) at Middle fork of Taylor Creek. PNmu: upper part; PNmumls: marker limestone PNmcls: crinoidal silty limestone, about 755 ft (230 m) below top of unit; 39- 52 ft (12- 16 m) thick. PNmush: shale & siltstone member PNmols: oolite limestone PNmt: main turbidite member; upward- fining units of sandstone, siltstone, & shale PNmbls: biohermal limestone unit PNml: lower part PNmq: quartzose red- beds; arkosic & quartzose sandstone & siltstone	High	Abundant crinoid columnals, brachiopods, sponge spicules, bryozoans	None documented	Rockfall?	Siltstone & shale in upper part is radioactive & copper-bearing; gypsum near Arkansas River Valley	None - in Preserve & wilderness	
		Unconformity							
MISSISSIPPIAN, DEVONIAN, ORDOVICIAN	Sedimentary rocks, undifferentiated (MDOr)	<u>Leadville Limestone</u> (Lower Mississippian): Dark gray cherty massive dolomitic limestone; locally contains limestone breccia; 230 ft (70 m) thick. <u>Chafee Group, Dyer Dolomite</u> (Mississippian- Devonian): Yellow- gray cherty dolomite; 100 ft (30 m) thick. <u>Chafee Group, Parting Quartzite</u> (Mississippian- Devonian): Gray, massive quartzite and dolomite; 50 ft (15 m) thick. <u>Fremont Dolomite</u> (Upper Ordovician): Dark- gray, coarsely crystalline dolomite; 230 ft (70 m) thick.	High	None documented	None documented	Rockfall?	Chert in Dyer Dolomite	None - in Preserve & wilderness	

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Paleontological Resources	Cultural Resources	Hazards	Mineral Resources	Suitability for Development	Other
MIDDLE ORDOVICIAN	Harding Sandstone (Oh)	Pale- red, thin- bedded quartzite; 100 ft (30 m) thick.	High	None documented	None documented	Rockfall?	None documented	None - in Preserve & wilderness	
LOWER ORDOVICIAN	Manitou Limestone (Om)	Dark- gray, fine- grained, cherty dolomitic limestone; 200 ft (60 m) thick.	High	None documented	None documented	Rockfall?	None documented	None - in Preserve & wilderness	
Unconformity									
MIDDLE PROTEROZOIC	Quartz Monzonite (Yqm)	Stock of gray to pink, medium- grained, equigranular, leucocratic, quartz monzonite, N of Willow Creek; 35% plagioclase, 30% microcline, 30 % quartz, 2%- 5% biotite & magnetite; locally small pegmatite dikes; extensively altered to chlorite, epidote, & muscovite; located along the Sangre de Cristo fault near Crestone; 1.45 billion years old. Vein quartz (Yqmqz)	High	None	None documented	Rockfall?	Microcline, plagioclase feldspar, quartz, biotite, sphene, magnetite	None - in Preserve & wilderness	
Unconformity									
LOWER PROTEROZOIC	Pegmatite (Xp)	Coarse- grained igneous rock; interlocking crystals; composition of granite	High	None	None	None	Feldspar, qtz, muscovite	None- in Preserve & wilderness	High altitude recreational activities (i.e., horse riding, hiking, climbing)
LOWER PROTEROZOIC	Tonalite gneiss (Xto)	White to light- gray- green, buff- weathering; 60% plagioclase, 30% quartz, 8% mafic minerals, 2 % or less potassium feldspar; porphyroblastic with aggregates of mafic minerals as much as 0.6 inches (1.5 cm) across; groundmass grain size generally 3- 4 mm; weak foliation; original mafic minerals thoroughly altered to epidote, chlorite, & muscovite; K- feldspar increases near major faults; contains numerous mafic dikes as much as several tens of feet across; dikes most abundant near contact with metadiorite (Xdi); contact with metadiorite is interlayered & metadiorite xenoliths occur in tonalite gneiss near contact; located near southern end of Sangre de Cristo wilderness area.	Plagioclase will erode faster than quartz	None	None documented	Rockfall?	Plagioclase, quartz, magnetite, apatite, sphene	None - in Preserve & wilderness	
LOWER PROTEROZOIC	Metagabbro (Xg)	Metamorphosed gabbro	High	None	None	Unknown	Unknown	Low	
LOWER PROTEROZOIC	Quartz diorite (Xqd)	Plagioclase, quartz, & hornblende or biotite; accessory apatite, zircon, & opaque oxides.	High	None	None documented	Unknown	Unknown	None - in Preserve & wilderness	
LOWER PROTEROZOIC	Diorite (Xdi)	Dark- green to dark- gray, fine- to medium- grained, seriate to equigranular, locally foliated hornblende diorite; 50- 705 euhedral to subhedral hornblende, 30%- 50% plagioclase, up to 5 % quartz as inclusions in plagioclase; quartz averages about 1% of rock; accessory minerals (about 2% of rock) are magnetite, sphene, & apatite; extensively altered to sericite, chlorite, epidote; locally injected by numerous interconnecting veins of leucocratic biotite granodiorite to tonalite.	Alteration of dark minerals	None	None documented	Unknown	Unknown	None - in Preserve & wilderness	
LOWER PROTEROZOIC	Mafic intrusive rocks (Xm)	Dark gray- green to black, aphanitic to coarse- grained, basaltic & gabbroic dikes & sills; generally massive, locally porphyritic; subequal amounts of plagioclase & hornblende with 5%- 10% opaque minerals; pyroxene- & olivine- bearing varieties occur locally; nonfoliated; sharp contacts with host rocks; map units may include mafic intrusive rocks of Tertiary age.	Mafic igneous rocks will erode faster than felsic igneous rocks	None	None documented	Unknown	Plagioclase, olivine, augite	None - in Preserve & wilderness	
LOWER PROTEROZOIC	Quartz Monzonite (of Music Pass) (Xqm)	Gray to pink, coarse- grained, foliated, quartz monzonite porphyry; white to pink, subhedral, microcline phenocrysts 25%- 45%; groundmass is about 60% plagioclase, 20% quartz, 20% biotite, up to 1% sphene and magnetite; foliation locally well developed; boudinage of microcline phenocrysts accompanies increased foliation intensity, particularly near contacts of unit; faulted contacts with Paleozoic sedimentary rocks; intrudes Xgn, Xlgn, & Xq; mafic pods & large mafic xenoliths common locally.	Biotite & feldspars will erode faster than quartz	None	None documented	Unknown	Microcline	None - in Preserve & wilderness	

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Paleo Resources	Cultural Resources	Hazards	Mineral Resources	Suitability for Development	Other
LOWER PROTEROZOIC	Quartzite (Xq)	Black & gray to purple & white, layered quartzite breccia; blocks of layered quartzite range from mm to tens of meters across; matrix is crushed quartzite with minor iron oxide & muscovite; numerous fractures crisscross blocks; 90%- 95% quartz, 3%- 8% opaque minerals, minor muscovite & biotite; opaque minerals include magnetite, specular hematite, earthy hematite; opaque minerals define layers in blocks probably reflecting original bedding; occurs as a narrow, fault-bounded 328- ft (100 m) wide layer between PPNsc & Xqm & as scattered, poorly exposed xenoliths within quartz monzonite.	High	None	None documented	Unknown	Colored quartz	None - in Preserve & wilderness	High altitude recreational activities (i.e., horse riding, hiking, climbing)
	Syenite & Monzonite (Xsm)	Reddish- tan, medium- to coarse- grained porphyry stock; nonfoliated to weakly foliated; subhedral microcline phenocrysts; 50%- 80% microcline, up to 35% plagioclase, 1%- 5% quartz, & up to 10% biotite with minor muscovite, zircon, & sphene; moderate alteration of plagioclase & biotite; fault contact with Paleozoic sedimentary rocks; interlayered with Xgn.	High	None	None documented	Unknown	Microcline	None - in Preserve & wilderness	
	Leucocratic gneiss (Xlgn)	80% of unit white to medium gray, light- pink to light- gray weathering; 30% quartz, 30% microcline; 35 % plagioclase, 4% biotite; variably massive, laminated and layered; foliated; locally migmatitic; locally has porphyroblasts of feldspar up to 2 inches (5 cm); 20% of unit is gray gneiss with composition of granodiorite; 40% plagioclase, 25% quartz, 20% microcline, 15% mafic minerals; original mafic minerals commonly altered to chlorite; complexly interlayered with light- colored gneiss; quartz veins & pods & small pegmatites common.	Biotite & feldspars will erode faster than quartz	None	None documented	Unknown	Quartz, microcline, plagioclase	None - in Preserve & wilderness	
	Hornblende gneiss (Xhgn)	Schistose to massive, fine- to medium- grained quartz- plagioclase- hornblende gneiss; dominantly a well- foliated, laminated gneiss having sharply bounded, continuous, dark- and light- colored layers 1- 5 mm thick.	Hornblende & plagioclase erodes faster than quartz	None	None documented	Unknown	Unknown	None - in Preserve & wilderness	
	Mixed gneiss (Xgn)	Mafic & felsic gneiss & micaceous schist; pink, gray & black; layered, laminated, & foliated; layers discontinuous, rarely traceable more than 0.3 miles (0.5 km); contains leucocratic, biotite- quartz- plagioclase- microcline gneiss & hornblende-bearing varieties of leucocratic gneiss interlayered with mafic quartz- plagioclase-hornblende gneiss; locally includes fine- to coarse- grained, weakly foliated to nonfoliated alaskitic gneiss; all varieties in this unit are extensively altered to chlorite, epidote, & sericite; dikes & sills ranging in composition from aplite & pegmatite to basalt cut the unit; exposed along west side of Sangre de Cristo Range for about 60 miles (100 km).	Dark minerals will erode faster than lighter minerals	None	None documented	Unknown	Unknown	None - in Preserve & wilderness	

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Great Sand Dunes National Park and Preserve and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the present landscape.

Precambrian

During the Early Proterozoic (about 1,800 – 2,000 Ma) (figure 12), erupting volcanoes formed a chain of islands in an ocean south of the edge of the North American craton in Wyoming (Reed et al. 1987; Scott et al. 2001). Like today's volcanic islands in the Pacific Ocean, these Proterozoic islands formed along the margins of converging lithospheric plates. Volcanic rocks, with compositions indicative of continental margin magmatism, and sedimentary rocks are widespread over a 300 mile- wide (500- km) belt in Colorado.

About 1,740 Ma, during a period of compressive mountain building, the rocks were folded into tight, chevron- like folds and metamorphosed to high- grade, metamorphic gneisses in a regional orogeny (mountain-building episode) that culminated with the suturing of Colorado onto the Wyoming province to the north (figure 13) (Hutchinson, 1976; Tweto 1980; Gregson 1992; Scott et al. 2001). This Precambrian orogeny converted the graywacke, arkose, and shale into the migmatitic metasedimentary rocks that are now exposed in the Sangre de Cristo Mountains.

After the end of this first period of compressional tectonics and mountain building, Middle Proterozoic granites (1470- 1390 Ma) intruded into the metamorphic rocks (Hutchinson 1976; Tweto 1980; Gregson 1992). Major faulting and shearing accompanied intrusion and another generation of folds was generated near the shear zones.

Rocks representing the next 1,170 million years were removed by erosion. Erosion cut deeply into the Early Proterozoic rocks, removing miles of the overlying, less metamorphosed rocks, and exposing the highly metamorphosed cores of ancient mountains.

The Pike's Peak Plutonic Event was the last major Precambrian intrusive event in Colorado (Hutchinson 1976; Gregson 1992). During this time (1040- 980 Ma), the Pike's Peak Granite intruded into considerably shallower depth than the 1,750 year- old granites. Restricted to the Pike's Peak area, the Pikes Peak granite may have even breached the surface to form volcanic rocks in places. Rocks representing about 400 million years of Precambrian time following emplacement of the Pikes Peak granite are missing from Colorado (Tweto 1980).

Beginning about 600- to 800 Ma, the tectonic regime in Colorado changed from one of compression to one of extension (Stone 1986; Hoffman 1989; Burchfiel et al. 1992). About 800 Ma, the west coast of North America began to rift apart. With rifting, a new western edge of the continent formed. The Late Proterozoic coastline trended south from what would eventually become northeastern Washington through western Idaho and eastern Oregon into the area occupied by the Sierra Nevada of California today.

Whenever continents begin to break apart, some of the basalt that rises in the rift produces swarms of diabase dikes and sills in the continental crust. Diabase, with the same composition as basalt, is often indicative of continental rifting. The diabase dikes and sills in the Sangre de Cristo Mountains attest to this period of tectonism in Colorado.

Paleozoic Era

Cambrian and Ordovician Periods (542-444 Ma): The Cambrian and Early Ordovician Periods in the western United States were a time of tectonic quiescence (figure 12) (Stewart 1980; Poole et al. 1992). A passive margin developed on the western margin of North America that prevailed until the advent of the Antler Orogeny in the Middle Devonian (figure 14A). Cambrian rocks are not exposed in the park and preserve, and Ordovician strata are mapped together with the Mississippian and Devonian rocks in the digital geologic map on the attached CD.

The dark- gray, fine- grained, cherty, dolomitic marine limestone of the Lower Ordovician Manitou Limestone, like the other Ordovician, Devonian, and Mississippian strata, is exposed in fault slices in the Sangre de Cristo Mountains. An unconformity separates the Manitou Limestone from the underlying Proterozoic rocks.

The Middle Ordovician Harding Sandstone that was metamorphosed to quartzite also is unconformable with underlying Proterozoic gneiss. The metamorphosed marine sandstones represent the initiation of widespread marine submersion in North America (Ross and Tweto 1980; Witzke 1980).

Marine carbonate deposition returned in the Upper Ordovician and is represented by the Fremont Dolomite (Johnson et al. 1989). Following deposition of the Fremont Dolomite, the shoreline along the western margin of the Transcontinental Arch moved westward as a major regressive episode affected Colorado. Regression would continue throughout the Silurian and into the Early Devonian.

The end of the Ordovician Period (444 Ma) is marked by one of the five most extensive mass extinctions recorded in the fossil record (figure 12). Meteor impacts, glaciation, sea level rise, sea level fall, and global warming have all been offered as mechanisms leading to various extinction episodes in the geologic record, but for the Ordovician Period, no definitive explanation has been accepted.

Devonian Period (416-359 Ma): About 100 million years of geologic record, from the Silurian to Upper Devonian, are missing in Great Sand Dunes. By the beginning of the Devonian, the seas that had covered most of the North American continent had receded, or regressed, and the shoreline formed a southwest- northeast trend through west- central Utah and southeastern Nevada. Offshore, a shallow carbonate ramp dipped westward while onshore, extensive tidal flats spread for miles from western Colorado to central Utah. Crustal plate collision along the western margin initiated the Antler Orogeny and the next major transgression in western North America.

Transgressions onto the continent were episodic and rapid. A gradual regression occurred in the late Middle Devonian followed by another transgression in the Upper Devonian (Johnson et al. 1991). The Dyer Dolomite and the Parting Formation in the Sangre de Cristo Mountains represent these episodic transgressions and regressions (Ross and Tweto 1980; Johnson et al. 1989).

Mississippian Period (359-318 Ma): The Lower Mississippian Leadville Limestone in southwestern Colorado is a dark- gray, massive limestone that locally contains limestone breccia (Johnson et al. 1989; Lindsey et al. 1986). In central Colorado in the vicinity of Great Sand Dunes, the formation increases in clastic material.

Although mapped together with Devonian and Ordovician sedimentary rocks, elsewhere the Leadville Limestone is subdivided into three members, in ascending order: Gilman Member, Redcliff Member, and the Castle Butte Member. The Gilman Member, at the base of the Mississippian, is comprised of fine- to- coarse- grained, well rounded, quartz sandstones, sandy dolomite breccias, and limestone- pebble conglomerates. Strata of the Redcliff Member rest unconformably on the Gilman Member with basal limestone- pebble conglomerates and sandstone lenses deposited locally in channels scoured into the underlying Gilman Member at the unconformity (De Voto 1980). Thinly bedded, stromatolitic dolomite mudstones, intraclast wackestone- packstones, and dolomite breccias characterize the Redcliff Member. A solution- erosion unconformity separates the Redcliff Member of the Leadville Limestone from the overlying Castle Butte Member. The unconformity is marked by a breccia soil-rubble zone and by collapse breccia- filled sinkholes and caves indicative of karst topography.

Resting unconformably above the Redcliff, the Castle Butte Member consists dominantly of pelletal, oolitic, and mixed- skeletal grainstones and packstones. The lime mud content in the grain- supported rocks generally decreases upward in the section. With uplift and subaerial exposure of these carbonate rocks during the Middle and Upper Mississippian, solution erosion developed a karst topography on the top of the Castle Butte Member strata similar to the paleo- karst topography marking the top of the Redcliff Member (De Voto 1980).

The Lower Mississippian Leadville Limestone represents the final transgressive pulse of the Antler Orogeny (figure 14B). As the highlands to the west were thrust above sea level at the beginning of the Mississippian, warm marine water spread over eastern Utah giving rise to an extensive carbonate platform. Transgression continued in the Lower Mississippian, and the shoreline encroached into western Colorado, forming intertidal and restricted subtidal environments. Stromatolitic dolomite and carbonate mudstones, pelletal packstones, and wackestones in the lower member of the Leadville Limestone in southwestern Colorado represent these shallow marine environments (De Voto 1980). In the Great Sand Dunes region, the sandstones in the Gilman Member may have been derived from erosion of the subaerially exposed, Devonian Chaffee Formation. The carbonate mudstones and dolomite of the Redcliff Member indicate shallow, restricted- circulation, subtidal environments as the transgression spread into central Colorado (De Voto 1980).

The sea transgressed into central Colorado one more time in the Middle Mississippian (Castle Butte Member of the Leadville Limestone). High- energy, shoal- water, oolite banks developed on topographic- structurally high areas while open- circulation, subtidal environments were created as the sea moved across central Colorado. When the thrust faulting ceased and the orogeny came to an end in the Middle Mississippian, the shoreline migrated back westward. As the sea regressed, and the ocean basin between the Antler Highlands and Colorado filled with clastics deposited in deltaic systems, fan- delta systems, alluvial fans and eventually, fluvial systems.

Pennsylvanian Period (318-299 Ma): In south- central Colorado, the Middle Pennsylvanian Minturn Formation can be subdivided into three distinct lithologic facies: a turbidite- bearing facies, a limestone- bearing facies, and a redbed facies (Lindsey et al. 1986). Turbidite deposits characteristically contain many turbidite cycles (density current), which consist of upward- fining subcycles of sandstone, siltstone, and shale. The contact is sharp between the shale of one turbidite cycle and the overlying sandstone or conglomerate of the next cycle.

The turbidite- bearing facies is interpreted to be the result of fluvial- dominated fan delta deposition that migrated seaward onto the sea bottom below the wave base. (Lindsey et al. 1986). A fan delta is an alluvial fan that builds into standing bodies of water. At the time the Great Sand Dunes region was located on the western margin of the central Colorado trough, a depression that developed along the eastern border of the uplifted late Paleozoic Uncompahgre Highland (part of the Ancestral Rocky Mountains). The turbidite- bearing facies is gradational into the overlying limestone- bearing facies.

The limestone- bearing facies consists of shallow marine limestone, shale, siltstone, as well as arkosic sandstone, conglomerate and conglomeratic sandstone. Upward- fining subcycles of arkosic sandstone, siltstone, and shale also are characteristic of this facies (Lindsey et al. 1986). Limestone beds contain marine fossils, oolites, skeletal fragments, and stromatolites along with sedimentary structures such as planar and wavy lamination, ripple cross- lamination, and trough cross- bedding. About 3,200 feet (1,000 m) below the top of the formation is a 980- foot (300 m) thick zone of lenticular biohermal limestone units that extend 4,900 feet (1,500 m) along the strike of the unit. The fossils include crinoid columnals as much as 1 foot (0.3 m) long, brachiopods, bryozoans, phylloid algae, gastropods, pelecypods, rugose corals, fusulinids, and conodonts. Associated with the limestone beds are burrowed sandstone and siltstone units. Interfingering with these deposits are upward- fining cycles of lenticular- bedded, channeled, and cross- bedded conglomerate and sandstone capped by thin intervals of siltstone and shale. Trunks of *Calamites* (horse- tail tree) were found in growth position in some of these clastic deposits.

The limestone- bearing facies of the Minturn Formation is also the result of fan deltas prograding over a sea bottom in the area of the Central Colorado Trough, but in contrast to the turbidite- bearing facies, the limestone- bearing facies represents deposition above wave base (Lindsey et al. 1986). Shallow marine limestone, shale, siltstone, and arkosic sandstone were deposited in the prodelta and interdeltaic regions.

The wide variety of textures and fossil debris in the limestone are the result of shallow marine environments impacted by energy regimes that range from low energy to strongly agitated waves. Conglomerate, conglomeratic sandstone, and sandstone mark the delta front. Sandy foreset beds are the most distinctive feature in delta front sandstone units and formed as small deltas prograded into shallow standing water. Arkosic sandstone, siltstone and shale in upward- fining subcycles represent braided streams. The trunks of *Calamites* in growth position are rooted in shale interpreted as a rare coastal swamp deposit and are engulfed by pebbly sand deposited by braided streams (Lindsey et al. 1986).

Upward- fining cycles of quartzose and arkosic sandstone and siltstone constitute the redbed facies. The assignment of the redbeds to the Minturn Formation is speculative and these deposits have not been studied in detail (Lindsey et al. 1986). The fining- upward cycles in the redbed facies have been interpreted as alluvial deposits, but this hypothesis needs more testing (Lindsey et al. 1986).

Upper Pennsylvanian and Permian Periods (333-251 Ma): The Pennsylvanian and Permian Periods were times of great tectonic upheaval around the globe. All the major landmasses were coming together to form one supercontinent, Pangaea. The paleo- Gulf closed as South America was sutured to the Gulf Coast, Africa and Europe collided with the eastern seaboard to form the Appalachian Mountains, and on the western margin, the Pacific lithospheric plate was subducting beneath the North American continent.

Ripple effects of the South America and North America suturing resulted in the uplift of the Ancestral Rocky Mountains (figure 14C). The Ancestral Rocky Mountains, less extensive than today's Rocky Mountains, are characterized by the Uncompahgre and Front Range Uplifts. In addition to the area of today's Uncompahgre Plateau, the Uncompahgre uplift encompassed the resurgent San Luis uplift to the south- southeast of the Uncompahgre highland and extended into north- central Mexico. Erosion of the Uncompahgre highland and episodic transgressive and regressive episodes are reflected in the Sangre de Cristo Formation.

North of Great Sand Dunes, the undivided Sangre de Cristo Formation is caught up in thrust slices and consists of red arkosic sandstone, conglomeratic sandstone, siltstone, shale, and minor limestone. The strata are arranged in upward- fining alluvial cycles estimated to be 3 to 100 feet (1- 30 m) thick (Lindsey et al. 1986). The sandstone and conglomeratic sandstone are cross- bedded. Ripple marks, cross- laminations, mudcracks, possible raindrop impressions, and burrows formed on the siltstone and shale and support a fluvial mode of deposition. The thin, (3 ft; 1 m) limestone beds are unfossiliferous, fine- grained, nodular to laminated and may be paleosol deposits. Marine limestone beds on Music Creek contain abundant bryozoan fossils typical of Permian and Pennsylvanian strata. An unconformity separates the Sangre de Cristo Formation from the overlying Entrada Sandstone at Loco Hill.

In some areas, the Sangre de Cristo Formation can be divided into two members: 1) a Crestone Conglomerate Member, and 2) a Lower Member. The red conglomerate, conglomeratic sandstone, and minor siltstone and shale of the Crestone Conglomerate Member represents debris flow, mudflow, streamflow, and sheetflow deposits on proximal parts of alluvial fans and are exposed in thrust sheets east of Great Sand Dunes (Johnson et al. 1989). The coarse conglomerate contains boulders, cobbles, and pebbles of Precambrian metamorphic and igneous rocks in a matrix of feldspathic sand and clay. The sandstone is horizontally laminated and cross- bedded. The Crestone Conglomerate Member unconformably overlies Early Proterozoic gneiss near Medano Creek but in other areas, it unconformably overlies the Minturn Formation.

The Lower Member is a red arkosic sandstone, conglomeratic sandstone, siltstone, and shale arranged in fining- upward cycles wherein the coarser conglomeratic sandstones grade upward to finer grained siltstones and shales. Sedimentary structures in the sandstone, siltstone, and shale include cross- bedding, ripple marks, cross- lamination, and mudcracks compatible with distal alluvial fan deposits (Lindsey et al. 1986). The Lower Member is conformable with the underlying Minturn Formation, and in the Horn Peak area, this unit interfingers with the Crestone Conglomerate Member.

The close of the Permian Period brought the third, and most severe, major mass extinction of geologic time (figure 12). Although not as well known as the extinction event that exterminated the dinosaurs at the end of the Mesozoic Era, the Permian extinction was much more extensive. Thousands of species of insects, reptiles, and amphibians died on land. In the oceans, coral formations vanished, as well as many species of snails, urchins, sea lilies, fish, and the once- prolific trilobites.

Mesozoic Era

Triassic Period (251-199 Ma): No Triassic rocks are exposed in the Great Sand Dunes area. During the Triassic, the supercontinent Pangaea reached its greatest size. All the continents had come together to form a single landmass that was located symmetrically about the equator (Dubiel 1994). Most of Colorado was above sea level and experienced nondeposition (Maughan 1980). The extensive epicontential seas that flooded the craton in the Paleozoic were gone. At the time, the Uncompahgre Highlands were still contributing sediment to western Colorado while erosion had created a nearly level plain in southwestern Colorado (Stewart et al. 1972A). Where exposed, continental rocks of the Western Interior form a complex assemblage of alluvial, marsh, lacustrine, playa, and eolian deposits (Stewart et al. 1972B).

Pangaea began to break apart in the Late Triassic and Early Jurassic (about 195 to 216 Ma), and the monsoon climate that characterized the Early Triassic changed as the western North American interior slowly rotated into a position farther north of the Triassic equator. In the Late Triassic, the Colorado Plateau became a desert.

Jurassic Period (199-145 Ma): During the Jurassic, extensive ergs (eolian sand seas) similar to the Sahara and Sahel regions today covered a region that was located about 18 degrees north latitude at the beginning of the Jurassic and about 30- 35 degrees north latitude at the end of the Jurassic (figure 15A) (Kocurek and Dott 1983; Peterson 1994). This is the latitude of the northeast trade wind belt. Most modern hot deserts of the world occur within the trade wind belt and during the Jurassic Period, the climate of the Colorado Plateau appears similar to the modern Western Sahara of Africa.

In the Sahara, the world's largest desert, only 10 percent of the surface is sand- covered. The Arabian Desert, Earth's sandiest desert, is only 30 percent sand- covered. The Jurassic deserts that inundated the Colorado Plateau for roughly 40 million years (not counting the time represented by erosion) contained sand dunes that may be the largest recorded in the history of Earth (Kocurek and Dott 1983). These were ergs that formed on a coastal and inland dune field affecting the present areas of southern Montana, eastern Utah, westernmost Colorado, southwest Colorado, northeastern Arizona, and northwestern New Mexico (Kocurek and Dott 1983; Peterson 1994).

No Early Jurassic strata are exposed in Great Sand Dunes, but the Middle Jurassic Entrada Sandstone is the most widespread of the preserved late Paleozoic and Mesozoic eolianites (wind deposited sandstone) in the western US. Unlike the dunes at Great Sand Dunes, however, the cross- stratified Entrada Sandstone was deposited in an extensive dune field in a back- beach area (Doelling 2000). The Entrada is a thinly- bedded, friable, white to tan quartz sandstone. Typical of eolian deposits, the fine- to medium- grained sandstone is well- sorted and well- rounded. The grains appear translucent or frosted as a result of its eolian origin (Lindsey et al. 1986).

Three marine transgressive- regressive cycles pushed the shoreline back and forth across the northern and northwestern parts of the Western Interior Basin during the Lower and Middle Jurassic Period. As the sea regressed to the north in the Upper Jurassic, the extensive Morrison Formation was deposited across the continental Western United States (figure 15A). World-renowned for its dinosaur fossils, the Morrison is exposed north of Great Sand Dunes in an overturned syncline at Loco Hill (Lindsey et al. 1986). In this area, the Morrison is an interbedded gray and brown shale, gray to brown sandstone, and minor gray, fine- grained limestone that ranges about 164- 230 feet (50- 70 m) thick. It was probably deposited in alluvial and near- shore marine environments.

Cretaceous Period (145-65 Ma): Cretaceous rocks have been eroded from the Great Sand Dunes region. Accelerated lithospheric plate collision in the Cretaceous caused mountains to build along the western margin of North America as the Sevier Orogeny formed a roughly north- south trending thrust belt that is well defined in present- day southern Nevada, central Utah, and western Montana. As the mountains rose in the west, the Gulf of Mexico separating North and South America continued to rift open in the south, and seawater began to move northward into the expanding Western Interior Basin. Marine water also began to transgress from the Arctic region. The Western Interior Seaway became an elongate basin that extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 3,000 miles (4,827 km) (figure 15B) (Kauffman 1977).

West- dipping thrust faults, high- angle reverse faults, and folds exposed in the Sangre de Cristo Mountains date from the Laramide Orogeny (Late Cretaceous to Mid- Tertiary, about 75- 35 Ma) (figure 16) (Lindsey et al. 1986; Kluth 1986). The Creston, Sand Creek, Deadman, and Spread Eagle thrusts displaced Precambrian basement rocks eastward over Paleozoic rocks (typically Pennsylvanian Sangre de Cristo Formation). The

Crestone Thrust is a complex fault zone at least 2,600 feet (800 m) wide. Within the fault zone are slivers of pre- Pennsylvanian sedimentary rocks.

Cenozoic Era

Tertiary Period: A hiatus of approximately 86 million years exists between the Jurassic Morrison Formation and the Eocene (55.8- 33.9 Ma) Blanco Basin Formation. The Blanco Basin Formation (0- 2,280 feet; 0- 696 m thick) is restricted, in the Great Sand Dunes region, to the Monte Vista graben, west of the Alamosa horst (Brister and Gries 1994). The reddish shales, siltstones, and sandstones of the Blanco Basin Formation represent alluvial sediments deposited in the Blanco Basin, a north- northwest trending basin formed sometime in the Paleocene to Eocene due to strike- slip faulting during late Laramide Orogeny (figure 16).

The andesitic lava flows and volcaniclastic rocks of the Conejos Formation (0- 7,550 feet, 0- 2,300 m thick) also are restricted to the western portion of the San Luis Valley. The volcanoclastic rocks and lava flows originated from the active volcanoes in the San Juan volcanic field from 35 to 30 Ma (Brister and Gries 1994).

Ash- flow tuffs (1,250- 1,900 feet, 380- 580 m thick) were deposited over the Conejos Formation in the Monte Vista graben and directly upon Precambrian basement rocks in what is now the Baca graben, east of the Alamosa horst. The ash- flow tuffs mark a tectonic regime change that occurred about 29 Ma. The region of south- central Colorado that had been deformed by compression during the Laramide Orogeny now began to be extended as the area was pulled apart by tectonic forces (Chapin and Cather 1994).

With extension came volcanism and the formation of the San Juan volcanic field. Regional ash- flow sheets were emplaced prior to the rift- related half grabens that would soon develop and fill with sediments. Volcanic rocks may include dark- brown (mafic) olivine basalt flows and flow breccias that are more than 246 feet (75 m) thick and light- gray to white (felsic) sills and dikes of ranging from 3- 26 feet (1- 8 m) to 164 feet (50 m) thick that erupted approximately 26.5 Ma (Lindsey et al. 1986; Bruce and Johnson 1991). The sills and dikes have intruded along thrust and reverse faults in both Paleozoic and Precambrian rocks (Lindsey et al. 1986; Bruce and Johnson 1991).

After the emplacement of the uppermost Oligocene ash- flow tuff, the Rio Grande rift extended northward and the northern part of the San Luis Basin began to split apart (Brister and Gries 1994; Chapin and Cather 1994). In the early stages of rifting, the eastern half of the San Luis Basin (Baca graben) was progressively tilted eastward along the Sangre de Cristo Range.

As the basin opened, streams carried sediments from the San Juan volcanic field and deposited them in alluvial fans much like the alluvial fan that has developed where the Rio Grande River enters the San Luis Valley today. Additional material was supplied to the basin from the Sangre de Cristo Range that was rapidly uplifted about 19 Ma in the Miocene. Shorter, steeper alluvial fans were constructed along the eastern margin of the Baca basin due to episodic movement along the basin- bounding fault. These sediments became the Santa Fe Group, which consists of the Santa Fe Formation and the overlying Alamosa Formation in the Great Sand Dunes area. Santa Fe Group strata are up to 3.5 miles (5.6 km) thick.

The Santa Fe Formation is found throughout the basin in the subsurface and locally, along the basin margin. The stratified volcanic and sedimentary clastics of the Santa Fe Formation came from two primary sources; 1) volcanic debris from the western San Juan volcanic field, and 2) Precambrian granitic and metamorphic rocks and Paleozoic limestones and clastic rocks from the rising Sangre de Cristo Range (Brister and Gries 1994). Sedimentary structures in the formation are indicative of fluvial processes.

The Alamosa Formation overlies the Santa Fe Formation in the subsurface but is not exposed in the Great Sand Dunes region. In the subsurface, the gray, black, and green claystones of the Alamosa Formation are conformable with the underlying beds of the Santa Fe Formation (Brister and Gries 1994). Wells drilled into the Alamosa Formation have uncovered fossil debris including ostracodes, bones, peat, wood fragments, and mollusk shell fragments.

Quaternary Period: Poorly cemented sandstone horizons that can be correlated over broad areas rest at the top of the Alamosa Formation, and these sandstone layers are the primary source of groundwater for irrigation in the San Luis Valley. The formation may be as much as 1,800 feet (550 m) thick. Pleistocene (0.6- 0.9 Ma) fossils of fish, birds, and mammals, along with volcanic ash and fresh- water mollusk shells, have been found at Hanson's Bluff near the town of Alamosa (Brister and Gries 1994). The discovery of methane in the Alamosa Formation helped stimulate intermittent oil and gas drilling in the San Luis Valley (Brister and Gries 1994).

A new round of flood basalts about 4.5 Ma barred the surface drainage from the northern to the southern part of the San Luis Valley. Environments favorable to lake and fluvial sedimentation were created by subsequent internal drainage. The basalts that solidified north of the San Luis Hills horst acted as a hydrologic divide until middle to late Pleistocene (somewhere between 0.69 to 0.3 Ma) when the Rio Grande River eroded a gorge through the basalt (Brister and Gries 1994).

Mapped in the Great Sand Dunes area are two Pleistocene (1.8 to 0.01 Ma) alpine glacial deposits: the Bull Lake glacial deposits and the Pinedale glacial deposits. The rounded crests of the Bull Lake moraines and the weathered surface of Bull Lake boulders suggest that the Bull Lake alluvium, outwash, and till are older than the Pinedale deposits (Meierding and Birkeland

1980). Bull Lake glaciation probably correlates with a major climatic event recorded in deep- sea cores about 130,000 to 150,000 years before present (BP) (Meierding and Birkeland 1980).

In contrast to the Bull Lake glacial deposits, the Pinedale glacial deposits retain many original depositional features (Meierding and Birkeland 1980). Pinedale moraines have steep sides (up to 35 degrees), sharp crests, large aerial extent, and a high frequency of surface boulders. Boulders in the sagebrush zone also appear to be relatively fresher than the Bull Lake boulders. Radiocarbon dates of organic matter between Pinedale tills indicate that the ice margin reached its maximum extent once before 30,000 years BP and three times between 30,000 and 12,000 years BP. Dated lake sediments in the eastern Front Range suggest a maximum stand of Pinedale ice between 23,000 and 21,000 years BP. Pinedale glaciers began receding from their outermost position in the Front Range about 14,000 years ago and retreated to the cirques by at least 10,000 years BP (Meierding and Birkeland 1980).

Glacial erosion formed a large debris fan where the Rio Grande River flowed out of the San Juan Mountains into the San Louis Valley. The Rio Grande flowed eastward into a large lake in the valley, the remnant of which remains as San Luis Lake. San Luis Lake still occupies the enclosed basin in the northern part of the valley. In the area of San Luis Lakes, the Rio Grande took a sharp 90 degree turn to the south. Since the Pleistocene, the river has gradually migrated to the southwest forming its present, gently curved channel.

About 12,000 years ago, the large valley glaciers in the mountains began to recede and the cooler, wetter climate that had prevailed in the San Luis Valley gradually became the arid climate of the valley today. The abundant vegetation disappeared and the prevailing southwest winds, blowing from 15 mph (24 km/hr) to 60 mph (97 km/hr), began moving sand across the valley floor to the eastern edge of the valley where the Sangre de Cristo Mountains formed a sand trap for the high altitude eolian deposits (Johnson 1967; Kiver and Harris 1999).

Alluvium, alluvial fan deposits, landslides, and rockfalls contribute to other Holocene deposits adjacent to the dune field and in the Sangre de Cristo Mountains. Sand, gravel, and clay deposited by streams compose the alluvium deposits and include both Holocene and Pleistocene stream deposits. Spread along the west side of the Sangre de Cristo Mountains, these deposits form alluvial fans. Landslide deposits form hummocky topography underlain by angular rock debris. These deposits may be as much as 100 feet (30 m) thick and differ from rockfall deposits in that rockfall deposits consist of the talus that accumulates at the base of large outcrops and cliffs (Lindsey et al. 1986; Johnson et al. 1989; Bruce and Johnson 1991).

Eon	Era	Period	Epoch	Ma		Life Forms	N. American Tectonics
Phanerozoic (Phaneros = "evident"; zoic = "life")	Cenozoic	Quaternary	Recent, or Holocene	0.01	Age of Mammals	Modern man	Cascade volcanoes
			Pleistocene	1.8		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary	Pliocene	5.3		Large carnivores	Uplift of Sierra Nevada
			Miocene	23.0		Whales and apes	Linking of N. & S. America
			Oligocene	33.9			Basin-and-Range Extension
			Eocene	55.8		Early primates	Laramide orogeny ends (West)
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	**Mass extinctions** Placental mammals Early flowering plants	Laramide orogeny (West) Sevier orogeny (West) Nevadan orogeny (West)
		Jurassic		199.6		First mammals Flying reptiles	Elko orogeny (West) Breakup of Pangea begins
		Triassic		251		First dinosaurs	Sonoma orogeny (West)
	Paleozoic	Permian		299	Age of Amphibians	**Mass extinctions** Coal-forming forests diminish	Super continent Pangea intact Ouachita orogeny (South) Alleghenian (Appalachian) orogeny (East) Ancestral Rocky Mts. (West)
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant	
		Mississippian		359.2		Variety of insects First amphibians First reptiles	Antler orogeny (West)
		Devonian		416	Fishes	**Mass extinctions** First forests (evergreens)	Acadian orogeny (East-NE)
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	**Mass extinctions** First primitive fish Trilobite maximum Rise of corals	Taconic orogeny (NE)
		Cambrian		542		Early shelled organisms	Avalonian orogeny (NE) Extensive oceans cover most of N.America
Proterozoic ("Early life")		Precambrian		2500		1st multicelled organisms Jellyfish fossil (670Ma)	Formation of early supercontinent First iron deposits Abundant carbonate rocks
Archean ("Ancient")				~3600		Early bacteria & algae	Oldest known Earth rocks (~3.93 billion years ago)
Hadean ("Beneath the Earth")				4600		Origin of life?	Oldest moon rocks (4-4.6 billion years ago) Earth's crust being formed
						Formation of the Earth	

Figure 12. Geologic time scale; adapted from the U.S. Geological Survey and International Commission on Stratigraphy. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

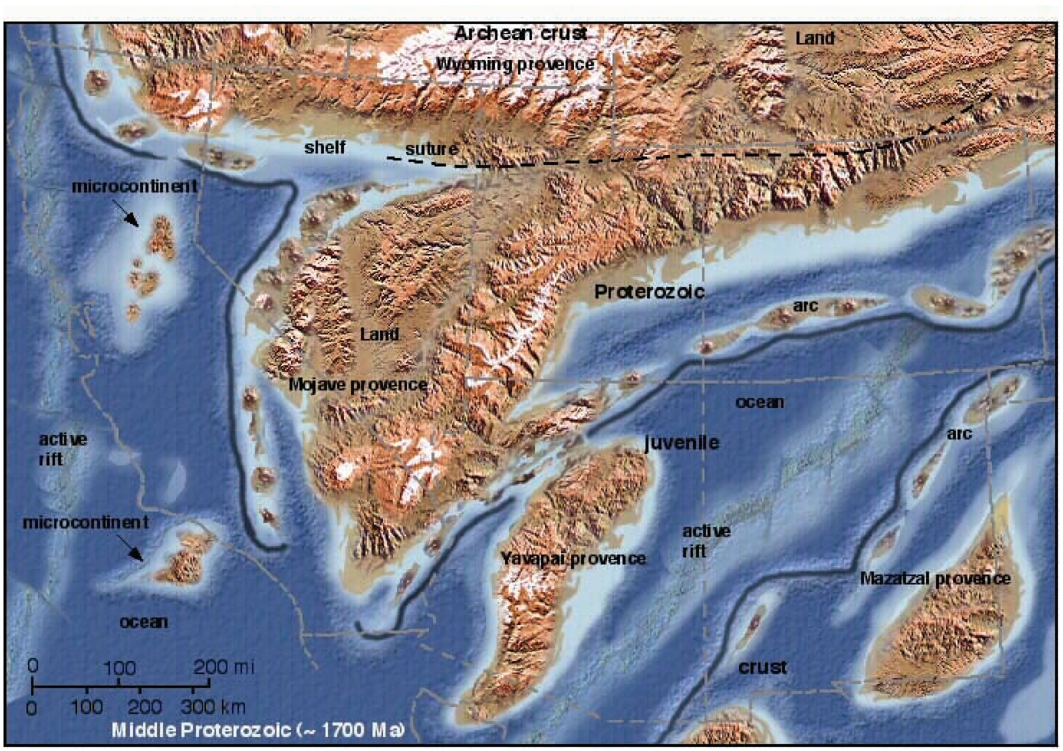
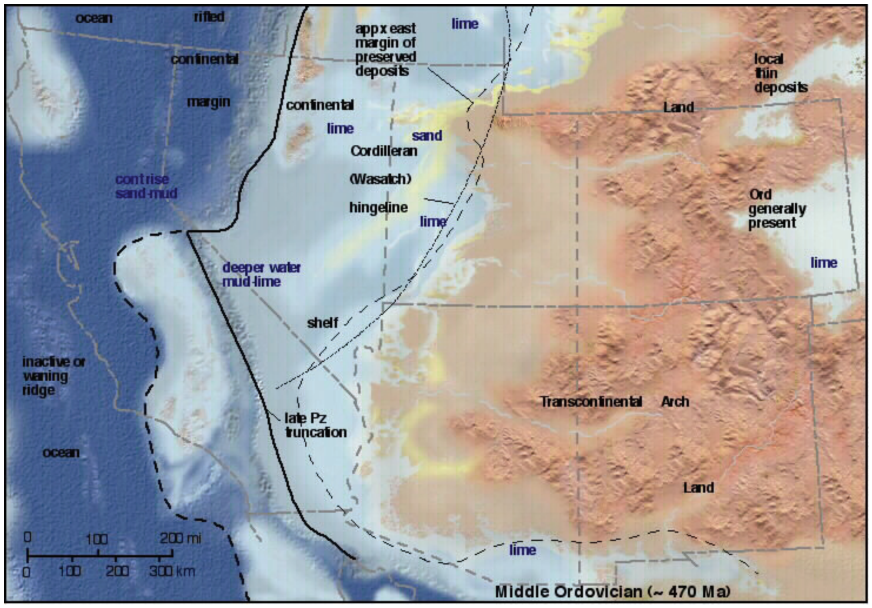
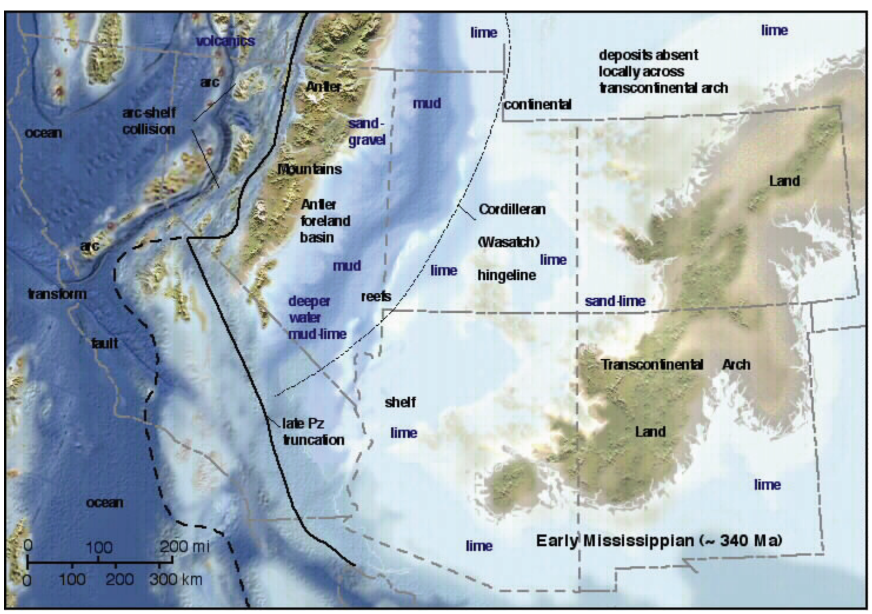


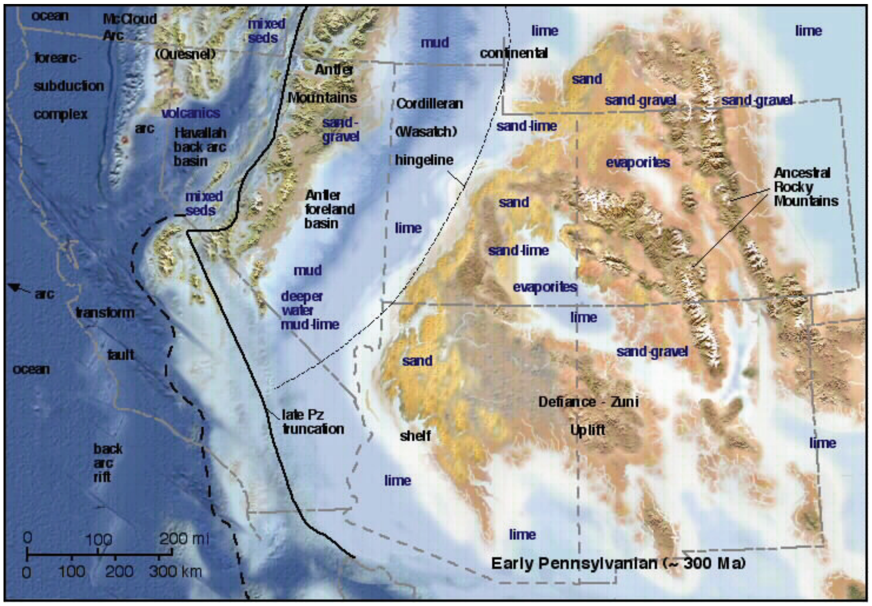
Figure 13. Speculative Paleogeographic map of the southwestern United States during the Middle Proterozoic, about 1700 Ma. Map courtesy of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/~rcb7/pcpaleo.html.



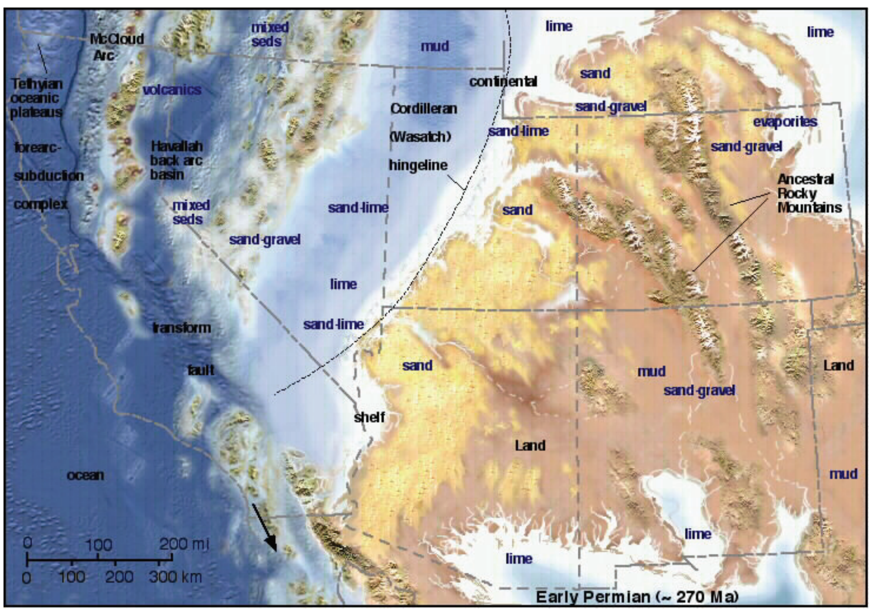
14 A. Middle Ordovician, about 470 Ma. Western North America was a passive tectonic margin.



14 B. Early Mississippian, about 340 Ma. Western North America was an active tectonic margin (Antler Orogeny).

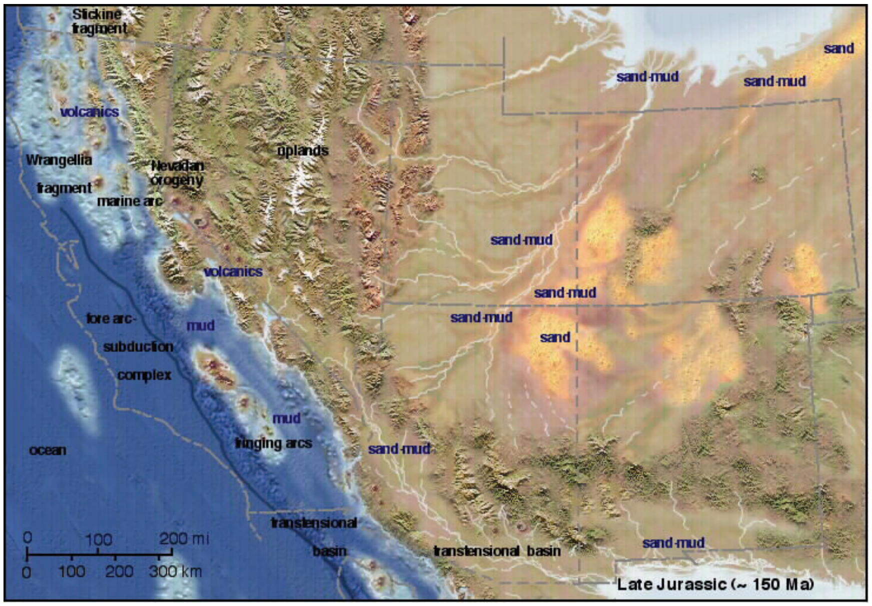


14 C. Early Pennsylvanian, about 300 Ma. Tectonic collisions between North and South America results in the Colorado Orogeny and the rise of the Ancestral Rocky Mountains in Colorado.



14 D. Early Permian, about 270 Ma. The Ancestral Rocky Mountains still supply sediment to the Great Sand Dunes vicinity.

Figure 14. Some time slices of Paleozoic paleogeography of the southwestern United States. A) Middle Ordovician. The Cambrian depositional and tectonic patterns continue. An oceanic arc approaches from the west. The ocean off western North America subducts below the arc, and the arc closes in on the North America coast. B) Early Mississippian. The colliding Antler arc emplaces strata deposited in deep water over the continental shelf to form the Antler Orogeny. The weight of the thickened crust causes eastern Nevada and western Utah to subside. Farther east a broad carbonate shelf blankets much of the Western Interior C) Early Pennsylvanian. The Ancestral Rockies rise across the southern Western Interior. The Antler Mountains are already being worn down by erosion and even begin subsiding in some areas. A marine basin covers most of western Utah and eastern Nevada. D) Early Permian. Parts of the Ancestral Rockies remain high and shed sediments into adjacent basins. Maps courtesy of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/~rcb7/pcpaleo.html.



15 A. Late Jurassic, about 150 Ma, paleogeographic map of the southwestern United States.

15 B. Late Cretaceous, about 75 Ma, paleogeographic map of the southwestern United States.

Figure 15. Some time slices of Mesozoic paleogeography of the southwestern United States. A) Late Jurassic paleogeography. The Morrison fluvial system expands eastward across the Western Interior. The Nevada Orogeny begins in the west. B) Late Cretaceous paleogeography. The Western Interior seaway slowly retreated to the northeast. Some of the World's greatest dinosaur remains are found in these deposits. The Sevier Orogeny along the western margin of North America was at its climax. Maps courtesy of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/~rcb7/pcpaleo.html.

Figure 16. Early Tertiary (Eocene), about 50 Ma at the end of the Laramide Orogeny. As the Rocky Mountains were uplifted, basins formed and subsided between major uplifts. Huge lakes filled the basins during the Eocene. Although the lakes were in basins, paleobotanical data suggests that their absolute elevation was near the current elevation of the deposits. This fact suggests that much of the Rocky Mountain region and the Colorado Plateau were uplifted in the Eocene. Mountainous terrain existed in Nevada, western Utah, and central and southern Arizona. Streams drained these uplands onto the Colorado Plateau and probably into the lakes. Map courtesy of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/~rcb7/pcpaleo.html.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit http://wrgis.wr.usgs.gov/docs/parks/misc/glossarya.html.

active margin. A continental margin where significant volcanic and earthquake activity occurs; commonly a convergent plate margin.
alluvial fan. A fan- shaped deposit of sediment that accumulates where a high gradient stream flows out of a mountain front into an area of lesser gradient such as a valley.
barchan dune. A crescent- shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of the inland desert regions.
baseflow. Stream flow supported by groundwater flow from adjacent rock, sediment, or soil.
baselevel. 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 the rocks of interest.
basin (structural). A doubly- plunging syncline in which rocks dip inward from all sides (also see dome).
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
batholith. A massive, discordant pluton, greater than 100 km^2, (39.6 mi^2) often formed from multiple intrusions.
breccia. A coarse- grained, generally unsorted, sedimentary rock consisting of cemented angular clasts.
clastic. Rock or sediment made of fragments or pre-existing rocks.
chlotitoid. A greenish mica- like mineral
climbing dune. A dune formed by the wind piling sand against a mountain slope.
craton. The relatively old and geologically stable interior of a continent (also see continental shield).
cross-bedding. Uniform to highly- varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions.
debris flow. A rapid and often sudden flow or slide of rock and soil material involving a wide range of types and sizes.
delta. A sediment wedge deposited at a stream's mouth where it flows into a lake or sea.
dike. A tabular, discordant igneous intrusion.
dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include the *barchan dune*, *longitudinal dune*, *parabolic dune*, and *transverse dune* (see respective listings).
eolian. Formed, eroded, or deposited by or related to the action of the wind.
evaporite. Chemically precipitated mineral(s) formed by the evaporation of solute- rich water under restricted conditions.
fan delta. An alluvial fan that builds into a standing body of water. The landform differs from a delta in that a fan- delta is next to a highland and typically forms at an active margin.
graben. A down- dropped structural block bounded by steeply- dipping, normal faults (also see horst).
horst. An uplifted structural block bounded by high-angle normal faults.
island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.
lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.
landslide. Any process or landform resulting from rapid mass movement under relatively dry conditions.
longitudinal dunes. Dunes elongated parallel to the direction of wind flow.
migmatite. Literally, "mixed rock" with both igneous and metamorphic characteristics due to partial melting during metamorphism.
mylonite. A fine- grained rock form in shear zones composed of pulverized rock.
orogeny. A mountain- building event, particularly a well-recognized event in the geological past (e.g. the Laramide orogeny).
packstone. A sedimentary carbonate rock composed of self- supporting granular material (wackestone).
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic Periods (also see Laurasia and Gondwana).
parabolic dunes. Crescent- shaped dunes with horns or arms that point upwind.
passive margin. A tectonically quiet continental margin indicated by little volcanic or seismic activity.
pluvial lakes. Lakes formed during earlier times of more abundant precipitation.
prodelta. The part of a delta below the level of wave erosion.
progradation. The seaward building of land area due to sedimentary deposition.
red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric oxide (hematite) coating individual grains.
regression. A long- term seaward retreat of the shoreline or relative fall of sea level.
ripple marks. The undulating, subparallel, usually small-scale, ridge pattern formed on sediment by the flow of wind or water.
reversing dune. A dune form by wind from variable (often opposite) directions.

sabkha. A coastal environment in an arid climate where evaporation rates are high. The term is also applied to interior flat areas where, from either deflation or evaporation, saline minerals are present (salt flat).

suture. The linear zone where two continental landmasses become joined due to subduction.

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

transverse dunes. Dunes elongated perpendicular to the prevailing wind direction. The leeward slope stands at or near the angle of repose of sand whereas the windward slope is comparatively gentle.

turbidite. A sedimentary rock fromed by a turbidity current,

turbidity current. A swift current laden with suspended sediment.

unconformity. A surface within sedimentary strata that marks a prolonged period of nondeposition or erosion.

wackestone. A mud- supported sedimentary carbonate rock (packstone).

References

This section provides a listing of references cited in this report. A more complete geologic bibliography is available and can be obtained through the NPS Geologic Resources Division.

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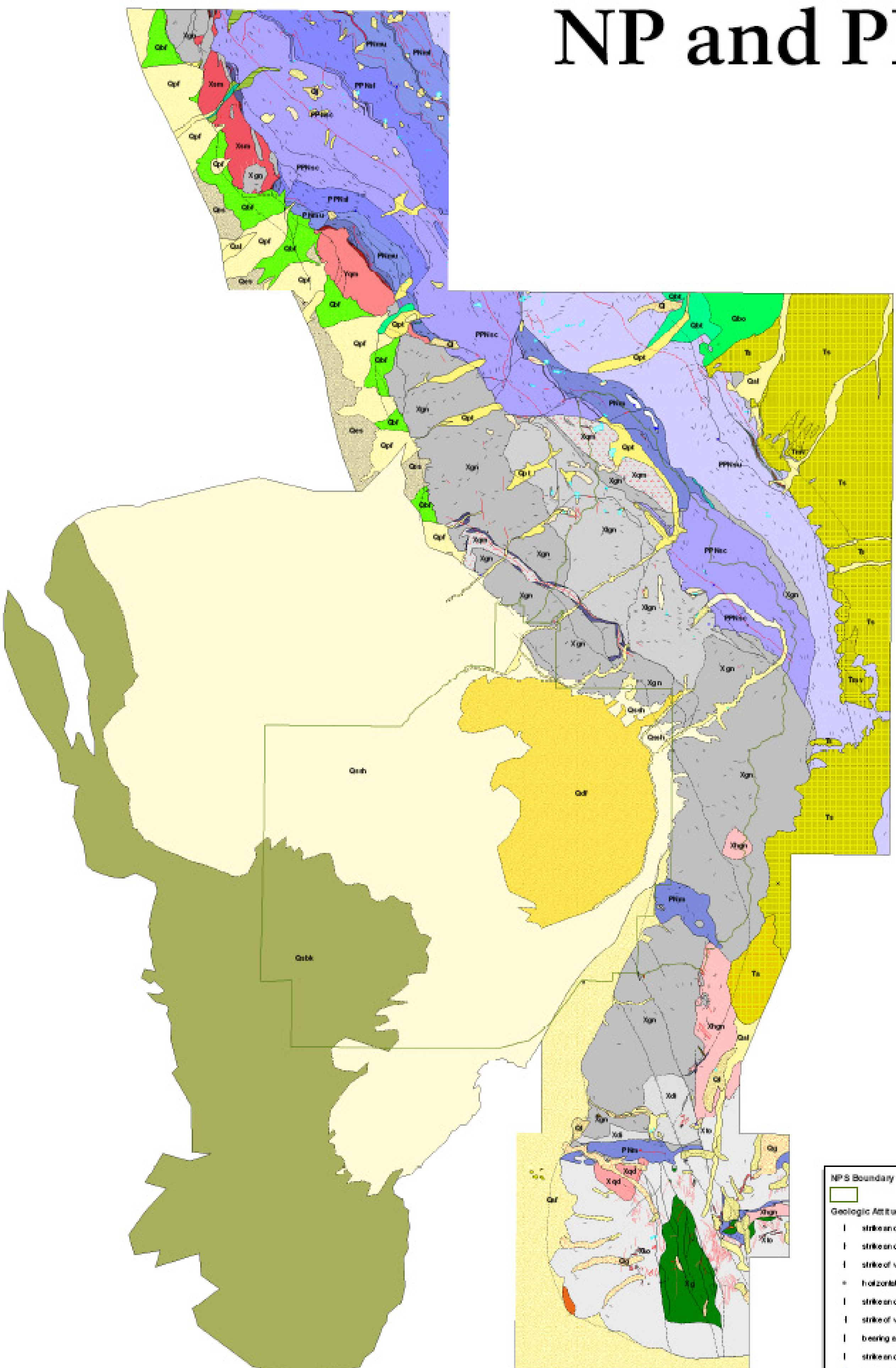
Appendix A: Geologic Map Graphic

The following page provides a preview or "snapshot" of the geologic map for Great Sand Dunes National Park and Preserve. For a poster size PDF of this map or for digital geologic map data, please see the included CD or visit the GRE publications webpage: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

Geologic Map of Great Sand Dunes NP and PRES



Geologic Units

- Qal - alluvium
- Qaf - alluvial-fan deposits
- Qes - eolian sand
- Qdf - dunefield
- Qsh - sand sheet
- Qsbk - sabkha
- Ql - landslide deposits
- Qrf - rockfall deposits
- Qrg - rock-glacier deposits
- Qpu - Pinedale glacial deposits, undifferentiated
- Qpf - Pinedale fan alluvium
- Qpl - Pinedale lacustrine clay
- Qpo - Pinedale outwash
- Qpt - Pinedale till
- Qpbu - Pinedale and Bull Lake glacial deposits, undifferentiated
- Qbf - Bull Lake fan alluvium
- Qbo - Bull Lake outwash
- Qbo2 - Bull Lake young outwash
- Qbt - Bull Lake till
- Qbt2 - Bull Lake young till
- Ts - Santa Fe Formation
- Tgr - granite and granodiorite
- Ta - andesite
- Tmv - mafic volcanic rocks
- Tf - felsic dikes
- Tm - mafic dikes
- Jm - Morrison Formation
- Je - Entrada Sandstone
- PPNsu - Sangre de Cristo Formation (undivided)
- PPNsc - Sangre de Cristo Formation, Crestone Member
- PPNscd - Sangre de Cristo Formation, Crestone Member
- PPNsl - Sangre de Cristo Formation, Lower Member
- PNm - Minturn Formation
- PNmu - Minturn Formation, upper part
- PNmumls - Minturn Formation, marker limestone
- PNmcls - Minturn Formation, crinoidal silty limestone
- PNmush - Minturn Formation, shale and siltstone member
- PNmols - Minturn Formation, oolite limestone
- PNmt - Minturn Formation, Main turbidite member
- PNmbls - Minturn Formation, biohermal limestone unit
- PNml - Minturn Formation, lower part
- PNmq - Minturn Formation, quartzose red-beds
- MDOr - Mississippian, Devonian and Ordovician Sed Rocks
- Oh - Harding Sandstone
- Om - Manitou Limestone
- Yqm - Quartz Monzonite
- Yqmqz - Quartz Monzonite, vein quartz
- Xp - pegmatite
- Xto - tonalite gneiss
- Xg - metagabbro
- Xqd - quartz diorite
- Xdi - diorite
- Xm - mafic intrusive rocks
- Xqm - quartz monzonite
- Xq - quartzite
- Xsm - syenite and monzonite
- Xlgn - leucocratic gniess
- Xhgn - hornblende gneiss
- Xgn - mixed gneiss
- WATER

NPS Boundary

Geologic Attitude and Observation Points

- strike and dip of beds
- strike and dip of overturned beds
- strike of vertical beds
- horizontal beds
- strike and dip of foliation
- strike of vertical foliation
- bearing and plunge of lineation
- strike and dip of cleavage
- fold plunge arrow head
- dip of fault plane
- upthrown side of fault
- downthrown side of fault
- monocline
- anticline
- syncline
- overturned anticline
- overturned syncline
- monocline, anticlinal bend

Age Date Points

- paleontological

Mine Point Features

- Prospect
- Adit
- Gravel Pit

Folds

- known location
- approximate location
- concealed

Faults

- known location
- approximate location
- concealed location

Linear Geologic Units

- PNmumls - Minturn Formation, marker limestone
- PNmcls - Minturn Formation, crinoidal silty limestone
- PNmubls - Minturn Formation, brown weathering limestone
- PNmupals - Minturn Formation, phylloids algal limestone
- PNmols - Minturn Formation, oolite limestone

Linear Dike Units

- Tf - felsic dike,
- Tm - mafic rock dike
- Yqmqz - vein quartz
- Xp - pegmatite dike
- Xm - mafic intrusives

Geologic Contacts

- known
- approximate
- approximate, queried
- map boundary
- shoreline

N
W E
S

0 3 6 12 Miles

0 5 10 20 Kilometers

The original maps digitized by NPS staff to create this product were:

Lindsey, David A., Soulliere, Sandra J., Hafner, Katrin,, and Flores, R.J., 1985, Geologic Map of Rito Alto Peak and Northeastern part of Mirage Quadrangles, Custer and Saguache Counties, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1787, scale 1:24,000 .

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Digital geologic data and cross sections for Great Sand Dunes National Park and Preserve, and all other digital geologic data prepared as part of the Geologic Resources Divisions Geologic Resource Evaluation program, are available online:
http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

Produced by Geologic Resources Division

February 2006

Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Great Sand Dunes National Park and Preserve. The scoping meeting occurred on August 21, 1998, therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

Notes from the field: Geologic Resources Inventory, Great Sand Dunes National Monument, CO

Date: August 21, 1998

Geology Workshop Report
Bruce Heise
Geologic Resources Division

Summary

Field Trip: Park resource specialist Andrew Valdez led NRPC staff on an afternoon field trip explaining the park's geology and identifying resource concerns and ongoing research. The sand that makes up the dunes is the primary resource of the park. The sand is constantly recycled as it is caught up in a complex cycle of winds alternately crossing the San Luis Valley to the west and the Sangre de Cristo Range to the east. Maintaining that cycle is essential to the preservation of the dunes. There are three geologic components to the park and dune system; a stable sand sheet surrounding the dunes; the active dune fields, and a sabka system (internally drained evaporative basin) to the west of the park. There are some xxx square miles of dunes in the field, of which xx square miles are in the park. Additionally, there are metamorphic crystalline rocks exposed in the northeast corner of the park, which, while having no impact on the dunes, none the less represent a significant geologic feature. We observed sites where the sand lapped onto the bedrock as well as onto alluvial fans extending from the mountain front.

Research: Sand traps identify the provenance of the sand and the effect varying levels of vegetation have on dune stabilization and motion. NRPP money funding for study?

Re- establishing abandoned USGS gauging stations at several of the creeks leading down off the mountain. Early 90s research revealed that the sand sheet west of the park provided a critical element in the sand cycle. Maintaining that sand sheet west of the park was critical to dune preservation.

There is ongoing research in the region related to an anticipated proposal to mine the ground water of the San Luis valley

Resource Concerns

In the early 1990s a proposal was put forth to mine the extensive ground water resources of the San Luis Valley. The park was concerned about the effect this would have on the dunes and the sand cycle. The local agriculture community was equally concerned about the impact on their irrigation source. Although that proposal was defeated, a similar one is anticipated in the near future. There will be significant state involvement in any future proposal.

RMP statements

Acquire MF maps from USGS multiple copies for park, I&M, GRD.

Talk to NRCS about soils mapping in Great Sand Dunes (and other CO parks) for status, including digital.

FAQ

- How old,
- How thick,
- How tall,
- Where do they come from,
- Are they changing?

Cannot answer age, have a minimum thickness of 710 + 130 well depth, height is 710 max, some changing/motion,

Coop sales data

- Geol Map of Colorado Hwy map – 127
- So. Rockies Hwy Map 60

Jim McCalpin:

Our Index Map indicates MF 2089, question about mapping extent, maps done in support of SdC wilderness Two new references: add to list.

Digital map use:

- General public – cobble together existing maps and pull out a compilation
- Best situation would be to dedicate a specific map a la ROMO
- State mapping projects probably of limited interest – no hazards in large population areas

Hazards

- VC on fault scarps,
- Campground location possible on landslide/debris flow,
- No interest shown by USGS on McCalpin proposal to investigate SdC fault for potential active status

Adams State: senior projects possible for mapping, break out Precambrian units.
CSM seismic work report available.
CGS study by Kirkham (sp) on seismic hazards for area?
Georef doesn't appear to be capturing PhD dissertations.
I-1594 displays fault lines taken from McCalpin map.

Recommended compilation pieces:

- Bedrock from two MF 2089, 2168
- Surficial from I 1594
- Dunes from 575- C
- Units would be the three sand units: active dunes, sand sheet, sabka
- There is flexibility to allow a GIS theme for the different units,
- General belief is that a popular publication, including a map showing informal units, would be popular and worthwhile for interp

Issues

1. Date the dunes: USGS lab closed, need funding, samples remain with USGS, cost about $600/sample,

Scientific investigations Water Resource Research Report

1. Surface shaking, earthquake issues, water tanks, pipelines – most facilities in the vicinity of fault lines, tie down to mapping
2. Ground water relation to faulting – 1976 thesis showing faults acting a barrier to ground water passage, another reason to study faults
3. May require another more complete map of faulting
4. Differentiate paleo fluvial channels within park – link to global warming studies, there is existing climatic history of dunes (also human history, hydrology history)
5. Depth to bedrock – major basin fault located west of major dune field, seismic in 1995? paper on Rio Grande rift, drilling for depth this next fiscal year, to confining layer then just below, maybe to 300 feet
6. Fryeberger issues – preservation of sand sheet critical to dune preservation – grazing of veg on sand sheet and its impacts on dunes
7. Water withdrawal – impacts on sabka
8. Main concern is with water QUANTITIES, wind and shape of mountain front cannot be managed, emphasis
9. Research into sands, light colored ripples are coarser grained, different mineralogy, is provenance different? Why don't they mix? Different wind regimes?
10. Infiltration of moisture into soil rates: Meteoric water? Ground water? What is vapor phase coming from?
11. Relationship of vegetation on dunes to soil moisture

Interpretive Needs

- Products
- Xbedding post card
- Geologic publications
- Other postcards – xbeds, geol map
- Exhibits
- Sand peel
- Rotating
- In house training document geologic piece of the story. Can we get a copy of this
- Publish proceedings
- Electronic Documents – online
- GSA proceedings from 1996 on San Luis Valley area
- Talk to Bob (Higgins) on including inland dune parks in coastal processes symposium. Bill Wellman, Jane Beyner? Possible initiators. Including academic community
- Report on the park – Andrew would edit/coordinate Possible Mary Mickelsen as author? Using Cooperating org, I&M, GRD project monies
- Additional data coming in – deep well
- Is there Lexam (Tom Watkins geologist) data available

Unique Geologic Features

Surge flows

Disturbed Lands – Steensen

- Some prospect pits and shafts

Hazards and Issues

- Water – from WRD
- Hazards – Jim McCalpin write up from proposal

History of Geologic Exploration in Area

- Human history – Mary
- Possible funding by I&M year end money

Great Sand Dunes National Park and Preserve

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/011
NPS D-71, March 2006

National Park Service

Director • Fran P. Mainella

Natural Resource Stewardship and Science

Associate Director • Michael A. Soukup

Natural Resource Program Center

The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring and Evaluation, and the Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross- cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the national park system.

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