National Park Service
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Natural Resource Program Center

Guadalupe Mountains National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2008/023





THIS PAGE:
Guadalupe Mountains National Park Geologist Gorden Bell shows a group of park visitors a limestone outcrop with hammer and chisel marks from illegal fossil collection. The outcrop is located near Stop 19 on the Permian Reef Trail in Guadalupe Mountains National Park.

ON THE COVER:
View of El Capitan (2,464 m [8,085 ft]) from the Permian Reef Trail in Guadalupe Mountains National Park. El Capitan is the eighth-highest peak in Texas, and is composed of Permian age limestone.

Photos by: Ron Karpilo

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

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Executive Summary

This report accompanies the digital geologic map for Guadalupe Mountains National Park in Texas, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research.

The geology of the Guadalupe Mountains is exceptional, so exceptional that the International Commission on Stratigraphy selected this section of rocks to serve as the standard against which all other rocks of Middle Permian age (270–260 million years ago) are compared. This distinction is a benefit to the National Park Service, supporting its mission, as well as a benefit to the international scientific community. It is also a bonus for backcountry visitors, providing an interesting hiking destination recognized for its geologic uniqueness.

A striking cross section of Middle Permian rocks is exposed at Guadalupe Mountains National Park in McKittrick Canyon (fig. 1). This cross section reveals the world's most extensive and significant Middle Permian limestone—the Permian Reef Complex. This complex of rocks includes not only the reef and forereef that paralleled the Permian shoreline but also backreef deposits between the reef and land and the sediments deposited in the deep waters of the Delaware Sea.

In addition to their scientific significance, the rocks of Guadalupe Mountains National Park are also the foundation for stunning scenery, possibly the most striking feature being the thousand- foot cliff of El Capitan, which is part of the Capitan forereef. The park is also notable for its cave resources, red quartz and white gypsum sand dunes, and flaggy dolomite and limestone. Abundant travertine deposits have helped the caves of the Guadalupe Mountains earn the reputation of being among the most beautiful in the world. The rocks in the park also host eye- catching sedimentary and structural features such as ripple marks, submarine slides, tepee structures, and a plethora of fossils.

Though preserved in time, geologic features are not stagnant. The following processes occur in the park:

- Abandoned Mine Land Mitigation—17 mine openings associated with the abandoned Texas and Calumet Mine in the park have been identified and were mitigated appropriately in the early 1990s. Following closure, routine monitoring and inspection by park staff will ensure the continued integrity of the closures.
- Flood Hazards—Simulations of the 100- year floodplain at Guadalupe Mountains National Park resulted in velocities up to 3.4 m/s (11.1 ft/s). Mass transport of debris in major channels and flash flooding in smaller ephemeral drainages are issues for park planning.
- Mass Wasting—The most prevalent mass- wasting hazard in the park is rockfall, whereby relatively large fragments of rock become detached and fall rapidly downslope. The most hazardous areas are on talus slopes, below cliffs of massive limestone. Factors that could trigger rockfalls are shock waves from distant or nearby earthquakes, repeated freeze- thaw cycles, airplane and vehicular noise and vibrations, high winds, and blasting during construction or mining.
- Seismicity—Study of microearthquakes in Guadalupe Mountains National Park show that this area is not seismically active. Nevertheless, the possibility that a large earthquake will occur at some point in the future cannot be ruled out. In 1995, the nearby Alpine earthquake recorded a magnitude 5.6 on the Richter scale. Significant shocks in the vicinity of the park can be expected to trigger a number of rockfalls.
- Solution Collapse—No solution sinks (sinkholes) are known to exist in the park; however, the nature of the rocks makes the existence of some subsurface cavities probable. Dissolution occurs in areas underlain by highly soluble rock formations, especially gypsum and halite, and to a lesser degree limestone. Removal of consolidated or unconsolidated materials by water solution leads to surface collapse. Hydrologic factors that may cause the solution and removal of material may be natural or anthropogenic.

Other issues of concern include the following:

- Cave Protection—Caves are a significant resource throughout much of the Capitan Reef. There are 27 known caves within Guadalupe Mountains National Park. The regional director approved a cave management plan for the park in 1972. More recently identified threats, such as those related to oil and gas drilling, may impair cave resources and point to the possible need to update the plan.
- Oil and Gas Development—Though oil and gas production is prohibited within Guadalupe Mountains National Park, oil and gas operations outside the boundary may directly impact park resources such as wildlife, vegetation, caves, air and water quality, and aesthetic values, including panoramic views and pervading quiet.
- Paleontological Resources Inventory—Fossil- rich geologic formations underlie approximately 31% of the park's acreage. Investigators have identified more than 500 Permian marine fossil species in the Guadalupe Mountains. Remains of Holocene (now extinct in the area) and Pleistocene amphibians, mammals, reptiles, and birds are also significant in the caves in the park. Neither the National Park Service nor its collaborators have conducted a thorough inventory of the park's paleontological resources.

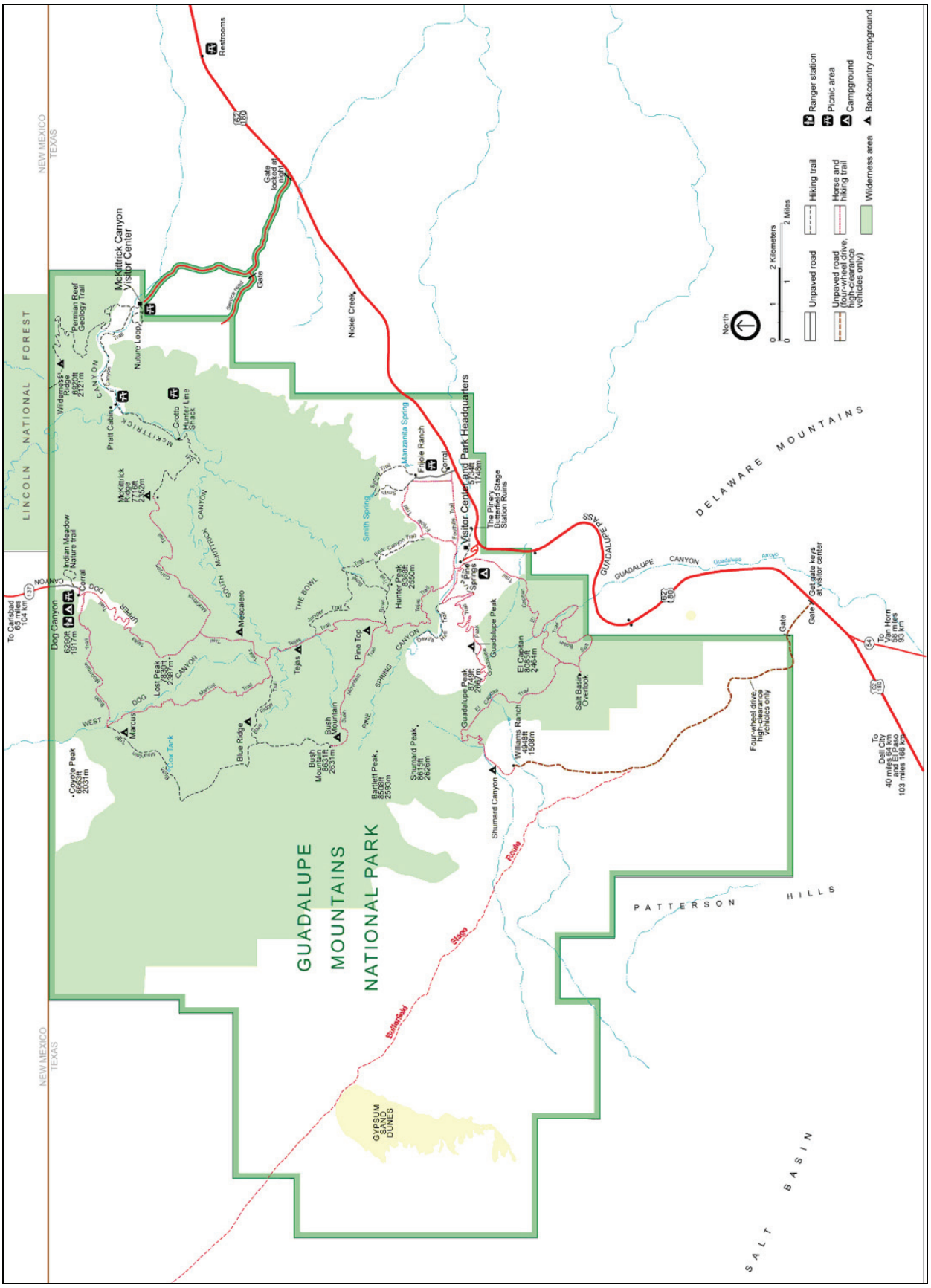


Figure 1. Generalized Map of Guadalupe Mountains National Park, Hudspeth and Culberson Counties, Texas.

Introduction

The following section briefly describes the NPS Geologic Resource Evaluation Program and the regional geologic setting of Guadalupe Mountains National Park.

Purpose of the Geologic Resource Evaluation Program

The Geologic Resource Evaluation (GRE) Program is one of 12 inventories funded under the NPS Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort from the development of digital geologic maps to providing park staff with a geologic report tailored to a park's specific geologic resource issues. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRE team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRE products.

The goal of the GRE Program is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS- 75, Natural Resources Inventory and Monitoring Guideline.

To realize this goal, the GRE team is systematically working towards providing each of the identified 270 natural area parks with a geologic scoping meeting, a digital geologic map, and a geologic report. These products support the stewardship of park resources and are designed for non- geoscientists. During scoping meetings the GRE team brings together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes. Scoping meetings are usually held for individual parks and on occasion for an entire Vital Signs Monitoring Network. The GRE mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their innovative Geographic Information Systems (GIS) Data Model. These digital data sets bring an exciting interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. As a companion to the digital geologic maps, the GRE team prepares a park- specific geologic report that aids in use of the maps and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and up to date GRE contact information please refer to the Geologic Resource Evaluation Web site (http://www2.nature.nps.gov/geology/inventory/).

Establishment of Guadalupe Mountains National Park

The Guadalupe Mountains host the finest example of an ancient fossil reef. The fault- block range displays portions of the world's most extensive and significant Middle Permian limestone, containing one of the most complete Permian marine fossil sequences in the world. So exceptional are the Guadalupe Mountains that the International Commission on Stratigraphy selected this section of rocks (Guadalupian Series) to be the Global Boundary Stratotype Section and Point (GSSP) for Middle Permian age (270–260 million years ago). Geologists from around the globe have studied this world- renowned reef, and it has been traversed by innumerable geology students and visitors.

Largely because of the area's geologic importance, the U.S. Congress authorized Guadalupe Mountains National Park on October 15, 1966, by Public Law 89-667, "to preserve in public ownership an area in the State of Texas possessing outstanding geological values together with scenic and other natural values of great significance" (16 U.S.C. § 283 et seq.). The national park was established on September 30, 1972, and 18,960 ha (46,850 ac) of wilderness was designated on November 10, 1978.

Texas Judge J. C. Hunter was years ahead of his time when, in 1925, he first proposed a park in the area. Hunter purchased land in McKittrick Canyon which he managed as a wildlife preserve. This land was part of the 29,140- ha (72,000- ac) Guadalupe Mountain Ranch, on which he raised sheep, goats, and cattle. Three years after establishment of the park, Hunter's son, J. C. Jr., sold these holdings to the National Park Service at a bargain price of $22 an acre.

The reef, rugged cliffs, wilderness setting, and the highest peak in Texas (Guadalupe Peak) led Wallace Pratt, an oil geologist, to purchase and later donate 2,279 ha (5,632 ac) of land in McKittrick Canyon to the National Park Service in 1959, prior to park authorization. Pratt's donation later formed the nucleus of the new park, and the purchase of the Hunter's land augmented it. The park, including wilderness area, now comprises 34,973 ha (86,416 ac) of mountains, canyons, and desert in western Texas.

Geologic Setting of Guadalupe Mountains National Park

The rocks that make up the Guadalupe Mountains formed in the Delaware Basin during the Permian Period (fig. 2). Sediments were deposited in an inland sea, which covered more than 26,000 km^2 (10,000 mi^2) of Texas and New Mexico at the time. Calcareous sponges, bryozoans, fusulinids, and algae, as well as calcium carbonate that precipitated from the water, built the Capitan Reef in the shallow water near the shore of this sea. In the park the reef forms a wedge pointing southward; El Capitan and Guadalupe Peak are two of its prominent points. The reef grew upward and seaward upon forereef talus broken loose by storms and persistent wave action, as well as upon the skeletal remains of algae and animals that fell or washed off the steep reef face. The south face of the Guadalupe Mountains marks the location of the seaward face of the Capitan Reef. The wide- open landscape was once covered by the deep waters of the Delaware Sea. The portion of the mountains that extends northward from the reef was once the backreef (lagoon and coastal plain).

The reef, which once paralleled the Permian shoreline, today extends across 563 km (350 mi) of western Texas and southeastern New Mexico. The majority of the reef is not exposed above ground, though reef exposures are revealed in canyons and caves throughout the Guadalupe Mountains. The famous caves of Carlsbad Caverns National Park formed within the same reef that is now exposed at the surface in Guadalupe Mountains National Park. The most extensive exposed portion is the 64- km- (40- mi-) long eastern Guadalupe escarpment that stretches northward through Guadalupe Mountains and Carlsbad Caverns National Parks. The reef is also exposed in the Apache Mountains (about 24 km [15 mi]exposed) and Glass Mountains (about 6.4 km [4 mi] exposed) near Van Horn and Alpine, Texas, respectively (fig. 3).

A striking cross section of the Capitan Reef is displayed in the north wall of McKittrick Canyon. The entire 609- m (2,000- ft) height of the reef is visible. By contrast, most canyons north of McKittrick Canyon do not incise deeply enough to expose the lower beds. Regional dip causes the reef to slope down to the northeast until it is completely buried near the city of Carlsbad, New Mexico (fig. 3).

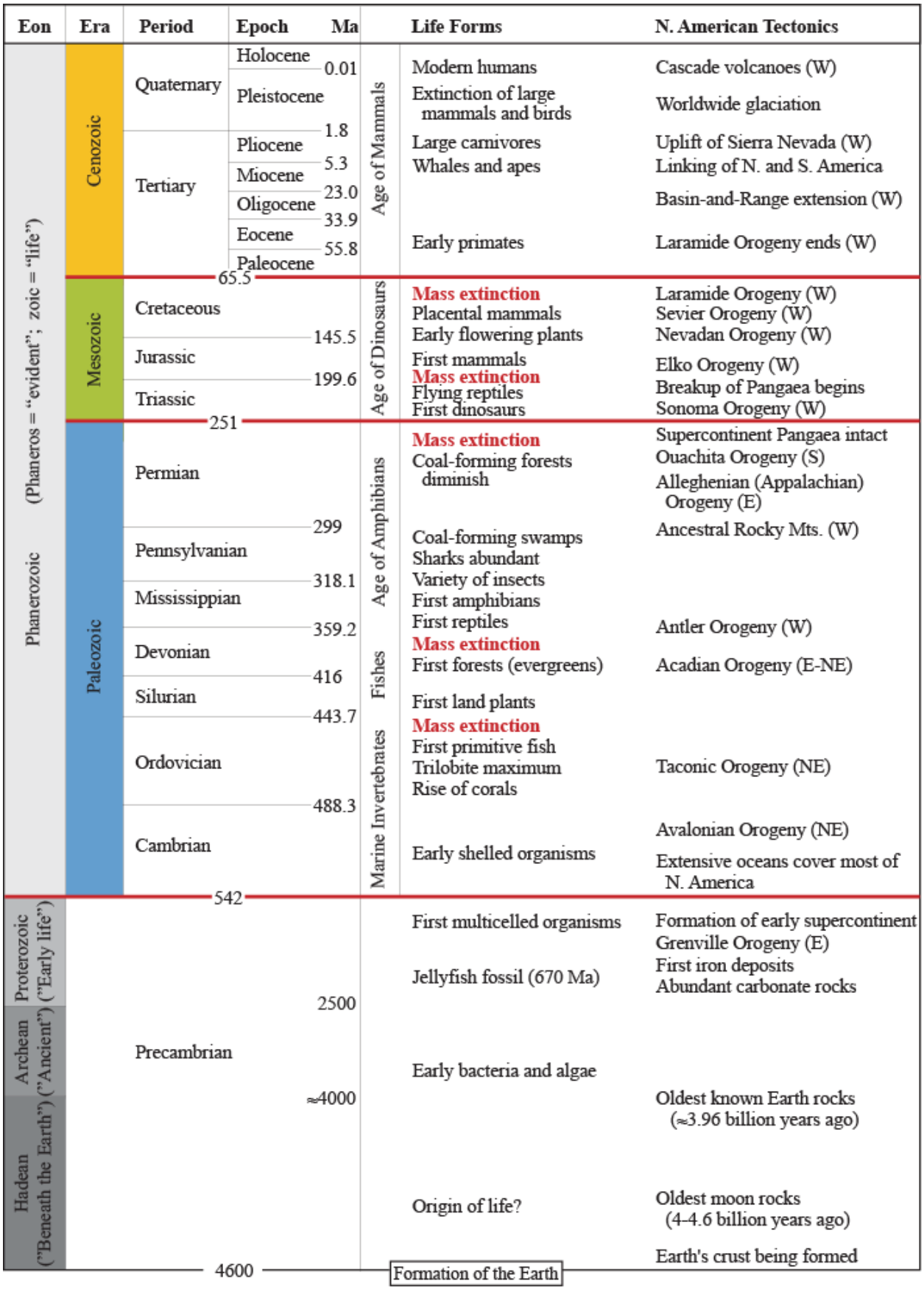


Figure 2. Geologic time scale; adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/). Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

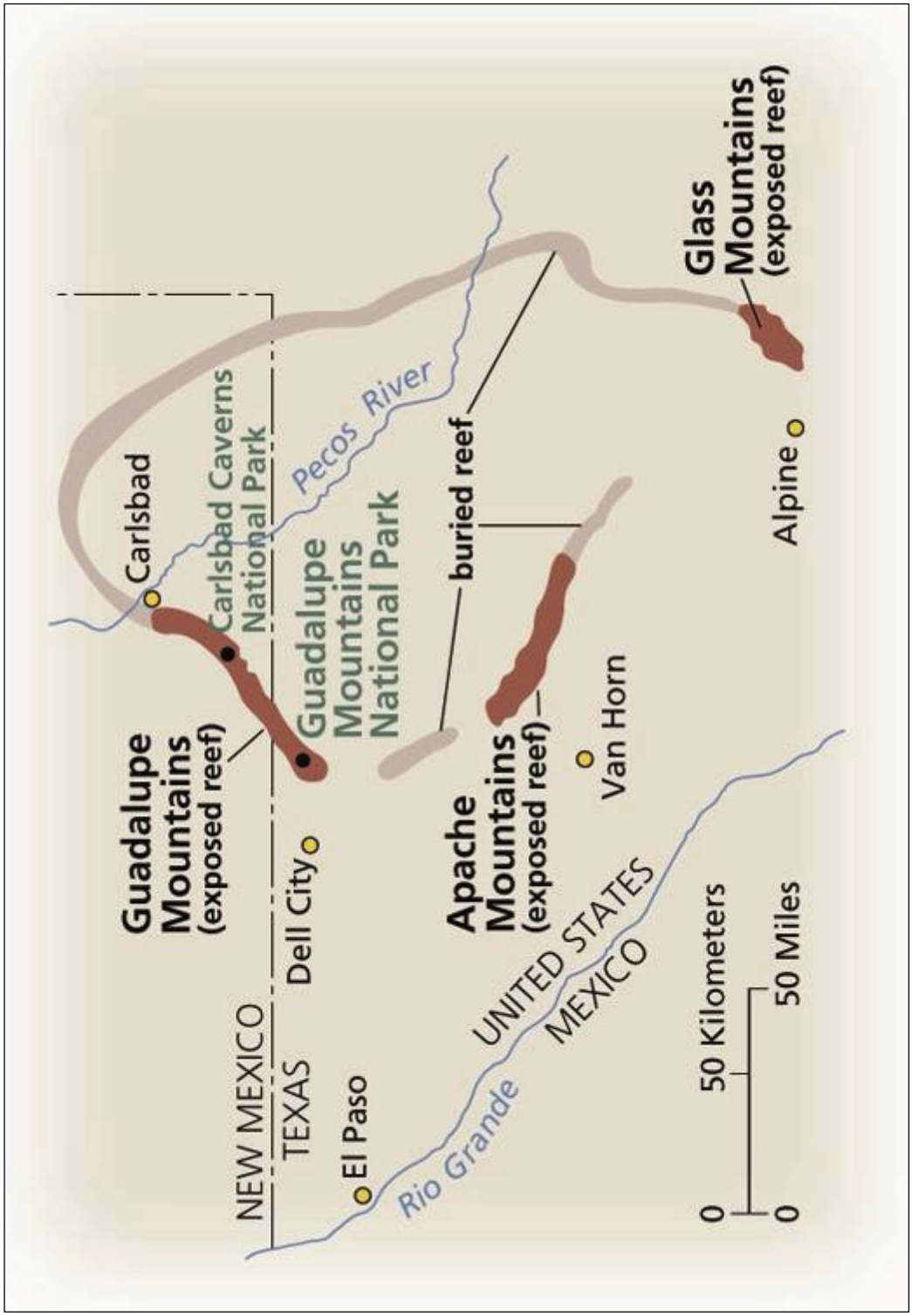


Figure 3. Map of Exposures of the Capitan Reef. The reef, which paralleled the Permian shoreline, extends across 563 km (350 mi) of western Texas and southeastern New Mexico. The majority of the reef is buried. The most extensive exposed portion is the escarpment in Guadalupe Mountains and Carlsbad Caverns National Parks. Other exposed segments occur in the Glass and Apache Mountains. *Source*: http://www.nps.gov/gumo/gumo/geology.htm.

Geologic Issues

On March 6–8, 2001, participants at the Geologic Resources Inventory (GRI) workshop for Guadalupe Mountains National Park addressed the status of geologic mapping and discussed resource management issues and needs. The Geologic Resources Inventory was a precursor to the Geologic Resource Evaluation (GRE) Program. The following section synthesizes the results of the workshop, as well as geologic literature and other NPS documents, highlighting issues that may require attention from resource managers.

The issues that appear in this section are listed in alphabetical order because participants at the workshop in 2001 did not prioritize them. The two issues listed in the workshop summary are (1) geologic hazards and (2) identification of paleontological locations. Additional issues are abandoned mine lands, the protection of cave resources, flood hazards, groundwater exploitation, and oil and gas development adjacent to the park.

Abandoned Mine Land Mitigation

In February 1990, the NPS Land Resources Division, Mining and Minerals Branch (MMB)—predecessor of the Geologic Resources Division—received an inventory of abandoned mine openings and oil wells in the park from staff at Guadalupe Mountains National Park. The inventory included 17 mine openings comprising the Texas and Calumet Mine, and four oil wells (see "Oil and Gas Development" section). Several of these openings presented significant hazards to park visitors and staff. The then Southwest Regional Office, now Intermountian Region, requested that division staff assist the park in inspecting the mines and wells, and help in seeking assistance for mitigation from the Railroad Commission of Texas, which administers funding for abandoned mine land (AML) mitigation and reclamation throughout the state.

The Texas and Calumet Mine operated intermittently from 1891 to 1938; its copper ore bodies were small, and operations ceased when they became uneconomic. The mine area is included on the Guadalupe Peak 7.5- minute USGS topographic quadrangle map on the northeastern flank of Lost Peak. The mine openings and associated waste rock piles are within 3 km (2 mi) of the Dog Canyon Ranger Station in the north- central portion of the park. The Tejas Trail passes within 30 m (100 ft) of seven of the openings. Park and division staff inspected the site in May 1991. The openings inventoried included one shaft (vertical mine working), seven adits (horizontal workings), and two prospects (small workings with minimal development) (table 1). The other seven features listed in the park's inventory were small prospect pits that either were not found during the 1991 fieldwork or required no mitigation (John Burghardt, Geologic Resources Division, written communication, January 12, 2007).

In September 1993, the NPS Southwest Region entered into a cooperative agreement with the Railroad Commission of Texas for closure of abandoned mines on NPS lands in Texas. In early 1996, the Southwest System Support Office (now Southwest Regional Office) completed an environmental assessment (EA) for closure of abandoned mine openings at the Texas and Calumet Mine. Because of the site's historical significance, the environmental assessment did not consider destructive closures such as blasting for the site's major features. All closure work was done with minimal impact to the historic fabric and maximum sensitivity to the environment (table 1). Underground wildlife surveys in 1993, particularly those of Dr. J. Scott Altenbach and Roy Powers (private wildlife/mine closure consultants), confirmed the presence of significant bat populations in four of the openings. For these four openings, the EA recommended 10- cm (4- in), angle- iron bat gates, as designed by the American Cave Conservation Association and approved by Bat Conservation International.

TABLE 1. Abandoned Mine Land Openings at Texas and Calumet Mine

Opening	Description	Closure
1	Vertical shaft: 10' × 11' × 25' deep	Backfill
2	Coyote prospect: 3' wide × 2' high × 15' deep	Backfill
3	Adit: 4.5' wide × 6' high × 125' long	Bat gate
4	Adit: 5' wide × 7' high × 64' long	Bat gate
5	Adit: 4' wide × 6'–9' high × 21' long	No action
6	Trench / adit prospect: 5' wide × 15' high × 20' deep	No action
7	Prospect pit: 4' × 7' × 5' deep	Backfill
8	Adit: 4.5' wide × 5.5' high × 205' long	Bat gate
9	Adit: 4.5' wide × 5' high × 17' long	Construct native stone/mortar bulkhead
10	Adit: 6' wide × 7' high × 800' long	Corrugated steel culvert with bat gate

Backfill closures were recommended for four other openings, and a no- action alternative was selected for the two shallow adit prospects that were neither hazardous nor suitable as bat habitat.

The Railroad Commission of Texas contracted and funded the closure project at the Texas and Calumet Mine in 1996. Although GRD staff were not present during closure work, park staff ensured that contractors followed the EA recommendations for the abandoned mine openings as summarized in table 1.

Following closure, routine monitoring and inspection by park staff will ensure the continued integrity of the closures and identify areas needing additional corrective action. Routine surveys of the mine openings for bat use and trends in bat population provide information that could guide the National Park Service in adopting new mitigation measures in the future (National Park Service 1995).

Cave Resources and Protection

According to the *Statement for Management, Guadalupe Mountains National Park, Texas* (1988, p. 14), "caves are a significant resource throughout much of the exposed Capitan Reef." Investigators have identified 27 caves within the park boundaries (Santucci et al. 2001), and many more are likely to exist (National Park Service 1988). Most of these caves are administratively closed to the public. Glori Cave is currently the largest known cave in the park with approximately 183 m (600 ft) of surveyed passage (National Park Service 1988).

The resource management plan and environmental assessment for Guadalupe Mountains National Park describe the caves of the Guadalupe Mountains as being large in volume but small in surveyed linear distance. The caves in the park are generally dry, though many are decorated with delicate speleothems. Such cave resources are nonrenewable and are particularly susceptible to human disturbance. Cave resources also include deposits of guano (see "Economic and Mineral Resources" section).

According to DuChene and Martinez (2000), most caves in the Guadalupe Mountains are located near the reef-backreef contact between the Capitan Formation and the Seven Rivers and Yates Formations (fig. 4). In areas such as Guadalupe Mountains National Park, canyons are deeply incised into cave- bearing strata, and a large amount of the limestone most likely to contain caves has been removed by erosion. Long cave systems probably once existed throughout the Guadalupe Mountains, but erosion has destroyed many of them, leaving only truncated remnants stranded high on canyon walls (DuChene and Martinez 2000).

As a result of post- formation erosion, caves at Guadalupe Mountains National Park differ significantly from the cave systems to the north (e.g., Lechuguilla Cave and Carlsbad Caverns). The caves in Guadalupe Mountains National Park are fewer in number per area, have smaller footprints, and their passageways are low and small, though several consist of very deep vertical pits. This suggests that even if they did form in a similar way to other caves in the Guadalupe Mountains, percolating groundwater has subsequently modified them significantly. Large caves are not known, and if they once existed, probably collapsed as a result of deeper weathering and dissolution in the older and higher parts of the mountain range (Gorden Bell, Guadalupe Mountains National Park, written communication, March 13, 2007).

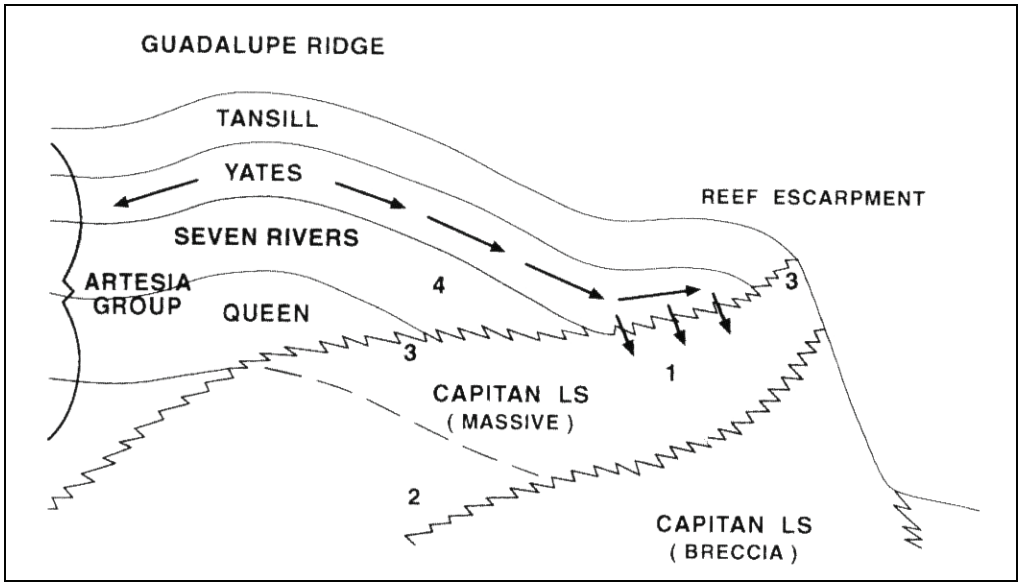


Figure 2. Zones of Cave Dissolution in Guadalupe Rocks. The four zones of preferential dissolution in the Guadalupe Mountains are (1) below the Yates transition into the massive Capitan Limestone, (2) at the contact between the massive and forereef members of the Capitan Limestone, (3) at the transition between the backreef Artesia Group members and the Capitan Limestone, and (4) immediately beneath the Yates Formation in the Seven Rivers Formation. Arrows indicate the movement of groundwater along the impermeable siltstone in the Yates Formation. *Source*: Hill (2000).

In 1972 the regional director approved a cave management plan for Guadalupe Mountains and Carlsbad Caverns National Parks (National Park Service 1972). The plan is based on the following management objectives:

- Protect and perpetuate natural cave systems.
- Provide educational and recreational opportunities for a broad spectrum of park visitors (from the casually curious to the avid caver) to discover, study, respect, and enjoy the parks' caves at their individual levels of interest.
- Provide opportunities for scientific study of cave resources and systems.
- Classify caves in management categories based on their resources and hazard characteristics.
- Establish regulations, guidelines, and permit stipulations that ensure maximum safety for the cave visitor and preservation of park resources.

The cave management plan also (1) establishes procedures for inventorying and maintaining files for all known caves; (2) contains programs for monitoring, protecting, and restoring cave resources; (3) outlines provisions for cave entry for research purposes; (4) identifies training needed by staff involved in cave search and rescue, interpretation, and wild cave trips; and (5) delineates staff responsibilities.

The caves of the Guadalupe Mountains are probably part of a large, pervasive cave complex that is spread throughout the rocks of the reef and backreef (DuChene et al. 1993). Because the rocks of the Guadalupe Mountains are broken by linear, vertical cracks (joints), pollutants introduced into the cave complex outside the park have the potential to contaminate caves within the park. Joints serve as conduits into cave passages through which hydrocarbons, hydrogen sulfide, formation waters from oil- and- gas drill holes, and drilling fluids can enter (DuChene et al. 1993). In addition to toxic and flammable materials such as hydrocarbon gases and hydrogen sulfide, saline water from lower rock formations could leak into the cave system through improperly sealed well bores. Drilling fluids and chemicals, lost circulation material, cement, and gravel can be introduced into cave passages during drilling. (See discussion about oil and gas development on page 10).

On the surface, roads, pipelines, drill pads, separators, tank batteries, and mud pits are potential sources of contamination that surface water can transport into the cave system. Pollutants carried into the ground by surface waters could eventually reach the water table. In addition to the preservation of underground ecosystems, this is a concern because northeast of Carlsbad Caverns National Park, the Capitan Reef contains fresh water that is used as a local water supply (DuChene et al. 1993).

Flood Hazards

Running water is a mechanism for mass transport of debris. In a study conducted in 1978, simulations of critical velocities of water in the 100- year floodplain at Guadalupe Mountains varied from 2.4 to 3.4 m/s (7.9 to 11.1 ft/s). This velocity range is highly erosive and can cause sudden bank failure and radical channel shifts (B. D. Lare, hydrologic report, *in* memorandum to assistant manager, Southeast/Southwest Team, Denver Service Center, from L. A. May, Environmental Investigations Unit, Denver Service Center, October 17, 1978). As emphasized in this memorandum, construction is not advisable in any of the major drainage systems in the park or in the smaller, more local, ephemeral stream valleys.

There is approximately 23 m (75 ft) of alluvial fill in most valley floors in Guadalupe Mountains National Park, and there could be massive undercutting of this fill during flooding (B. D. Lare, hydrologic report, *in* memorandum to assistant manager, Southeast/Southwest Team, Denver Service Center, from L. A. May, Environmental Investigations Unit, Denver Service Center, October 17, 1978). Therefore, investigators recommend that structures be built on bedrock, where possible, to reduce the danger of removal of underlying material by erosion. A considerable margin of safety is required in the placement of construction sites because many of these areas (particularly in the low country) may be subject to flash flooding (Railsback and Reeves 1976).

Geologic Hazards

Participants at the GRI workshop in 2001 identified the need for an assessment of geologic hazards at Guadalupe Mountains National Park. However, they suspected that the areas most susceptible to slope failure and rock falls do not include park infrastructure. Geologic hazards would nonetheless have the potential to affect any future development. Therefore, careful planning and engineering are necessary to minimize geologic hazards and future problems. Any unmitigated disturbance (e.g., the clearing of vegetation and soil removal) has the potential to greatly accelerate natural erosion and may result in irreparable damage to the landscape (Railsback and Reeves 1976). Recommendations for projects with geotechnical requirements are to be carefully integrated with ecological and environmental considerations (Railsback and Reeves 1976).

Geologic hazards at Guadalupe Mountains National Park include mass wasting (landslides and rockfall), seismicity, and solution collapse, each is discussed below.

Mass Wasting

According to Murphy (1984), the landslide deposit north of the Pine Springs Campground is jumbled debris of a different density and texture than the rest of the slope. Water moves through this deposit in a way that causes water and soil to collect at the edges, resulting in a slightly different plant community and different overall color. The green border includes a few more trees that have managed to take root and survive. Mass wasting thus plays a role in the ecological development of park landscapes.

Mass wasting becomes hazardous when park infrastructure or human activities come in contact with the transfer of debris. The most prevalent hazard in the park is rockfall, whereby "relatively large fragments of rock become detached and by means of free- fall, rolling, and bounding move rapidly downslope under the force of gravity" (Rogers et al. 1974, p. 30). Rockfall events are common on cliffs of massive, broken, faulted, or jointed bedrock (e.g., Capitan Limestone). Solution by groundwater and surface water widens joints in the limestone, and natural erosion in turn removes underlying, thin- bedded layers of limestone and sandstone, thus undercutting the massive limestone and creating a number of unstable areas (Railsback and Reeves 1976). Generally, factors that trigger rockfalls are shock waves earthquakes, repeated freeze- thaw cycles of groundwater or surface water, airplane and car noise and vibration, high winds, and blasting for construction or mining (Railsback and Reeves 1976).

Seismicity

According to Rogers et al. (1974), seismicity results from naturally occurring earthquakes and from effects created directly by humans or triggered by human activities. The effects from naturally occurring earthquakes include (1) ground displacement due directly to surface faulting or other abrupt earthquake- related land level change; (2) damage from earthquake- generated ground shaking; and (3) ground failure such as landsliding, soil liquefaction, lurching, dam failure, and ground cracking. Potentially hazardous seismic effects due to human activities include those resulting from (1) nuclear testing; (2) injection of fluids under high pressure into the ground, which may trigger earthquakes; (3) large underground mine cave- ins; and, (4) impoundment of large bodies of water, which is known to increase the seismicity of an area.

Three relatively recent earthquakes have been recorded in the Delaware Basin region. The first was the Valentine earthquake in 1931, which occurred in the vicinity of Valentine, Texas (just west of the Delaware Basin). It measured an equivalent 6.0 on the Richter scale. The second was a moderate earthquake (magnitude 5.0) on January 2, 1992. It was centered approximately 60 km (37 mi) east- southeast of the Waste Isolation Pilot Plant (WIPP) site. The third was the Alpine earthquake, on April 13, 1995, having a magnitude of 5.6 and an epicenter located about 32 km (20 mi) east- southeast of Alpine, Texas, at a depth of 13 km (8 mi).

In addition to these three earthquakes, more than 1,300 earthquakes have been recorded from depths of 3–5 km (2–3 mi) in the War- Wink gas field in Ward and Winkler Counties on the east side of the Delaware Basin (Luo et al. 1991). These earthquakes are probably the result of a non- uniform stress field associated with hydrocarbon generation and mitigation (Hill 1996).

In 1976 investigators conducted a study of microearthquake activity in Guadalupe Mountains National Park (Railsback and Reeves 1976). This report concluded that no more than 19 earthquakes of magnitude 2 or less on the Richter scale can be expected every year. Such earthquakes are probably not felt. Two or three shocks of magnitude 3 or greater per year are predicted; magnitude 3 vibrations could be felt indoors, with hanging objects swinging. No more than four earthquakes of magnitude 5 or greater can be expected in this area within a 100- year time span. Domestic impacts of a magnitude 5 earthquake are furniture moving or being overturned, and cracking of weak, non- reinforced masonry.

Data from this study do not indicate that this area is very seismically active; however, the possibility that a large earthquake will occur at some point in the future cannot be ruled out (Railsback and Reeves 1976). Moreover, any significant shocks in the park area can be expected to trigger a number of rockfalls. Due to the highly fractured nature of the rocks in this area, distant earthquakes may also play a role in triggering rockfalls.

Solution Collapse

According to Rogers et al. (1974), dissolution of soluble rock or soil materials results in ground subsidence and surface collapse. This occurs in areas underlain by highly soluble rock formations, especially gypsum and halite, and to a lesser degree limestone. Hydrologic factors that may cause the solution and removal of material may be natural or anthropogenic. Natural solution is the result of the normal hydrologic processes of downward percolation of surface water or lateral movement of groundwater. Human activities, or results of them, can have much the same effect on soluble earth materials. Examples include stream channel changes, irrigation and irrigation ditches, leaking or broken pipes, impoundment of surface waters, or the mining of soluble material by means of forced circulation of water into the subsurface.

The existence of closely spaced faults and joints offers planes along which dissolution can take place. The action of groundwater is evidenced by active springs in the park, such as Guadalupe, Manzanita, and Smith Springs; and springs in McKittrick Canyon (figs. 1 and 5). Though no solution sinks are known to exist in the mountains, the nature of the rocks makes the existence of some subsurface cavities probable (Railsback and Reeves 1976).

According to Railsback and Reeves (1976), solution is most likely to affect the massive limestone in the area; however, other rock types, in particular Quaternary alluvium, may also be affected. Quaternary alluvium is often partially consolidated at the surface and unconsolidated at depth, reflecting the action of groundwater. Solution in Quaternary deposits generally occurs near bluffs along stream channels; construction in such areas should be avoided because of undercutting.

Groundwater

Areas immediately south and west of Guadalupe Mountains National Park currently support large tracts of irrigated farmland. The source of irrigation water is groundwater, which may be part of the groundwater flow system underlying the park. The NPS Water Resources Division does not have enough information to determine whether groundwater pumping for irrigation or possible export of some of this irrigation water to distant municipalities (e.g., El Paso) poses a threat to the water and water- dependent resources of the park (Larry Martin, National Park Service, Water Resources Division, oral communication, April 5, 2007).

Exploration for hydrocarbon energy sources is occurring in two areas adjacent to the park. One area in the Otero Mesa, a few miles north and west of the park, has been leased by the Bureau of Land Management (BLM) for test drilling and energy development (see "Oil and Gas Development" section). An area southeast of the park is being tested for deep gas production. Such development and production have the potential to contaminate groundwater supplies significant to Guadalupe Mountains NP (Larry Martin, NPS, Water Resources Division, written communication, April 6, 2007).

As of January 12, 2007, park staff had submitted a proposal to the Project Management Information System (PMIS 107571) to characterize groundwater quality, potential water- quality risks, and the hydrogeologic framework for the park and surrounding area. Hydrogeologic characterization of local aquifers and geologic formations would help managers better understand the park's water resources for the purpose of protecting caves, springs and associated ecosystems and maintaining water levels and water quality in aquifers that provide the park water supply of the park. To develop the hydrogeologic framework, investigators would use existing data and also inventory, characterize, and evaluate existing wells and springs in the park. The hydrogeologic framework would facilitate evaluation of geochemical and hydrologic processes within the areas that affect the park's water quality and water resources. The framework would also provide a basis for addressing whether, and how, adjacent groundwater pumping might affect groundwater resources in the park.

Oil and Gas Development

Oil and gas production is a significant part of the regional economy of western Texas and southeastern New Mexico. Recent emphasis on U.S. energy development and self- sufficiency is reflected in increased oil and gas activity in the local area. Oil and gas operations outside the park's boundary may directly affect park resources. Nearby exploration and extraction activities could potentially impact scenic views, air quality, wildlife, vegetation, water resources, and visitor activities. Federal oil and gas exploration is prohibited within Guadalupe Mountains National Park; however, the enabling legislation for the park (Public Law 89- 667, appended) stipulates that if an act of Congress provides that the national welfare in an emergency requires the development and production of subsurface minerals within the park, the Secretary of the Interior may lease the park lands for mineral exploration and development. In addition 226 acres of private land exist within the park. At this time, no interest has been expressed regarding the development of mineral rights, including oil and gas, associated with this acreage.

In the three units of the National Park System where leasing is permissible (i.e., Glen Canyon, Lake Mead, and Whiskeytown National Recreation Areas), the Bureau of Land Management—the federal government's onshore mineral leasing agent—must obtain the consent of the National Park Service prior to the issuance of a lease. The National Park Service can only grant its consent if it finds that the leasing and subsequent development will not have a significant, adverse impact on park resources and administration; the governing regulations are provided in 43 CFR 3100–3500. However, GRD staff cannot predict if the same process would apply to Guadalupe Mountains National Park under a declared national emergency (Pat O'Dell, Geologic Resources Division, written communication, July 19, 2006).

Guadalupe Mountains National Park is located in Culberson and Hudspeth Counties. According to the Railroad Commission of Texas (http://www.rrc.state.tx.us/divisions/og/statistics/wells/wellcount/), Culberson County had 81 regularly producing oil wells and 19 regularly producing gas wells as of February 2007 (the month in which new results are posted). Hudspeth County had no regularly producing oil or gas wells.

The Bureau of Land Management (BLM) issues the majority of oil and gas leases in the vicinity of Guadalupe Mountains National Park on lands managed by the USDA Forest Service (USDA- FS) and BLM. The BLM approves exploration and drilling permits and prepares National Environmental Policy Act (NEPA) compliance documents for these operations. Oil and gas leasing was once proposed for USDA- FS and BLM lands adjoining the park's northeastern boundary. If these lands were leased, drilling would be permitted on Camp Wilderness Ridge at the head of North McKittrick Canyon. Leasing has also been proposed for the Brokeoff Mountains Wilderness Study Area (National Park Service 1988) and Otero Mesa (Otero County, New Mexico), both northwest of the park. The plan for leasing in Otero County (and Sierra County, farther from the park, near White Sands National Monument) calls for "very limited development," possibly 5% surface occupancy. However, according to the BLM, it will only allow for the surface disturbance of 1/10 of 1% of Sierra and Otero Counties combined (Kerry Moss, Geologic Resources Division, e- mail, April 4, 2007). The Environmental Working Group, a source of minerals- related leasing information, particularly in the West, reports the 5% surface occupancy in their publications (see http://www.ewg.org/oil_and_gas/part7.php, accessed April 6, 2007).

The public and the Governor of Texas voiced concerns about the approved BLM plan, which resulted in the Bureau of Land Management "deferring" a lease sold in 2005 in the Bennett Ranch Unit of Otero County. This unit is located in the southern part of Otero County and could impact the surrounding area, potentially including Guadalupe Mountains National Park. As of April 2007, GRD staff concluded that the Bureau of Land Management is leasing on Otero Mesa, but drilling locations are not close to the park yet (see http://www.ewg.org/issues_content/publiclands/20050929/images/Otero_Mesa_150.png, accessed April 6, 2007).

Establishing effective communication with the USDA Forest Service and Bureau of Land Management and monitoring their activities are critical to assuring that oil and gas operations do not impair park values. This will require the National Park Service (i.e., park and Geologic Resources Division staffs) being assertive and keeping informed of all proposed oil and gas operations in the vicinity of Guadalupe Mountains National Park and maintaining cooperative relations with the Bureau of Land Management, USDA Forest Service, and U.S. Geological Survey. Operations involving access through the park would be reviewed and approved as provided in 36 CFR 9B and 43 CFR 3100. If the National Park Service determines that external operations might affect park resources, appropriate recommendations would be made to the BLM and the Texas Railroad Comission (i.e., state permitting agency) for mitigating actions (National Park Service 1988).

Paleontological Resources

In 1855 G. G. Shumard—geologist and member of a party exploring for a feasible railroad route to California along the newly established United States–Mexico border—recorded strata of the southern tip of the Guadalupe Mountains and collected fossils from the thousand-foot- thick "upper or white limestone" unit (i.e., Capitan Limestone) in the vicinity of Guadalupe Pass and El Capitan. In 1858 he reported the circumstances of his field work in the *St. Louis Academy of Science Transactions*. His brother, B. F. Shumard, used this collection to identify the Guadalupe Mountains as the first known marine Permian outcrops in North America (B. F. Shumard 1858). Little further work was done in the region in the ensuing half- century (Pray 1988). However, in early 1901 G. H. Girty, a USGS geologist, extensively collected invertebrate fauna from the strata of the southern Guadalupe Mountains, mostly of the Capitan Limestone on the southern slopes of Guadalupe Peak. In 1908, the U.S. Geological Survey published Girty's 651-page monograph based on these collections as Professional Paper 58.

Since the 1950s the majority of paleontological studies of Guadalupe Mountains National Park have focused on paleoecology, in particular, understanding of the sedimentological origin of the Permian (Guadalupian) Capitan Reef and equivalent backreef (i.e., the Yates and Tansill Formations) and basin (i.e., Bell Canyon, Cherry Canyon, and Brushy Canyon Formations) depositional systems.

Investigators have found more than 500 Permian fossil species in the Guadalupe Mountains (Rennicke 1985). Principal frame- building organisms include calcareous sponges, encrusting calcareous algae, and bryozoans. A group of common fossils is the brachiopods—shelled creatures abundant in the Permian Basin. While some 200 species of brachiopods survive today, investigators have identified 30,000 forms as fossils. Also abundant during reef building in the Delaware Basin were fusulinids, which date back 250 to 350 million years. These creatures became extinct in the latter part of the Permian Period. Fusulinids are members of a major group of fossils called foraminifera that possess lime-rich shells, which helped build the Capitan Reef. During the reef- building period, foraminifers covered thousands of miles of the ocean floor with lime (Rennicke 1985). A third abundant group of fossils in the Permian reef is echinoderms, such as crinoids (sea lilies) and echinoids (sea urchins). Echinoderms are solitary, bottom- dwelling, marine organisms. An endoskeleton with bilateral symmetry, which is formed of plates or ossicles composed of crystalline calcite, characterizes these organisms. Various mollusks are also part of the reef complex, for example, gastropods (snails), cephalopods with chambered shells (modern cephalopod species include octopi and squid), and pelecypods (clams) (DuChene 2000), as well as corals, trilobites, and conodonts (Santucci et al. 2001).

Since the 1930s investigators have recognized the Guadalupe Mountains for their significant Pleistocene/Holocene cave fossils, including herptefauna; avian remains (i.e., bones and feathers); small mammals; and extinct sloth remains (i.e., dung and hide with hair). Four of the 10 known localities in the world for fossil sloth dung occur in Guadalupe Mountains National Park: Lower Sloth Cave, Upper Sloth Cave, Dust Cave, and Williams Cave (Spaulding and Martin 1979).

Based on plant macrofossils and pollen collected from caves in Guadalupe Mountains National Park, investigators have established a 13,000- year- long chronological sequence of late Pleistocene and Holocene plant communities in the Guadalupe Mountains (Van Devender et al. 1977). The plant communities in the Guadalupe Mountains have gradually changed from relatively mesic (moist) woodland and forest associations during pluvio- glacial climates in the Late Wisconsin glacial epoch to the present xeric (dry) Chihuahuan desert scrub (Van Devender et al. 1977).

In 2001 Greg McDonald (GRD paleontologist) suggested that an encompassing, systematic inventory of paleontological resources at Guadalupe Mountains National Park be conducted. Such an inventory would describe known paleontological resources and provide recommendations on how to best manage these resources. A related task is establishing the geographic

position of cited localities. Older literature does not pinpoint localities on a map, and many localities have been reported outside but immediately adjacent to the park boundaries.

As of January 2008, neither the National Park Service nor its collaborators had conducted a formal inventory of the paleontological resources at the park. However, Santucci et al. (2001) discusses the paleontological resources in the park's caves, and Santucci et al. (2007) provides a general overview, brief descriptions of rock units and their depositional settings, and a preliminary literature review of the paleontological resources in the park.

A more comprehensive inventory is unlikely to be completed in the near future for two reasons (Gorden Bell, Guadalupe Mountains National Park, written communication, March 30, 2005). First, the lack of human and fiscal resources precludes the ability to plan, organize, and implement an in- depth inventory. Second, compiling the voluminous amount of published material that is available and continues to grow would be very time consuming. Paleontological research at the national park constantly yields new information and even new fossil species (e.g., Bell et al. 2002, Rigby and Bell 2005, and Rigby et al. 2007).



Figure 3. Manzanita Spring. Active springs in the park such as Guadalupe, Manzanita, and Smith Springs, and springs in McKittrick Canyon are evidence of the action of groundwater. Solution collapse—a geologic hazard and the result of groundwater dissolution—commonly occurs in limestone in semiarid regions. NPS photo by Ron Kerbo.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Guadalupe Mountains National Park.

Guadalupe Mountains National Park is both nationally and internationally significant because of a combination of outstanding geologic, scientific, and scenic resources. The park preserves an important section of the Capitan Reef—one of the most extensive non- coral, fossil reefs in the world—and serves as the Global Boundary Stratotype Section and Point (GSSP) for Middle Permian time. The reef complex also hosts stunning El Capitan and interesting sedimentary and structural features.

The first recognition of the Capitan Limestone as a reef deposit was published in 1928 (Ruedemann letter cited in King and King, 1928, p. 139). Several authors apparently made these conclusions almost simultaneously (Lloyd 1929; Crandall 1929; Blanchard and Davis 1929). According to Hill (1996), most of these early authors believed the formation to have resulted from a barrier reef type of deposition.

Other distinctive geologic features in the park include dunes and various economic and mineral resources.

Global Boundary Stratotype Sections and Points

Guadalupe Mountains National Park contains an international geologic reference point. The International Union of Geological Sciences (IUGS), Subcommission on Permian Stratigraphy, selected the Guadalupian Series to be the world's reference standard for the Middle Permian—a major unit of the geologic time scale. Predicated mostly on the outcrops within Guadalupe Mountains National Park, this section of rock is one of only a few chronostratigraphic references selected within the United States. The International Union of Geological Sciences also ratified three component chronostratigraphic stages within the Guadalupian Series. The lowest is the Roadian Stage, the base of which coincides with the base of the Guadalupian Series. This point is located in Stratotype Canyon, 1 km (0.6 mi) south of Bone Canyon (Williams Ranch House; fig. 1) in the Middle of the El Centro Member of the Cutoff Formation. The base of the middle stage, the Wordian, is located near the park boundary at the top of the east wall of Guadalupe Canyon within the Getaway Limestone Member of the Cherry Canyon Formation. The base of the highest stage (Capitanian) is located at the crest of Nipple Hill, 1.1 km (0.7 mi) east of Frijole Ranch (fig. 1) within the Pinery Limestone Member of the Bell Canyon Formation.

One of the strengths of the Guadalupian Series' candidacy is that the National Park Service agreed to set the area aside as a geologic preserve, with dedicated international scientific access. In a memorandum to the superintendent of Guadalupe Mountains National Park on March 27, 1992, the regional director, of the then Southwest Region, discussed the potential benefits to both the mission of the National Park Service and the scientific community of this "prestigious designation." Moreover, a designation such as this one "will have no impact on our management polices or our conservation mandates" with respect to site designation, accessibility, and collecting. Another bonus for the National Park Service is that backcountry hikers gained an interesting destination, one that emphasizes the internationally recognized geologic uniqueness of Guadalupe Mountains National Park (Glenister and Wardlaw 2000).

El Capitan

One of the most striking features of Guadalupe Mountains National Park is the thousand- foot- high El Capitan cliff, composed entirely of forereef limestone (fig. 7). Early settlers used it as "a leader" ("capitan") on the route through Guadalupe Pass, and it remains a landmark for visitors today. In 1854 J. R. Bartlett wrote about the landmark when he journeyed by wagon from San Antonio to El Paso:

Our road led in a direction nearly west, towards the bold head of the great Guadalupe Mountain, which had been before us some eight or ten days. This is a most remarkable landmark, rising as it does far above the surrounding plain. The sierra which ends with it comes from the northeast. It is a dark, gloomy looking range, with bold and forbidding sides, consisting of huge piles of rocks, their debris heaped far above the surrounding hills. As it approaches its termination the color changes to a pure white, tinted with buff or light orange, presenting a beautiful contrast with the other portions of the range, or with the light blue of the sky beyond, for in this elevated region the heavens have a remarkable brilliancy and depth of color.

Sedimentary and Structural Features

The Guadalupe Mountains area and the northwestern part of the Delaware Basin are exceptional for the wealth of remarkable sedimentary features formed during and soon after the deposition of Permian sediments. Three of these distinctive features are highlighted here: (1) ripple marks, (2) submarine gravity features, and (3) tepee structures.

Ripple Marks

Various investigators observed ripple marks in the Cherry Canyon and Brushy Canyon Formations (King 1948) and the Grayburg- Queen sequence (Boyd 1958). In other cases (e.g., in the rocks immediately behind the Capitan Reef) the lack of ripples is notable (Newell et al. 1953). The older sandstone beds of the backreef facies exhibit these structures, which are indicative of deposition in agitated waters—that is, formed by currents. To explain the rarity of ripples in some of the

backreef deposits, investigators have suggested that the growth of algae or other vegetation may serve as an inhibitor (Boyd 1958). N. D. Newell and D. W. Boyd surmised that perhaps the growth of algal or other vegetation in the Permian shelf seas during times of carbonate deposition prevented rippling of the surface by current action. Using the Bahamas as an analogy, Newell and Boyd suggested that ocean bottoms with even scattered vegetation are usually free of ripples because the plants break up the regular oscillations of bottom currents.

Submarine Gravity Features

The talus apron below and basinward of the reef forms one of the most important features of the Permian Reef Complex. The apron consists of steeply dipping beds of reef rubble with minor contributions from the outer shelf and upper slope of the reef. Brachiopods, bryozoans, and echinoderms living on the slope and siliceous sponges living at the base of the slope trapped fine sediments descending from the reef face and bound the loose material together (Scholle 2000). However, slope sedimentation was overwhelmingly dominated by fragmented material transported as a result of rockfall, grain flow, debris flow, and turbidity currents. Thereby, the forereef deposits consist of numerous small- scale, individual accumulations that have coalesced to form a relatively uniform debris apron (Bebout and Kerans 1993).

Occasionally, a large area of the reef front would collapse under its own weight, producing a massive submarine landslide. These Permian slides had little effect on the substratum: large boulders weighing many tons floated on highly mobile mud. The well- exposed Permian slides are clearly defined across the eastern escarpment and up to 10 km (6 mi) into the basin (Rigby 1950). According to Newell et al. (1953, p. 11), "they are perhaps as impressive as any submarine slides known from the stratigraphic record."

Tepee Structures

The small, irregularly spaced, chevron or V- shaped, symmetrical folds (non- tectonic) in the Capitan backreef deposits are known as "tepees" because of their resemblance to this type of tent (Adams and Frenzel 1950). Investigators have documented tepee structures in the Yates, Seven Rivers, and Tansill Formations (Hayes 1964; Smith 1974) and similar structures in the Grayburg-Queen sequence (Boyd 1958). Tepee structures range in amplitude from a few inches to 1.2 m (4 ft), and in width from 0.6 m (2 ft) to 4.6 m (15 ft). Tepees, once established, tend to be "stacked" (Smith 1974). With few exceptions, tepees are not truncated above by erosion but die out upward as though progressively buried beneath accumulating sediments. Upward propagation may continue for tens or hundreds of feet.

The origin of tepees has been the subject of numerous studies and considerable controversy. Since the 1950s, investigators have provided various explanations for the formation of tepees: compression, desiccation-contraction, breakout and injection of confined formation fluids or liquefied sediments, and vadose soil-forming processes. Advocates of any of these models can point to modern analogs, mainly from the Persian Gulf, Red Sea, and Australia, as "proof." Nevertheless, no one has yet found an exact analog that comes close to modeling the breadth and abundance of the tepees (and associated pisoliths) seen in the Permian record (Scholle 2000).

In 1974 D. B. Smith concluded that "tepees are probably large- scale pressure polygons caused by the expansion of newly formed carbonate sediments because of the growth of interstitial cement—probably aragonite—during contemporaneous lithification" (p. 63). Additionally Smith (1974) found that most tepees underwent considerable erosion after formation; in many crests were nearly planed off. These observations hold true today (Scholle 2000).

Smith interpreted the close association of tepees with fenestral mat- bound sediments as indicating formation in an intertidal or supratidal setting, rather than a wholly subaqueous one as other investigators have suggested (e.g., Shinn 1969). The distribution of tepees suggests that at any one time they formed patchily in parts of a belt a few hundred yards wide on a flat or gently sloping platform within a few feet of mean sea level. From time to time as sea level fell relative to the platform, tepee-bearing sediments were exposed subaerially for lengthy periods (Smith 1974).

Dunes

An expansion of the park boundary in 1987 added about 4,050 ha (10,000 ac) to the park's western boundary and resulted in a significant portion of the red quartz and white gypsum dunes becoming incorporated into Guadalupe Mountains National Park. The National Park Service, various organizations, and individuals had long been interested in preservation of these dunes because of their scenic beauty. As the only area of gypsum dunes in United States outside of White Sands National Monument in New Mexico, these dunes are also geologically significant. In addition, the dunes contain unusual plant associations and rare species, marking their biological significance (National Park Service 1988).

In 1948 P. B. King described the dunes as "a conspicuous feature of the basin floor" (p. 138). Reaching a maximum height of 9 m (30 ft) in the northern area, the quartz dunes spread over the edge of the basin floor and appear to be moving up the slopes of the bajada to the east. The overall form and depressions within the dunes are irregular. Many of the dune surfaces are bare and ripple marked, though mesquite and yucca commonly grow between the dunes.

One possible origin of dune sand is reworked Permian sandstone of the Delaware Mountain Group (King 1948; see "Map Unit Properties" section). This model is based on observations that the sands are spatially restricted with the distribution of sand correlating with the toes of

alluvial fans that drain the western slopes of the Guadalupe and Delaware Mountains on the eastern margin of Salt Basin (see fig. 1). An absence of eolian sands in areas where runoff from the mountains is blocked by foothills further supports this model (King 1948).

In 1999 Wilkins and Currey proposed a second source for the dune sands: thin sheets of reworked sands originally deposited on the basin floor at the mouths of ephemeral tributaries (i.e., in a delta). This model is based on observations of pockets of loose, drifting sand, similar to those found in the red dunes, the channel, and on the delta front of Eight- Mile Draw—a large, ephemeral tributary located across the playa floor to the south- southwest (i.e., upwind) of the quartz dunes area.

In addition to these quartz sand deposits, gypsum deflated from the playa surface forms active dunes in the northeastern portion of the basin. These dunes are much less extensive than the dunes of quartz sand; only one large tract in the Salt Basin covers about 10 km^2 (4 mi^2). The northeastern end of the tract is a crescent- shaped ridge a mile across, made up of white, shifting dunes, bare of vegetation, with an appearance similar to the well- known White Sands area of the Tularosa Basin in New Mexico (King 1948). The gypsum sand dunes include an active front approximately 15 m (50 ft) high. According to Wilkins and Currey (1999), these dunes are advancing to the northeast as evidenced by the alignment of the limbs of the parabolas. To the southwest, nearer the playa margins, the gypsum dunes are mostly stable and covered with vegetation.

Mineral Resources

In 1948 P. B. King considered the resource most worthy of investigation and conservation in the Guadalupe Mountains to be groundwater because "it makes life possible in a land that is otherwise barren" (p. 160; also see "Groundwater" section of this report). Though King's comment may still hold true, since his time, "liquid gold" has made the Permian Basin famous. The backreef environments account for greater than 90% of all hydrocarbon production in the area, with basin sediments accounting for the rest. Reef deposits are nonproductive (Scholle 2000).

The oil and gas development in the vicinity of the park is discussed in the "Geologic Issues" section of this report. Other significant mineral resources in the area around the park include building stone, calcareous tufa and travertine, copper, guano, road material, and evaporite minerals.

Building Stone

No high- quality building stone is present in the area, but flaggy dolomite from the Tansill Formation (see "Map Unit Properties" section) has found local use, notably for the construction of buildings at Carlsbad Caverns National Park. Some of the buildings at Frijole Ranch in the park are made of cobbles of Capitan Limestone obtained from the gravel deposits washed out from the mountains (King 1948). Local residents have used other rocks for houses and stone walls (Hayes 1964). In addition, the rocks of the Delaware Mountain Group (see "Map Unit Properties" section) include several varieties of stone that are used locally for building purposes. Of them the most distinctive and useful are the even- bedded, flaggy limestone and sandstone. These rocks are used in building houses and in making fences and other structures along the highway. The most extensively used bed is the McCombs Limestone Member of the Bell Canyon Formation. This bed is about 3 m (10 ft) thick and crops out over an extensive area (e.g., southeast of the mouth of McKittrick Canyon). Local residents have excavated numerous small quarries into it (King 1948); none of which are in the park (Gorden Bell, Guadalupe Mountains National Park, e-mail, January 16, 2008). However, one small quarry in the in the Rader Limestone Member, shown on the King (1948) map, is in close proximity to the McKittrick Canyon road and is within the park's McKittrick Canyon access road right of way. The National Park Service owns this outright through purchase; it is not simply an easement (Gorden Bell, Guadalupe Mountains National Park, e- mail, January 16, 2008).

Copper Mining and Mineralization

The almost complete absence of igneous rocks in the area results in a lack of mineralization, except at a few localities such as the abandoned Texas and Calumet Mine in the park. The mine was excavated where veins in the Capitan Limestone contained copper minerals, for example, in the headwaters of Dog Canyon about a mile northeast of Lost Peak (fig. 1). Prospecting for various minerals has occurred since about 1900, but the workings are small and had been abandoned by 1938. The copper ore was hauled over a wagon road to a smelter in El Paso, Texas. Remnants of this road, an old miners' cabin, and six mine shafts, including one with a short section of rail and an ore car, are evident near Lost Peak.

Mining was never a major endeavor in the area due to the remote location and the distance from El Paso. Nevertheless, this unique aspect of the area's history and development has not been addressed in any existing report (National Park Service 1988). Therefore the park's resource management plan recommends a thorough study of the copper mining operation in Dog Canyon and any other mining activities in the present park area. The plan recommends an on- site investigation and photographic documentation of mine shafts, interviews with local people, and a search of legal documents and records of companies involved in this mining enterprise (National Park Service 1988).

A letter from Wallace Pratt to P. B. King in January 1945 identifies other locations of past mining activity:

There are two other openings (shallow shafts) on mineralized limestone in the area; one is about a mile west of Bell Spring; the mountain flank, the prospector having camped at Bell Spring; the other opening is on the edge of the high plateau, a couple of hundred yards northeast of the

trail from the Grisham- Hunter Lodge on South McKittrick Canyon to Grisham- Hunter Camp, at a point about a mile as the crow flies west of Grisham- Hunter Lodge. Both these openings uncover concentrated black iron oxides, with a trace of copper. Local tradition claims that silver also is present. The first described opening is in the upper part of the Bell Canyon formation and the second is in the Carlsbad limestone [now called Capitan Limestone]*, at the base of a sandstone phase.*

Evaporite Minerals

Adjacent to the western border of Guadalupe Mountains National Park is a major basin or graben called Salt Flat (fig. 1). It is about 100 km (60 mi) long and 16 km (10 mi) wide at the easternmost edge of the Basin and Range Province. Salt Flat has been the site of continuous alluvial, fluvial, and lacustrine sedimentation since middle Tertiary time (see fig. 2). In a region of low rainfall (about 25 cm [10 in] per year) and high evaporation (about 200 cm [80 in] per year) (Dunham 1972), modern saline playas occur in Salt Flat. Without a natural outlet, all drainage is internal. Groundwater, which stands at a level near the playa surface, is drawn upward and evaporated. This groundwater has percolated through evaporite- bearing Permian strata (e.g., Castile Formation) and is thereby already charged with considerable dissolved solids, which are further concentrated through evaporation at the surface, leading to very elevated salinities (exceeding 250–300 parts per thousand). These high salinities greatly restrict vegetation and allow eolian deflation of the fine- grained playa precipitates.

Gypsum and halite are the dominant evaporite minerals, but calcite, aragonite, and dolomite also occur in the playa sediments (Friedman 1966; Dunham 1972). Carbon- 14 dating and geologic mapping of rock units in the basin indicate that much of the sediment found at the surface today may be relict from a larger Pleistocene pluvial lake (King 1948; Dunham 1972). Wind erosion and deposition has piled up some of the primary and secondary minerals from this sediment (mainly gypsum) as dunes along the margins of the playa area (see "Dunes" section).

Though not preserved to any extent in buried sediments, halite has been mined from the surface of the playa. Used for food preservation and the final curing of hides, halite was a highly valued commodity in the 1880s. Mule- and ox- drawn vehicles hauled the substance for many hundreds of miles over the Southwest Trail to Fort Quitman, then to San Elizaro, Franklin (now El Paso), Paso del Norte (now Juarez), and on to Chihuahua City. Disputes between Mexican and American mining interests in the area led to the El Paso Salt War of 1877. The conflict culminated in the Battle of San Elizaro (then the county seat of El Paso County). Modern food-preservation techniques and more economical sources of salt have eliminated the relatively small- scale mining in this area since the 1950s.

Guano

According to Hayes et al. (1983), guano is found in small amounts in Cottonwood Cave along the Guadalupe Ridge in the Guadalupe Escarpment Wilderness Study Area (fig. 6) and possibly in other small solution caves in the study area. Guano was formerly mined as nitrate-rich fertilizer from caves now in Carlsbad Caverns National Park. Today most nitrate fertilizer is obtained from the destructive distillation of coal and coke, sewage treatment plants, and by fixation from the atmosphere. Present or future demand for guano seems minimal; therefore, the incentive to mine guano in the area is low, except at large, easily mined deposits. Investigators from the U.S. Geological Survey and Bureau of Land Management consider the guano that exists in the study area to be of negligible importance (Hayes et al. 1983). Nevertheless, guano finds its way into novelty shops where for a price interested buyers can purchase a bag to use on cherished flowers and potted plants (Moore and Sullivan 1997).

Aside from its economic value, guano is an important source of food for cave- dwelling animals. Cave explorers may find crawling into a guano deposit unpleasant because of the guano's mushy consistency and fetid ammoniac odor, and also because of the innumerable beetles, ticks, lice, and mites that swarm over it. To these creatures, however, guano is welcomed food, and the heaviest concentrations of cave life occur where guano abounds (Moore and Sullivan 1997).

Road Material

Historically, the Texas Department of Transportation has quarried limestone gravel at several places along U.S. Highway 62 for use as road base (Hayes 1964). These quarries are part of the Texas Department of Transportation's right of way (Gorden Bell, Guadalupe Mountains National Park, e- mail, January 16, 2008). In many places the highway extends across patches of gravel, some of which are too coarse to use as road base and require screening to remove the larger stones. In places, the gravels and other alluvial deposits are strongly cemented by caliche, which has been used for surfacing the highway (King 1948). Park staff used the gravel from one pit near the mouth of McKittrick for surfacing the McKittrick Canyon access road. This borrow pit is just outside park land. In coordination with the Geologic Resources Division, park managers have prepared a sand and gravel management plan that outlines best management practices for minimizing the amount of sand and gravel needed for roads and trails and reducing potential impacts so that natural, cultural, and scenic values of the area are preserved (Greco et al. 2007).

Travertine and Tufa

The waters of McKittrick Canyon are laden with calcium carbonate ($CaCO_3$). As the water splashes over the creek bed, dissolved calcium carbonate is released and deposited. Calcium carbonate is also precipitated from very limy spring water, which loses carbon dioxide as it is warmed by the atmosphere, thus decreasing the solubility of calcium carbonate. The hard, dense deposit

that results is travertine; a spongy or less compact variety is tufa. Algae, which use the carbon dioxide in the water, are often abundant on $CaCO_3$ deposits in the spring- fed pools. These organisms likely play a role in the precipitation of the calcium carbonate (Hayes 1964).

Calcium- carbonate deposits have an important effect on the streambed and the course of the creek in McKittrick Canyon. Travertine cements the gravel of the streambed, sealing it so the water cannot run underground. Dams also form across the stream and convex to the flow, creating pools. Floods occur every few years, changing the flow of the stream and altering the deposition of travertine. After each flood, travertine deposits gradually re- cement the streambed (Rennicke 1985). Travertine is also an important cave deposit, forming stalactites, stalagmites, and other cave features.

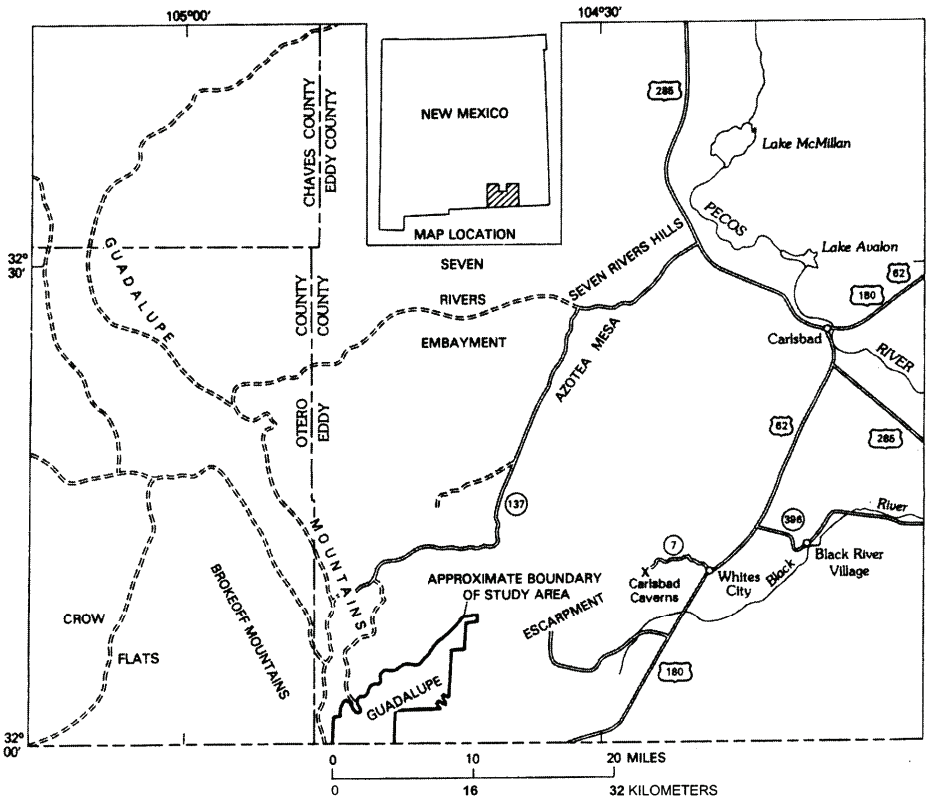


Figure 4. Guadalupe Escarpment Wilderness Study Area. In 1983 investigators from the U.S. Geological Survey and Bureau of Land Management classified the potential for oil and gas beneath the study area as moderate. *Source*: Hayes et al. (1983).



Figure 5. El Capitan. The thousand-foot-high El Capitan cliff, possibly the most striking feature in Guadalupe Mountains National Park, is composed entirely of Permian forereef limestone. NPS photo by Ron Kerbo.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resource Evaluation digital geologic map of Guadalupe Mountains National Park. The accompanying table is highly generalized and is provided for background purposes only. Ground- disturbing activities should not be permitted or denied on the basis of information in this table. More detailed map unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the National Park Service Geologic Resources Division.

The geologic map that accompanies this report is a digital version of King (1948, pl. 3). This map includes both bedrock and surficial units. Since publication of King (1948), investigators have refined many of the map units, and some units have been granted formation status. Nevertheless, "there has been nothing to match [King's] treatment since" (Pray 1988, p. 5). The map unit descriptions in the accompanying table are primarily from King (1948); however, if these have been superseded, the new descriptions appear in the table.

In 1948 King noted abrupt changes from one rock type into another within short distances and drastic changes in character from southeast to northwest across the region. The sequences of rocks in the northwestern and southeastern parts of the area are so different that constructing a single stratigraphic column for the park would have been awkward; hence, King divided the rocks into two separate columns on his map. Later investigators discovered that a rare sequence of exposed evaporites, carbonates, and sandstones in the Guadalupe Mountains shows all of the lateral transitions resulting from deposition of a massive reef at the edge of a deep marine basin. The abrupt changes that King noted are represented in this sequence of rocks called the Permian Reef Complex. This complex includes rocks formed in lagoons and shoals of the shallow shelf (backreef), the organic buildup of the reef and the debris shed down the steep reef front (forereef), and sediments deposited in the deep waters of the Delaware Sea (basin). This complex of rocks contains one of the largest fossil reefs in the world, the Capitan Reef, which overlies the slightly older Goat Seep Reef.

The consolidated rocks of Guadalupe Mountains National Park are marine and coastal sediments of Permian age. The four series of the Permian System previously used in Texas and New Mexico are, from oldest to youngest, the Wolfcampian, Leonardian, Guadalupian, and Ochoan (Adams et al. 1939). Three of these series are represented in Guadalupe Mountains National Park (i.e., Ochoan, Guadalupian, and Leonardian); Wolfcampian rocks are not exposed at the surface. Designation of the Middle Permian global stratotype as the Guadalupian Series necessitated a reorganization of the international terminology for the Permian System. The Wolfcampian and Leonardian of regional usage are now included in the Lower Permian Cisuralian Series, and the Ochoan is considered the Lopingian Series of Late Permian age (Glenister et al. 1999). Cisuralian and Guadalupian rocks in the Delaware Basin reach a maximum thickness of about 2,130 m (7,000 ft). The rocks consist chiefly of sandstone and limestone with various textures and structures.

Table 2 shows the stratigraphic relationship among rock formations of the three provinces, which are stratigraphically contemporaneous but very dissimilar. Table 2 also relates the three sections of the map unit properties table. For instance, the Seven Rivers, Yates, and Tansill Formations were being deposited in the backreef at the same time that the Capitan Limestone was being deposited as reef and forereef and the Bell Canyon Formation was being deposited in the Delaware Basin. The map unit properties table highlights features such as age, name and map symbol, description, suitability for development and recreation, hazards, and the occurrence of various resources (e.g., paleontological, cave and karst, and mineral).

TABLE 2. Permian Rock Formations in Stratigraphic Provinces

AGE	BACKREEF		REEF and FOREREEF	BASIN	
Lopingian (formerly Ochoan)				RUSTLER (dolomite with gypsum, also sandstone and siltstone)	
				SALADO (salt , anhydrite, and potash)	
				CASTILE (anhydrite and gypsum) with SALADO solution breccia	
Guadalupian	TANSILL (dolomite and siltstone)		CAPITAN (limestone)	Reef Trail	BELL CANYON (sandstone with limestone members)
	YATES (dolomite and sandstone)	C		Lamar	
		B		McCombs	
		A		Rader	
	SEVEN RIVERS (separate layers of dolomite and gypsum)			Pinery	
				Hegler	
	QUEEN (dolomite and sandstone)		GOAT SEEP (limestone)	Manzanita	CHERRY CANYON (sandstone with limestone members)
				South Wells	
				Quartzite	
	GRAYBURG (dolomite)			Getaway	
	SAN ANDRES, upper (limestone and dolomite)		CHERRY CANYON sandstone tongue		
			BRUSHY CANYON (sandstone) Basal shale (Pipeline Member)		
Cisuralian (formerly Leonardian)	SAN ANDRES, lower (limestone and dolomite)		CUTOFF (shale)	CUTOFF (limestone and shale)	
	YESO (gypsiferous dolomite)		VICTORIO PEAK (limestone)	BONE SPRING (limestone)	

Sources: Newell et al. (1953), Hayes (1964), Bebout and Kerans (1993), Hill (1996).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Guadalupe Mountains National Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

A portion of the rock record, spanning more than 1 billion years, is preserved in the Delaware Basin. These deposits range in age from the 1.3- billion- year- old Precambrian basement to the 10,000- year- old Holocene sediments of the Pecos River Valley (Hill 1996). This geologic summary focuses on about 50 million years of this record, that is, the rocks of the Permian Period (299–251 million years ago). Because an estimated 95% of all the outcrops in the Delaware Basin date from this period, more is known about the Permian- age rocks than all of the pre- Permian rocks combined (Hill 1996).

Globally speaking, the supercontinent Pangaea had not yet broken apart during the Permian Period, and Texas and New Mexico occupied the western edge of this landmass near the equator. A vast Permian ocean, called the Tethys Ocean, surrounded Pangaea; a narrow inlet connected this ocean to the "Permian Basin," which consisted of four subbasins: Val Verde, Midland, Delaware, and Marfa (fig. 8). The Delaware Basin contained the 240- km- (150- mi-) long, 120- km- (75- mi-) wide Delaware Sea. This sea was the depositional setting for the rocks now exposed in Guadalupe Mountains National Park.

Before and during the Cisuralian (formerly Leonardian) Epoch (see table 2), the Delaware Basin subsided rapidly, accumulating sediments that would form limestone (e.g., Bone Spring and Victorio Peak Formations), dolomite (e.g., Yeso Formation), and shale (e.g., Cutoff Formation). Starting in the Cisuralian and continuing into the Guadalupian, these sediments record marine transgressions (e.g., San Andres Formation) and regressions (e.g., Grayburg Formation). Some of this material was deposited in incised submarine canyons, such as the Brushy Basin and Cutoff Formations; the Cutoff Formation is also notable for its debris flows. Ultimately, 3–5 km (2–3 mi) of sediments accumulated in the Permian Delaware Basin. Also during Cisuralian time, a reef bordering the Delaware Sea began to develop at the margins of the basin, and the general backreef- reef- basin sequence was established. Initially the reef was not a reef in the strictest sense of the word. Multiple reefs, really banks of carbonate sand, accumulated locally along the margins of the basin. These banks became the foundation upon which the later, more massive, Guadalupian reefs grew (Hill 1996). The earlier "reef" banks were composed of mainly fusulinid foraminifers, oolitic grainstone, or other high- energy carbonate material (Hill 1996).

As the ocean floor continued to slowly sink, reef deposits grew upward, remaining relatively near the water's surface. By middle to late Guadalupian time, the sea had shrunk to the confines of the Delaware Basin, and conditions became favorable for massive reef growth. Over millions of years, calcareous sponges, algae, and other lime- secreting marine organisms, along with calcium carbonate that precipitated from the water (a source of lime recently discovered to be primary in this process) built up to form the 640- km- (400- mi-) long, horseshoe- shaped Capitan Reef. This "stratigraphic reef" contains a small organic component and larger inorganic component bound together into a wave-resistant structure (Hill 1996). According to Hill (1996), the Capitan Reef was a barrier reef in the Guadalupe, Apache, and Glass Mountains, but was broken into discontinuous mound- like structures by submarine canyons on the north and east sides of the basin. Part of the reef environment is the "forereef," where the massive reef grew over (prograded) its own debris. The forereef was composed of material from the front (seaward) side of the reef that had broken away from the steep slope, slipped to the bottom, and collected as sediments. The Goat Seep and Capitan Formations are the rock units composing the Guadalupian reef (see table 2).

Behind the reef, a broad, shallow shelf or "backreef" composed of eolian, tidal flat, and lagoon deposits formed. The Guadalupian backreef consists of the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations. Based on variations in the types of sediments composing these rock units, geologists have divided the backreef into four environments: outer shelf, shelf crest, inner shelf, and evaporite shelf (fig. 9). The evaporite shelf was the area nearest the shore and consisted of coastal sabkha and playa settings; as characterizes such settings, eolian processes were probably active. The deposits are red siltstone and evaporites (e.g., gypsum and some halite). The red color of the clastic deposits of the evaporite shelf is due to the oxidation of iron in the very shallow, nearshore zone. An abrupt transition of rock type—from evaporites (sabkha) to dolomite (lagoon)—occurs between the evaporite shelf and inner shelf. The inner shelf consisted of tidal flats and lagoons. Heading basinward, the shelf crest, sometimes called the pisolite shoal, existed a few miles behind the reef front. The shelf crest represents an alternately emerged and submerged, peritidal environment characterized by pisolite and tepee structures (see "Sedimentary and Structural Features" section). Finally, the immediate backreef or outer shelf was located seaward from the shelf crest where the water

became deeper. The outer shelf is noted for a thickening of sediment (i.e., interbedded siliciclastics) adjacent to the reef and its increasing, basinward dipping of strata towards the reef.

The Cherry Canyon and Bell Canyon Formations represent the strata of the Guadalupian- age Delaware Basin. Earlier (Cisuralian) basin deposits are the Bone Spring and Cutoff Formations (see table 2). Because of differences in lithology, geologists have separated the basin setting into the "basin" and "basin margin" (fig. 9). Reef sediments (i.e., limestone and dolomite) interfinger with basin sediments (i.e., siltstone and sandstone) in the basin margin. The basin sediments are primarily siliciclastics (rather than carbonates or fine- grained sedimentary rocks as in the basin margin), which is indicative of the long, an anastomosing channels that covered much of the basin floor.

During the 10- million- year span of Guadalupian time, the Delaware Basin decreased in size. Sedimentation blocked the connection to the Permian Ocean and left the Delaware Basin as the last site of deep- water sedimentation and massive reef growth. Eventually the sea began to shrink and by evaporation the water became saltier, killing the reef- building organisms. Normal marine carbonate deposition in the Delaware Basin ceased at the end of Guadalupian time (Hill 1996).

With an abrupt end to its growth, the reef was buried in thousands of feet of sediments during Lopingian (formerly Ochoan) time. Rivers deposited debris and playa lakes evaporated, infilling the basin and forming the Castile and Salado Formations. Dolomites and evaporites of the Rustler Formation were deposited later in mudflats. The Castile Formation occurs in the Patterson Hills area (see fig. 1); the Salado and Rustler Formations are not present in the park. Ultimately sedimentation entombed the reef for millions of years.

The Delaware Basin remained buried as part of a stable platform during the Mesozoic Era, but faulting on the west side of the basin resulted in the uplift of the Guadalupe Mountains about 26 million years ago. Uplift exhumed the Capitan Reef and created the Western Escarpment, which runs from Bartlett Peak to El Capitan and includes 2,666- m (8,749- ft) Guadalupe Peak, the highest mountain in Texas. During uplift sediments were shed onto the High Plains and the ancestral Pecos River Valley. Stream erosion has removed softer sediment and lowered the region to its present level (Budd and Giles 2003). In addition, caves in the area formed in the limestone units; the largest are those in Carlsbad Caverns National Park (Budd and Giles 2003). Wind and rain also helped to erode softer overlying sediments, leaving the more resistant limestone of the reef exposed. Because of the steep relief and sparse vegetation, landslides have eroded some hillsides, a process of mass wasting that continues in the present (see "Geologic Hazards" section).

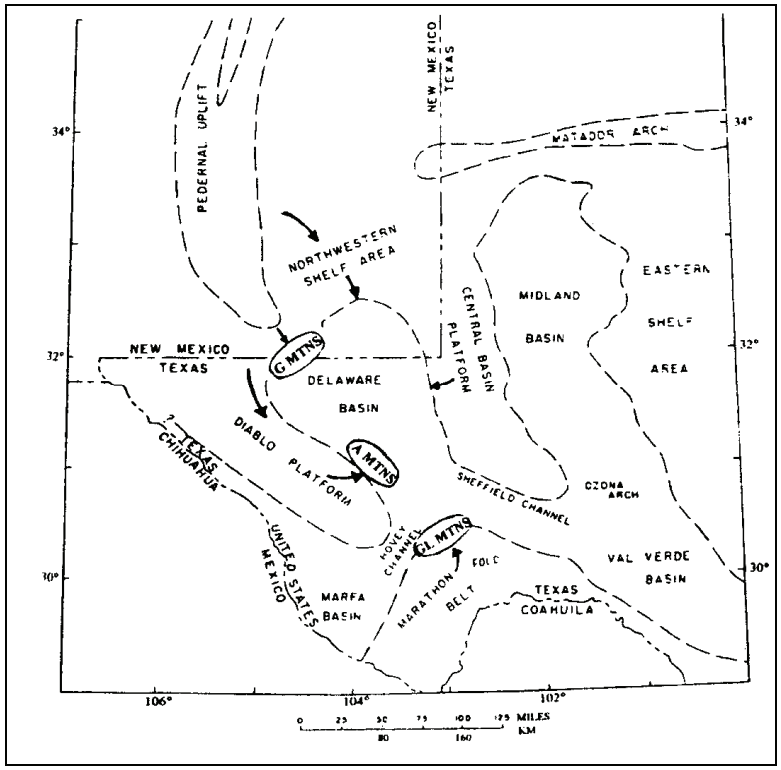


Figure 6. Permian Geography of West Texas and Adjoining New Mexico. Guadalupe Mountains National Park straddles the northwestern shelf and the Delaware Basin, which was one of four basins of the sea during Permian time. In the figure, G MTNS = Guadalupe Moutains, A MTNS = Apache Mountains, and GL MTNS = Glass Mountains. *Source:* Hill (1996).

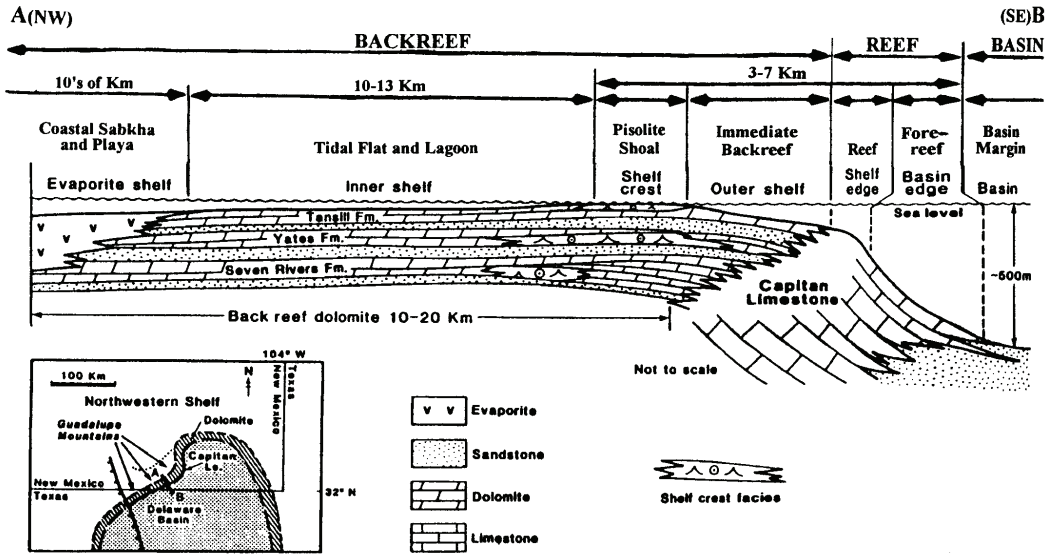


Figure 7. Depositional Environments of the Capitan Reef Complex. Geologists have divided the Capitan Reef Complex into backreef, reef, and basin settings. Pisolite, tepees, and fenestral carbonates of the shelf crest developed at times of peritidal shoals. Inset map (lower left) shows the regional relationship among the northwestern shelf (evaporite and sandstone), carbonate marginal mound (dolomite and limestone), and the basin (sandstone). *Source*: Hill (1996).

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Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. More detailed definitions and additional terms are available at http://wrgis.wr.usgs.gov/docs/parks/misc/glossarya.html.

anastomosing stream. The channel pattern of a braided stream is anastomosing, meaning branching and recombining.

alluvium. Stream- deposited sediment that is generally rounded, sorted, and stratified.

aquifer. Rock or sediment that is sufficiently porous, permeable, and saturated to be useful as a source and reservoir of water.

bajada. A convergence of neighboring alluvial fans into a single apron of deposits against a slope, also called a compound alluvial fan.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie the deposits at the surface. In many regions the basement is of Precambrian age, but it may be much younger.

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

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

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

bedding. Depositional layering or stratification of sediments.

block (fault). A crustal unit bounded by faults, either completely or in part.

breccia. A coarse- grained, generally unsorted, sedimentary rock consisting of cemented angular clasts.

clastic. Rock or sediment made of fragments of preexisting rocks.

cross section. A graphical interpretation of geology, structure, or stratigraphy in the third (vertical) dimension based on mapped and measured geologic extents and attitudes depicted in an oriented vertical plane.

crystalline. Describes the structure of a regular, orderly, repeating geometric arrangement of atoms

debris flow. A rapid and often sudden flow or slide of rock and other earth material involving a wide range of types and sizes.

deformation. A general term for the process of faulting, folding, shearing, extension, or compression of rocks as a result of various Earth forces.

dolomite. The name of both a carbonate rock and a mineral consisting of calcium magnesium carbonate ($CaMg(CO_3)_2$). Limestone which is partially replaced by dolomite is referred to as dolomitic limestone.

dune. A low mound or ridge of sediment, usually sand, deposited by wind.

eolian. Formed, eroded, or deposited by or related to the action of the wind.

escarpment. A long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the continuity of the land by separating two levels or gently sloping surfaces, and produced by erosion or faulting. The term is often used synonymously with *scarp*, although *escarpment* is more often applied to a cliff formed by differential erosion, and *scarp* is identified more with faulting.

evaporite. Chemically precipitated mineral(s) formed by the evaporation of solute- rich water under restricted conditions.

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

fanglomerate. A sedimentary rock consisting of waterworn fragments of various sizes, deposited in an alluvial fan and later cemented into a firm rock.

fault. A subplanar break in rock along which relative movement occurs between the two sides.

fault-block mountain. A linear mountain range that is formed by normal block faulting where surfaces of adjacent blocks typically end up with different elevations or tilts, also called "block mountain."

fenestrate. Having openings or transparent areas. The term has been applied especially to bryozoans, corals, and pollen.

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

graben. A down- dropped structural block bounded by steeply dipping normal faults.

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

intertidal. The same as "littoral," meaning the benthic ocean environment (and organisms) between high water and low water.

joint. A semiplanar break in rock without relative movement of rocks on either side of the fracture surface.

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

landslide. Any process or landform resulting from rapid mass movement under relatively dry conditions.

lithology. The description of a rock or rock unit, especially the texture, composition, and structure of sedimentary rocks.

member. A lithostratigraphic unit with definable contacts that subdivides a formation.

mesa. A broad, flat- topped erosional hill or mountain that is bounded by steeply sloping sides or cliffs.

mesic. Refers to a habitat or plant that requires a moderate amount of moisture.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

normal fault. A fault in which the hanging wall moves down relative to the footwall.

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

paleontology. The study of the life and chronology of Earth's geologic past based on the stratigraphic distribution, morphology, and phylogeny of fossil organisms.

parabolic dunes. Crescent- shaped dunes with horns or arms that point upwind.

pisolite. A sedimentary rock, commonly limestone, made up chiefly of coated, pea- sized grains (oölites).

plateau. A broad, flat- topped topographic high of great extent and elevation above the surrounding plains, canyons, or valleys (both land and marine landforms).

playa. A dry lakebed, generally the shore or remnant of a lake in a closed basin.

pluvial lakes. Lakes formed during earlier times of more abundant precipitation.

potash. An impure form of potassium carbonate (K_2CO_3) mixed with other potassium salts. Potash has been used since antiquity in the manufacture of glass and soap, and as a fertilizer.

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

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

sabkha. A supratidal environment of sedimentation, formed under arid to semiarid conditions on restricted coastal plains just above normal high- tide level (a saline marine marsh).

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

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

sedimentary rock. A consolidated and lithified rock consisting of detrital or chemical sediment(s).

sequence. A major informal rock- stratigraphic unit that is traceable over large areas and defined by a major sea level transgression- regression sediment package.

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

shoal. A relatively shallow place in a body of water.

sierra. An often used Spanish term for a rugged mountain range.

silt. Clastic sedimentary material intermediate in size between fine- grained sand and coarse clay (1/256–1/16 mm).

siltstone. A variable- lithified sedimentary rock with silt-sized grains.

slope. The same as "gradient," meaning the inclined surface (or its measurement) of any geomorphic feature.

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

speleothem. A formal term for a cave formation, from the Greek for "cave deposit." Speleothems are the result of the interactions among water, rock, and air within caves. Examples of speleothems are stalactites, stalagmites, columns, cave popcorn, aragonite crystals, and cave bacon.

spring. A site where water flows out at the surface due to the water table intersecting the ground surface.

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

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

stream. Any body of water moving under gravity flow and confined within a channel.

subaerial. Formed, existing, or taking place on the land surface.

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

supratidal. The same as "supralittoral," referring to the shore area just above high- tide level.

system (stratigraphy). The group of rocks formed during a period of geologic time.

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

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

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

travertine. A limestone deposit or crust, often banded, formed from precipitation of calcium carbonate from saturated waters, especially near hot springs and in caves. A spongy variety is tufa.

trend. The direction or azimuth of elongation of a linear geologic feature.

turbidity current. Rapidly moving, sediment- laden current moving down a slope and spreading horizontally. The term is most commonly used to describe underwater currents in lakes and oceans. They are believed to have produced the submarine canyons, notching the continental slope.

type locality. The geographic location where a stratigraphic unit is well displayed, is formally defined as a typical section, and derives its name.

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

vadose. Refers to being unsaturated or occurring in the zone above the water table.

water table. The upper surface of the saturated (phreatic) zone.

xeric. Refers to a habitat or plant that requires only a small amount of moisture.

Appendix A: Geologic Map Graphic

The following page is a preview or snapshot of the geologic map for Guadalupe Mountains National Park. For a poster- size PDF of this map or for digital geologic map data, please see the included CD or visit the Geologic Resource Evaluation publications Web page (http://www2.nature.nps.gov/geology/inventory/gre_publications).

Appendix B: Scoping Summary

This appendix contains excerpts from the summary of a Geologic Resources Inventory (GRI) workshop for Guadalupe Mountains National Park on March 6–8, 2001. The Geologic Resources Inventory was the precursor to the Geologic Resource Evaluation (GRE) Program. The contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

The purpose of the GRI workshop was to view and discuss the geologic resources at Carlsbad Caverns and Guadalupe Mountains National Parks, address the status of geologic mapping for compiling both paper and digital maps, and assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Carlsbad Caverns (CAVE), Guadalupe Mountains (GUMO), Colorado School of Mines, the New Mexico Bureau of Geology and Mineral Resources, and the Texas Bureau of Economic Geology were present at the workshop (table 3).

The workshop included single- day field trips to view the geology of both Guadalupe Mountains (led by Gorden Bell, Mike Gardner, and Charles Kerans) and Carlsbad Caverns (led by Paul Burger), as well as a full- day scoping session to present overviews of the NPS Inventory and Monitoring (I&M) Program, the Geologic Resources Division, and the ongoing geologic resource inventory. Round table discussions about geologic issues for both parks included the status of geologic mapping efforts, interpretation, paleontological resources, sources of available data, and action items generated from this meeting.

Existing Geologic Maps

The U.S. Geological Survey has published professional papers about both the Texas and New Mexico portions of the Guadalupe Mountains. Professional Paper 215 (King 1948) covers the Texas portion of the Guadalupe Mountains and contains a 1:48,000- scale geologic map that ends at the Texas State line. Professional Paper 446 (Hayes 1964) covers the New Mexico portion of the Guadalupe Mountains (i.e., Carlsbad Caverns) and contains a 1:62,500- scale geologic map. Both were excellent, very comprehensive publications for their day and are still quite useful even though interpretations have been refined since their publications.

The U.S. Geological Survey has also published a few other maps that cover the CAVE area. *Mineral Resource Potential and Geologic Map of the Guadalupe Escarpment Wilderness Study Area, Eddy County, New Mexico* (MF-1560- A) is mapped at 1:24,000 scale. The U.S. Geological Survey published two separate geologic maps (i.e., GQ-112 and GQ- 98), which predate Professional Paper 446 and are both at 1:62,500 scale. Of note, however, is that MF- 1560- A only covers the most southwestern portion of Carlsbad Caverns National Park.

Scoping participants considered all of these maps worthy of digitizing as they represent some of the best sources of existing "baseline" data. GRI staff will incorporate the digitization of these maps into their future work plan.

Also the Colorado School of Mines (under the direction of Mike Gardner), has been concentrating efforts on large- scale mapping of the Permian reef at Guadalupe Mountains National Park, specifically the Brushy Canyon unit. They have digital versions of this mapping in ArcView format and are willing to share them with the National Park Service.

Desired Enhancements to the Existing Maps

Refinements to King's 1948 map would involve splitting out the Carlsbad Group into three formations (Yates, Tansill, and Seven Rivers) to seamlessly edge- match with Hayes' 1964 map and thereby eliminate the New Mexico–Texas "boundary fault." Gorden Bell thought that aerial and satellite photos could be used to do this with minimal field checking.

Other actions include the following items:

- Integrate Mike Gardner's large- scale mapping of the western escarpment with the King map for better detail of the Brushy Canyon unit members, which also include some minor faults that are not shown on King's maps.
- Work out the subdivision of the Bone Spring versus the Cutoff Formations where the units are shown but the interpretations have changed over time.
- Work out the Victorio Peak–San Andres problem which relates to Goat Seep (which is really now known as the Grayburg and Queen).
- Resurvey road cuts in and around both parks.
- Conduct hazard and rockfall assessments, although most susceptible areas do not seem to affect facilities.
- Essentially remap approximately one quadrangle worth of Carlsbad Group in Guadalupe Mountains National Park (not quad specific); New Mexico Bureau estimates ~$100,000 to do that work.

Use of Lidar Technology for Higher Resolution

Charles Kerans and Mike Gardner see the use of lidar technology as a great asset to refining any mapping and future research and would like to have these data available for the Guadalupe Mountains and Delaware Basin in the very near future.

They "rough" estimated the data acquisition at between $60,000 for a "poor- man's DEM" and $100,000 for full lidar coverage.

Various ideas were proposed on how to go about accomplishing this task; cooperators need to follow up with these items. Joe Gregson told the group of the Department of the Interior (DOI) high- priority program to obtain funding through regions for lidar information. He mentioned that leveraging with adjacent land-management agencies (e.g., USDA Forest Service and BLM) often is the most successful way to acquire funding for obtaining this technology.

Digital Geologic Map Coverage

As stated earlier, it was agreed upon by the consensus of the group that the King and Hayes maps were worthy of digitization with the caveat of the "desired enhancements" already listed. Once the maps exist in a digital format, they are easier to refine both in the field and electronically.

GRI staff in Denver will attempt to accomplish this digitization in their work plan in FY- 2002. Of note is the existence of digital line work for Hayes' map in Professional Paper 446, but there is no accompanying metadata. GRI staff would also like to get it attributed as per their NPS digital geologic map model. Dave Roemer (Carlsbad Caverns National Park, GIS) will need to be consulted for more specifics on metadata for this coverage.

Charles Kerans thought that another additional piece of information that should be tied to any digital geologic database would be measured stratigraphic sections that could be geo- referenced and brought up in a GIS. This should be easy to add in to the NPS digital geologic database model.

Other Desired GIS Data

Soils

Pete Biggam (NPS soil scientist) supplied the following information in reference to soils for both parks:

We currently have in place an interagency agreement with the NRCS to map all National Park System units in Texas, based upon an estimated completion by 2005 (as funding allows).

We are estimating that we might initiate soils mapping at Guadalupe Mountains National Park in 2003, and would be utilizing the NRCS soil survey crew that is currently located in El Paso, Texas. This, of course, is dependent on funding being provided by NPS I&M for this effort.

We operate similar to the GRI: we would schedule a soil scoping session, look at soils research that was already performed at Guadalupe Mountains National Park, map it to National Cooperative Soil Survey standards with local input from Guadalupe Mountains National Park in regards to their soil resource management concerns.

Products would be a digital soils map, digital soil attributes, metadata, soil report, as well as potentially some soil information/education products that could be incorporated into interpretive programs. There would be data that would be utilized within the NPS GIS theme manager as well, similar to what is being done with GRI.

We would also have a "last acre mapped session," where we would have a soils field tour of the park.

Please note: The Soil Resources Inventory for Guadalupe Mountains National Park is currently in progress and completion is anticipated in 2010 (Judy Daniels, Soil Resources Inventory Program, e- mail, January 17, 2008).

Geologic Hazards

Guadalupe Mountains National Park has a published hazards map from R. R. Railsback (University of Texas at Dallas) that was done in 1976. It has been digitized by Parsons Engineering. It is titled, *Geologic Hazards in the Pine Springs Canyon Area, Guadalupe Mountains National Park.*

Paleontology

Greg McDonald (GRD paleontologist) would like to see an encompassing, systematic paleontological inventory for both Guadalupe Mountains and Carlsbad Caverns National Parks, describing the known resources in both parks with suggestions on how to best manage these resources.

Other Sources of Data

- Charles Kerans did a presentation, "Hierarchical Stratigraphic Analysis of a Carbonate Platform, Permian of the Guadalupe Mountains." He mentioned that much of this information will be available on CD-ROM in the near future. It will likely be available from the Texas Bureau of Economic Geology Web site (http://www.beg.utexas.edu). GRI staff is interested in obtaining a copy of this once it is available to the public.
- The Colorado School of Mines has a Web site for research on the slope and basin consortium at http://www.mines.edu/Academic/geology/sbc/

Interpretation

Participants discussed interpretation of geologic resources; topics included the following:

- The Permian Reef Complex should be better utilized in both parks as the major interpretive focus, and the tie of the Guadalupe escarpment between both parks should be made to illustrate the importance of the Capitan Reef as a world- class feature. This should also serve to illustrate the regional GUMO- CAVE story for Permian time.
- Make better use of park trails to showcase and interpret the geology for visitors.
- A reef diorama showing modern analogs and the process of reef building could be added to the displays in each visitor center.
- Mike Gardner has offered to assemble a Bone Springs–Shumard trail guide for Guadalupe Mountains National Park (for free).
- Make better use of the story of P. B. King's "interpretations" of the reef as a major contribution to the science of geology in general.

Geologic Interpretation (*action items)

- Geology trails: surface and *cave
- 3D geologic and geomorphic representation of cave and trails
- *Geologic story / core knowledge (need to get the word out to resource managers, interpreters, and visitors)
- GUMO—Roadside geology waysides targeting lay people
- Include both ancient and modern processes
- GUMO—Global Boundary Stratotype Section and Point of the Middle Permian
- How do we relate geology to a visitor's own experiences?

GIS

- East and West Carlsbad 15- minute geology maps (ca 1957) digitized
- Staff at Guadalupe Mountains National Park has applied for SEPAS funding for 7.5- minute geologic mapping (field assistant); GRD would digitize.

Other digital data needs:

- Linear features (lineaments)
- Springs/seeps
- Soils maps
- GUMO—Springs/seeps
- GUMO—Caves
- Paleontological locations
- Geologic hazards

Data synthesis could be done by GRD or Albuquerque GIS shop.

Research

- David Hunt—Syndepositional faulting in the back reef
- Cave microbiology—Spider and Lechuguilla Caves
- Cave development in the Guadalupes—Synthesis publication due out this fall
- Infiltration study—Used for environmental assessment; proposed dye trace of Bat Cave Draw (CAVE staff)
- GUMO—Fossil sponges, geopetals, Sr- isotope dating
- GUMO—Deep channels (Mike Gardner's group)
- Add hydrologic studies, Quaternary studies, gypsum dunes
- David Wilkins did Quaternary mapping of the Salt Flat basin

Gorden Bell says investigators' annual reports (IAR) get done, but investigators do not catalog paleontological specimens.

Potential Partnerships

(e.g., money, technical guidance and reviews, library materials)

- Course materials
- Updating park libraries
- Technical assistance
- Presentations and programs
- WIPP and other national labs
- Universities—students and faculty
- NSF monies
- NCKRI (caves and karst institute)
- GRD
- USGS
- Oil industry

Oil companies that close down may be very willing to give their publications holdings to NPS libraries; therefore, contact AAPG for donations of collections from retirees ready to donate their collections.

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Guadalupe Mountains National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2008/023
NPS D-181, February 2008

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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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