National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/1046

ON THE COVER: Visitors hike along the Canadian River in October 2012. The colorful Permian red beds provide a scenic backdrop for hiking, as well as birdwatching, camping, swimming, hunting, horseback riding, boating, and fishing in Lake Meredith National Recreation Area. National Park Service photograph available at http://www.nps.gov/lamr/planyourvisit/things2do.htm.

THIS PAGE: Alibates Dolomite is a distinctive layer in the Permian red beds at Alibates Flint Quarries National Monument. The dolomite yields the famous Alibates flint, which prehistoric peoples used for making tools. The dolomite also served as a "canvas" for prehistoric people to chip and peck petroglyphs. National Park Service photograph from National Park Service (2014a, p. 9).

Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/1046

Katie KellerLynn

Colorado State University Research Associate
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

September 2015

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

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

KellerLynn, K. 2015. Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/1046. National Park Service, Fort Collins, Colorado.

NPS 618/129982, 434/129982, September 2015

Contents

Contents (continued)

Figures

Page

Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument on 11 May 2011, which was held by the NPS Geologic Resources Division to identify geologic resources of significance and geologic resource management issues and needs, as well as the status of geologic mapping. It is a companion document to previously completed GRI GIS data.

Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument are adjacent units of the National Park System in the Canadian River Valley, which cuts through the Texas Panhandle. In this report, the park units are referred to separately by their respective designations or collectively as "the parks." Although the parks were established by Congress at different times to meet different purposes, the National Park Service operates them using the same staff and facilities. Consistent with a joint approach for administration, this Geologic Resources Inventory (GRI) report and accompanying GRI GIS data provide information for both park units.

This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information. The NPS Geologic Resources Division conducted no new fieldwork in association with this report. Chapters of this report discuss distinctive geologic features and processes within the parks, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI GIS data. A poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each map unit in the GRI GIS data, as originally mapped by Eifler and Barnes (1969).

Geologic features and processes of significance for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument include the following. They are ordered with respect to geologic time, with older features discussed before younger features.

- **Geologic Structures**. The Amarillo uplift and Anadarko and Palo Duro basins are the primary geologic structures of interest for the parks. These features formed about 300 million years ago during the Pennsylvanian Period. They are important because they controlled the areas of erosion and deposition, including deposition about 260 million years ago of the Permian red beds so prominently displayed at the parks. Also, these structures influenced the locations of oil and gas reservoirs.
- **Permian Red Beds**. The Permian red beds at the parks consist of sandstone, evaporites (sediments deposited from an aqueous solution as a result of evaporation), and carbonates (sediments composed of carbonate minerals) that accumulated in a vast ocean 260 million years ago. These brightly colored rocks—which were mapped as the undivided Quartermaster Formation, Cloud Chief Gypsum, and Whitehorse Sandstone (map unit **Pqw**)—are exposed in the Canadian River Valley, which is also known as the Canadian Breaks.
- **Alibates Dolomite and Alibates Flint**. Alibates Dolomite (**Pqwa**) is situated amongst the Permian red beds at the parks. In places, silica replaced the dolomite in a process called "chertification," creating multi-hued, mottled or banded Alibates flint, which was mined in prehistoric times from more than 700 quarries. Alibates Dolomite boulders in the parks provided a medium for prehistoric Indians to carve or peck images, called "petroglyphs," into stone. These are a rare resource in the Texas Panhandle.
- **Triassic Rocks**. Similar to Permian red beds, Triassic rocks are brightly colored. They crop out on the western edge of Lake Meredith National Recreation Area and consist of two formations—Tecovas (**TRdv**) and Trujillo (**TRdj**). These terrestrial rocks were deposited approximately 230 million–220 million years ago and are contemporaneous with the famous Chinle Formation, which is exposed in the Painted Desert of Petrified Forest National Park in Arizona and throughout the American Southwest.

- **Ogallala Formation**. The Tertiary Ogallala Formation (**To**) overlies the Permian red beds, or where they are present in Lake Meredith National Recreation Area, Triassic rocks. The formation underlies much of the Great Plains and is significant because it contains the Ogallala aquifer—the main source of water for agricultural and domestic use on the Southern High Plains of Texas and New Mexico. In the panhandle, the Ogallala Formation is exposed at the surface; it forms the rim of the Canadian Breaks within the parks.
- **Paleontological Resources**. Permian, Triassic, Tertiary, and Quaternary fossils have been documented from the rocks and unconsolidated deposits in Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument.
- **Dissolution of Red Beds.** Evaporite rocks—commonly composed of halite (“salt”) or gypsum—dissolve as groundwater runs through them. Regionally, a broad zone of dissolution occurs beneath the Canadian River Valley, and caused large areas of land to “settle” or subside. The High Plains surface on the northern side of the valley is 75 m (250 ft) lower than the High Plains surface on the southern side of the valley as a result of dissolution. “Chimneys,” which are filled with collapsed material that fell into a dissolution void, are a distinctive feature at the parks. Sinkholes are a significant dissolution-related feature in the region, though scoping participants noted only one sinkhole in the national recreation area and none in the national monument.
- **Karst**. Karst is a type of landscape that forms through the dissolution of soluble bedrock, characteristically limestone and dolomite, but also halite (“salt”) and gypsum, which is the case in the Texas Panhandle. Karst features of the Texas Panhandle are not well documented, but the parks are considered “karst areas” because evaporite rocks occur at or near the land surface.
- **Rock Shelter**. True caves, hosting environmental conditions conducive to cave climate or cave life, are not known to occur at the parks, but at least one “rock shelter” is known. Although investigation is needed, this rock shelter is thought to have formed as a result of erosion of a less resistant rock layer below a more resistant rock layer, probably in Permian strata. It is not associated with dissolution typical of a karst area.
- **Canadian River**. The Canadian River flows 1,458 km (906 mi) from its headwaters in southern Colorado to where the river joins the Arkansas River in eastern Oklahoma, passing through Lake Meredith National Recreation Area on its way. Many intermittent tributaries, locally known as “side streams,” join the Canadian River in the national recreation area. Eifler and Barnes (1969) mapped fluviatile (“belonging to a river”) terrace deposits (**Qt**) at the parks. These deposits are significant features that record past floodplains and downcutting of the Canadian River and tributaries.
- **Canadian Breaks and Caprock Escarpment**. As the Canadian River cut its course into the Ogallala Formation and underlying bedrock, it carved a notable canyon referred to as the “Canadian Breaks.” Incision by the river and many tributaries created a rough and broken topography that is in stark contrast to the surrounding, relatively flat plain. A widespread erosional scarp (line of cliffs), called the “Caprock Escarpment,” marks the top of the Canadian Breaks and delineates the edge of the Central High Plains and Southern High Plains. The upper rim of the Caprock Escarpment is composed of the Ogallala Formation, which has a hardened zone of caliche (calcium carbonate) as much as 10 m (30 ft) thick in its upper part.
- **Lake Meredith**. Lake Meredith was created in 1965 by the construction of Sanford Dam at a narrow point in the Canadian Breaks. Water in the reservoir is managed by the Canadian River Municipal Water Authority, which operates and maintains the dam and manages water supply for 11 municipalities. Water level fluctuates on account of municipal water demands, rainfall in the watershed, and releases from upstream reservoirs. The National Park Service is responsible for providing public access to recreational opportunities, including water-based recreation in Lake Meredith and land-based recreation beyond the lake basin.
- **Aeolian Features and Processes**. Sand dunes (**Qsd**), sand sheets (**Qs**), and loess (windblown silt; **Ql**) occur in the vicinity of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. At a scale of 1:250,000, none of these features were mapped within the parks, however. Scoping participants noted sand dunes in the Rosita area. Sources of aeolian material include the Canadian River Valley and playa lakes (**Qp**). In the geologic past, aeolian processes were

significant for the development of the Ogallala Formation caprock, which required a considerable influx of aeolian carbonate dust. Windblown ash from volcanic fields along the Yellowstone hot-spot track is a distinctive aeolian feature in the Texas Panhandle; this material was used in making Borger cordmarked pottery.

Geologic resource management issues at Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument identified during the GRI scoping meeting include the following. They are ordered with respect to management priority, though some similar issues of lower priority are grouped with higher priority issues.

- **Oil and Gas Production**. The parks are within the Panhandle Field, which has produced oil and gas since the first well was drilled in 1918. Oil and gas production continues in and near the parks. As of September 2013, there were 174 operations in Lake Meredith National Recreation Area and five operations in Alibates Flint Quarries National Monument. In 2002, the National Park Service completed an oil and gas management plan that guides management of oil and gas activities at the parks.
- **Accelerated Erosion and Sedimentation**. Fine-grained sediment, which washes from slopes onto Stilling Basin Road and the Sanford-Yake boat ramp, creates slippery mud and poses a hazard for people and vehicles. Unmaintained oil and gas access roads become severely gullied during rainstorms. In the past decade, the National Park Service has improved many roads by installing water bars and diversion ditches to more adequately handle heavy rains. Managing runoff is a consideration during planning for projects in the parks.
- **Off-Road Vehicle Use and Disturbed Land Restoration**. Off-road vehicle (ORV) use is allowed in two designated areas of Lake Meredith National Recreation Area—Big Blue Creek at the north end of the park and Rosita at the south end. ORV use is a geologic issue as it relates to wind- and precipitation-induced erosion and associated dust storms and accelerated sedimentation. In 2015, the National Park Service completed an ORV management plan.
- **Wind Erosion and Dust Storms**. Wind in the Texas Panhandle is constant. Wind erosion and dust storms are the primary issues, particularly in areas of oil and gas activities and ORV use, which denude vegetation and expose the ground surface, making sediment available for wind transport. Lower lake levels during periods of drought expose formerly submerged areas of Lake Meredith to wind erosion. By contrast, when lake levels are high, wind creates nearly constant wave action, which erodes the shorelines. In areas not impacted by wave action, wind processes can help in protecting resources, such as dust in-filling of historic flint quarries.
- **Wind Energy Development**. Texas is first in the nation in the production of wind-powered energy. Wind turbines and wind farms have been constructed near the parks. The primary impacts of wind turbines include noise, turbine strikes, and visual impacts. Other impacts are due to construction and development activities, such as power lines and "fugitive dust" churned up and transported by vehicles. Specific concerns are habitat fragmentation and loss, and the spread of transmission infrastructure.
- **Abandoned Mineral Lands and Borrow Site**. Alibates Flint Quarries National Monument does not contain any abandoned mineral lands. The national recreation area contains two abandoned surface mines where rock, sand, and gravel were removed during construction of Sanford Dam. The National Park Service has mitigated one of these features and the other requires no mitigation. The national recreation area has an active borrow site, which provides sand and gravel for NPS and Canadian River Municipal Water Authority projects.
- **Slope Movement Hazards**. Slope movements are gravity-driven, naturally occurring or human-caused geologic hazards that can impact park resources, infrastructure, and human safety. Slope movements at the parks include slumping as a result of fluctuating lake levels and rockfall, for example dolomite boulders on erodible slopes.
- **Sinkhole Collapse and Erosion**. Sinkholes are not as common in the parks as they are in other parts of the Texas Panhandle, but scoping participants noted one in the Plum Creek area. This sinkhole may be an issue with respect to protection of infrastructure or visitor safety as a result of locally accelerated erosion. The sinkhole was not in need of mitigation at the time of GRI scoping in 2011; its present condition is unknown.

- **Lake Level**. Since 2001, water volume in Lake Meredith has dropped to less than 1% of its available storage capacity as an outcome of drought. Fluctuating water levels will occur and are part of management at the national recreation area. As lake level has dropped ephemeral wetlands have developed in the lake basin. In the long term, a cycle of wetland inundation or desiccation and regrowth is the norm. The 2014 general management plan emphasized flexibility in order to accommodate varying lake levels and a management approach that takes better advantage of lands beyond the lake basin.
- **Changes to Hydrology**. Human activities—such as water use by 11 municipalities; flood control, which has encouraged the spread of salt cedar; and interception of groundwater discharge at springs/stock ponds outside the national recreation area that would otherwise provide streamflow within the park—have affected the hydrology of the Canadian River system. Furthermore, an increasing demand for water in Amarillo may result in additional wells drilled in the area, which could result in the loss of flow in some of the tributaries. The current drought is another factor in a decreasing water table and decreasing discharge at springs, which in turn by affect streamflow.
- **Paleontological Resource Inventory, Monitoring, and Protection**. The oil and gas management plan for the parks was the first in the National Park System to provide standard operating procedures for locating and protecting fossils in area with oil and gas operations. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation. A field-based inventory has not been conducted at the parks, but a variety of publications and resources provide park-specific information and resource management guidance. The NPS Geologic Resources Division can provide assistance in conducting a field-based survey.
- **Seismic Hazards**. The Texas Panhandle has a long history of tectonic activity, though the current risk is relatively low. Scoping participants noted that magnitude-4 earthquakes have been felt at Lake Meredith but no seismically related damage has occurred. A moderate (magnitude 5.0) earthquake has a probability of 0.02–0.03 (2%–3% "chance") of occurring near the parks in the next 100 years. Tectonic activity created significant now-buried structures (uplifts and basins) about 300 million years ago. Folds and faults in the Permian red beds record minor movement since 251 million years ago, but this movement may have resulted from dissolution, rather than tectonic forces.
- **Cave Management**. The development of a park-specific cave management plan for Lake Meredith National Recreation Area would evaluate the significance of the rock shelter at Rosita and the need for monitoring and protection. The NPS Geologic Resources Division can facilitate the development of a cave management plan.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products. This chapter describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

The GRI team thanks **Ed Kassman**, **Steve Simon**, and **Jeremiah Kimbell** (NPS Geologic Resources Division) for their input about oil and gas issues at the parks, and **Dale Pate** (NPS Geologic Resources Division) for guidance about karst and rock shelters in the National Park System. Also, thanks very much to **Eddie Collins** (University of Texas at Austin, Bureau of Economic Geology) for reviewing the report and providing photographs. We greatly appreciate his time and expertise. **Arlene Wimer** (Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument) provided information from the draft natural resource condition assessment that was relevant to this report. **Hal Carspecken** and **Carol Simpson** from the NPS library and Technical Information Center (Denver, Colorado) put in much effort to obtain some documents (including Wilson 1988) and their assistance is appreciated. **Trista Thornberry-Ehrlich** (Colorado State University) drafted a number of graphics used in this report.

Review

Eddie Collins (University of Texas at Austin, Bureau of Economic Geology)
Jason Kenworthy (NPS Geologic Resources Division
Hal Pranger (NPS Geologic Resources Division)

Editing

Rebecca Port (NPS Geologic Resources Division)

Report Formatting and Distribution

Jason Kenworthy (NPS Geologic Resources Division)
Rebecca Port (NPS Geologic Resources Division)

Source Maps

University of Texas at Austin, Bureau of Economic Geology
Texas Water Development Board
Texas Commission on Environmental Quality

GRI GIS Data Production
Andrea Croskrey (NPS Geologic Resources Division)
Heather Stanton (Colorado State University)

GRI Poster Design
Georgia Hybels (Colorado State University)

GRI Poster Editing
Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

Geologic Setting and Significance

This chapter describes the regional geologic setting of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument and summarizes connections among geologic resources, other park resources, and park stories.

Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument are in the Texas Panhandle of the Great Plains physiographic province (figs. 1 and 2; plate 1). The surface of the Great Plains is broken by the valley of the Canadian River. The river flows eastward from the Sangre de Cristo Mountains into the western part of the national recreation area, and onward to Oklahoma. The Canadian River Valley, also known as the "Canadian Breaks," separates the Central High Plains on the north from the Southern High Plains on the south (fig. 2).

Figure 1. Regional map showing the location of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. See plate 1 (in pocket) for a larger scale map of the parks. National Park Service graphic available at http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=LAMR (accessed 28 September 2015).

The Canadian Breaks are as much as 60 km (40 mi) wide and 300 m (1,000 ft) deep (Gustavson 1986). They provide a dramatic departure from the otherwise flat-lying, continuous Great Plains surface of the Texas Panhandle. This divergence from the surrounding high, flat, windswept plains offers scenic values and recreational, educational, and scientific opportunities not found elsewhere in the region. The breaks provide landscape diversity by exposing colorful bedrock known as "red beds" (fig. 3). In the parks, red beds include the Permian Whitehorse Sandstone, Cloud Chief Gypsum, and Quartermaster Formation, which were mapped together ("undivided") as unit **Pqw** (see poster, in pocket).

The Permian Period occurred 299 million–252 million years ago (fig. 4). The red beds at the parks are approximately 260 million years old. Alibates Dolomite (**Pqwa**), which contains the renowned Alibates flint, is situated amongst the red beds. For thousands of years, people came to the red bluffs above the Canadian River to dig the colorful, banded or mottled flint to make projectile points, knives, and other tools (fig. 5).

On the western edge of the national recreation area, Triassic strata—Tecovas (**TRdv**) and Trujillo (**TRdj**) formations—are also exposed in the Canadian Breaks. These Triassic rocks are approximately 230 million–220 million years old and have been correlated to the famous Chinle Formation at Petrified Forest National Park in Arizona and throughout the American Southwest.

A widespread erosional scarp (line of cliffs), called the Caprock Escarpment, marks the top of the Canadian Breaks (fig. 2). The upper rim of the Caprock Escarpment is composed of the Tertiary Ogallala Formation (**To**). The formation underlies much of the Great Plains and is the primary source of water for agriculture and a substantial source for domestic use in

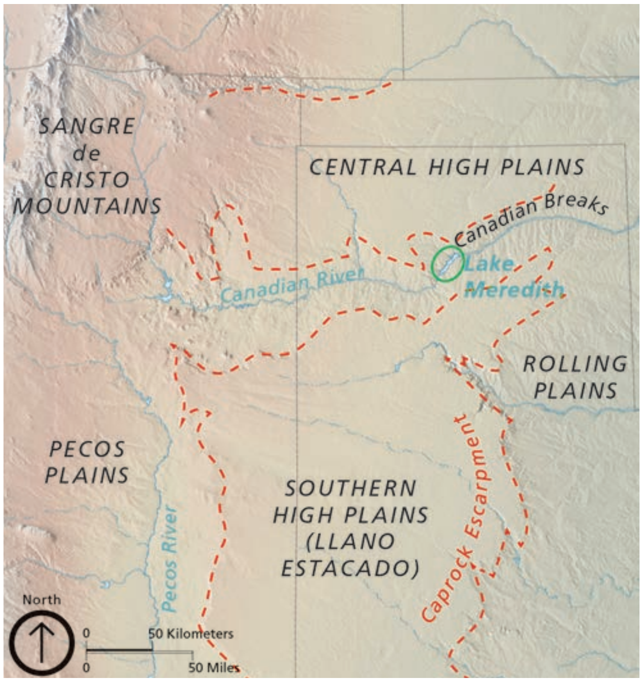


Figure 2. Physiographic map. Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument (green oval) are within the Canadian Breaks, a major physiographic feature that cuts across the Texas Panhandle. In the vicinity of the parks, the breaks, which are outlined by the Caprock Escarpment (red dashed line), divide the High Plains physiographic province into the Central High Plains to the north and the Southern High Plains to the south. The Southern High Plains are also called the Llano Estacado, meaning "Staked Plains" in Spanish, which refers to the laying out of stakes across the plains by early Spanish explorers to find their way back (or so the story goes; Spearing 1991). The Canadian River flows from the Sangre de Cristo Mountains in southern Colorado into the national recreation area. Graphic by Jason Kenworthy (NPS Geologic Resources Division) after Gustavson and Finley (1985, figure 2). Base map by Tom Patterson (National Park Service).

the region (Gustavson 1996). In the High Plains region of Texas and New Mexico, the Ogallala Formation overlies Permian through Cretaceous strata and is overlain by the Quaternary Blackwater Draw Formation (**Qbd**).

The Sanford Dam at the northeastern end of the national recreation area created Lake Meredith. In 1962, the Bureau of Reclamation began construction of the dam, which was named for the nearby town of Sanford, Texas. The dam impounds water in the Canadian River basin for use by 11 municipalities in the Texas

Figure 3. Photograph of red beds at Alibates Flint Quarries National Monument. As mapped by Eifler and Barnes (1969), the Permian red beds at the parks are composed of the Quartermaster Formation, Cloud Chief Gypsum, and Whitehorse Sandstone, which were mapped as an undivided unit (Pqw). Alibates Dolomite (Pqwa) is a sedimentary layer amongst these strata. Photograph by Katie KellerLynn (Colorado State University).

Panhandle. Although Lake Meredith is primarily a water supply reservoir, recreation is also among its intended uses. Visitors enjoy hiking, fishing, hunting, picnicking, camping, and when lake levels allow, boating and other forms of water-based recreation.

The national recreation area encompasses 18,203 ha (44,978 ac). It was originally established as "Sanford National Recreation Area" in 1965 and administered in cooperation with the Bureau of Reclamation; the National Park Service was designated to manage recreation. In 1972, the name of the recreation area was changed to "Lake Meredith Recreation Area" to honor A. A. Meredith, an early promoter of the dam. In 1990, the recreation area was re-designated as part of the National Park System, and the name was changed

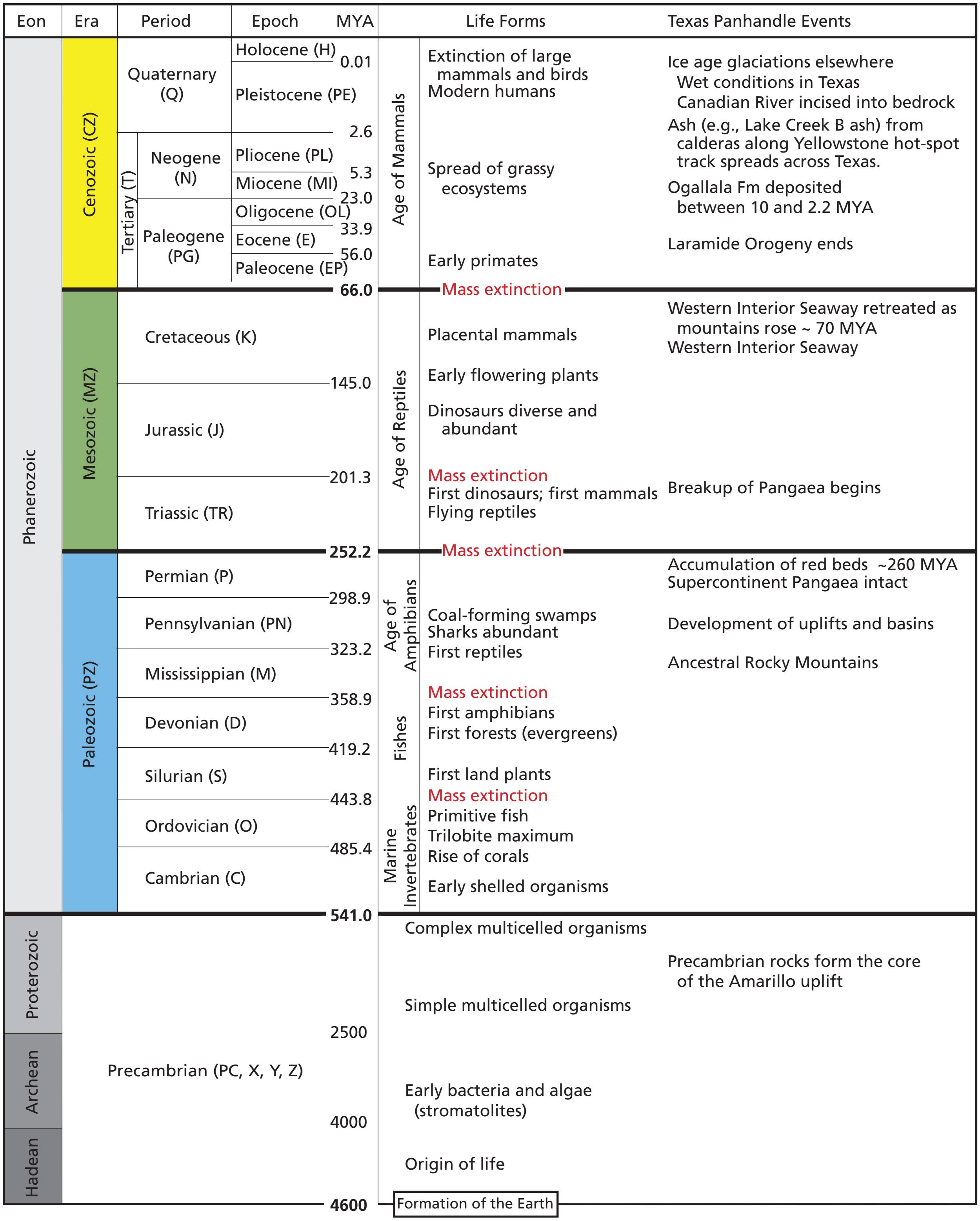


Figure 4. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). The right column of the time scale summarizes significant events in the geologic story of the parks. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

Figure 5. Photograph of Alibates flint projectile points. Prehistoric Indians mined flint—a colorful form of chert (microcrystalline quartz)—from more than 700 quarries in the national monument and used it to make projectile points and other tools. Presumably, it was prized for both its ability to hold an edge and its beauty. National Park Service photograph available at http://commons.wikimedia.org/wiki/File:Alfl_arrowheads_from_flint_20060717161306.jpg.

to "Lake Meredith National Recreation Area." The Canadian River Municipal Water Authority manages the water of Lake Meredith.

In 1965 Congress authorized "Alibates Flint Quarries and Texas Panhandle Pueblo Culture National Monument." The national monument was renamed "Alibates Flint Quarries National Monument" in 1978. Because of the need to protect archeological sites and resources, access to the national monument is limited to guided tours, many of which are led by trained volunteers (National Park Service 2012). The national monument encompasses 555 ha (1,371 ac) of land adjacent to Lake Meredith National Recreation Area (fig. 1; plate 1).

The national monument is noted for more than 700 flint quarries. These quarries and other cultural sites (within both parks) show evidence of 13,000 years of human occupation, including the only remaining village of the Antelope Creek people and a series of petroglyphs (National Park Service 2012). The Antelope Creek people lived in the Texas and Oklahoma panhandles between 1150 and 1450 CE (common era [preferred to AD]). Over this 300-year period, hundreds of quarries were dug and mined along a small section of the Canadian River, much of which is preserved in the national monument. Early archeologists thought that the Antelope Creek people were descendants of New Mexican Pueblo Indians, thus reflecting the original name of the monument. Now, however, investigators think that they probably came from Eastern Woodland tribes. The Antelope Creek people left the Texas Panhandle abruptly around 1450 CE, perhaps forced to leave by drought, disease, or hostile Apaches. They may have gone east and joined other Caddoan-speaking tribes, such as the Pawnee or Wichita (National Park Service 2015a).

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument.

During the 2011 scoping meeting (see scoping summary by KellerLynn 2011), participants (see Appendix A) identified the following geologic features and processes. They are ordered with respect to geologic time, with older features discussed before younger features.

- Geologic Structures
- Permian Red Beds
- Alibates Dolomite and Alibates Flint
- Triassic Rocks
- Ogallala Formation
- Paleontological Resources
- Dissolution of Red Beds
- Karst
- Rock Shelter
- Canadian River
- Canadian Breaks and Caprock Escarpment
- Lake Meredith
- Aeolian Features and Processes

Geologic Structures

Geologic structures such as uplifts and basins make up Earth's architecture. The Amarillo uplift, Anadarko Basin, and Palo Duro Basin are the primary geologic structures of interest for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument (fig. 6). The Amarillo uplift—the "high" upon which the parks lie—is a buried mountain range with a core of rock more than 500 million years old (Precambrian; fig. 4). The geologic structures themselves developed about 300 million years ago (Pennsylvanian Period; fig. 4); the adjacent basins developed as the mountains rose.

The ancient mountains of the Amarillo uplift are now buried by as much as 1,800 m (6,000 ft) of sediment (Dutton and Goldstein 1988). The Anadarko Basin is one of the deepest basins in the continental United States; it is now filled with approximately 12,000 m (40,000 ft) of sedimentary rock (Ball et al. 1991). The Palo Duro Basin contains about 3,000 m (10,000 ft) of sediment (Dutton et al. 1979).

Although they are not visible at the surface, the importance of these features is at least twofold: (1) they controlled the areas of erosion and deposition, including deposition of the red beds so prominently displayed at the parks, during multiple mountain-building events (see "Permian Red Beds" section); and (2) they host oil and gas source rocks in the Texas Panhandle.

The rocks in the vicinity of the parks that produce oil and gas are "granite washes" and "Permian carbonates" from what is now known as the Cisuralian Series (formerly classified as Wolfcampian Series and Leonardian Series, formed 299 million–272 million years ago). These rocks are older than those exposed as red beds within the parks. Granite washes, which eroded from the granitic bedrock core of ancient mountains (Amarillo uplift), represent coarse-grained alluvial sediments in fan, delta, and possibly braided streams that flowed near the margin of the uplift. Permian carbonates consist of various dolomites and limestones that represent deposition on large-scale, shallow-water marine environments known as carbonate platforms, which developed in the area of the Amarillo uplift (USGS Central Region Assessment Team 2002).

Permian Red Beds

Colorful, layered rocks, known as "red beds" dominate the scenery at the parks. These rocks are exposed in the Canadian Breaks (see "Canadian Breaks and Caprock Escarpment" section). The color is due to oxidation, combining oxygen from the air with iron in the sediments; the result is similar in appearance and process to a rusting nail. Gray, bedded zones in the strata represent times when freshwater input from the land temporarily increased and offset the oxidation process (West Texas A&M University Geological Society 2001).

Most of the red beds at the parks were deposited in a vast ocean that occupied the area about 260 million years ago. They consist of sandstone, evaporites (sediments deposited from an aqueous solution as a result of evaporation), and carbonates (sediments

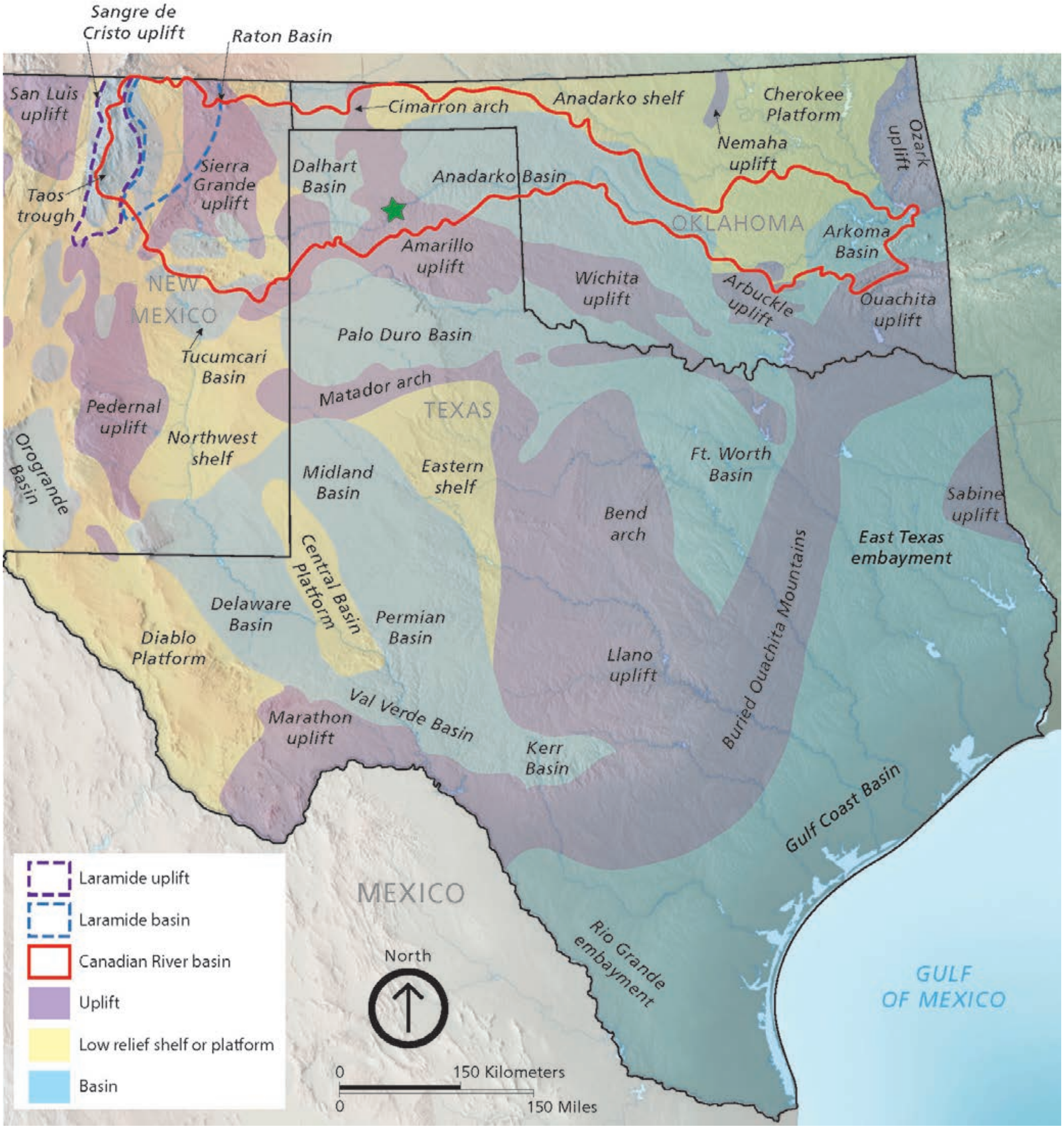


Figure 6. Map of regional geologic structures. The Amarillo uplift and the Anadarko and Palo Duro basins are structures of significance for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. The red outline superimposes the area of the modern-day Canadian River basin over structural features. The purple and blue dashed outlines represent structures formed at the time of the Laramide Orogeny, which occurred some 230 million years after development of the structures in Texas. The parks straddle the Amarillo uplift which is a structural "high" between the Palo Duro and Anadarko basins. Today these structures are buried in thousands of feet of sediment. During the Permian Period, seas covered these basins, as well as the Delaware Basin, where today a spectacular Permian reef complex is exposed in Guadalupe Mountains National Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Dolliver (1984, figure 4), Spearing (1991, p. 27), and Giles (2005). Base map by Tom Patterson (National Park Service).

composed of carbonate minerals) that accumulated during the last minor incursion and subsequent regression of continental seas over the Texas Panhandle (McGillis and Presley 1981).

Eifler and Barnes (1969) mapped the Permian reds beds at the parks as an undivided unit consisting of Whitehorse Sandstone, Cloud Chief Gypsum, and Quartermaster Formation (map unit **Pqw**). These rock formations are difficult to distinguish except by stratigraphic position. Elsewhere in the Texas Panhandle, their stratigraphic position clearly defines them. In the parks, however, the red, orange, brown, and gray sandstone, sand, siltstone, shale, gypsum, and dolomite are interbedded. Furthermore, in places, distinctive ledges of Alibates Dolomite have been removed by erosion, further blurring stratigraphic position of these red-bedded rocks.

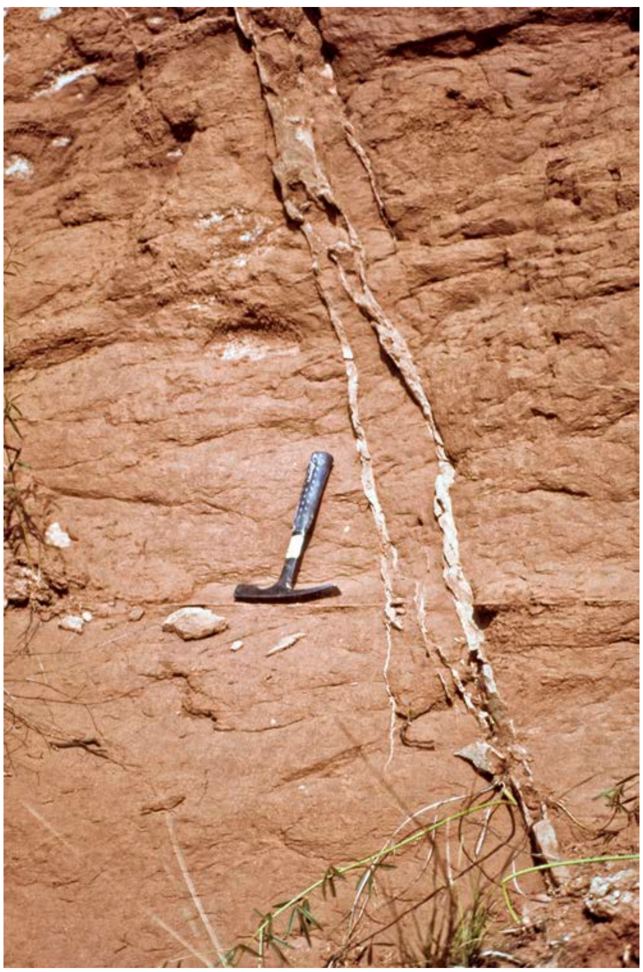


Figure 7. Photograph of sandstone dikes. Sandstone dikes in Permian rocks may represent liquefaction in the geologic past. Today, liquefaction is a geologic hazard in places such as the San Francisco Bay area where earthquake shaking causes water-saturated sediment to temporarily lose strength and act as a fluid. Photograph by Eddie Collins (University of Texas at Austin, Bureau of Economic Geology).

Sandstone dikes—tabular bodies of sandstone that fill fractures—are an interesting feature in the red-bedded strata at the parks. Sandstone dikes can range in thickness from a few centimeters to more than 10 m (30 ft); the ones in the Canadian River Valley are primarily on the centimeter scale (Eddie Collins, University of Texas at Austin, Bureau of Economic Geology, geologist, written communication, 11 June 2015). Although sandstone dikes are uncommon sedimentary structures, they have been reported from numerous localities in rocks ranging in age from Precambrian to Pleistocene (Boggs 1995). The ones at Lake Meredith National Recreation Area and along the Canadian River Valley mostly cut Permian Quartermaster and Whitehorse deposits (**Pqw**), though some are within Triassic deposits. Sandstone dikes also may have disrupted the lower sandstone and conglomerate of the Ogallala Formation (**To**) at local areas within the Canadian River Valley.

Sandstone dikes appear to have formed from liquefied sand injected into fractures of host rocks (fig. 7), though a detailed study of their source beds has not been conducted in the Canadian River Valley, and the timing for the formation of these features is unknown (Eddie Collins, written communication, 11 June 2015). Interestingly, these features may represent liquefaction—a geologic hazard, particularly in "built environments," where earthquake shaking causes water-saturated sediment to temporarily lose strength and act as a fluid. They also may be an indicator of subsidence.

Notable sandstone dikes occur in other National Park System units such as Gila Cliff Dwellings National Monument in New Mexico, where Ratté et al. (2014) mapped them as volcaniclastic rocks of Adobe Canyon (see GRI report by KellerLynn 2014), which formed as the Gila Hot Springs graben dropped down along normal faults during mid-Tertiary time. Additionally, sandstone dikes within the Upheaval Dome structure in Canyonlands National Park in Utah provide important clues for assessing a possible impact origin of that feature (Kenkmann 2003; see report by KellerLynn 2005).

Alibates Dolomite and Alibates Flint

Alibates Dolomite (**Pqwa**), a marine sedimentary rock, is among the red-bedded strata at the parks (fig. 8). It is included as a linear feature in the GRI GIS data (see poster, in pocket). Most exposures of Alibates Dolomite in the national monument yield Alibates flint. Alibates flint is a beautifully mottled or banded, multi-hued (red, pink, pale blue, pale purple, gray, brown, or black) form of chert (fig. 9). Chert is a hard, dense sedimentary rock, consisting of interlocking, microscopic crystals of quartz (silica). Alibates flint is also referred to as "Alibates chert," "Alibates agate," "Alibates agatized dolomite," and "Alibates silicified dolomite" (Quigg et al. 2009). In keeping with the name of the national monument, this report uses "Alibates flint."

Geologist Charles Newton Gould named the Alibates Dolomite for Alibates Creek in Potter County (Gould 1907). The type section (place of original description) is along the creek about 2 km (1.2 mi) south of the national monument. According to Bowers (1975), "Alibates" was a modification of the name Allen Bates, who was the son of a local rancher.

Bowers and Reaser (1996) subdivided the Alibates Dolomite in the national monument into three informal members: lower dolomite, middle red beds, and upper dolomite (fig. 8). The presence of two beds of dolomite (a marine sedimentary rock) suggests a sequence of transgression (sea level rise) when dolomite was deposited, followed by regression (sea level fall) when red beds were deposited, finishing with another transgression when dolomite was deposited again (Boyd 1987; see "Geologic History" chapter).

At the national monument, the upper dolomite member forms massive layers as much as 0.6 m (2 ft) thick that extend laterally for more than 1,000 m (3,300 ft) along a ridge that was the source for the Alibates Flint Quarries (Bowers and Reaser 1996). Although flint is much more abundant in the upper member, it is not confined to any particular bed or stratigraphic horizon. The lower dolomite member contains minor amounts of flint in the form of spheres and nodules (Bowers and Reaser 1996). The lower member ranges between 1 and 3 m (3 and 10 ft) thick and is very resistant to erosion, commonly forming ledges. The lower member provides a local "capstone" on the bluffs in the parks. This capstone is different from the regional-scale Caprock Escarpment, which marks the top of the Ogallala Formation throughout the Texas Panhandle. On

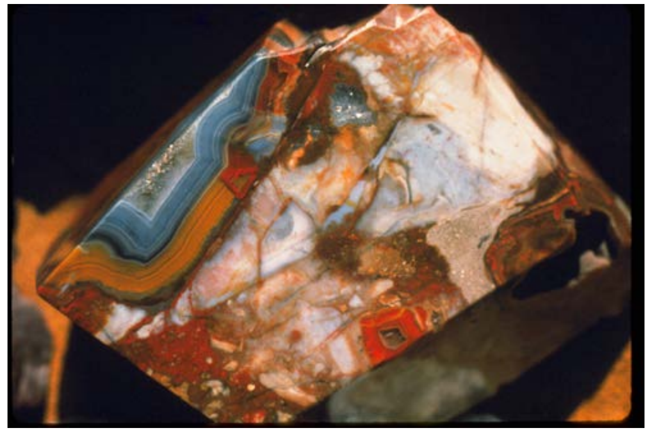
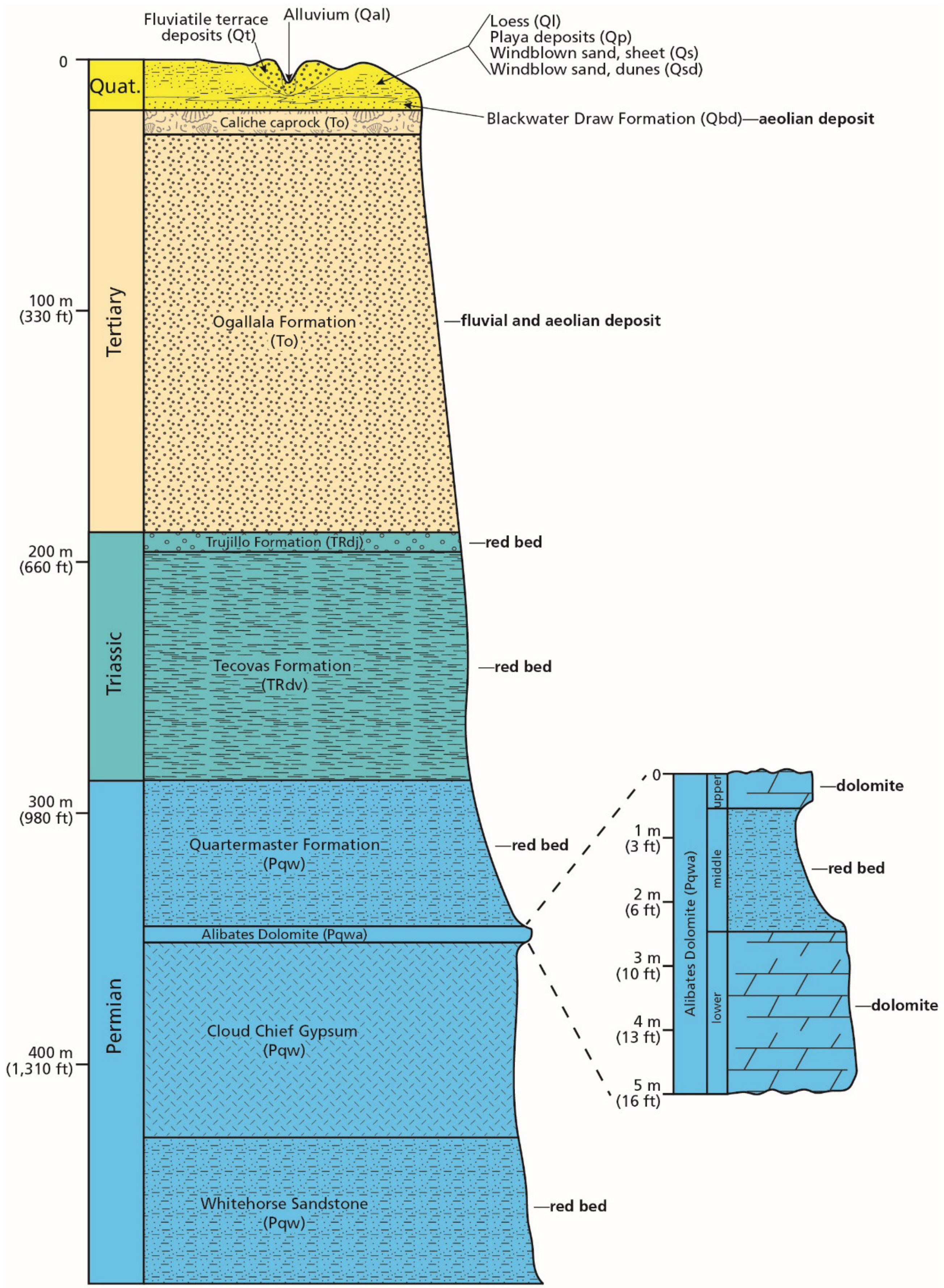


Figure 9. Photograph of cut and polished Alibates flint. Also known as "Alibates chert," "Alibates agate," "Alibates agatized dolomite," and "Alibates silicified dolomite," Alibates flint formed as silica (silicon dioxide, SiO_2) replaced dolomite in a process called chertification. The colors in the flint are caused by trace mineral elements within the silica. The most common colors of red, orange, and yellow are caused by iron; blues and deep greens are usually caused by manganese. National Park Service photograph available at http://www.nps.gov/pub_aff/imagebase.html.

Figure 8 (facing page). Generalized stratigraphic column. The Quartermaster Formation, Cloud Chief Gypsum, and Whitehorse Sandstone, undivided (Pqw) and Alibates Dolomite (Pqwa) compose the Permian strata in Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. Eifler and Barnes (1969)—the source map for the GRI GIS data—did not subdivide these units, but Bowers and Reaser (1996) subdivided the 5-m- (16-ft-) thick Alibates Dolomite into three informal members—lower, middle, and upper (as shown in the figure). The upper dolomite member is locally absent, but where present contains the most abundant flint; it averages 0.6 m (2 ft) thick. The lower dolomite member is resistant to erosion and forms prominent ledges; it averages 1.5 m (5 ft) thick. The upper and lower members are separated by a middle red-to-brown, calcareous mudstone or shale ("red bed"), which ranges between 1 and 3 m (3 and 10 ft) thick. The Ogallala Formation (To) makes up the top of the Caprock Escarpment, which is an impressive feature in the Texas Panhandle and separates the Central High Plains from the Southern High Plains (Llano Estacado) in the Great Plains physiographic province. Incision by the Canadian River followed deposition of the Ogallala Formation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Boyd (1987, figure 3) and Bowers and Reaser (1996, figure 2).


Fluviatile terrace deposits (Qt)
Alluvium (Qal)
Loess (Ql)
Playa deposits (Qp)
Windblown sand, sheet (Qs)
Windblow sand, dunes (Qsd)
Blackwater Draw Formation (Qbd)—aeolian deposit
0
Quat.
Caliche caprock (To)
100 m
(330 ft)
Tertiary
Ogallala Formation
(To)
—fluvial and aeolian deposit
Trujillo Formation (TRdj)
—red bed
200 m
(660 ft)
Triassic
Tecovas Formation
(TRdv)
—red bed
300 m
(980 ft)
Permian
Quartermaster Formation
(Pqw)
—red bed
Alibates Dolomite (Pqwa)
400 m
(1,310 ft)
Cloud Chief Gypsum
(Pqw)
Whitehorse Sandstone
(Pqw)
—red bed
0
1 m
(3 ft)
2 m
(6 ft)
3 m
(10 ft)
4 m
(13 ft)
5 m
(16 ft)
Alibates Dolomite (Pqwa)
upper
middle
lower
—dolomite
—red bed
—dolomite

average, the caliche caprock is as much as 10 m (30 ft) thick or twice as thick as the dolomite capstone (Hunt and Santucci 2001; see “Canadian Breaks and Caprock Escarpment” section).

Alibates flint formed via a process called chertification, first proposed by Norton (1939), where silica (silicon dioxide, SiO_2) replaces the original dolomite. Percolating groundwater transported silica from overlying strata into the underlying dolomite; silica surrounded and eventually replaced individual dolomite crystals.

The source of silica in Alibates flint is unknown, but various investigators have hypothesized about its origin. Bowers and Reaser (1996) concluded that most of the silica comes from overlying rocks. Thus flint formed long after Permian seas receded from the area. Potential source rocks of silica include the following:

- Triassic Rocks. In the western part of the national recreation area, Triassic rocks crop out. These rocks are mostly terrestrial in origin and contain chert and petrified logs (see “Paleontological Resources” section), which are evidence of significant quantities of silica.
- Tertiary Ogallala Formation. Extensive deposition of opal (amorphous silica) in some places of the Ogallala Formation indicates a more recent possible source of silica (Norton 1939; Frye and Leonard 1959; Bowers and Reaser 1996).
- Volcanic Ash. Starting about 16.5 million years ago (Miocene Epoch; fig. 4), ash erupted from volcanic centers such as the Jemez Mountains in New Mexico (see GRI report about Bandelier National Monument by KellerLynn 2015a) or Yellowstone in Wyoming (see “Aeolian Features and Processes” section). This ash may be a source of silica. Cepeda (2001) and Cepeda and Perkins (2006) discussed a 9.5-million-year-old, vitric (“glassy”) ash bed on the east bank of West Amarillo Creek (two tributaries west of the national recreation area), and hypothesized its source as the Twin Falls volcanic field in southern Idaho. That volcanic field is part of the Yellowstone hot-spot track (fig. 10). Their published findings, however, did not specifically associate this ash layer with chertification of Alibates Dolomite, though scoping participants suspected a connection (see KellerLynn 2011).

Flint breaks into smooth curves known as conchoidal fractures because of its resemblance to a conch shell. The smooth curves are ideal for scraping. Additionally, chert is capable of holding a sharp edge, making it an excellent cutting tool.

An unusually high number and variety of artifacts representing the entire spectrum of flint extraction and manufacturing have been recovered from Alibates Flint Quarries National Monument. These artifacts provide opportunities for scientific research and study of prehistoric quarrying techniques (National Park Service 2014a).

Subsequent to mining, the quarries have partially filled with windblown dust (see “Aeolian Feature and Processes” section). Scoping participants estimated that 23 cm (9 in) of fine-grained sediment has settled in the quarries over the last 500 years (see KellerLynn 2011). This, along with vegetation growth, provides protection from weathering and erosion (National Park Service 2014a).

Transport of Alibates Flint

Scoping participants noted that the Canadian River, which cuts into the Permian red beds, has transported pieces of Alibates flint downstream into western Oklahoma (KellerLynn 2011). Fluvially transported flint appears in gravel deposits along the Canadian River as far as 275 km (170 mi) away. Some of the material is cobble-sized and would be suitable for the production of stone tools (Quigg et al. 2009). In general, Alibates flint transported downstream by fluvial processes will have the rounded and polished surfaces of “river rock” in contrast to quarried sources that were transported by humans, which exhibit rough or pitted surfaces.

Alibates flint has been found in archeological sites across Texas and the Great Plains, and as far away as Montana and the Great Lakes (Spearing 1991). Scoping participants noted that specimens of Alibates flint have been identified 360 km (225 mi) west of the national monument at Pecos National Historical Park in New Mexico (see GRI report by Port 2015).

Although generally distinctive, the precise identification of Alibates flint (and other types of archeologically significant chert) can be tenuous because materials overlap in color, banding patterns, texture, and translucency. Thus archeologists may inadvertently associate artifacts with the incorrect geological source.

Figure 10. Map of Yellowstone hot-spot track and extent of the Lava Creek B ash. The Yellowstone hot spot remained stationary as the North American plate moved to the southwest (arrow). The ages (in millions of years, on the figure) of the various volcanic fields indicate this progression, starting with the McDermitt volcanic field (approximately 16.5 million–15 million years ago) to the present location under Yellowstone. The purple shading on the figure shows the estimated area covered by the Lava Creek B ash, which erupted from the Yellowstone caldera approximately 639,000 years ago. This is the most recent eruption from Yellowstone. A sample site used by Izett and Wilcox (1982) for this ash occurs on the border of Moore and Potter counties, though not in the parks. Ash from the Twin Falls volcanic field is exposed in the banks of West Amarillo Creek (see fig. 18). The green star represents the approximate location of the parks. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Izett and Wilcox (1982). Ages from Smith and Siegel (2000).

To help resolve this visual identification problem, Quigg et al. (2009) sampled two spatially distinct Alibates outcrops in the national monument; five spatially distinct outcrops in the Tecovas Formation (**TRdv**) of the lesser known Tecovas jasper (a typically red variety of chert) at the western end of the national recreation area and in Caprock Canyon State Park in Quitaque, Texas; and one gravel source from the Canadian River. Samples were analyzed using instrumental neutron activation at the Research Reactor Archaeometry Laboratory at the University of Missouri. The method geochemically separated Tecovas and Alibates samples and further differentiated geochemical signatures of multiple Tecovas source areas. According to Quigg et al. (2009), these chemical results can be used to correctly identify and sort chipped stone tools and debitage (waste material produced during the production of stone tools) from far-reaching archeological contexts well beyond the Alibates and Tecovas source areas. Future studies will strive to make quarry-specific identifications of the materials (Quigg et al. 2009).

Petroglyphs

Alibates Dolomite (**Pqwa**) boulders provided surfaces for carving or pecking images into stone, called "petroglyphs." The images resemble animals such as turtles (fig. 11) and bison, a large footprint (fig. 11), and a humanlike figure with its arms spread above its head (National Park Service 2012). The Antelope Creek people, who occupied the area between 1150 CE and 1450 CE, are thought to be responsible for creating most of the petroglyphs (Derrick 2007). The parks contain petroglyphs, which are rare in the Texas Panhandle (National Park Service 2014a).

Figure 11. Photographs of petroglyphs. Images such as a turtle (top) and foot (bottom) were chipped into Alibates Dolomite by Antelope Creek people between 1150 CE and 1450 CE. National Park Service photographs of foot available at http://www.nps.gov/media/photo/view.htm?id=55B94515-155D-451F-6751C41AA6589B2D and turtle available at http://www.nps.gov/media/photo/view.htm?id=55B89FF7-155D-451F-67402117E28DFFAD.

The petroglyphs at the parks have not been fully documented (National Park Service 2014a). This is a resource-management need because some of the petroglyphs are at present barely visible and will eventually weather away. The types of weathering most detrimental to petroglyphs are unknown but may include wind erosion via abrasion ("sand blasting") (see "Wind Erosion and Dust Storms" section). Digital imaging of petroglyphs and recording locations in GIS are means of documentation. Digital imaging also could be used to measure the effects and rates of weathering on petroglyphs in the Texas Panhandle. The NPS Geologic Resources Division may be able to assist with photogrammetric documentation of the petroglyphs, as well as establishing a baseline for monitoring.

Triassic Rocks

Triassic strata—Tecovas (**TRdv**) and Trujillo (**TRdj**) formations—crop out on the western edge of the national recreation area. Similar to the parks' Permian red beds, these rocks are brightly colored. In places, the Tecovas Formation consists of three distinguishable layers. The top layer is orange shale; the middle layer is light-colored soft sandstone; and the bottom layers consist of variegated shale layers with maroon and yellow as the dominant colors, but also dark red, purple, and white (Boyd 1987). In places, the Trujillo Formation is prominent brown sandstone with interbedded red and gray shales. In contrast to the marine origin of the parks' Permian rocks, the Tecovas and Trujillo formations were deposited in continental environments such as lakes and streams (see "Geologic History" chapter).

Two outcrops of Tecovas jasper are reported from Potter County and one in Oldham County (Cameron 1980). Other outcrops are known (Boyd 1987). Tecovas jasper is not as high quality as Alibates flint, but along the eastern Caprock Escarpment of the Texas Panhandle, it was a dominant tool-making material (Boyd 1987).

Ogallala Formation

The Tertiary Ogallala Formation (**To**) overlies the Permian red beds at the parks. In the western part of the national recreation area, the formation overlies Triassic rocks. The Ogallala Formation has particular significance for the area because it contains the Ogallala aquifer—the main source of water for agricultural and domestic use in the Southern High Plains (Gustavson 1996). In addition, the aquifer has long been the source of water for many natural springs along the Caprock Escarpment and in the Canadian River Valley (Boyd 1987; see "Canadian Breaks and Caprock Escarpment" section). These springs provide water to many of the side streams that flow into the Canadian River (see "Canadian River" section). Moreover, the Ogallala Formation yields fossils (see "Paleontological Resources" section). Also, it may be a source of silica in Alibates flint (see "Alibates Dolomite and Alibates Flint" section).

The Ogallala Formation ranges in thickness from a feather-thin edge to as much as 170 m (550 ft) (Eifler and Barnes 1969). Most Ogallala sediments were transported from mountainous areas west of the Texas Panhandle (e.g., Sangre de Cristo Mountains; fig. 2) by ancestral rivers along a few entrenched stream courses that flowed east and southeastward across northeastern New Mexico. Fine-grained fluvial, lacustrine, and aeolian deposits eventually filled fluvial valleys and collapse basins, forming a relatively flat plain of alluvial material, rather than a series of alluvial fans. As the climate became increasingly arid, development of the plain ended with the formation of caliche (erosion-resistant, calcium-carbonate rock) on a relatively stable landscape, that is, in the absence of tectonic upheaval or significant erosion (Dolliver 1984).

Deposition of the Ogallala Formation has not been precisely dated but probably began less than 10 million years ago during the late Miocene Epoch and continued throughout most of the Pliocene Epoch until 3 million–2 million years ago (fig. 4; Dolliver 1984). Interestingly, basalt flows in the Raton–Clayton volcanic field in New Mexico helped to date the end of Ogallala deposition. Capulin Volcano National Monument is part of this volcanic field (see GRI report by KellerLynn 2015b). Lava flows of Raton Basalt (9.0 million–3.5 million years old) overlie the Ogallala Formation; Clayton Basalt (3.0 million–2.2 million years old) occupies ancient valleys that were incised into the Ogallala Formation (Gustavson and Finley 1985; Stroud 1997). These dates bracket the deposits and indicate that Ogallala fluvial sedimentation in northeastern New Mexico probably ceased 3.5 million years ago and certainly by 2.2 million years ago (Dolliver 1984).

Paleontological Resources

Hunt and Santucci (2001), Koch and Santucci (2003), and Tweet et al. (2015) documented information about the paleontological resources at the parks. In addition, Santucci et al. (2001) provided information about procedures for locating and protecting paleontological resources in areas with oil and gas operations (see "Paleontological Resource Inventory, Monitoring, and Protection" section).

Permian Fossils

The parks contain evidence of past life from as long ago as 260 million years (Permian Period). Alibates Dolomite (**Pqwa**) preserves algal mats (fig. 12), sometimes referred to as stromatolites (Tweet et al. 2015). These mats formed on supratidal mud flats along the global ocean "Panthalassa" where algal filaments trapped and bound together mud composed of a calcium-carbonate mineral called "aragonite" and gypsum crystals (McGillis and Presley 1981). Modern environments, such as the wind-tidal flats in Padre Island National Seashore, host algal mats (see

Figure 12. Photograph of algal mat at Alibates Flint Quarries National Monument. During the Permian Period, algal filaments in supratidal mud flats bound together mud and crystals forming the algal mats seen today along the trail to Alibates Flint Quarries. The fossil shown is approximately 25 cm (10 in) across. Photograph by Katie KellerLynn (Colorado State University).

GRI report about Padre Island National Seashore by KellerLynn 2010a). These living algal mats support the productive and diverse benthic communities in Laguna Madre and may serve as a modern analog for a similar depositional setting of Alibates Dolomite.

Triassic Fossils

In Lake Meredith National Recreation Area, the Triassic Tecovas Formation (**TRdv**) yields petrified wood (fig. 13). The formation also contains fragments of amphibian and reptile fossils (Tweet et al. 2015). The other Triassic rock unit in the park—the Trujillo Formation (**TRdj**)—has not yielded any fossils to date, but fragmentary vertebrate fossils are likely (Tweet et al. 2015). Interestingly, these Triassic rocks have been correlated to the famous Chinle Formation of Petrified Forest National Park in Arizona (Lucas 1993, 2001; Hunt and Santucci 2001; see GRI report about Petrified Forest National Park by KellerLynn 2010b).

Tertiary Fossils

The Tertiary Ogallala Formation (**To**) is perhaps the most notable fossil-bearing unit in the parks (KellerLynn 2011). Hunt and Santucci (2001) reported six fossil localities in the Ogallala Formation in the Lake Meredith area, three of which are definitely attributed to NPS lands (Tweet et al. 2015). The other three occurrences were reported by Wilson (1988) but lack detailed locality information and cannot be attributed definitively to either park (Tweet et al. 2015). Wilson (1988) noted bone scraps, reworked Cretaceous bivalves (perhaps *Texigryphaea*), and limestone in the "Potter Creek Member" (informal member of the Ogallala Formation introduced by Wilson 1988); root casts, silicified grass anthoecia ("flower"), *Celtis* (hackberry) endocarps ("pit" or "stone" in some fruits), insect burrows, and vertebrate remains in the "LX Member" (informal name in Wilson 1988); and gastropod molds, imprints of two fish, and vertebrate fossils in the thin flaggy upper bed of the "Coetas Member" (informal name in Wilson 1988). One of the fossil localities within Lake Meredith National Recreation Area yielded a now-lost proboscidean (elephants and relatives) tooth, which was tentatively identified as from a mastodon but probably is from a gomphothere (Tweet et al. 2015). This fossil was recovered from Cedar Canyon near the eastern end of the national recreation area during the placing of a restroom pipe. A second fossil locality identified in the national recreation area was a bone bed with unspecified fossils in the Turkey Creek area. The third locality yielded turtle remains and other in situ bones at the southern end of the national monument.

Figure 13. Photograph of petrified wood. Paleontological resources at Lake Meredith National Recreation Area include petrified wood from Triassic rocks, which have been correlated with the famous Chinle Formation of Petrified Forest National Park in Arizona. The palm of the hand provides a sense of scale. Fossil collecting is prohibited in the parks. Photograph by Katie KellerLynn (Colorado State University).

Quaternary Fossils

Quaternary sediments, including Pleistocene fluviatile ("belonging to a river") terrace deposits (**Qt**), have yielded plant debris and invertebrate burrows as old as 80,000 years, as well as gastropods, a mammoth humerus, a *Bison latifrons* skull, and a bison rib fragment, which range in age from 2.6 million to 11,700 years ago. The skull found in the national recreation area is a rare, well-preserved specimen of a 40,000-year-old female *Bison latifrons*. It is displayed at the Panhandle-Plains Historical Museum in Canyon, Texas, which is the repository for both paleontological and archeological materials from the parks.

A deposit of Lava Creek B ash, known to be 639,000 years old (Lanphere et al. 2002), yielded crayfish burrows and abundant plant material at the national recreation area (Hunt and Santucci 2001). Additionally, a rodent burrow with charcoal, as well as reworked petrified wood and Cretaceous oysters (*Texigryphaea*), occur in Quaternary sediments (Tweet et al. 2015).

Deposits of Holocene alluvium (**Qal**), aeolian sand in sheets and dunes (too small to have been mapped by Eifler and Barnes 1969, scale 1:25,000), and soils have yielded some fossil material within the national recreation area. Many of these fossils are associated with archeological sites (Panhandle Aspect or Culture, approximately 1200–1450 CE) and include bones of turtles, snakes, owls, hawks, ducks, geese, swans, grouse, corvids, rodents, rabbits, canids, bobcats, badgers, deer, pronghorn, cows, and bison at the national monument; and bony fish, frogs/toads, turtles, snakes, ducks, perching birds, moles, rodents, rabbits, dogs, badgers, deer, pronghorns, and bison at the national recreation area (Tweet e al. 2015). Cultural contexts can be significant localities for paleontological material (see "Paleontological Resource Inventory, Monitoring, and Protection" section).

Figure 14. Photograph of collapse chimney near Fritch Fortress. Chimneys formed as a result of dissolution of salts in the Permian red beds and subsequent collapse of overlying strata into voids. Most chimneys, such as this one (outlined with white dashed line) near Fritch Fortress, are exposed in road cuts or bluffs, although some stand in relief (see fig. 15). GRI scoping team for scale. Photograph by Katie KellerLynn (Colorado State University).

Dissolution of Red Beds

Evaporite rocks—commonly composed of the minerals halite ("salt") and gypsum—are particularly susceptible to dissolution by groundwater, notably from the Ogallala aquifer. Groundwater percolates along fractures in red-bedded rocks and dissolves the layers of salt and gypsum. At the parks, the undivided Quartermaster Formation, Cloud Chief Gypsum, and Whitehorse Sandstone (**Pqw**) is the unit most susceptible to dissolution. Dissolution in Permian strata results in the collapse of overlying material—such as Triassic rocks (**TRdv** and **TRdj**) and the Ogallala Formation (**To**)—into voids below.

"Chimneys" are a distinctive dissolution-related feature at the parks. They are circular or elliptical in cross section and filled with collapse debris. During excavation for the Sanford Dam, 27 chimneys were discovered in the Permian rocks (Eck and Redfield 1963). The largest chimney exposed at the dam site is approximately 305 m (1,000 ft) across (Gustavson et al. 1980). Most chimneys are buried and only exposed in road cuts or bluffs (fig. 14). Some chimneys, however, stand in relief. One such chimney may be highlighted along a proposed geology trail in the national recreation area (fig. 15; "Lake Level" section). This feature is an estimated 7 m (24 ft) tall. Erosion stripped away the rock surrounding the collapsed material, leaving a solid column above the ground surface.

Figure 15. Photograph of exposed chimney. This distinctive chimney stands in relief in Lake Meredith National Recreation Area, just north of Alibates Flint Quarries National Monument. The red strata are composed of an undivided unit consisting of the Quartermaster Formation, Cloud Chief Gypsum, and Whitehorse Sandstone (Pqw). The white boulders in the background are composed of Alibates Dolomite (Pqwa). Photograph by Katie KellerLynn (Colorado State University).

Dissolution collapse is ultimately a self-limiting process because as overlying rocks collapse into a void, they break up, and the many smaller pieces occupy a larger space than the original undisturbed rock. In this way, a void created by dissolution can be "used up" and the upward propagation of collapse may never reach (or be visible at) the surface (Gustavson et al. 1982).

Where dissolution collapse does reach the surface, sinkholes commonly form (see “Sinkhole Collapse and Erosion” section). Sinkholes have formed in historic times. These and saline springs, with as much as 3,000 parts per million dissolved salts, are evidence of ongoing dissolution in the area (Spearing 1991; KellerLynn 2011).

Regionally, a broad zone of salt dissolution occurs beneath the Canadian River Valley (fig. 16; Gustavson et al. 1980). At this scale, dissolution has caused large areas of land to “settle” or subside. As a result of this process, the High Plains surface on the northern side of the valley is 75 m (250 ft) lower than the High Plains surface on the southern side of the valley (Gustavson 1986). Up to 300 m (1,000 ft) of dissolution-related regional subsidence has occurred; 25%–60% of this probably took place during the Pleistocene Epoch (2.6 million–11,700 years ago; fig. 4) when climate was much wetter (Gustavson et al. 1980). Also, subsidence basins, which formed on the surface of the Ogallala Formation (**To**), intercepted easterly and southeasterly flowing streams, including the headwaters of the Canadian River (Gustavson and Finley 1985). Thus subsidence markedly influenced the position of the Canadian River (Dolliver 1984).

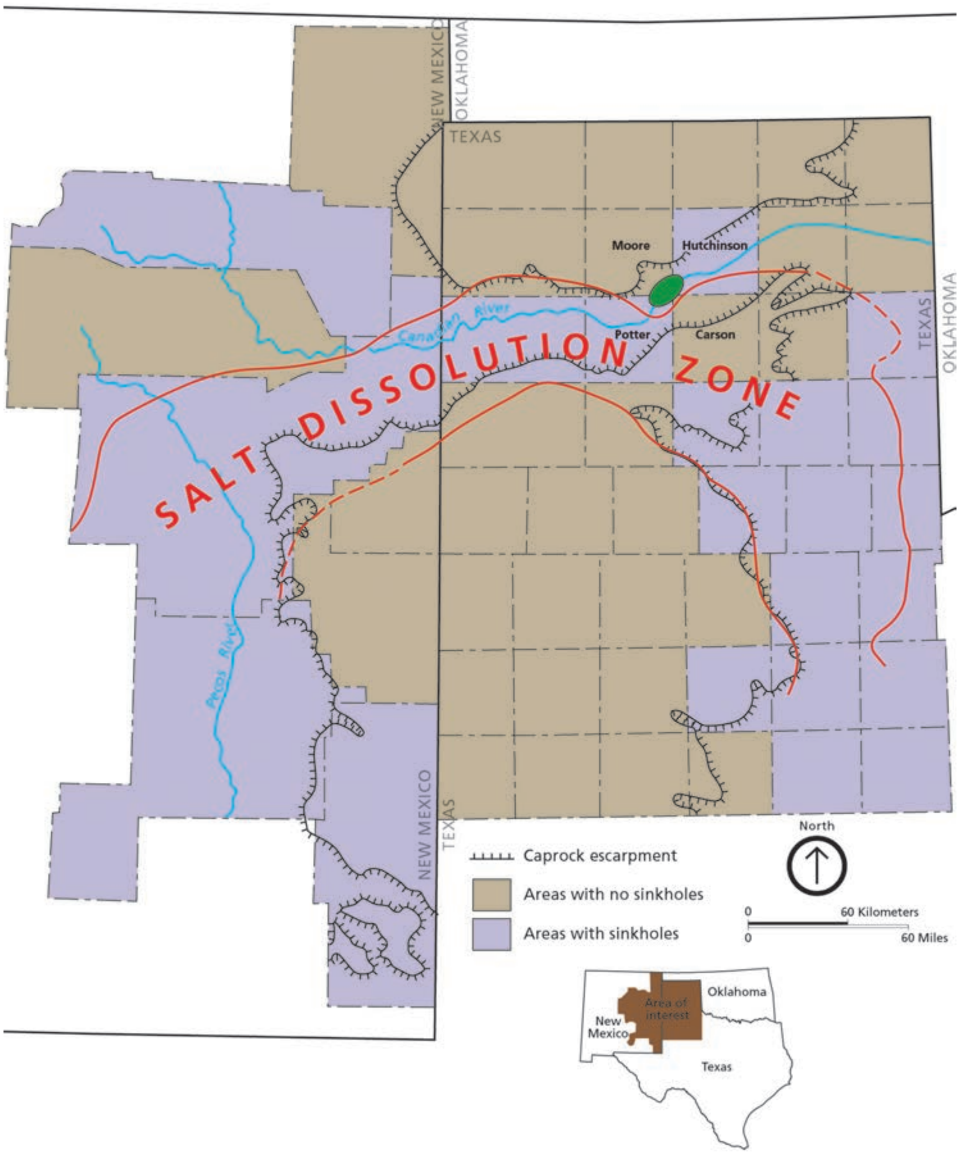


Figure 16. Map of salt dissolution zone. Bedded Permian evaporites underlie the Texas Panhandle. Dissolution of these evaporites, primarily halite (“salt”) and secondarily gypsum, has created a zone of dissolution, which influenced the position of the Canadian River Valley. Subsidence basins intercepted easterly and southeasterly flowing steams. Note that Lake Meredith (green oval) is on the northern edge of this zone. Also, note the general distribution of areas with and without sinkholes. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Gustavson et al. (1982, figure 1).

Karst

In a study about caves and karst in the National Park System, Ek (2008) defined karst as any carbonate, sulfate, or other rock capable of relatively rapid dissolution by water under naturally occurring pH ranges. That study identified the parks as karst areas. Additionally, the US Geological Survey’s digital map compilation and database of karst shows the Texas Panhandle as karst underlain by evaporite rocks (fig. 17; Weary and Doctor 2014).

Karst features of the Texas Panhandle are not well known, but have been described by Miotke (1969) and Smith (1971), who attributed these features mainly to dissolution of

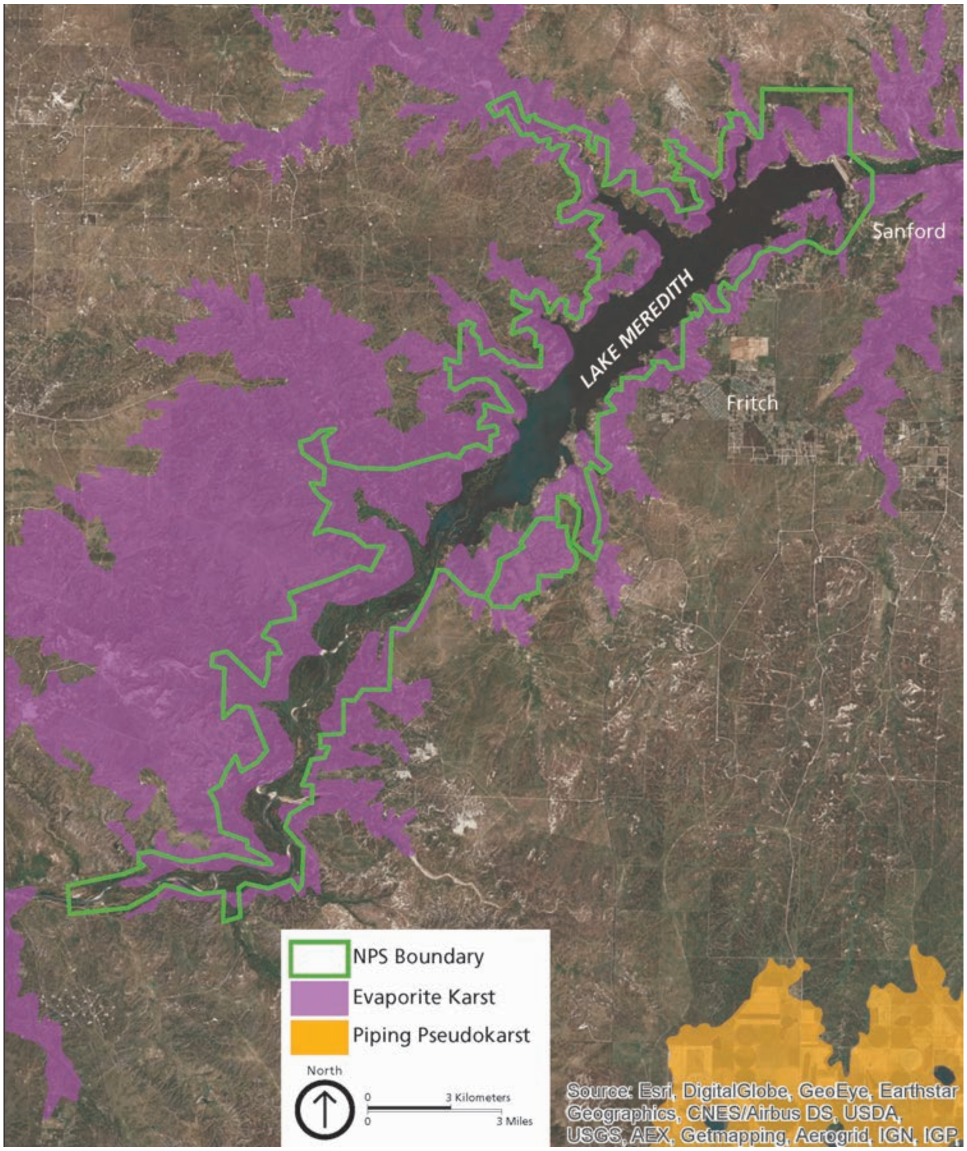


Figure 17. Map of karst area. Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument (green outline) intersect carbonate and evaporite rocks that are susceptible to dissolution (purple area; mapped by Weary and Doctor [2014] as "Evaporite rocks at or near the land surface in a dry climate"). In the parks, that area is mapped as Pqw (see poster). Outside of the parks, rocks are susceptible to piping pseudokarst (orange area). Graphic by Jason Kenworthy (NPS Geologic Resources Division) with data from Weary and Doctor (2014).

gypsum. Baker (1977) recognized the relationship between karst features and the dissolution of both salt and gypsum and suggested a preliminary model for the movement of saline groundwater through karst terrain.

Karst features at the parks are probably "gypsum karst," similar to the "salt karst" of the Anadarko Basin to the north (Johnson 2013). Salt karst and associated collapse structures in the Anadarko Basin are an outcome of partial or total dissolution of salt layers near the surface; dissolution results in the collapse of overlying strata. Gypsum karst and resultant collapse of overlying strata have been proposed in many parts of the Anadarko Basin. Typically, gypsum beds in the basin are only 1–6 m (3–20 ft) thick and beneath more than 100 m (330 ft) of overlying strata. As such, they do not contribute to the disruption of surface strata, except where they are within about 10–20 m (30–70 ft) of the surface (Johnson 2013).

Rock Shelter

In 2011, scoping participants noted an "overhang" or "rock shelter" in the Rosita area of the national recreation area (see poster, in pocket). This feature is probably not the result of dissolution. Rather, it formed via erosional processes removing softer materials from underneath a harder ledge of rock. Rock shelters beneath overhangs could have easily formed in several different geologic units in both parks (Dale Pate, NPS Geologic Resources Division, cave specialist, written communication, 1 April 2015). The feature at Rosita probably occurs in Permian strata (Eddie Collins, University of Texas at Austin, Bureau of Economic Geology, geologist, written communication, 8 June 2015). Further investigation is needed to appropriately categorize this feature and identify its rock type (see "Cave and Associated Landscape Management" section).

Canadian River

The Canadian River flows 1,458 km (906 mi) from its headwaters in southern Colorado to a confluence with the Arkansas River in eastern Oklahoma. The main river and several major tributaries drain the eastern flank of the Sangre de Cristo Mountains of southern Colorado and north-central New Mexico; these rarely breach the Ogallala Formation (**To**). Farther east, including within the national recreation area, however, a dense network of short ephemeral streams occupies narrow terraced valleys (see "Terraces" section) that are incised as much as 180 m (600 ft) below adjacent uplands capped by the Ogallala Formation.

In Lake Meredith National Recreation Area, many short creeks drain into the Canadian River or Lake Meredith from the north and south (plate 1). Those on the north flow through named canyons such as Martins, Evans, Devils, Big, and Saddle Horse. On the south side of Lake Meredith, South Canyon contains an ephemeral stream. Most of the creeks in the national recreation area, including Bugbee, North Turkey, Rosita, Bonita, Chicken, Coetas, Mullinaw, Alibates, South Turkey, and Short, have intermittent flows (plate 1 and fig. 18). Big Blue Creek and Plum Creek are larger, with perennial flows. Alibates Flint Quarries National Monument contains a segment of intermittent Alibates Creek.

Terraces

Pleistocene terraces are a significant fluvial feature at Lake Meredith National Recreation Area. Eifler and Barnes (1969) mapped these features as fluviatile terrace deposits (**Qt**) composed of gravel, sand, and silt. These landforms line the Canadian River corridor, including side channels, and represent the location of past floodplains.

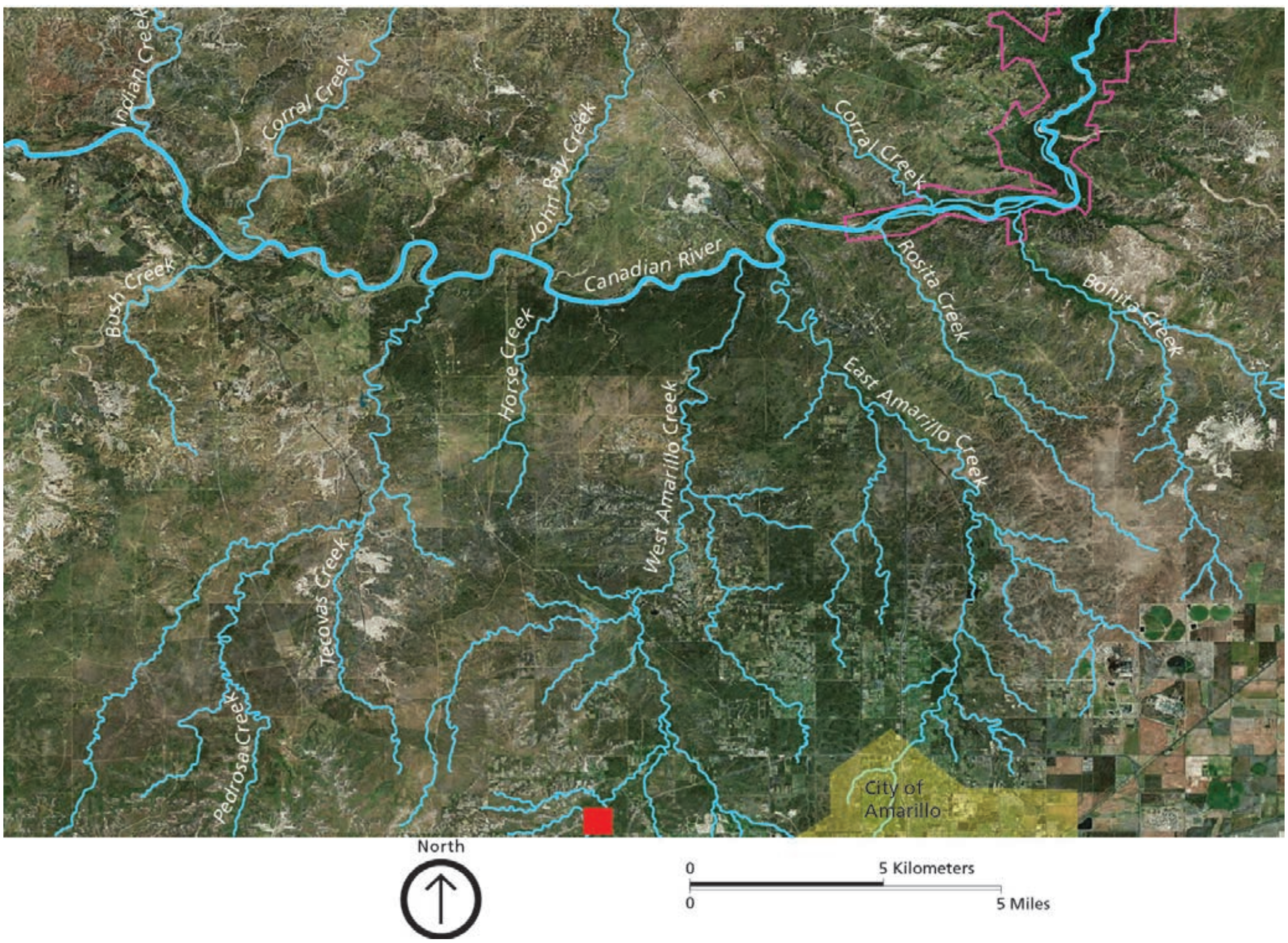


Figure 18. Map of major tributaries to the Canadian River. The red square on the map marks the location of an outcrop of volcanic ash along West Amarillo Creek, upstream from Lake Meredith. The source of this 9.5-million-year-old ash was most likely the Twin Falls volcanic field of southern Idaho (see fig. 10). Portions of Rosita, Corral, and Bonita creeks are within Lake Meredith National Recreation Area. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Cepeda and Perkins (2006, figure 1). Base imagery by ESRI World Imagery.

Commonly, investigators will divide terraces into levels, which show where a river paused in its downcutting and provide a record of incision. Multiple terraces indicate that incision was not constant, stopping and starting over time (Elston et al. 1965; Connell et al. 2005). Eifler and Barnes (1969) did not divide the fluviatile terraces deposits in the national recreation area into levels, but southwest of the national recreation area, Cepeda and Allison (1997) provided more detailed information about the terraces along West Amarillo Creek. This creek is a tributary to the Canadian River (fig. 18). It has three prominent alluvial terraces that flank the channel. The highest terrace is 7–8 m (23–26 ft) above the present-day channel and extends as much as 100 m (330 ft) away from it. An intermediate terrace, 3–3.9 m (10–13 ft) above the creek, occurs on both sides of the channel and within about 20 m (70 ft) of it. The lowest terrace, 1.4–2 m (4.6–7 ft) above the creek, is only locally present and restricted to areas immediately adjacent to the modern channel. According to Cepeda and Allison (1997), incision of the two lowest terraces took place since the middle 1800s as shown by a radiocarbon date of 106.2 years ago and the presence of large, mature cottonwoods with trunks as large as 2 m (7 ft) across on the middle terrace.

Terraces approximately 60 m (200 ft) above the Canadian River on the southern side of the valley near Lake Meredith contain Lava Creek B ash (Izett and Wilcox 1982; see "Aeolian Features and Processes" section). Investigators have revised the age of this ash to approximately 639,000 years old (Lanphere et al. 2002). This age, along with the presence of several lower (younger), undated terraces indicate that incision by the Canadian River has been active throughout the late Quaternary Period (Gustavson 1986).

Canadian Breaks and Caprock Escarpment

After deposition of the Ogallala Formation (**To**), the Canadian River carved its canyon, which is a considerable geologic feature in the region. Incision by the river and many tributaries created a rough and broken topography, referred to as the "Canadian Breaks," which is in stark contrast to the surrounding, relatively flat plain. The breaks are as much as 64 km (40 mi) wide and 300 m (1,000 ft) deep and expose millions of years of geologic history (Gustavson 1986). The top of the breaks is marked by a widespread erosional scarp (line of cliffs), called the Caprock Escarpment. The upper rim of the Caprock Escarpment is composed of an indurated (hardened into rock) caliche zone up to 9 m (30 ft) thick, which is the upper part of the Ogallala Formation (fig. 8).

The presence of carbonate and caliche horizons within Ogallala sediments indicates a prolonged and considerable influx of aeolian carbonate dust, which was likely transported by prevailing winds sweeping across extensive carbonate exposures. Measurement of the accumulation of modern, calcareous, desert loess (windblown silt) (e.g., Ruhe 1967) and soil studies throughout eastern New Mexico and western Texas (e.g., Reeves 1970) support this conclusion (Dolliver 1984; see "Aeolian Features and Processes" section). Surface infiltration of dissolved carbonate during intermittent or seasonal wet periods eventually produced the Ogallala "climax soil" or caprock (Dolliver 1984).

Lake Meredith

Lake Meredith was created by the construction of Sanford Dam on the Canadian River at a narrow point in the Canadian Breaks. Water in the reservoir is managed by the Canadian River Municipal Water Authority, not the National Park Service. The water authority operates and maintains the dam and manages water supply for 11 municipalities through 518 km (322 mi) of pipeline, 10 pumping plants, and three regulating reservoirs, including Lake Meredith. Lake level fluctuates on account of municipal water demands, rainfall in the watershed, and releases from upstream reservoirs (National Park Service 2012).

The National Park Service is responsible for providing public access to recreational opportunities at Lake Meredith National Recreation Area, including water-based recreation in Lake Meredith and land-based recreation beyond the lake basin. Much of the land-based recreation is associated with the lake, including picnic areas and campgrounds near or overlooking the water, and hunting for waterfowl on or near shallow waters in the upper part of the reservoir (see "Lake Level" section). All recreational opportunities are intended to be consistent with the protection of the area's scenic, scientific, and cultural resources and with other values that contribute to public enjoyment (National Park Service 2014a).

According to Canadian River Municipal Water Authority (2015b), reservoir storage of Lake Meredith at the top of its conservation pool is 896.5 m (2,941.3 ft) above sea level. At maximum pool, the reservoir would hold 3.003 billion m^3 (2,434,200 acre feet) of water, which would result in a reservoir area of 12,330 ha (30,470 ac). The reservoir has never reached its projected capacity, however. The highest measured lake level to date was in April 1973 at 888.5 m (2,914.9 ft) above sea level or a lake depth of 31.04 m (101.85 ft) (Canadian River Municipal Water Authority 2015b). The average storage of the reservoir until the year 2000 was around 370 million m^3 (300,000 acre feet), which resulted in a reservoir area of about 4,000 ha (10,000 ac), or about 20% of the national recreation area (National Park Service 2012). The depth of Lake Meredith as of 30 March 2015 was 13.80 m (45.26 ft), which corresponds to 81,733,000 m^3 (66,262 acre feet). The lowest recorded level in the lake was 7.967 m (26.14 ft) on 7 August 2013 (Canadian River Municipal Water Authority 2015b). Water has not been withdrawn from the reservoir since 2011 (Canadian River Municipal Water Authority 2015a).

Aeolian Features and Processes

The GRI GIS data show three types of aeolian features: windblown sand in sheets (**Qs**), windblown sand in dunes (**Qsd**), and loess (**Ql**; windblown silt). At a scale of 1:250,000, the GRI source maps show none of these features within the parks. During the scoping meeting, however, participants noted that sand dunes occur at Rosita near the south end of the national recreation area (plate 1). Notably, off-road vehicle use is permitted in that area (see "Off-Road Vehicle Use and Disturbed Land Restoration" section). Furthermore, loess covers lands south of the national recreation area. The GRI GIS data contain only one polygon delineating loess (**Ql**); it occurs at the southeastern corner of the data.

The valleys of the Pecos and Canadian rivers are sources of aeolian sediment today and also were in the geologic past (McCauley et al. 1981; Gustavson 1996). Additionally, scoping participants surmised that playa lakes (**Qp**)—which are a significant feature in the Texas Panhandle though not mapped within the parks—may be a source of loess (see KellerLynn 2011). The nearest playas to the parks are northwest of Lake Meredith in the Blackwater Draw Formation (**Qbd**), which is itself an aeolian mantle of material, referred to as "cover sands" by Frye and Leonard (1964). Aeolian processes when the Ogallala and Blackwater Draw formations were deposited were probably similar to Holocene (i.e., historic and present-day) aeolian sediment deposition on the High Plains, which is primarily as thin sand sheets and loess (Gustavson 1996).

A distinctive aeolian feature in the Texas Panhandle is windblown ash from the Yellowstone hot-spot track (fig. 10). Izett and Wilcox (1982) mapped material erupted from the Huckleberry Ridge, Mesa Falls, and Lava Creek volcanic fields across the Great Plains. These are the most recently erupted ashes from Yellowstone and referred to as "Pearlette family" ashes. Two of the sampling sites of Izett and Wilcox (1982) are in the vicinity of Lake Meredith; they obtained a Huckleberry Ridge ash sample from a fluvial terrace in Hutchinson County, and a possible Lava Creek B ash sample on the border of Moore and Potter counties. More recently, Lanphere et al. (2002) dated the Yellowstone ashes using the argon-40/argon-39 method: the Huckleberry Ridge, Mesa Falls, and Lava Creek ashes erupted 2.059 ± 0.004, 1.285 ± 0.004, and 0.639 ± 0.002 million years ago, respectively. Cepeda and Perkins (2006) identified a much older—9.5 million years old (Miocene Epoch; fig. 4)—ash bed on the eastern bank of West Amarillo Creek in Potter County (fig. 18). Occurrences of Miocene ash are rare in Texas compared to ash of the Pearlette family. Cepeda and Perkins (2006) suggested that the source of the West Amarillo Creek ash was the Twin Falls volcanic field in southern Idaho, which is part of an earlier explosive stage of volcanism along the Yellowstone hot-spot track (fig. 10).

A further distinction of volcanic, windblown ash in the Texas Panhandle is that it was used in making Borger cordmarked pottery. This style of pottery is best known from a 160-km (100-mi) stretch of the Canadian River and its tributaries in the north-central part of the panhandle (Lynn and Black 2003), including the parks. The exterior surface of a cordmarked pot has hundreds of cord impressions (parallel indentations) left by the use of a cord-wrapped paddle in concert with an anvil stone. Ash is used to "temper" the clay because pure clay may be too flexible to hold its shape, shrinking and cracking as it dries (Lynn and Black 2003).

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument Area. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2011 scoping meeting (see scoping summary by KellerLynn 2011), participants (see Appendix A) identified the following geologic resource management issues. They are ordered with respect to management priority, though some similar issues of lower priority are grouped with higher priority issues.

- Oil and Gas Production
- Accelerated Erosion and Sedimentation
- Off-Road Vehicle Use and Disturbed Land Restoration
- Wind Erosion and Dust Storms
- Wind Energy Development
- Abandoned Mineral Lands and Borrow Site
- Lake Level
- Changes to Hydrology
- Paleontological Resource Inventory, Monitoring, and Protection
- Seismic Hazards
- Cave Resource Management

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring. This manual is available online at http://go.nps.gov/geomonitoring.

The National Park Service completed a foundation document for the parks in 2014 (National Park Service 2014a). A natural resources condition assessment for the parks is underway (summer 2015). The foundation document lists the following as "fundamental" resources or values:

For Lake Meredith National Recreation Area

- Public land
- Recreation opportunities
- Exposed geologic features of the Canadian Breaks

For Alibates Flint Quarries National Monument

- Alibates flint
- Alibates ruin archeological site
- Quarries
- Museum collection

For both parks

- Diverse habitats and ecological transition zones
- Wide range of sites and artifacts
- Opportunity for scientific research

Fundamental resources or values warrant primary consideration during planning and management because they are essential to achieving the purpose of a park and maintaining its significance. Geologic features and processes and some of the resource management issues described in this chapter affect the values and resources highlighted in the foundation document.

Oil and Gas Production

Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument are within the Panhandle Field, which underlies the Texas Panhandle and extends into Oklahoma and Kansas. Since the late 1920s, oil and gas exploration and development have been actively pursued in the Panhandle Field, including the land area that is now within the parks (National Park Service 2000). The earliest well on record in the vicinity of Lake Meredith is the W. T. Mudget well in the Sanford-Yake area, which was completed in 1927. The first well of the Panhandle Field was drilled in 1918 and came about through geologic mapping by Gould (1906, 1907).

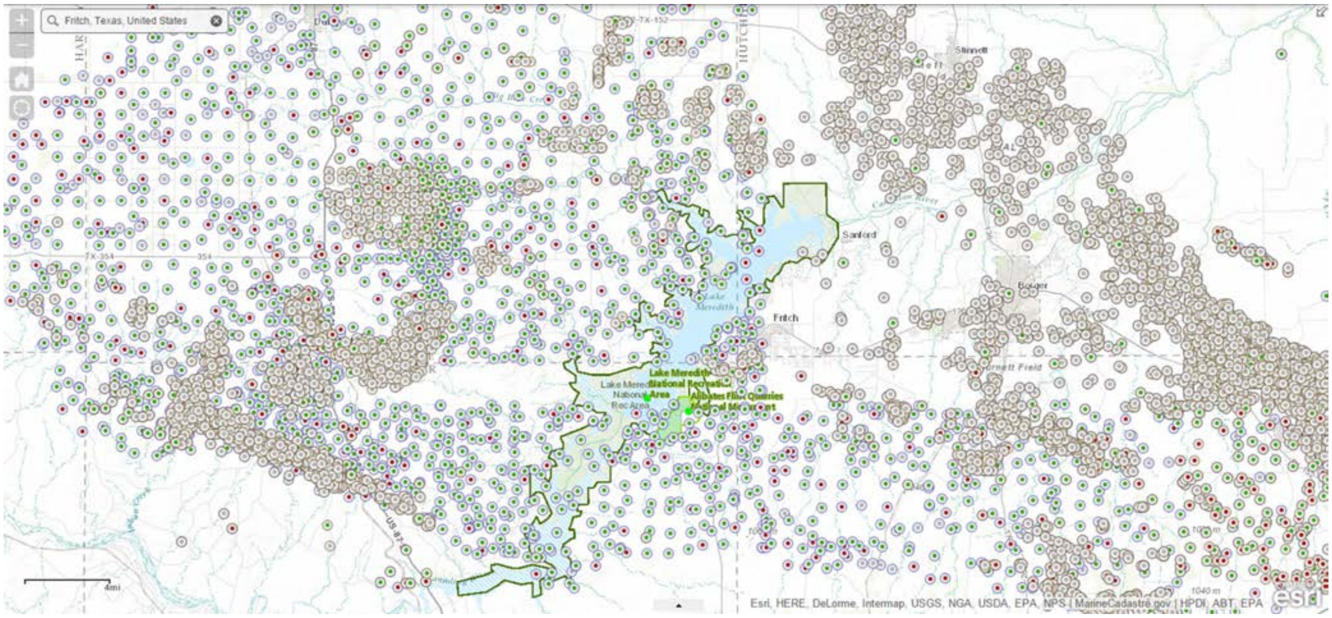


Figure 19. Map of oil and gas wells. As of September 2013, Lake Meredith National Recreation Area contained 174 active oil and gas operations and Alibates Flint Quarries National Monument contained five operations. The GRI GIS data include the location of 594 wells as mapped by Eifler and Barnes (1969). Today, approximately 9,200 additional wells occur in the surrounding four-county area. Green dots indicate active wells. Red dots indicate inactive wells. Brown dots indicate documented wells of other or unknown activity. Screenshot of data layer available from Environmental Protection Agency/DrillingInfo, Inc., as of June 2013.

Oil and gas production continues in and near the parks. As of September 2013, there were 174 operations in Lake Meredith National Recreation Area (fig. 19; fig. 20) and five operations in Alibates Flint Quarries National Monument. Operations are administered using an oil and gas management plan that was completed in 2002 and conforms with Title 36 Code of Federal Regulations Part 9, Subpart B (or simply "9B regulations"; see Appendix B of this report), which the National Park Service is currently updating (Ed Kassman, NPS Geologic Resources Division, regulatory specialist, telephone communication, 1 April 2015). The NPS Geologic Resources Division assisted with development of this plan (see National Park Service 2002) and prepared a reasonably foreseeable development (RFD) scenario for future oil and gas exploration and production at the parks. The RFD scenario defined a direction for long-term management of existing and anticipated oil and gas operations associated with the exercise of nonfederal oil and gas interests underlying the parks and for management of existing trans–park oil and gas pipelines and activities in their rights-of-way.

The National Park Service works with land managers, permitting entities, and operators to help ensure that NPS resources and values are not adversely impacted by oil and gas production. Potential impacts include groundwater and surface water contamination, accelerated erosion and sedimentation, introduction

Figure 20. Photograph of oil and gas operation. Oil and gas operations at Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument are administered using an oil and gas management plan completed in 2002. The operation pictured here is near Fritch Fortress. Note the windblown dust in the upper right corner of the figure. Photograph by Katie KellerLynn (Colorado State University).

of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns. Additionally, the impact of oil and gas operations on paleontological resources in the parks is a concern as outlined by Santucci et al. (2001). Santucci and McDonald (2002) provided standard operating procedures for locating and protecting paleontological resources in areas with oil and gas operations (see "Paleontological Resource Inventory, Monitoring, and Protection" section). The NPS Geologic Resources Division Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information. The NPS Geologic Resources Division is available to provide park managers with policy and technical assistance regarding minerals and energy issues.

The foundation document identified the following as needs with respect to oil and gas sites: locating (georeferencing) sites in need of restoration, and preparing a plan for recovering, removing, or remediating these sites (National Park Service 2014a). Sites in need of restoration include inactive oil and gas sites, dump sites, and carbon black plants.

Accelerated Erosion and Sedimentation

Accelerated erosion and sedimentation are a concern at Lake Meredith National Recreation Area (Pranger 2000). For example, the fine-grained sediment that washes from slopes composed of red beds (**Pqw**) onto Stilling Basin Road and the Sanford-Yake boat ramp creates slippery mud and poses a hazard for people and vehicles. Also, oil and gas access roads—many of which are unsurfaced, not adequately sloped, and lack drainage structures such as culverts and ditches (National Park Service 2000)—become severely eroded during rainstorms (fig. 21). The roads act as spillways for runoff, cutting gullies into the road surface and adjacent slopes.

Simkins and Gustavson (1984) documented rates of hillslope erosion and deposition at six stations on the High Plains, including Lake Meredith National Recreation Area. These findings may be of use for park managers as a baseline for future monitoring. Simkins and Gustavson (1984) established erosion pins on outcrops of Permian siltstone, Triassic mudstone, Tertiary Ogallala sandstone, alluvial sediment, and

Figure 21. Photograph of severe erosion on access road. Inadequate surface water drainage caused gullying on a poorly maintained oil and gas access road in Lake Meredith National Recreation Area. Many of these roads have been improved with the installation of erosion control measures. National Park Service photograph by Hal Pranger (taken in June 2000) from National Park Service (2002, p. 3-24).

poorly developed soils on these parent materials. They analyzed 3,770 erosion-pin measurements taken at approximately six-month intervals between 1978 and 1982. Analysis indicated that net erosion was more common than net deposition, although two of the sites experienced net deposition (Quitaque, Texas, and Buffalo Lake National Wildlife Refuge). Lake Meredith National Recreation Area showed net erosion, -0.11 cm (-0.04 in).

Managing runoff water is a consideration during project planning in the parks (Arlene Wimer, Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, chief of resource management, written communication, 7 July 2015). In the past decade, the National Park Service has improved many problem roads in the parks by installing water bars and diversion ditches to more adequately handle heavy rains (KellerLynn 2011). Access roads that cross federal lands are subject to 9B regulations (see "Oil and Gas Production" section).

Off-Road Vehicle Use and Disturbed Land Restoration

Off-road vehicle (ORV) use is allowed in two designated areas in Lake Meredith National Recreation Area: (1) Big Blue Creek (fig. 22), which covers 79 ha (194 ac) at the north end of the park; and (2) Rosita (also known

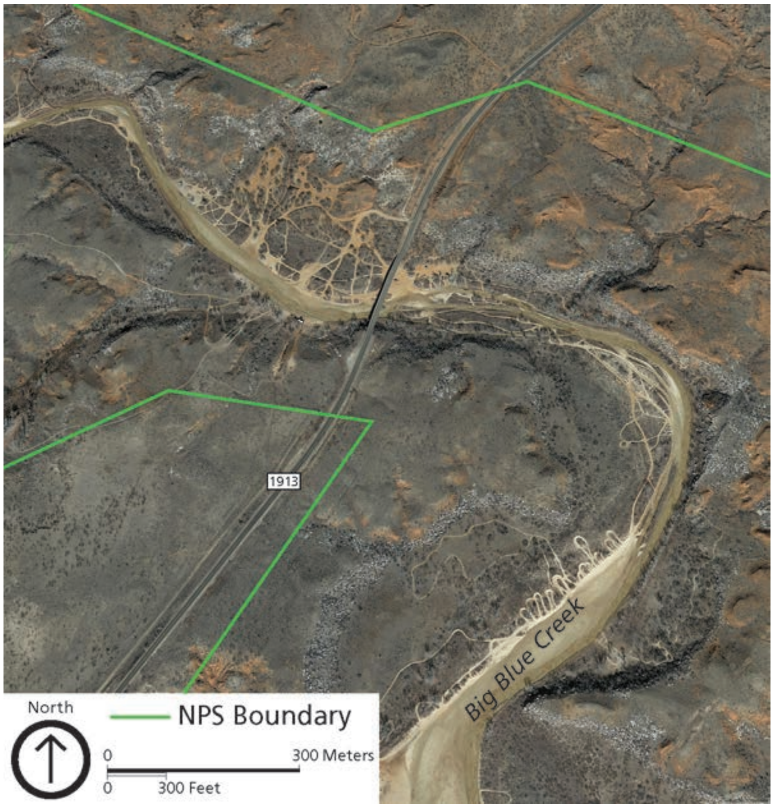


Figure 22. Aerial photograph of Big Blue Creek area. Off-road vehicle (ORV) use is permitted in the Big Blue Creek area, which covers 79 ha (194 ac) in the northwest part of the national recreation area. Note the plethora of ORV trails that form a web across the area. Landsat imagery from 13 February 2015, extracted from Google Earth.

as Rosita Flats), which covers 980 ha (2,421 ac) at the south end. A special regulation in Title 36 of the Code of Federal Regulation, Section 7.57, authorized ORV use in these two areas. Management is addressed in the national recreation area's ORV management plan (National Park Service 2015b).

ORV use at the national recreation area has changed drastically in intensity and type of vehicle since establishment of the special regulation in the 1970s. Modern all-terrain vehicles (ATVs) are the primary off-road vehicles used today; these types of vehicles were not in use when the original regulation took effect. The intensity of use at the national recreation area affects natural and cultural resources and results in visitor-use conflicts (National Park Service 2015b). The foundation document noted that ORV use will continue to increase (National Park Service 2014a).

ORV use is a geologic issue as it relates to both wind and water erosion, and associated dust storms and sedimentation (see "Wind Erosion and Dust Storms" and "Accelerated Erosion and Sedimentation" sections). The primary threat, as noted in the foundation document, is ORV use outside legislated areas, which adds to ruts and erosion problems. Additionally, a continuation of the present drought may reduce vegetation in the ORV areas, causing erosion and blowing sand. The foundation document proposed light detection and ranging (LiDAR) as a data need and possible planning tool for ORV areas (National Park Service 2014a).

Scoping participants noted that some restoration efforts are occurring at Big Blue Creek, namely minimizing and closing unauthorized trails (see KellerLynn 2011). Disturbed land restoration (DLR) is the process of restoring lands to unimpaired natural conditions where natural conditions and processes have been impacted by development such as facilities, roads, mines, dams, and abandoned campgrounds and/or by agricultural practices such as farming, grazing, timber harvest, and abandoned irrigation ditches. The NPS Geologic Resources Division assists park managers with disturbed land restoration in the National Park System (see http://go.nps.gov/grd_dlr).

Wind Erosion and Dust Storms

Wind is ubiquitous in the Texas Panhandle and is one reason why Texas leads the national in generation of wind-powered energy (see "Wind Energy Development" section). At Lake Meredith, near-constant winds average 19–24 kilometers per hour (kph; 12–15 mph) and can reach 48–64 kph (30–40 mph) during early spring (National Park Service 2012).

During the recent drought (see "Lake Level" section), receding lake levels have exposed large areas of the lake basin to wind erosion. Areas of ORV use and oil and gas operations are particularly susceptible to wind erosion (see "Off-Road Vehicle Use and Disturbed Land Restoration" section). Vehicular traffic and creation of access roads denude vegetation, exposing the ground surface to wind erosion. Furthermore, vehicles churn up and transport dust, referred to as "fugitive dust." At some sites, oil and gas operators have placed mats to reduce the amount of material available for windblown transport (KellerLynn 2011; see "Oil and Gas Production" section).

When lake level is high, prevailing southwesterly winds create almost constant wave action, which is a major factor in shoreline erosion and a concern for the preservation of archeological resources located along the shore (Etchieson and Couzzourt 1987). High winds can induce waves up to 2 m (6 ft), which erode soil and flood infrastructure in this zone (National Park Service 2012). Furthermore, when lake level is high, the development of whitecaps is common. Wind warnings for boaters are frequent occurrences during spring and summer. The National Weather Service issues lake wind warnings for the panhandle region when wind speeds exceed 40 kph (25 mph); this occurs about 200 times per year (National Park Service 2012).

Winds create dust storms, which are severe weather conditions in which visibility is reduced to 1 km (0.6 mi) or less by blowing dust. In recent years, the National Weather Service has reported blowing-dust advisories in the region on no less than 40 days and as many as 60 days per year (Gill et al. 2000b).

In *Geological Monitoring*, Lancaster (2009) described the following methods and vital signs for monitoring aeolian resources: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes. In addition to the methods described by Lancaster (2009), some information may also be obtained from the visibility monitoring programs maintained by the NPS Air Resources Division and its cooperators at http://www.nature.nps.gov/air/monitoring/index.cfm.

Wind Energy Development

Texas leads the nation in generation of wind-powered energy, with more than one-fifth of the US total. The state has six of the 10 largest wind farms in the nation, including three of the top five. It was the first state to reach 10,000 megawatts of installed wind energy generation (fig. 23; US Energy Information Administration 2014). Many wind turbines and proposed locations for turbines are south of the national recreation area (fig. 24).

Substantial new wind energy generation capacity is under construction in the state (US Energy Information Administration 2014), and Dumas, Texas, which is about 40 km (25 mi) northwest of Fritch, is considered a "hot spot" for wind-energy development (Dumas Economic Development Corporation 2013). According to scoping participants, wind farms are encroaching on Fritch (KellerLynn 2011). The development of renewable wind energy in the area could involve individual structures or groups of structures (National Park Service 2012).

According to National Park Service (2014b), the following are the primary impacts of wind turbines:

- Noise. Turbine blades operating at normal speeds can generate noise beyond ambient background levels and interrupt natural soundscapes, which may reduce bird nesting, breeding, population density, and cause behavioral disturbances.
- Turbine Strikes. This refers to the collision or barotrauma (physical damage to body tissue from changes in air pressure) that birds or bats may experience from wind turbines.
- Visual Impacts. The height of wind turbines, which can be hundreds of feet tall, can decrease the value of natural viewsheds, particularly in areas of recreational, historical, cultural, or archeological importance. Aviation lighting placed on top of turbines may also impact the natural lightscape and dark night skies of an area. Wind farms typically cover thousands of acres of land and each turbine is connected by a road for construction and maintenance purposes. This network of roads can scar an area and adversely affect visitors' visual experiences.

Construction and development activities, such as the construction of power lines and fugitive dust events, are other impacts associated with wind energy development. In addition, habitat loss, land conversion, and transmission infrastructure are concerns (National Park Service 2014b).

In the event of new construction and development adjacent to NPS lands, the National Park Service will work with landowners and energy developers to minimize impacts on scenic views and other important natural and cultural resources (National Park Service

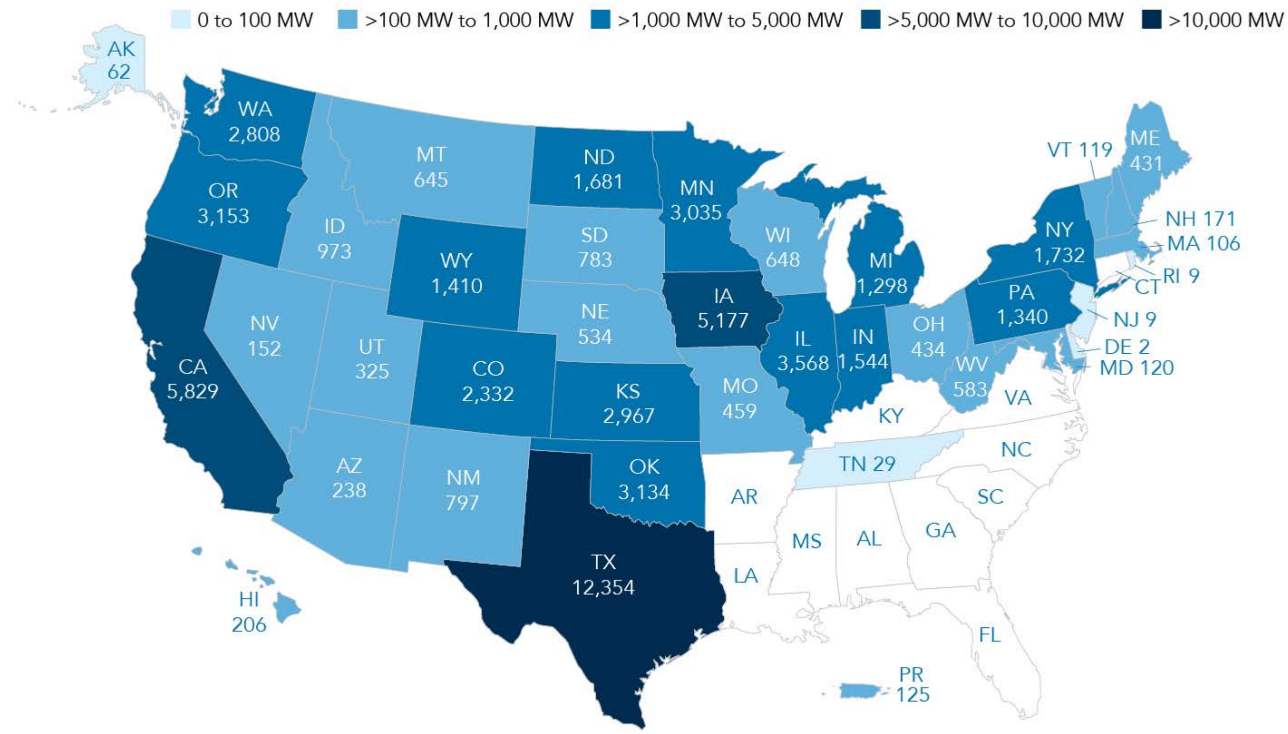


Figure 23. Map of US wind energy production. According to the American Wind Energy Association (2015), Texas produced the most megawatts of wind energy of any state in 2014. American Wind Energy Association graphic available at http://www.awea.org/Resources/Content.aspx?ItemNumber=5059.

2012). The National Park Service uses a combined technical and policy approach to manage and protect park resources and values as renewable energy resources are identified and developed near NPS areas (National Park Service 2014b). The NPS Geologic Resources Division Renewable Energy website, http://go.nps.gov/grd_renewable, provides more information.

Abandoned Mineral Lands and Borrow Site

Abandoned mineral lands (AML), including waters and watersheds, in the National Park System contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. AML features also may include those associated with past oil and gas operations. The National Park Service takes action under various authorities to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts to resources (see Appendix B of this report and Burghardt et al. 2014). AML features pose a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals, some of which may be protected under the Endangered Species Act or state species listings.

Resource management of abandoned mineral lands requires accurate inventory and reporting. According to the NPS AML database and Burghardt et al. (2014), Lake Meredith National Recreation Area contains two AML features. The National Park Service has already mitigated one of these features and the other requires no mitigation. Both were surface mines. Rock, sand, and gravel were removed from these areas by Bureau of Reclamation contractors during construction of Sanford Dam. Alibates Flint Quarries National Monument contains no AML features. The NPS AML website, http://go.nps.gov/grd_aml, provides further information.

Lake Meredith National Recreation Area contains an active borrow site between Farm to Market (FM) Road 1319 and North Canyon. The borrow pit is within Permian sediments, probably of Quartermaster Formation (Eddie Collins, University of Texas at Austin, Bureau of Economic Geology, geologist, written communication, 8 June 2015). This borrow site provides fill material (sand and gravel) for NPS and Canadian

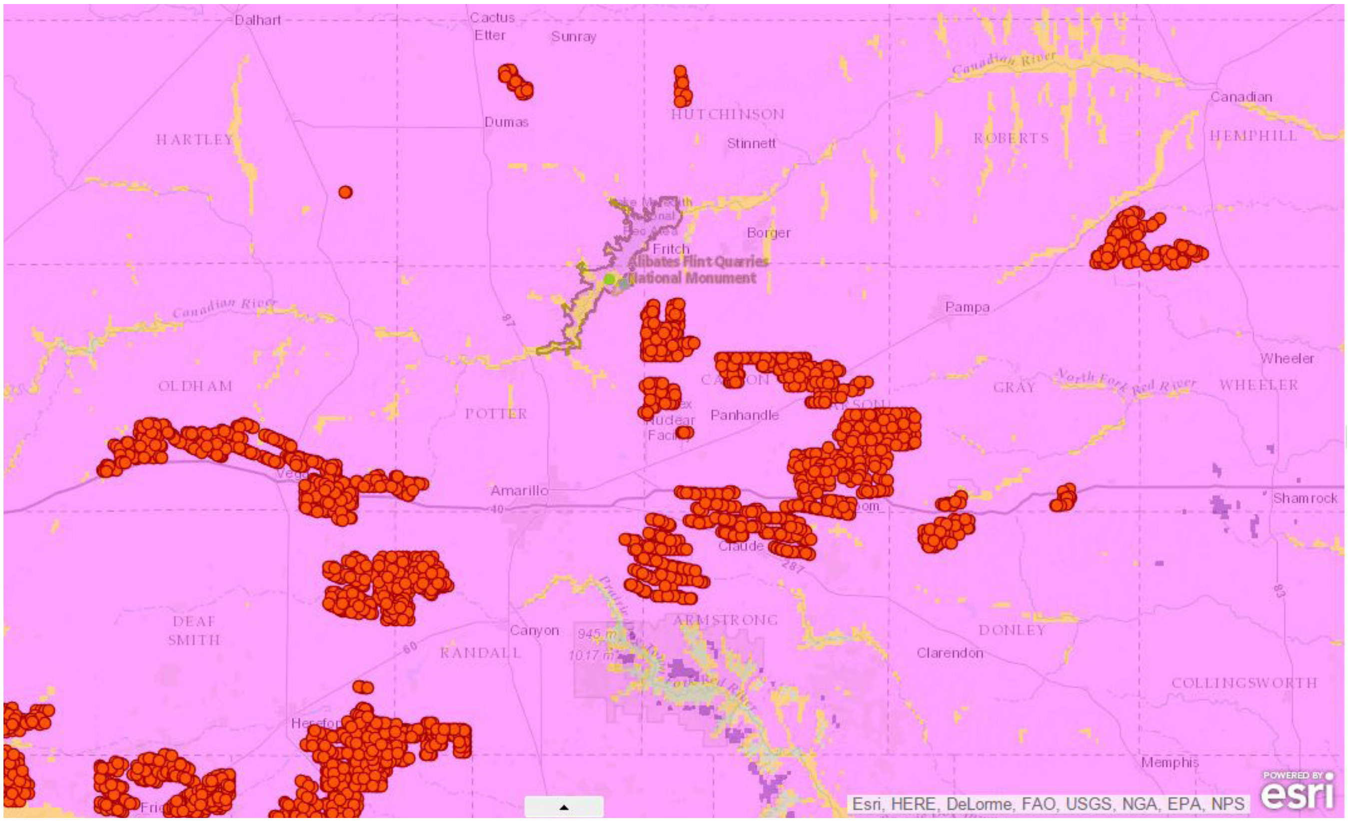


Figure 24. Map of wind resources. On a scale of 1–7 of wind power class, the parks and surrounding area are class 4 ("good," pink on figure) or class 3 ("fair," yellow). Class 4 winds have an annual average wind speed of 7–7.5 m/s (16–17 mph) at 50 m (164 ft) height. Class 3 winds have an average annual wind speed of 6.5–7 m/s (15–16 mph). The dots indicate locations of determined and proposed wind turbine or meteorological evaluation tower ("MET") projects between 2008 and 8 October 2014 as compiled by the Federal Aviation Administration. Wind power class data from National Renewable Energy Laboratory as of May 2009.

River Municipal Water Authority projects. Under all alternatives outlined in the parks' general management plan, this borrow site would continue to serve as a source for fill material (National Park Service 2012). Refer to Appendix B for laws and NPS management policies associated with park use of sand and gravel.

Slope Movement Hazards

Slope movements—the downslope transfer of material (soil, sediment, and rock) under the influence of gravity—are a type of naturally occurring or human-caused geologic hazard (fig. 25). Slope movements take place over time scales from seconds to years and result in a hazard where the dislodged or moving material has the potential to impact park resources, infrastructure, or visitor safety.

A shoreline survey (Etchieson and Couzzourt (1987) and technical report (Pranger 2000) identified slope movements at Lake Meredith National Recreation Area, including rotational slumping and rockfall (fig. 26). Most of the slumps are on the northern side of Lake Meredith on south-facing slopes, for example at North Turkey Creek. When lake levels are high, wave action is a primary trigger in slumping (see "Wind Erosion and Dust Storms" section). Pranger (2000) documented slumping as a result of fluctuating lake levels at Blue West boat ramp. During the GRI site visit in 2011, scoping participants noted slump features at Fritch Fortress (fig. 26). Slumping also occurs at the borrow site between North Canyon and FM Road 1319 (plate 1; see "Abandoned Mineral Lands and Borrow Site" section). Boulders of Alibates Dolomite (Pqwa) up to 2 m (7 ft) in diameter commonly dislodge from the dolomite "capstone" (see "Alibates Dolomite and Alibates Flint" section) and roll down slopes (fig. 27). Some settle on the lake bed, for example at Cedar Canyon. Pranger (2000) noted dolomite boulders on slopes above Stilling Basin Road and Blue West Road.

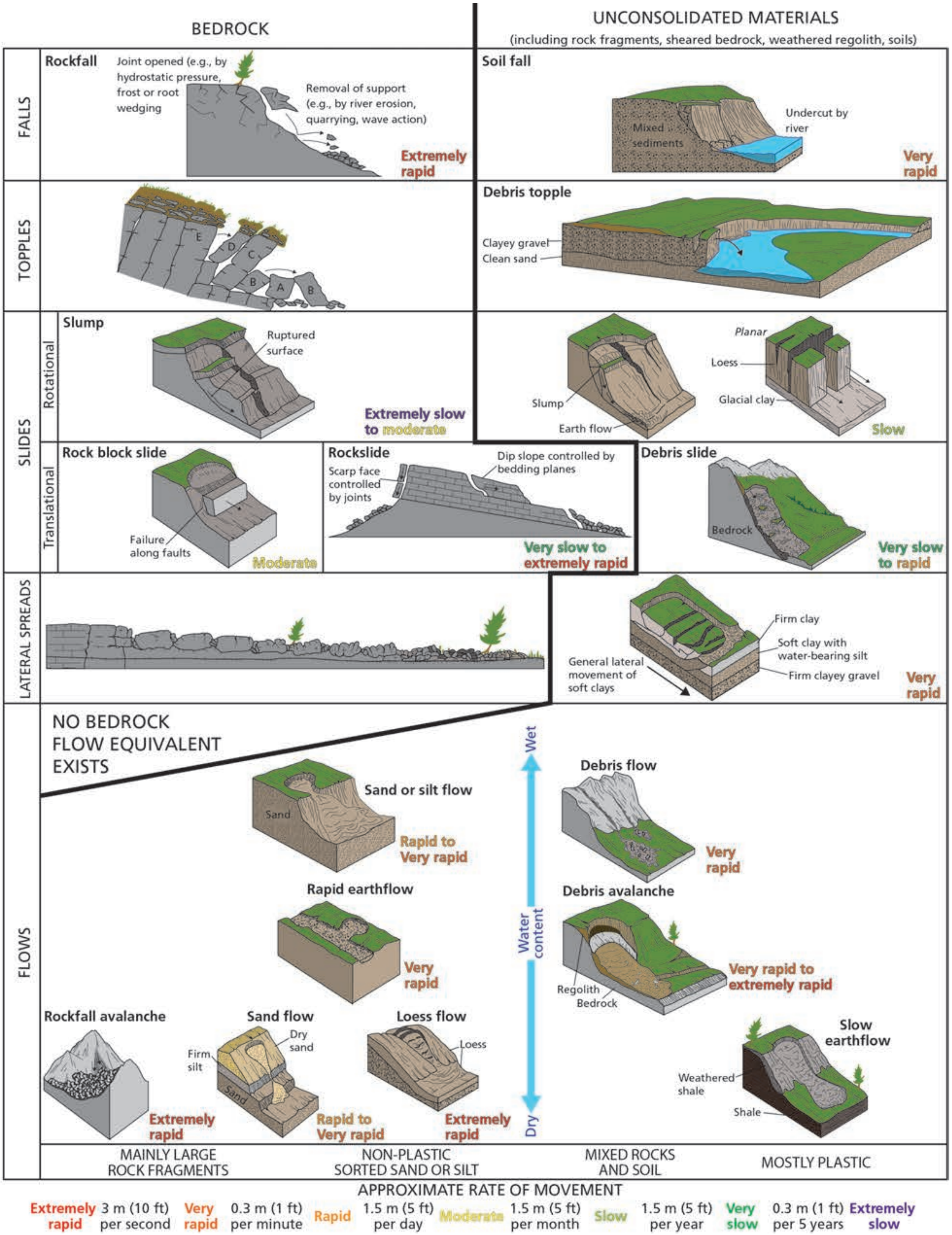


Figure 25. Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Notable slope movements, in particular rotational slumps, occur around the perimeter of Lake Meredith. Rockfall occurs along cliffs. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

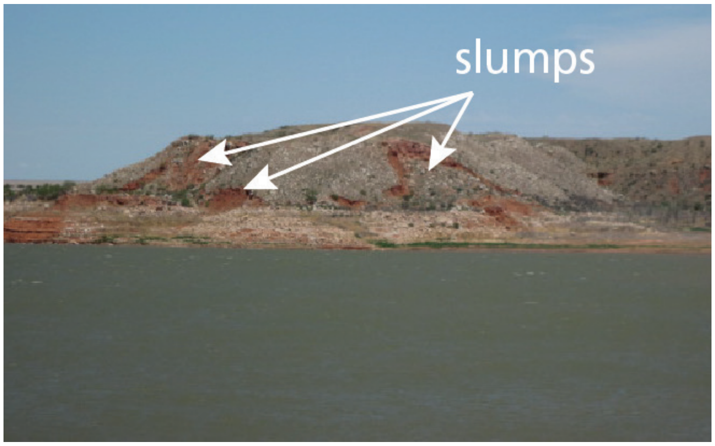


Figure 26. Photograph of slumping along the Lake Meredith shoreline. Slope movements in the form of rotational slumps, shown at Fritch Fortress in the figure, occur primarily around the perimeter of Lake Meredith. Slope movements are induced by wave action and fluctuating lake levels. Photograph by Katie KellerLynn (Colorado State University, taken in 2011).

Figure 27. Photograph of slope movements. In addition to slumping, dolomite boulders scattered across a slope are prone to rockfall. National Park Service photograph by Hal Pranger (taken in June 2000) from National Park Service (2002, p. 3-25).

In *Geological Monitoring*, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements, and for evaluating landslide hazards and risks: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. In addition, Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards) and Slope Movement Monitoring (http://go.nps.gov/monitor_slopes) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Sinkhole Collapse and Erosion

Unlike other areas of the Texas Panhandle, sinkholes (circular depressions) are not common at the parks. Scoping participants noted one sinkhole (of unknown dimensions) in the Plum Creek area of the national recreation area. Investigation is needed, but scoping participants suspected that erosion was accelerated around this feature. At the time of scoping, however, park staff did not think mitigation for the protection of infrastructure or visitor safety was needed (KellerLynn 2011).

Lake Level

Severe droughts have occurred in the Texas Panhandle throughout recorded history (Dunn 2010). Based on tree-ring data, one or two droughts per century have occurred for the past 2,000 years (Foster 2008). The current drought in the Canadian River Valley and much of Texas began in 2001. Since then, water level in Lake Meredith has dropped to less than 1% of its available storage capacity (National Park Service 2012; see "Lake Meredith" section). Lake waters are now a fraction of that depicted in the GRI GIS data from 1969 and 1983. The poster (in pocket) shows the lake's extent as of November 2014.

As the water level in Lake Meredith has dropped, wetlands, which are a natural resource of special interest (National Park Service 2014a), have developed in areas of the former lake basin, primarily near the river channel in the upstream part of the national recreation area (National Park Service 2012). Notably, all Lake Meredith wetlands are ephemeral, drying up as a drought continues or becoming inundated by water when a drought breaks. In the long term, a cycle of wetland inundation or desiccation and regrowth is the "norm" for Lake Meredith National Recreation Area (National Park Service 2012).

Recent drought conditions are a reminder that widely fluctuating water levels will occur and are part of management at the national recreation area. Lake levels can rise dramatically in a short period of time if a significant weather event occurs in the Canadian River watershed (National Park Service 2014a).

Drought conditions and lower lake levels have created a growing number of beaches available for recreation and increased accessibility for visitors without boats (KellerLynn 2011). The recent fluctuation highlights the need to manage the recreation area in a way that provides a wider range of appropriate recreational activities at both high and low water levels (National Park Service 2012). During scoping, park managers emphasized a focus on more land-based activities, including a proposed geology trail. The 2014 general management plan stressed the need for flexibility to accommodate varying lake levels and a management approach that takes better advantage of the 80% of the national recreation area that is outside the lake basin.

Changes to Hydrology

In 1964, the natural flow of the Canadian River in Texas was obstructed by construction of Sanford Dam, which created Lake Meredith. The subsequent depletion of flow resulted in impressive changes downstream into Oklahoma, including peak and mean annual discharge and channel morphology (Buchanan 1994). Human activities—such as water use by 11 municipalities; flood control, which has encouraged the spread of salt cedar (*Tamarix* spp.); and interception of groundwater discharge at springs/stock ponds outside the national recreation area that would otherwise provide streamflow within the park—have affected the hydrology of the Canadian River system. The current drought is another factor in a decreasing water table and decreasing discharge at springs.

Impacts to Tributaries

Most of the tributaries, locally known as "side streams," that enter Lake Meredith are spring fed (from the Ogallala aquifer). The locations of individual springs are included in the GRI GIS data as point features. Most of these springs are outside the national recreation area, and most of the discharge is intercepted by artificial stock ponds (KellerLynn 2011). Retention of groundwater in these stock ponds impacts streamflow within the national recreation area. In addition, an increasing demand for water in Amarillo and vicinity may result in additional groundwater wells drilled in the area. This could result in the loss of flow in some of the tributaries, for example Chicken Creek, near the south end of the national recreation area (KellerLynn 2011).

Salt Cedar Invasion

In the absence of unregulated flows and floods, salt cedar, also known as tamarisk, has spread along the Canadian River in the Texas Panhandle and become a major concern. This aggressive colonizer covers thousands of acres of the riparian corridor, resulting in the loss of habitat and native species such as cottonwood. The stems and leaves of mature plants secrete salt, forming a crust above and below ground that inhibits other plants (Sudbrock 1993). Furthermore, salt cedar is an enormous water consumer. A single large plant can absorb 760 L (200 gal) of water a day. Salt cedar's high water consumption further stresses native vegetation by lowering groundwater levels and can also dry up springs and marshy areas (Hoddenbach 1987).

The National Park Service is using herbicides to treat the invasion, and 3,600 ha (9,000 ac) at the national recreation area host "skeletal remains" of this invasive plant (KellerLynn 2011). To help minimize the impact of the drought, the Canadian River Municipal Water Authority has expended significant effort to reduce the amount of "thirsty" salt cedar along the Canadian River between Ute Reservoir and Lake Meredith. The reduction of salt cedar has resulted in beneficial channel improvements (Canadian River Municipal Water Authority 2015a).

Paleontological Resource Inventory, Monitoring, and Protection

As described in the "Paleontological Resources" section, fossils are preserved in the rocks and unconsolidated deposits in the parks. These fossils are nonrenewable paleontological resources subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). Department of the Interior regulations associated with this act are under development.

Prior to the development of the oil and gas management plan (National Park Service 2002), no standard operating procedures existed in the National Park Service to provide specific guidance for how to survey and protect paleontological resources in areas with oil and gas production (see Santucci and McDonald 2002). Santucci et al. (2001) introduced the concept and provided information about locating and protecting fossils in areas with oil and gas operations.

Cultural contexts may be a source of paleontological material. Fossils occurring in these contexts may have been fashioned into or used as tools, jewelry, or spiritual items. Additionally, many building stones in prehistoric and historic structures in the National Park System contain fossils. Also, various archives, journals, memoirs, and photographs include historical accounts of fossils in NPS areas. Kenworthy and Santucci (2006) introduced the concept of an inventory for these types of fossils.

No field-based paleontological survey, including cultural contexts, has been completed for the parks to date. Such a survey would furnish detailed, site-specific descriptions. The NPS Geologic Resources Division can provide assistance in conducting a paleontological survey.

A variety of publications and online resources provide park-specific or servicewide information and paleontological resource management guidance, for example, the NPS Geologic Resources Division Paleontology website, http://go.nps.gov/grd_paleo. Tweet et al. (2015) provided preliminary recommendations for paleontological resource management at the parks. In *Geological Monitoring*, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Seismic Hazards

Seismic activity is the phenomenon of movements in Earth's crust, including vibrations induced by natural processes, such as movements along faults (earthquakes) and landslides, as well as human activities, such as blasting, drilling, road building, and vehicular traffic (King et al. 1985, 1991). In *Geological Monitoring*, Braile (2009) described the following

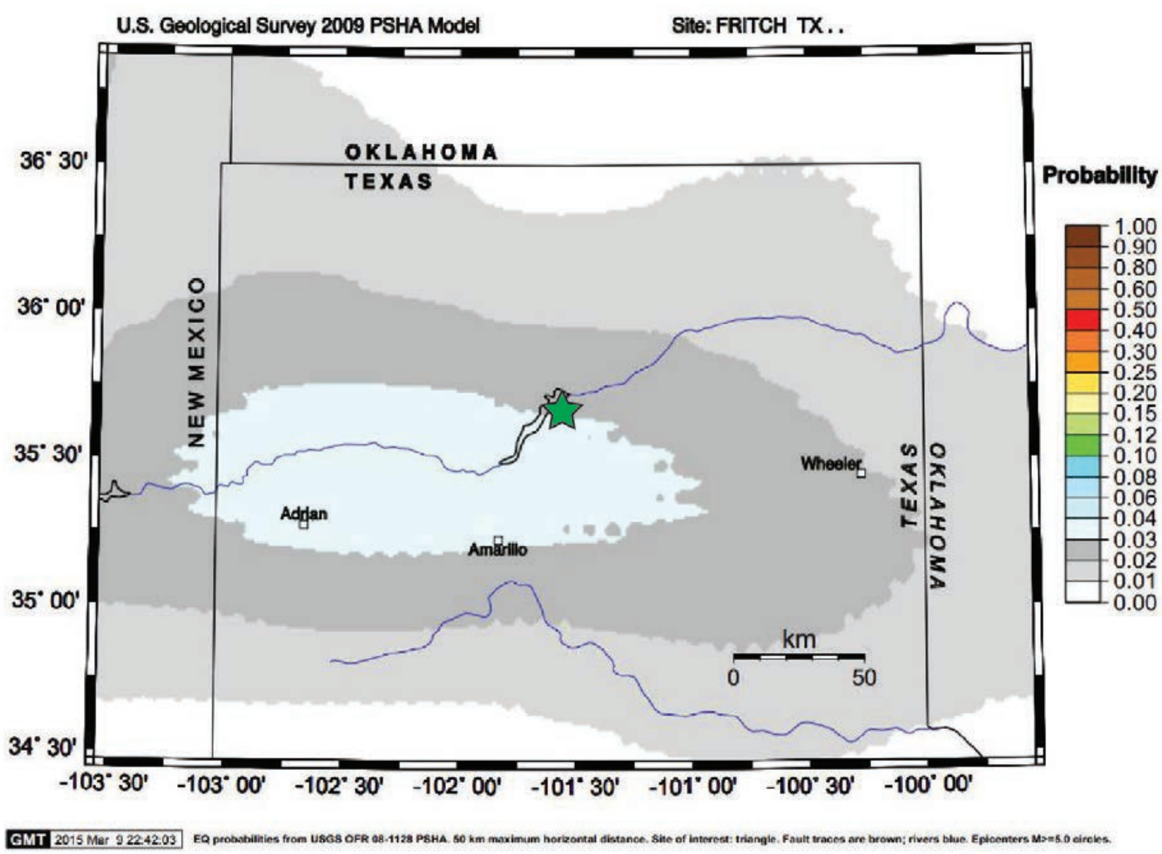


Figure 28. Map of earthquake probability. The map shows the probability of an earthquake with a magnitude 5.0 (moderate earthquake) within 100 years and 50 km (30 mi) of Fritch, Texas. The green star represents the approximate location of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. Graphic generated using US Geological Survey Probabilistic Seismic Hazards Assessment (PSHA) mapping program (http://geohazards.usgs.gov/eqprob/2009/index.php).

methods and vital signs: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. The NPS Geologic Resources Division Seismic Monitoring website (http://go.nps.gov/seismic_monitoring) and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide additional information.

Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety.

The Texas Panhandle was seismically active about 300 million years ago when tectonic forces created the Amarillo uplift and the Palo Duro and Anakarko basins (see "Geologic Structures" section) but the current risk is relatively low. The Potter County fault formed during the initial Amarillo uplift and is one of the major faults that bound the southeastern margin of that uplift (Wilson 1988; Crone and Wheeler 2000). This fault is recorded in a database of Quaternary faults, liquefaction, and other tectonic features (Crone and Wheeler 2000) as a "Class C" fault. Class C and D faults either lack convincing geologic evidence of Quaternary tectonic faulting (in the recent geologic past, or the last 2.6 million years) or have been studied carefully enough to determine that they do not pose a significant seismic hazard.

The GRI GIS data include segments of only one fault (see poster, in pocket). This unnamed fault displaced rocks of the Tecovas Formation (**TRdv**) and undivided Permian strata (**Pqw**). Overlying rocks of the Ogalalla Formation (**To**) were not displaced, suggesting that movement on that fault occurred at least tens of millions (if not hundreds of millions) of years ago, after deposition of **TRdv** but before deposition of **To**. By contrast, Wilson (1988) interpreted faulting in the John Ray Dome area of Potter County, which is about 14 km (9 mi) south of Fritch, to have affected Ogallala deposits, as well as Pleistocene and Holocene terraces and alluvium.

A challenge regarding such topics, as well as summarizing the geology of this area in general, is that regional evaporite dissolution has deformed the rocks, so workers commonly cannot prove or disprove post–Ogallala tectonic deformation (Eddie Collins, University of Texas at Austin, Bureau of Economic Geology, geologist, written communication, 8 June 2015).

Scoping participants noted that earthquakes of estimated magnitude 4 have been felt at Lake Meredith, but no seismic-related damage has occurred (KellerLynn 2011). According to a USGS earthquake probability map (fig. 28), a Richter magnitude 5.0 earthquake has a probability of 0.02–0.03 (2%–3% "chance") of occurring near Lake Meredith National Recreation Area in the next 100 years. Magnitude 5.0 earthquakes are considered moderate.

Cave Resource Management

Caves are nonrenewable resources. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. The Federal Cave Resources Protection Act of 1988 also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a FOIA request (see also Appendix B).

Commonly, rock shelters, such as the one in the Rosita area of the national recreation area, are classified as caves or cavelike features. A study by Ek (2008), however, which compiled information about caves and karst in the National Park System, emphasized "cave environment" in defining a cave, and did not include "rock shelters" as true caves because they lack a sufficient length-to-entrance width ratio to noticeably modify or alter cave climate or ecology. The development of a park-specific cave management plan for Lake Meredith National Recreation Area would evaluate the significance of the rock shelter at Rosita and the need for monitoring and protection. The NPS Geologic Resources Division can facilitate the development of a cave management plan for thenational recreation area. The NPS Geologic Resources Division Cave and Karst Resources website, http://go.nps.gov/grd_caves, provides more information.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument.

Created and shaped over hundreds of millions of years by geologic processes, the geologic resources at the parks have facilitated human survival, subsistence, enjoyment, and adaptation in the Texas Panhandle for the past 13,000 years (National Park Service 2012). Modern humans built the Sanford Dam; only a few steps away from the reservoir, human industry from another time is revealed in hundreds of quarries. The abundance of fine quality flint in the bluffs above the Canadian River was the controlling factor in the growth of a Pueblo type culture at this location (Horn 1963).

Significant events in the geologic history of the parks include the following:

- 323 million–299 million years ago (Pennsylvanian Period; fig. 4)—structural basins and uplifts formed.
- 299 million–252 million years ago (Permian Period)—basins inundated by ocean water and filled with sediments. "Uplifts" (e.g., Amarillo uplift) remained above sea level 300 million years ago but were buried by shallow marine deposits by about 260 million years ago.
- 252 million–201 million years ago (Triassic Period)—ocean waters retreated; terrestrial environments dominated.
- 201 million–66.0 million years ago (Jurassic and Cretaceous periods)—major gap in the parks' rock record.
- 66.0–23.0 million years ago (Tertiary time)—Rocky Mountains rose to the west of the Texas Panhandle, and a thick layer of sediment, which eroded from these newly formed mountains, spread across the Great Plains.
- The past 2.6 million years (Quaternary Period)—ice ages during the Pleistocene Epoch (fig. 4) resulted in wet conditions in the Texas Panhandle. Enhanced streamflow facilitated incision of the Canadian River Valley, ample groundwater

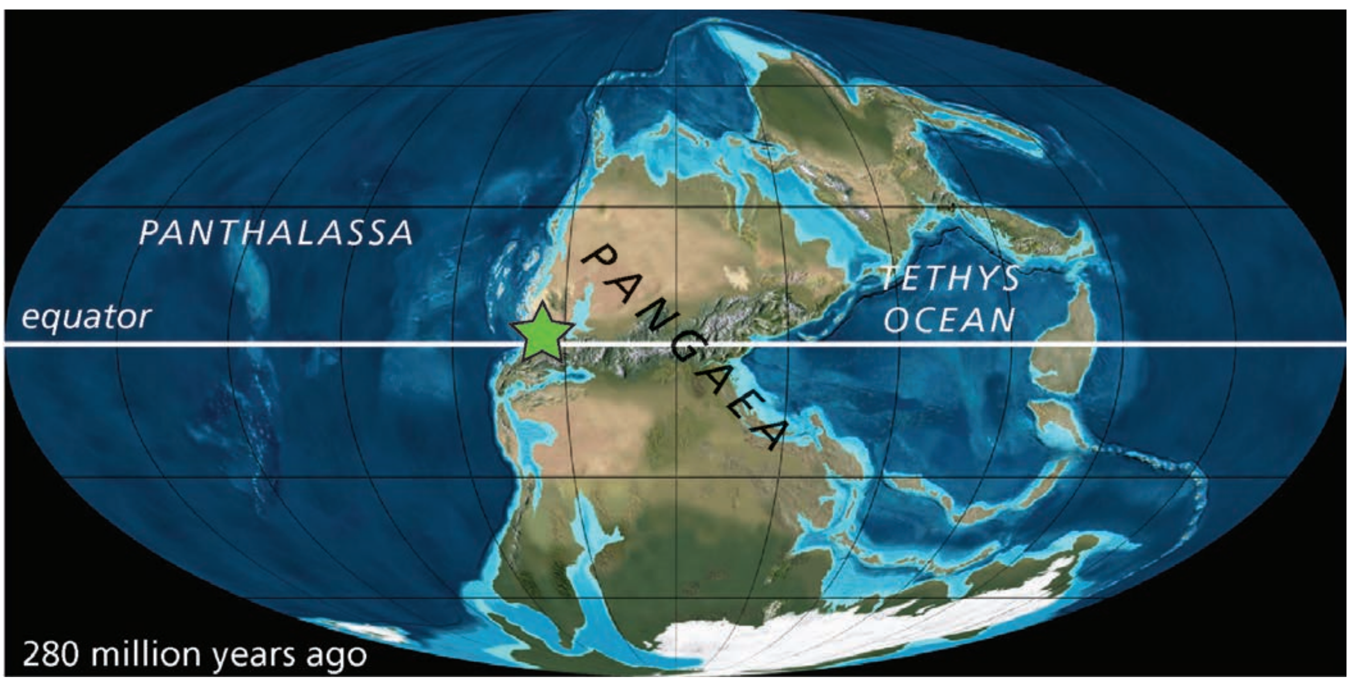


Figure 29. Paleogeographic map of Earth, approximately 280 million years ago. This paleogeographic map shows the configuration to continents during the Permian Period. At that time, the supercontinent Pangaea dominated the globe. Note the locations of Texas (green star) near the equator and the uplifted swath of ancient mountains—including the Ouachita, Ancestral Rocky, and Appalachian mountains—spanning the continent. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.) available at http://cpgeosystems.com/paleomaps.html.

promoted dissolution of bedrock, and lower evaporation rates resulted in the formation of playas. As the ice ages drew to a close, drier conditions allowed the transport of loess that had built up on Pleistocene floodplains. Wind formed sand dunes and sand sheets, while streams deposited alluvium. These processes continue to the present day (Holocene Epoch).

Pennsylvanian–Permian Periods: Structural Basins and Uplifts

About 300 million years ago, Earth's major continents joined to form the supercontinent Pangaea, which spread from pole to pole (fig. 29). Pangaea was shaped like a huge letter "C." Texas occupied the western edge of this landmass near the equator. The remainder of Earth's surface was covered by a vast ocean called "Panthalassa."

The final assembly of Pangaea involved the collision of Laurentia (most of what is now North America) and Gondwana (Africa and South America). This event caused enormous upheavals in what is now the eastern part of North America, giving rise to the Appalachian Mountains. In western North America, these upheavals produced the Ancestral Rocky Mountains 320 million–290 million years ago. In Texas, uplift of the Ancestral Rocky Mountains coincided with development of the Ouachita Mountains, which extended across Texas. Less extensive buckling of Earth's crust such as the Amarillo uplift also occurred at that time. Today, these old mountain ranges in the Texas Panhandle are mostly buried by younger rocks, though remnants of the Ouachita Mountains are exposed at the surface in the Marathon Basin of West Texas and in southeastern Oklahoma.

Adjacent to uplifts, Earth's crust subsided into basins. In the Texas Panhandle, the Anadarko and Palo Duro basins formed on the north and south sides, respectively, of the Amarillo uplift (fig. 6). Of particular note for Texas and the National Park System, a world-class reef complex formed in the Delaware Basin (fig. 6). The exposed section of reef at Guadalupe Mountains National Park is so exceptional that the International Commission on Stratigraphy selected it as the global standard against which all rocks of the Guadalupian Series (middle Permian, formed 272.3 million–259.8 million years ago) are compared (see GRI report about Guadalupe Mountains National Park by KellerLynn 2008). El Capitan, which is part of the fore reef, highlights the scenic and scientific values of the reef, in particular, and Permian rocks, in general (fig. 30).

Figure 30. Photograph of Permian reef complex at Guadalupe Mountains National Park. Guadalupe Peak and El Capitan are composed of Permian limestone that consists of sponges and other marine life that built a reef in a Permian sea between 272 million and 260 million years ago. These reef rocks form the Guadalupian Series of the Permian Period, which predate the red beds exposed at Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, though both the reef and the red beds were deposited in Permian basins. National Park Service photograph.

Permian Period: Red Beds

Globally, the supercontinent Pangaea had not yet broken apart when the red beds (**Pqw**) of the parks were deposited between 260 million and 250 million years ago. Red beds formed in marine basins (siltstone and shale), on the continental shelf (sandstone), and along Panthalassa in tidal and supratidal environments (gypsum and dolomite). Massive amounts of ocean salt were deposited with these rocks, ultimately making them susceptible to dissolution hundreds of millions of years later.

Among the red beds at the national monument, one layer literally stands out as much harder and more persistent than the others—the Alibates Dolomite (**Pqwa**). This layer is the source of the well-known flint used by prehistoric people for manufacturing tools and weapons. Alibates strata accumulated as sea level rose, depositing dolomite, and fell, depositing evaporites (McGillis and Presley 1981).

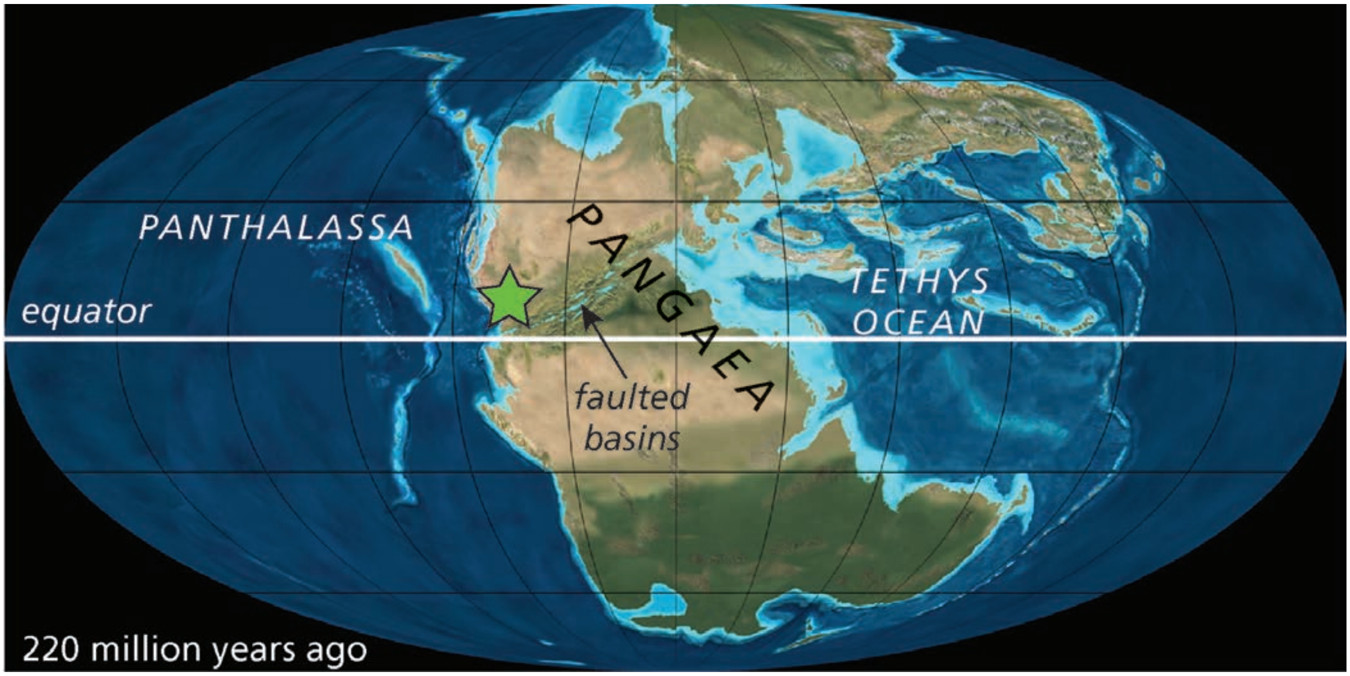


Figure 31. Paleogeographic map of Earth, approximately 220 million years ago. This paleogeographic map shows the configuration of continents during the Triassic Period. At the beginning of the Triassic Period, Pangaea began to pull apart in a great continent-wrenching episode that produced the present configuration of continents and oceans on Earth. As North America and South America separated, a series of faulted basins or rifts formed. Along this rifting crust, which extended from Mexico to Nova Scotia, the Gulf of Mexico began to drop away from the old line of the Ouachita Mountains. The green star on the figure represents the approximate location of Texas. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.) available at http://cpgeosystems.com/paleomaps.html.

Triassic Period: Terrestrial Rocks

About 250 million years ago, Pangaea was still intact, although terrestrial environments had replaced the earlier marine environments as sea level dropped. The Tecovas (**TRdv**) and Trujillo (**TRdj**) formations were deposited in lakes and streams about 230 million–220 million years ago (fig. 31). In Texas, these rocks are referred to as the Dockum Group and are equivalent in age and environment to the well-known Chinle Formation in New Mexico, Utah, and Arizona, which is famous for petrified wood and other fossils (see GRI report about Petrified Forest National Park by KellerLynn 2010b). The Dockum Group also yields fossils, though not in the abundance common in the Chinle Formation (see “Paleontological Resources” section). These rocks have mostly been eroded away at the parks, but outcrops occur in the southwest part of the national recreation area.

Jurassic–Cretaceous Periods: Gap in the Rock Record

A break in deposition took place from 201 million to 145 million years ago. No evidence suggests that Jurassic sediments were ever deposited in the region (West Texas A&M University Geological Society 2001). Cretaceous rocks are also missing, although fossil oysters (*Gryphaea*) occur in gravel at the base of the overlying Ogallala Formation (**To**). These water-worn fossils indicate that marine sediments in the Western Interior Seaway, which inundated the continent between about 100 million and 70 million years ago (fig. 32), were deposited nearby and possibly covered the Triassic deposits in the region. The Western Interior Seaway made its final retreat from the North American continent as the Laramide Orogeny—a massive mountain-building event, beginning about 70 million years ago—dramatically changed the landscape. The orogeny created features such as the Colorado Plateau and Rocky Mountains, including the Sangre de Cristo uplift west of the Texas Panhandle (figs. 2 and 6). Upper Cretaceous rocks were then eroded away sometime

Figure 32. Paleogeographic map of North America, approximately 90 million years ago. The Western Interior Seaway, which was hundreds of kilometers wide and stretched from the Arctic Ocean to the Gulf of Mexico, bisected North America for 30 million years during the Cretaceous Period. Reworked oyster (Gryphaea) fossils from the Western Interior Seaway occur in the Ogallala Formation and fluviatile terrace deposits at the parks. The green star on the figure represents the approximate location of the parks. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.) available at http://cpgeosystems.com/paleomaps.html.

between 66 million and 5 million years ago (West Texas A&M University Geological Society 2001).

Tertiary–Quaternary Periods: Ogallala Formation

Erosion of highlands associated with the Laramide Orogeny shed terrestrial sediments across the western plains. Rivers and tributaries transported these sediments to form the Ogallala Formation (**To**), which covers northwestern Texas, western Oklahoma, and eastern New Mexico (fig. 33). Wind also played a role in deposition of the Ogallala Formation; aeolian sand and silt blanketed older fluvial deposits.

Figure 33. Paleogeographic map of North America, approximately 5 million years ago. The Ogallala Formation was deposited from about 10 million to 3 million years ago. The sediments that make up the formation were shed from rising mountains to the west and deposited by fluvial and aeolian processes across the Great Plains. The green star on the figure represents the approximate location of the parks. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.) available at http://cpgeosystems.com/paleomaps.html.

The transition from mostly fluvial to mostly aeolian sedimentation on the Southern High Plains was an outcome of diversion of streams that drained east and southeast across Texas and New Mexico. Drainage of the Texas Panhandle region was largely directed into an irregular array of solution-collapse depressions, which formed on the surface of the Ogallala Formation. Subsidence was the result of dissolution of as much as 200 m (660 ft) of Permian bedded salt that had been deposited in Permian seas. Subsidence and accompanying diversion of streams effectively ended active deposition of Ogallala fluvial sediments and led to the development of the Canadian River Valley over the past 3.5 million years (Gustavson and Finley 1985; Gustavson 1986). The final stage of Ogallala deposition is marked by layers of caliche, which comprise the caprock that delineates the Central and Southern High Plains.

Figure 34. Paleogeographic map of North America, approximately 126,000 years ago. North American ice ages translated to "wet" periods in the Texas Panhandle. Evaporation was lower, groundwater recharge was higher, and streams aggressively incised their channels. The green star on the figure represents the approximate location of the parks. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.) available at http://cpgeosystems.com/paleomaps.html.

Aeolian deposition continued throughout much of the Quaternary Period, forming the Pleistocene Blackwater Draw Formation (**Qbd**) that overlies the Ogallala Formation (Machenberg et al. 1985). Deposition of this aeolian mantle of material, referred to as "cover sands," began about 1.6 million years ago (Holiday 1989).

Quaternary Period: Canadian River Valley

The Quaternary Period is divided into two epochs: The Pleistocene Epoch took place from 2.6 million to 11,700 years ago and is known for its ice ages (fig. 34). The Holocene Epoch, which covers the past 11,700 years, is the current period of geologic time.

In Texas, Pleistocene ice ages translated to wetter conditions, resulting from cooler temperatures and less evaporation, than at present. As an outcome, groundwater recharge was abundant and stream erosion was aggressive. Heightened groundwater recharge accelerated dissolution of Permian evaporites, triggering widespread vertical collapse and the formation of "chimneys" (Dolliver 1984). Furthermore, the Canadian River cut an impressive canyon across the northern panhandle to form the colorful Canadian Breaks during the Pleistocene Epoch. Similarly, the Prairie Dog Fork of the Red River carved the spectacular Palo Duro Canyon south of the parks (fig. 35). Today's stream hardly seems capable of such a feat, but ample Pleistocene waters allowed such incision (Spearing 1991).

Fluviatile terrace deposits (**Qt**) provide a record of past activity by the Canadian River and indicate that incision has been active throughout the Late Quaternary Period (Gustavson 1986). As the river and tributaries episodically dissected the surfaces over which they flowed, they left terraces and gravel deposits that represent the locations of past floodplains and indicate greater stream power. These deposits are rich in fossils of extinct mammals (Schultz 1972; see "Paleontological Resources" section). Alluvium (**Qal**) represents modern fluvial activity in the Canadian River Valley.

In areas where drainages were poorly developed, playas (**Qp**) formed during the Pleistocene Epoch. Thousands of playa lake basins punctuate the surface of the Southern High Plains (Woodruff et al. 1979). Today, when the weather is dry, playas are dusty, round, gray flats, usually void of vegetation, but after a thunderstorm, water quickly fills them, only to later evaporate or soak into the ground, adding groundwater in the Ogallala aquifer (Spearing 1991).

The deposition of loess (windblown dust, **Ql**) is another outcome of a wet Pleistocene climate turning drier during the Holocene Epoch. Broad floodplains created by Pleistocene streams provided ample fine-grained sediment for aeolian transport. Loess originated during the Pleistocene Epoch (Eifler and Barnes 1969), but ongoing transport of loess, including dust storms and dust devils, continues to the present day. Additionally, Holocene windblown sand—in dunes (**Qsd**) and sheets (**Qs**)—moves by saltation, within a meter or two of the ground surface.

Figure 35. Photograph of red beds in Palo Duro Canyon. The strata of Capitol Peak, including a pillarlike erosional remnant called a “hoodoo” at the tip of its southern promontory, display Permian red beds of the Quartermaster Formation, and overlying Triassic layers of the Tecovas Formation. The view is from a hiking trail at the southern foot of the mountain in the northern part of Palo Duro Canyon. Palo Duro Canyon State Park is about 80 km (50 mi) south of Lake Meredith. Photograph by Clinton Steeds available at Wikimedia Commons (http://upload.wikimedia.org/wikipedia/commons/b/bc/Palo_Duro_Canyon_1.jpg).

Geologic Map Data

This chapter summarizes the geologic map data available for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. A poster (in pocket) displays the GRI GIS data draped over imagery of the parks and vicinity. The Map Unit Properties Table (in pocket) summarizes this report's content for each map unit in the GRI GIS data. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI GIS product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The GRI team used the following sources to produce the GRI GIS data for the parks. These sources also provided information for this report.

Eifler, G. K. Jr., and V. E. Barnes. 1969 (reprinted 1981 with limited revisions). Amarillo sheet (scale 1:250,000). Leroy Thompson Patton Memorial Edition. Sheet GAT0002 in V. E. Barnes, project director. Geologic Atlas of Texas. University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Note: The 1981 version of Eifler and Barnes (1969) included the Alibates Dolomite (**Pqwa**) as a map unit. This unit contains Alibates flint, which is significant for the national monument. The map was reprinted in 1998 but that version did not include **Pqwa**.

Texas Commission on Environmental Quality. 2004. Tucumcari sheet (scale 1:250,000). Sheet GAT0712 in Geologic Atlas of Texas. University of Texas at Austin, Bureau of Economic Geology, and Texas Commission on Environmental Quality, Austin, Texas.

Texas Water Development Board. 2007. Geologic database of Texas: 1:250,000 geologic data for Amarillo and Tucumcari sheets derived from the Geologic Atlas of Texas. Texas Water Development Board, Austin, Texas.

Note: Texas Water Development Board (2007) adapted Eifler and Barnes (1969; reprinted in 1981) and the original Tucumcari sheet of the Geologic Atlas of Texas (Eifler et al. 1983):

Eifler, G. K. Jr., F. D. Trauger, Z. Spiegel, J. W. Hawley, and V. E. Barnes. 1983. Tucumcari sheet (scale 1:250,000). Henryk Bronislaw Stenzel Memorial Edition. Sheet GA0034 in V. E. Barnes, project director. Geologic Atlas of Texas. University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data:

- A GIS readme file (aflm_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (see table below);

- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (aflm_geology.pdf) that contains information captured from source maps;
- An ESRI map document (aflm_geology.mxd) that displays the digital geologic data; and
- A KML/KMZ version of the data viewable in Google Earth (see table below).

GRI GIS for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument.

Data Layer	On Poster?	Google Earth Layer?
Geologic Point Features (springs)	Yes	No
Mine Point Features (oil and gas wells)	Yes	No
Map Symbology	Yes	No
Faults	Yes	Yes
Linear Geologic Units (Alibates Dolomite)	Yes	Yes
Geologic Contacts	No	Yes
Geologic Units	Yes	Yes

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the parks and vicinity is included with this report. Not all GIS feature classes are included on the poster (see table above). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact the GRI team for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, map symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact the GRI team with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data and on the poster. Based on the source map scale (1:250,000) and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are horizontally within 127 m (417 ft) of their true locations.

Glossary

These are brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

abandoned mineral lands (AML). Lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the National Park Service takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources.

abandoned mineral lands (AML) feature. An individual element of an AML site, such as vertical shaft, adit, open stope, open pit, highwall, and prospect. Features include structures such as headframes, mills, wellheads, and storage facilities; landform modifications such as access roads, drainage diversions, and drill pads; and piles of ore, protore (marginal-grade ore), waste rock, soil stockpiles, and hardrock or placer tailings.

abandoned mineral lands (AML) site. An area composed of AML features grouped by past ownership, geographical, or other logical grouping containing facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation operations.

adit. A horizontal passage into a mine from the surface.

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvial terrace. A stream terrace composed of unconsolidated alluvium produced by a rejuvenated stream via renewed downcutting of the floodplain or valley floor, or by the covering of a terrace with alluvium.

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

ash. Fine-grained material, less than 2 mm (0.08 in) across, ejected from a volcano.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

basalt. A volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica or less, and is rich in iron and magnesium.

base flow. Streamflow supported by groundwater and not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream channel can erode. The ultimate base level is sea level, but temporary, local base levels exist.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

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

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

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

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

calcium carbonate. $CaCO_3$. A solid occurring in nature as primarily calcite and aragonite.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

caliche. A hard layer of cemented calcium carbonate, commonly on or near the surface in arid and semiarid regions.

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

carbonate rock. A rock, for example, limestone, calcite, and dolomite, that consist primarily of carbonate minerals.

channel. The bed of a stream or river. Also, a natural passageway or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water.

chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.

chertification. A type of silicification in which fine-grained quartz or chalcedony is introduced into limestone or dolomite.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

clay mineral. Any mineral occurring in the clay-sized fraction with the understanding that size imposes physical and chemical characteristics.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

collapse structure. Any rock structure resulting from the removal of support and consequent collapse by the force of gravity, for example, gravitational sliding on fold limbs, salt solution causing collapse of overlying rocks in salt basins, sinkhole collapse, or collapse into mine workings.

conchoidal. Resembling the curve of a conch shell and used to describe a smoothly curved surface on a rock or mineral; characteristic of quartz and obsidian.

continental. Formed on land rather than in the sea. Continental deposits may be of lake, swamp, wind, stream, or volcanic origin.

continental shelf. The shallowly submerged—covered by water depths of less than 200 m (660 ft)—part of a continental margin that extends from the shoreline to the continental slope.

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

crust. Earth's outermost layer or shell.

cryptocrystalline. Describes a rock texture in which individual crystals are too small to be recognized or distinguished with an ordinary microscope.

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

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drainage basin. A region or area bounded by a drainage divide and occupied by a drainage system, specifically the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water.

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

ephemeral lake. A short-lived lake.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

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

fault. A break in rock characterized by displacement of one side relative to the other.

fine-grained. Describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller. Also, describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in).

flint. The homogeneous, dark-gray or black variety of chert.

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

fluviatile. Belonging to a river; produced by river action; growing or living in freshwater rivers. It is an approximate synonym of "fluvial," but particularly used for the physical products of river action such as "fluviatile dam."

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

fore reef. The seaward side of a reef.

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

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical. Range: Upper Cambrian to Holocene.

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

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

granite. A coarse-grained, intrusive igneous rock in which quartz constitutes 10%–50% of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%; perhaps the best known of all igneous rocks.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

gully. A small channel produced by running water in unconsolidated material.

gypsum. A sulfate (sulfur + oxygen) mineral of calcium and water, $CaSO_4 \cdot 2H_2O$.

halite. A halide (chlorine or fluorine) mineral composed of sodium and chloride, NaCl. Synonymous with "native salt," "rock salt," and "common salt."

hoodoo. A bizarrely shaped column, pinnacle, or pillar of rock, commonly produced in a region of sporadic heavy rainfall by differential weathering or erosion of horizontal strata, facilitated by layers of varying hardness and joints.

hot spot. A volcanic center, 100–200 km (60–120 mi) across, persistent for at least a few tens of millions of year, with a surface expression, commonly at the center of a plate, that indicates a rising plume of hot mantle material.

hot-spot track. A ridge of volcanic rock formed when a lithospheric plate moves over a hot spot. The active hot-spot volcano lies at the end of the track. Extinct volcanoes lie along the track, with the oldest extinct volcano farthest from the active hot spot.

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

jasper. A variety of chert associated with iron ores and containing iron-oxide impurities that give it various colors, especially red.

karst. A type of topography that is formed on limestone, gypsum, and other soluble rocks, primarily by dissolution. It is characterized by sinkholes, caves, and underground drainage.

lacustrine. Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

lithology. The physical description or classification of a rock or rock unit based on characteristics such as color, mineral composition, and grain size.

loess. Windblown silt-sized sediment.

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

metamorphic. Pertaining to the process of metamorphism or to its results.

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

mud flat. A relatively level area of fine silt along a shore or around an island, alternately covered and uncovered by the tide, or covered by shallow water; a muddy tidal flat, barren of vegetation.

oil field. A geographic region rich in petroleum resources and containing one or more wells that produce, or have produced, oil and/or gas.

opal. A hydrous silicate (silcon + oxygen) mineral or mineral gel, $SiO_2 \cdot nH_2O$, consisting of packed spheres of silica and varying amounts of water (as much as 20% but usually 3%–9%).

orogeny. A mountain-building event.

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 fossil record.

parent material. The unconsolidated organic and mineral material from which soil forms.

period. The fundamental unit of the worldwide geologic time scale. It is lower in rank than era and higher than epoch. The geochronologic unit during which the rocks of the corresponding system were formed.

pisolite. A sedimentary rock, usually limestone, made up of pisoids (round or ellipsoidal accretionary bodies commonly composed of calcium carbonate) cemented together. playa. A dry, vegetation-free, flat area at the lowest part of an undrained desert basin.

playa lake. A shallow, intermittent lake in an arid region, covering up or occupying a playa in the wet season but subsequently drying up.

Precambrian. A commonly used term to designate all rocks older than the Cambrian Period of the Standard Global Chronostratigraphic Scale. It includes the Archean and Proterozoic eons and represents 90% of geologic time.

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

red bed. Sedimentary strata that is predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains; usually sandstone, siltstone, or shale.

reef. A ridgelike or moundlike structure, layered or massive, built by sedentary calcareous organisms (e.g., corals) and consisting mostly of their remains.

regression. Long-term seaward retreat of the shoreline or relative fall of sea level.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

saltation. A mode of sediment movement, driven by wind or water, whereby materials move through a series of intermittent leaps or jumps.

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

sand sheet. A sheetlike body of surficial sediment, commonly sand, that veneers the underlying stratigraphic units (unconsolidated deposits or bedrock) and can range in thickness from a few centimeters to tens of meters, with a lateral persistence of a few meters to tens of kilometers.

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

scarp. A steep cliff or topographic step resulting from displacement on a fault or as a result of slope movement or erosion. Synonymous with "escarpment."

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

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

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

silica. Silicon dioxide, SiO_2, an essential constituent of many minerals, occurring as crystalline quartz, cryptocrystalline chalcedony, and amorphous opal.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

siltstone. A clastic sedimentary rock composed of silt-sized grains.

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

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slump. A generally large, coherent slope movement with a concave failure surface and subsequent backward rotation relative to the slope.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

strata. Tabular or sheetlike layers of sedimentary rock that are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

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

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

stream channel. A long, narrow depression shaped by the concentrated flow of stream water.

stream terrace. A planar surface alongside a stream valley representing the remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, primarily on a moderate to small scale. The subject is similar to tectonics, but the latter term is generally used for the analysis of broader regional or historical phases.

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

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

supratidal. Describes a feature or process at an elevation higher than normal tidal range on a given shoreface. Synonymous with "supralittoral."

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

topography. The general morphology of Earth's surface, including relief and locations of natural and human-made features.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

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

type section. The originally described sequence of strata that constitute a stratigraphic unit. It serves as an objective standard with which spatially separated parts of the unit may be compared. It is preferably in an area where the unit shows maximum thickness and is completely exposed (or at least shows top and bottom).

unconformable. Describes strata that do not succeed the underlying rocks in immediate order of age or in parallel position, especially younger strata that do not have the same dip and strike as the underlying rocks. Also, describes the contact between unconformable rocks.

unconformability. The quality, state, or condition of being unconformable, such as the relationship of unconformable strata.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

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

water table. The surface between the saturated zone and the unsaturated zone. Synonymous with "groundwater table" and "water level."

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

Literature Cited

These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them.

American Wind Energy Association. 2015. Get the facts. Online information. American Wind Energy Association, Washington, DC. http://www.awea.org/index.aspx.

Ball, M. M., M. E. Henry, and S. E. Frezon. 1991. Petroleum geology of the Anadarko Basin region, Province (115), Kansas, Oklahoma, and Texas. Open-File Report 88-450W. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/of/1988/0450w/report.pdf.

Baker, R. C. 1977. Hydrology of karst features in evaporite deposits of the Upper Permian in Texas. Pages 333–339 *in* S. C. Csallany, editor. Hydrologic problems in karst regions. Western Kentucky University, Bowling Green, Kentucky.

Boggs, S. Jr. 1995. Principles and sedimentology and stratigraphy. Second edition. Prentice Hall, Englewood Cliffs, New Jersey.

Bowers, R. L. 1975. Petrography and petrogenesis of the Alibates Dolomite and chert (Permian), northern panhandle of Texas. Thesis. University of Texas, Arlington, Texas.

Bowers, R. L., and D. F. Reaser. 1996. Replacement chert in the Alibates Dolomite (Permian) of the Texas Panhandle. Texas Journal of Science 48(3):219–242.

Boyd, D. K. 1987. Geology of the Canadian River and the Alibates Formation in the Texas Panhandle. Appendix I (pages i–I-14) *in* G. M. Etchieson and J. E. Couzzourt. Shoreline survey at Lake Meredith Recreation Area in the Texas Panhandle. US Department of the Interior, Bureau of Reclamation, Southwest Region, Amarillo, Texas.

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young, R. and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/seismic.cfm.

Buchanan, J. P. 1994. River channel changes through time: Red, Canadian, and Niobrara rivers on the Great Plains. Pages 285–312 (chapter 14) *in* S. A. Schumm, editor. The variability of large alluvial rivers. American Society of Civil Engineers, New York, New York.

Burghardt, J. E., E. S. Norby, and H. S. Pranger, II. 2014. Abandoned mineral lands in the National Park System—comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2014/906 National Park Service, Fort Collins, Colorado. http://nature.nps.gov/geology/aml/inventory/index.cfm.

Cameron, D. 1980. Study of Tecovas jasper of the Texas Panhandle. Unpublished paper prepared for Anthropology 402. West Texas State University, Canyon, Texas.

Canadian River Municipal Water Authority. 2015a. CRMWA/Lake Meredith facts. Canadian River Municipal Water Authority, Sanford, Texas. http://www.crmwa.com/Sites/CRMWA/Resources/Lake%20Meredith%20Facts.pdf.

Canadian River Municipal Water Authority. 2015b. Lake Meredith. Online information and statistics. Canadian River Municipal Water Authority, Sanford, Texas. http://www.crmwa.com/.

Cepeda, J. C. 2001. A 10 Ma silicic fallout tuff in the Texas Panhandle—comparisons with the Pearlette ash. Geological Society of America Abstracts with Programs 33(6):397.

Cepeda, J. C., and P. S. Allison. 1997. Geomorphology of West Amarillo Creek, a tributary of the Canadian River in the Texas Panhandle. Geological Society of America Abstracts with Programs 29(6):A-316–A-317.

Cepeda, J. C., and M. E. Perkins. 2006. A 10 million year old ash deposit in the Ogallala Formation of the Texas Panhandle. Texas Journal of Science 58(1):3–12.

Connell, S. C., J. W. Hawley, and D. W. Love. 2005. Late Cenozoic drainage and development in the southeastern Basin and Range of New Mexico, southeasternmost Arizona, and western Texas. Pages 125–150 *in* S. G. Lucas, G. S. Logan, and K. E. Zeigler, editors. New Mexico's ice ages. Bulletin 28. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Crone, A. J., and R. L. Wheeler. 2000. Data for Quaternary faults, liquefaction features, and possible tectonic features in the central and eastern United States, east of the Rocky Mountain front. Open-File Report 00-260. US Geological Survey, Geologic Hazards Team, Denver, Colorado. http://pubs.usgs.gov/of/2000/ofr-00-0260/ofr-00-0260.pdf

Derrick, R. 2007. Canvas of stone: an overview of the petroglyphs of Alibates National Monument, Amarillo, TX. http://www.panhandlenation.com/history/prehistory/petroglyphs.html (cited in National Park Service 2012 but no longer available online).

Dolliver, P. N. 1984. Cenozoic evolution of the Canadian River basin. Baylor Geological Studies Bulletin No. 42. Baylor University, Department of Geology, Waco, Texas.

Dumas Economic Development Corporation. 2013. No slowing of wind projects in Dumas, Texas; new transmission projects creating new opportunities. Online information. Dumas Economic Development Corporation, Dumas, Texas. http://www.dumasedc.org/index.php/2013-03-01-22-49-33/92-news-releases/192-no-slowing-of-wind-projects-in-dumas-texas-new-transmission-projects-creating-new-opportunities.

Dunn, R. S. 2010. Droughts. Online information. Handbook of Texas online. Texas State Historical Association, Austin, Texas. http://www.tshaonline.org/handbook/online/articles/ybd01.

Dutton, S. P., R. J. Finley, W. E. Galloway, T. C. Gustavson, C. R. Handford, and M. W. Presley. 1979. Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of Nuclear Waste Isolation Feasibility Studies (1978). Geological Circular 79-1. The University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Dutton, S. P., and A. G. Goldstein. 1988. Palo Duro, Hardeman, and Dalhart basins. Pages 341–346 *in* L. L. Sloss, editor. Sedimentary cover—North American craton: US. The geology of North America, volume D-2. Geological Society of America, Boulder, Colorado.

Eck, W., and R. C. Redfield. 1963. Geology of Sanford Dam, Borger, Texas. Pages 54–61 *in* E. D. Anthony Jr., editor. Field trip, September 14, 1963, Alibates Flint Quarries, Alibates Indian ruin, Santa Fe Trail, Sanford Dam. Panhandle Geological Society, Amarillo, Texas.

Eifler, G. K. Jr., and V. E. Barnes. 1969 (reprinted 1981 with limited revisions). Amarillo sheet (scale 1:250,000). Leroy Thompson Patton Memorial Edition. Sheet GAT0002 in V. E. Barnes, project director. Geologic Atlas of Texas. University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Ek, D. A. 2008. Caves and karst of the National Park Service. Updated paper. Originally published as pages 16–32 *in* Proceedings of the 2001 National Cave and Karst Management Symposium. 15th National Cave and Karst Management Symposium, 16–19 October 2001, Tucson, Arizona. http://www.karstportal.org/FileStorage/NCKMS/2001_Arizona.pdf.

Elston, W. E., R. H. Weber, and F. D. Trauger. 1965. Road log from Silver City to junction of New Mexico Highways 61 and 90. Pages 45–62 *in* J. P. Fitzsimmons and C. Lochman-Balk, editors. Guidebook of southwestern New Mexico II. Fall Field Conference Guidebook 16. New Mexico Geological Society, Socorro, New Mexico.

Etchieson, G. M., and J. E. Couzzourt. 1987. Shoreline survey at Lake Meredith Recreation Area in the Texas Panhandle. US Department of the Interior, Bureau of Reclamation, Southwest Region, Amarillo, Texas.

Foster, N. M. 2008. Drought evaluation using tree-ring based reconstructed streamflows for rivers in New Mexico. Thesis. The University of Texas at El Paso, El Paso, Texas. http://gradworks.umi.com/14/53/1453860.html.

Frye, J. C., and A. B. Leonard. 1959. Correlation of the Ogallala Formation (Neogene) in western Texas with type localities in Nebraska. Report of Investigations 39. University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Frye, J. C., and A. B. Leonard. 1964. Relation of Ogallala Formation to Southern High Plains in Texas. Report of Investigations 51. University of Texas at Austin, Bureau of Economic Geology, Austin Texas.

Giles, K. A. 2005. Late Proterozoic (Ancestral Rocky Mountains) basins. *Graphic on reverse side of* M. E. Wilks, compiler. New Mexico geologic highway map (scale 1:1,000,000). New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Gill, T. E., D. L. Westphal, G. Stephens, and R. E. Peterson. 2000b. Integrated assessment of regional dust transport from West Texas and New Mexico, spring 1999. Pages 370–375 *in* Preprints of the 11th Joint Conference on Applications of Air Pollution Meteorology with the Air and Waste Management Association. American Meteorological Society, Boston, Massachusetts

Gould, C. N. 1906. The geology and water resources of the eastern portion of the panhandle of Texas. Water-Supply Paper 154. US Geological Survey, Washington, DC.

Gould, C. N. 1907. The geology and water resources of the western portion of the panhandle of Texas. Water-Supply Paper 191. US Geological Survey, Washington, DC.

Gustavson, T. C. 1986. Geomorphic development of the Canadian River Valley, Texas Panhandle: an example of regional salt dissolution and subsidence. Geological Society of America Bulletin 97(April):459–472.

Gustavson, T. C. 1996. Fluvial and eolian depositional systems, paleosols, and paleoclimate of the upper Cenozoic Ogallala and Blackwater Draw formations, Southern High Plains, Texas and New Mexico. Report of Investigations 239. University of Texas, Bureau of Economic Geology, Austin, Texas.

Gustavson, T. C., and R. J. Finley. 1985. Late Cenozoic geomorphic evolution of the Texas Panhandle and northeastern New Mexico—case studies of structural controls on regional drainage development. Report of Investigations 148. University of Texas, Bureau of Economic Geology, Austin, Texas.

Gustavson, T. C., R. J. Finley, and K. A. McGillis. 1980. Regional dissolution of Permian salt in the Anadarko, Dalhart, and Palo Duro basins of the Texas Panhandle. US Department of Energy contract DE-AC97-80ET-46615. Report of Investigations 106. University of Texas, Bureau of Economic Geology, Austin, Texas.

Gustavson, T. C., W. W. Simkins, A. Alhades, and A. Hoadley. 1982. Evaporite dissolution and development of karst features on the rolling plains of the Texas Panhandle. Earth Surface Processes and Landforms 7:545–563.

Highland, L. M., and P. Bobrowsky. 2008. The landslide handbook—a guide to understanding landslides. Circular 1325. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/circ/1325/.

Hoddenbach, G. 1987. *Tamarix* control. Pages 116–125 *in* M. R., Kunzmann, R. R. Johnson, and P. S. Bennett, technical coordinators. Tamarisk control in southwestern United States. Special Report 9. National Park Service, Cooperative National Park Resources Studies Unit, University of Arizona, School of Renewable Natural Resources, Tucson, Arizona. https://archive.org/details/tamariskcontroli00kunz.

Holiday, V. T. 1989. The Blackwater Draw Formation (Quaternary): a 1.4-plus-m.y. record of eolian sedimentation and soil formation on the Southern High Plains. Geological Society of America Bulletin 101:1598–1607.

Horn, P. 1963. Geology and topography of Alibates Flint Quarries. Pages 30–31 *in* E. D. Anthony Jr., editor. Alibates Flint Quarries, Alibates Indian Ruin, Santa Fe Trail, and Sanford Dam, field trip, 14 September 1963. Panhandle Geological Society, Amarillo, Texas.

Hunt, A. P., and V. L. Santucci. 2001. Paleontological resources of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, West Texas. Pages 257–264 *in* S. G. Lucas and D. Ulmer-Scholle, editors. Geology of the Llano Estacado. Fall Field Conference Guidebook 52. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0257_p0264.pdf.

Izett, G. A., and R. E. Wilcox. 1982. Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada (scale 1:4,000,000). Miscellaneous Investigations Series Map I-1325. U.S. Geological Survey, Washington, DC. http://ngmdb.usgs.gov/Prodesc/proddesc_9153.htm.

Johnson, K. S. 2013. Salt karst and collapse structures in the Anadarko Basin of Oklahoma and Texas. Pages 103–112 *in* L. Land, D. H. Doctor, and J. B. Stephenson, editors. Sinkholes and the engineering and environmental impacts of karst. Proceedings of the Thirteenth Multidisciplinary Conference, 6–10 May 2013, Carlsbad, New Mexico. NCKRI Symposium 2. National Cave and Karst Research Institute, Carlsbad, New Mexico. http://www.karstportal.org/sites/karstportal.org/files/KIP-0011735-25.pdf.

KellerLynn, K. 2005. Canyonlands National Park geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2005/003. National Park Service, Denver, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2008. Guadalupe Mountains National Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2008/023. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2010a. Padre Island National Seashore: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/246. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2010b. Petrified Forest National Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/218. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2011. Geologic resources inventory scoping summary, Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Texas. National Park Service, Geologic Resources Division, Lakewood, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2014. Gila Cliff Dwellings National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/849. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2015a. Bandelier National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR–2015/1036. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

KellerLynn, K. 2015b. Capulin Volcano National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR–2015/1031. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Kenkmann, T. 2003. Dike formation, cataclastic flow, and rock fluidization during impact cratering: an example from the Upheaval Dome structure, Utah. Earth and Planetary Science Letters 214:43–58.

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary inventory of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. Fossils from federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

King, K. W., S. T. Algermissen, and P. J. McDermott. 1985. Seismic and vibration hazard investigation of Chaco Culture National Historical Park. Open-File Report 85-529. US Geological Survey, Denver, Colorado. http://pubs.er.usgs.gov/publication/ofr85529.

King, K., D. Carver, and B. Winlow. 1991. Bonito vibration tests, Chaco Culture Historical Park [sic.]. Open-File Report 91-444. US Geological Survey, Denver, Colorado. http://pubs.er.usgs.gov/publication/ofr91444.

Koch, A. L., and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Southern Plains Network. Technical Information Center (TIC) publication number D-107. National Park Service, Fossil Butte National Monument, Kemmerer, Wyoming.

Lancaster, N. 2009. Aeolian features and processes. Pages 1–25 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/aeolian.cfm.

Lanphere, M. A., D. E. Champion, R. L. Christiansen, G. A. Izett, and J. D. Obradovich. 2002. Revised ages for tuffs of the Yellowstone Plateau volcanic field: assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event. GSA Bulletin 114(5):559–568.

Lucas, S. G. 1993. The Chinle Group: revised stratigraphy and biochronology of Upper Triassic nonmarine strata in the western United States. Pages 27–50 *in* M. Morales, editor. Aspects of Mesozoic Geology and Paleontology of the Colorado Plateau. Bulletin 59. Museum of Northern Arizona, Flagstaff, Arizona.

Lucas, S. G. 2001. Abandon the term Dockum! Pages 12–16 *in* S. G. Lucas and D. Ulmer-Scholle, editors. Geology of the Llano Estacado. Fall Field Conference Guidebook 52. New Mexico Geological Society, Socorro, New Mexico.

Lynn, A., and S. Black. 2003. Making cordmarked pottery. Online information. Texas Beyond History, University of Texas, Austin, Texas. http://www.texasbeyondhistory.net/theme/cordmarked/.

Machenberg, M. D., J. R. DuBar, T. C. Gustavson, and V. T. Holiday. 1985. A deposition model for post-Ogallala sediments on the Southern High Plains. Geological Society of America Abstracts with Programs 17:165.

McCauley, J. R., C. S. Breed, M. J. Grolier, and D. J. MacKinnon. 1981. The US dust storm of February 1977. Pages 123–147 *in* T. L. Pewe, editor. Desert dust: origin, characteristics, and the effect on man. Special Paper 186. Geological Society of America, Boulder, Colorado.

McGillis, K. A., and M. W. Presley. 1981. Tansill, Salado, and Alibates formations: upper Permian evaporite/carbonate strata of the Texas Panhandle. Geological Circular 81-8. University of Texas, Bureau of Economic Geology, Austin, Texas.

Miotke, F. -D. 1969. Gipskarst oestlich Shamrock/Nordtexas [English translation: Gypsum karst in eastern Shamrock, northern Texas]. Pages M 22.1–M 22.16 *in* Morphologie des Karstes. Proceedings of the International Congress of Speleology, issue 5, volume 1. International Union of Speleology, United States.

National Park Service. 2000. Draft oil and gas management plan. Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Fritch, Texas.

National Park Service. 2002. Final oil and gas management plan / environmental impact statement for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Hutchinson, Moore and Potter counties, Texas. Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Fritch, Texas.

National Park Service. 2012. Draft general management plan / environmental impact statement, Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Hutchinson, Moore, and Potter counties, Texas. National Park Service, Fritch, Texas.

National Park Service. 2014a. Foundation document: Lake Meredith National Recreation Area [and] Alibates Flint Quarries National Monument, Texas (April 2014). Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Fritch, Texas.

National Park Service. 2014b. Onshore wind energy. Online information. National Park Service, Geologic Resources Division, Lakewood, Colorado. http://nature.nps.gov/geology/energy/onshorewind.cfm.

National Park Service. 2015a. Antelope Creek Culture (1150 AD to 1450 AD). Online information. Alibates Flint Quarries National Monument, Fritch, Texas. http://www.nps.gov/alfl/learn/historyculture/antelope-creek-culture.htm.

National Park Service. 2015b. Lake Meredith National Recreation Area final off-road vehicle management plan / environmental impact statement (January 2015). National Park Service, Lake Meredith National Recreation Area, Fritch, Texas. http://parkplanning.nps.gov/document.cfm?parkID=76&projectID=20192&documentID=62567.

Norton, G. H. 1939. Permian redbeds of Kansas. American Association of Petroleum Geologists Bulletin 23:1751–1819.

Port, R. 2015. Pecos National Historical Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR–2015/951. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Pranger, H. 2000. Technical report—preliminary recommendations and cost estimates to restore the Stilling Basin road, Blue West boat ramp and Sanford-Yake boat ramp sites at Lake Meredith NRA (LAMR). Memorandum to superintendent, Lake Meredith National Recreation Area (February 9, 2000). National Park Service, Geologic Resources Division, Lakewood, Colorado.

Quigg, J. M., M. T. Boulanger, and M. D. Glascock. 2009. Geochemical characterization of Tecovas and Alibates source samples. Presented Paper. 67th Annual Plains Anthropological Conference, 14–17 October 2009, Norman, Oklahoma.

Ratté, J. C., D. L. Gaskill, and J. R. Chappell. 2014. Geologic map of the Gila Hot Springs 7.5' quadrangle and the Cliff Dwellings National Monument, Catron and Grant counties, New Mexico (scale 1:24,000). Open-File Report OFR-2014–1036. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/of/2014/1036/.

Reeves, C. C. Jr. 1970. Origin, classification, and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico. Journal of Geology 78:352–362.

Ruhe, R. V. 1967. Geomorphic surfaces and surficial deposits in southern New Mexico. Memoir 18. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Santucci, V. L., A. P. Hunt, and L. Norby. 2001. Oil and gas management planning and the protection of paleontological resources: a model application at Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. Park Science 21(1):36–38.

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/paleo.cfm.

Santucci, V. L., and H. G. McDonald. 2002. Part II: standard operating procedures for locating and protecting paleontological resources. Appendix F (pages F-9–F-11) *in* Final oil and gas management plan / environmental impact statement for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Hutchinson, Moore and Potter counties, Texas. National Park Service, Denver, Colorado.

Schultz, G. E. 1972. Vertebrate paleontology of the southern High Plains. Pages 129–133 *in* V. C. Kelley and F. D. Trauger, editors. East-central New Mexico. Fall Field Conference Guidebook 23. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/downloads/23/23_p0129_p0133.pdf.

Simkins, W. W., and T. C. Gustavson. 1984. Rates of hillslope erosion and deposition at six stations on the High Plains and rolling plains of the Texas Panhandle. Geological Society of America Abstracts with Programs 16(4):256.

Smith, A. R. 1971. Cave and karst regions of Texas. Pages 1–14 *in* E. L. Lundelius and B. H. Slaughter, editors. Natural history of Texas caves. Gulf National History, Dallas, Texas.

Smith, R. B., and L. J. Siegel. 2000. Windows into the Earth: the geologic story of Yellowstone and Grand Teton national parks. Oxford University Press, New York, New York.

Spearing, D. 1991. Roadside geology of Texas. Mountain Press Publishing Company, Missoula, Montana.

Stroud, J. R. 1997. The geochronology of the Raton-Clayton volcanic field, with implications for volcanic history and landscape evolution. Thesis. New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Sudbrock, A. 1993. Tamarisk control. I. Fighting back: an overview of the invasion, and a low-impact way of fighting it. Restoration and Management Notes 11:31–34.

Tweet, J. S., V. L. Santucci, and T. Connors. 2015. Paleontological resource inventory and monitoring: Southern Plains Network. Natural Resource Report NPS/SOPN/NRR–2015/971. National Park Service, Fort Collins, Colorado.

US Energy Information Administration. 2014. Texas state profile and energy estimates. Online information (updated 20 November 2014). US Energy Information Administration, Washington, DC. http://www.eia.gov/state/print.cfm?sid=TX.

USGS Central Region Assessment Team. 2002. Assessment methodology and results for remaining oil and gas resources beneath Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. Appendix E (pages E-1–E-13) *in* Final oil and gas management plan / environmental impact statement for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Hutchinson, Moore and Potter counties, Texas. US Geological Survey, Denver, Colorado.

Varnes, D. J. 1978. Slope movement types and processes. Pages 11–33 *in* R. L. Schuster and R. J. Krizek, editors. Landslides: analysis and control. Special Report 176. Transportation and Road Research Board, National Academy of Science, Washington, DC.

Weary, D. J., and D. H. Doctor. 2014. Karst in the United States: a digital map compilation and database. Open-File Report 2014–1156. US Geological Survey, Washington, DC. http://pubs.usgs.gov/of/2014/1156/.

West Texas A&M Geological Society. 2001. Guidebook of Palo Duro Canyon. West Texas A&M University, Canyon, Texas.

Wieczorek, G. F. and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/slopes.cfm.

Wilson, G. A. 1988. The effects of subsurface dissolution of Permian salt on the deposition, stratigraphy and structure of the Ogallala Formation (late Miocene age), northeast Potter County, Texas. Thesis. West Texas State University [now West Texas A&M University], Canyon, Texas.

Woodruff, C. M. Jr., T. C. Gustavson, and R. J. Finley. 1979. Playas and draws on the Llana Estacado—tentative findings based on geomorphic mapping of a test area in Texas. Texas Journal of Science 31(3):213–223.

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

Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of August 2015. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division
  Energy and Minerals; Active Processes and Hazards; Geologic Heritage:
  http://nature.nps.gov/geology/
- NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/
- USGS Geology of National Parks (including 3D imagery): http://3dparks.wr.usgs.gov/

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- University of Texas at Austin, Bureau of Economic Geology: http://www.beg.utexas.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, held on 11 May 2011. Discussions during this meeting supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2011 Scoping Meeting Participants

Name	Affiliation	Position
Glendon Jett	Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument	Volunteer
Eddie Collins	University of Texas at Austin, Bureau of Economic Geology	Geologist
Tim Connors	NPS Geologic Resources Division	Geologist
Steve Fisher	Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument	GIS Specialist–Fire/Biologist
Bruce Heise	NPS Geologic Resources Division	Geologist/Program Coordinator
Paul Katz	Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument	Volunteer
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Phil Reiker	NPS Geologic Resources Division	Geologist/Writer-Editor
Gerry Schultz	West Texas A&M University *Note*: GRI team met with Gerry Schultz at the university on 12 May 2011.	Vertebrate Paleontologist/ Professor of Geology
Arlene Wimer	Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument	Acting Superintendent/Chief of Resource Management

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2015. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**Mining in the Parks Act of 1976, 16 USC § 1901 et seq**. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 16 USC § 1 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to -demonstrate bona fide title to mineral rights; -submit a plan of operations to NPS describing where, when, how they intend to conduct operations; -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability.	**Section 8.7.3** requires operators to comply with 9B regulations.
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil and Gas, Salable Minerals, and Non-locatable Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq**. do not authorize the BLM to lease federally owned minerals in NPS units. Exceptions: Native American Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, (25 USC § 396)**, and the **Indian Leasing Act of 1938 (25 USC §§ 396a, 398 and 399)** and **Indian Mineral Development Act of 1982 (25 USC §§ 2101-2108)**, all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. BLM regulations at 4**3 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. Regulations re: Native American Lands within NPS Units: **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the I**ndian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC §§ 2101-2108)**. **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

NPS 618/129982, 434/129982, September 2015

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov

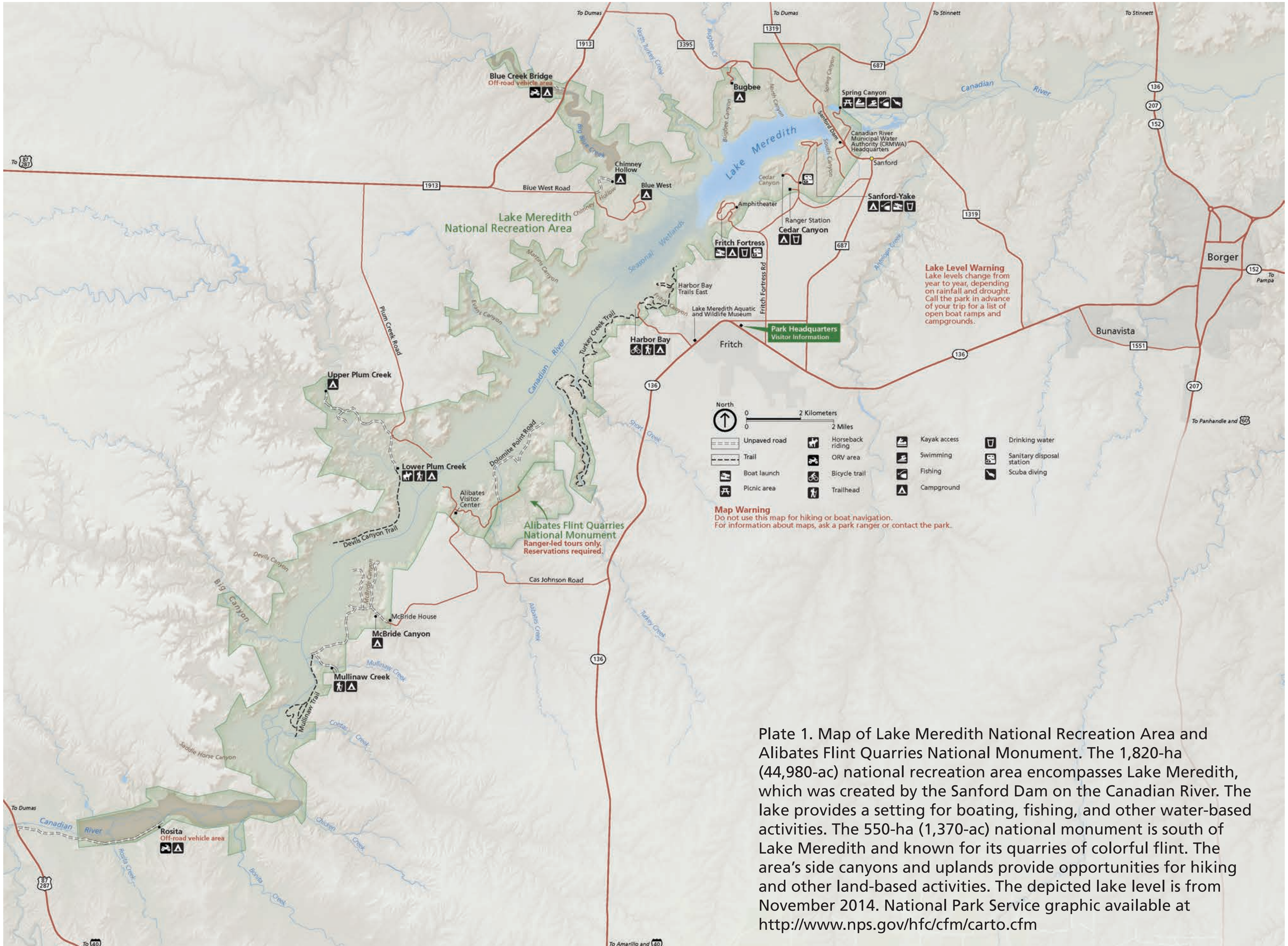


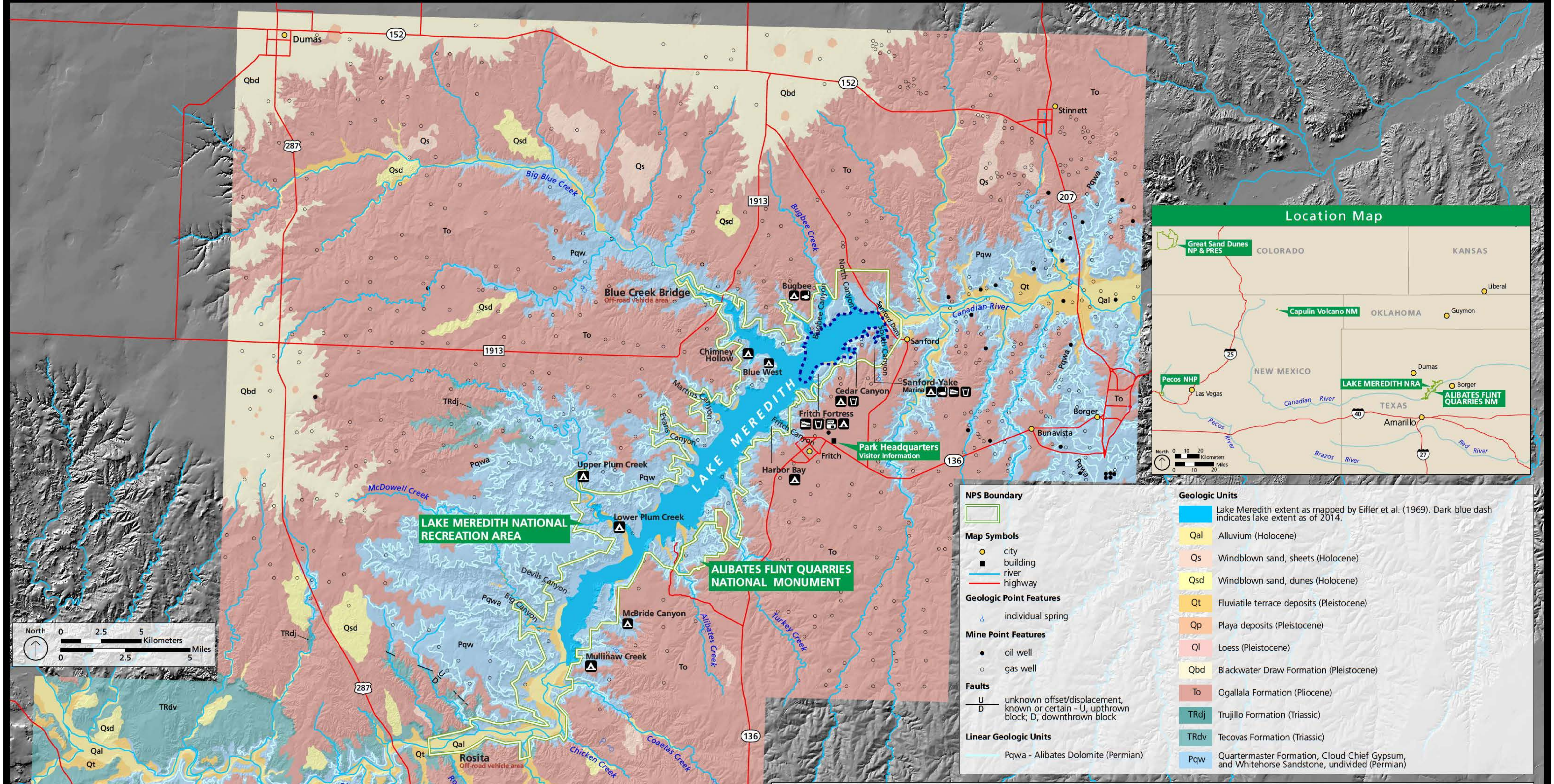
Plate 1. Map of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. The 1,820-ha (44,980-ac) national recreation area encompasses Lake Meredith, which was created by the Sanford Dam on the Canadian River. The lake provides a setting for boating, fishing, and other water-based activities. The 550-ha (1,370-ac) national monument is south of Lake Meredith and known for its quarries of colorful flint. The area's side canyons and uplands provide opportunities for hiking and other land-based activities. The depicted lake level is from November 2014. National Park Service graphic available at http://www.nps.gov/hfc/cfm/carto.cfm

Geology of Lake Meredith NRA and Alibates Flint Quarries NM

Texas

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science



This map was produced by Kari Lanphier and Georgia Hybels (Colorado State University) in October 2015. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of the digital geologic data were:

Eifler, G. K. Jr., and V. E. Barnes. 1969 (reprinted 1981 with limited revisions). Amarillo sheet (scale 1:250,000). Leroy Thompson Patton Memorial Edition. Sheet GAT0002 in V. E. Barnes, project director. Geologic Atlas of Texas. University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Texas Commission on Environmental Quality. 2004. Tucumcari sheet (scale 1:250,000). Sheet GAT0712 in Geologic Atlas of Texas. University of Texas at Austin, Bureau of Economic Geology, and Texas Commission on Environmental Quality, Austin, Texas.

Texas Water Development Board. 2007. Geologic database of Texas: 1:250,000 geologic data for Amarillo and Tucumcari sheets derived from the Geologic Atlas of Texas. Texas Water Development Board, Austin, Texas.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 127 m (416 ft) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Map Unit Properties Table: Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument

Colored map units are mapped within Lake Meredith National Recreation Area and/or Alibates Flint Quarries National Monument (colors match those on GRI poster [in pocket]). Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY PERIOD Holocene Epoch (0.01–0)	Alluvium (**Qal**)	No description provided with respect to rock type or geologic materials, but Holocene alluvium typically consists of unconsolidated clay, sand, silt, and gravel deposited by modern streams. **Qal** only mapped within Lake Meredith National Recreation Area. **Qt** (see description below) mapped along intermittent Alibates Creek within Alibates Flint Quarries National Monument.	**Canadian River**—**Qal** consists of channel and floodplain deposits and includes lowest terrace along the Canadian River. **Paleontological Resources**—**Qal** has yielded some fossil material within Lake Meredith National Recreation Area. Many of these paleontological resources are associated with archeological sites.	**Changes to Hydrology**—in the absence of unregulated flows and floods, salt cedar (*Tamarix* spp.) has spread along the Canadian River corridor. **Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting their usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Canadian River Valley**—**Qal** represents modern fluvial activity in the Canadian River Valley and its tributaries. Many tributaries also contain **Qt** (see description below).
QUATERNARY PERIOD Holocene Epoch (0.01–0)	Windblown sand, sheet (**Qs**)	Sand and silt, in sheets; locally modified by surface wash (overland flow). At scale 1:250,000, **Qs** was not mapped within the parks, but sand sheets are known to occur there.	**Paleontological Resources**—sand sheets have yielded some fossil material within Lake Meredith National Recreation Area. Many of these paleontological resources are associated with archeological sites. **Aeolian Features and Processes**—one of three types of aeolian features in the GRI GIS data; the other two are sand dunes (**Qsd**) and loess (**Ql**).	**Oil and Gas Production**—blowing sand is a concern at oil and gas operations that lack vegetation. **Off-Road Vehicle Use and Disturbed Land Restoration**—blowing sand is a concern where off-road vehicle (ORV) use has denuded vegetation and kicks up sand, making it available for aeolian transport. **Wind Erosion and Dust Storms**—blowing sand is a concern in areas that permit ORV use and at oil and gas operations. **Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Canadian River Valley**—aeolian processes continue to the present day, depositing windblown sand as sheets (**Qs**).
QUATERNARY PERIOD Holocene Epoch (0.01–0)	Windblown sand, dunes (**Qsd**)	Dunes and dune ridges; locally modified by surface wash (overland flow). At scale 1:250,000, **Qsd** was not mapped within the parks, but sand dunes are known to occur there.	**Paleontological Resources**—sand dunes have yielded some fossil material within Lake Meredith National Recreation Area. Many of these paleontological resources are associated with archeological sites. **Aeolian Features and Processes**—one of three types of aeolian features in the GRI GIS data; the other two are sand sheets (**Qs**) and loess (**Ql**). Notable sand dunes occur in the Rosita area at the south end of Lake Meredith National Recreation Area.	**Oil and Gas Production**—blowing sand is a concern at oil and gas operations that lack vegetation. **Off-Road Vehicle Use and Disturbed Land Restoration**—blowing sand is a concern where ORV use has denuded vegetation and kicks up sand, making it available for aeolian transport. **Wind Erosion and Dust Storms**—blowing sand is a concern in areas that permit ORV use. **Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Canadian River Valley**—aeolian processes continue to the present day, depositing windblown sand as dunes (**Qsd**).

Colored map units are mapped within Lake Meredith National Recreation Area and/or Alibates Flint Quarries National Monument (colors match those on GRI poster [in pocket]). Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY PERIOD Pleistocene Epoch (2.6–0.01)	Fluviatile terrace deposits (**Qt**)	Composed of gravel, sand, and silt. Gravel—sandy, composed of pebbles and cobbles of much older quartz, quartzite, chert, igneous rock, metamorphic rock, caliche, and rare abraded oyster (*Gryphaea*) fossils. Sand—fine to coarse-grained quartz, cross-bedded to massive, lenticular, reddish brown, pink, gray. Silt—sandy, lenticular. Mapped in both parks.	**Paleontological Resources**—**Qt** has yielded a bison (*Bison latifrons*) skull, mammoth bones, rodent burrows, and gastropods. **Qt** gravel hosts reworked Cretaceous oyster (*Gryphaea*) fossils. **Canadian River**—**Qt** is a significant fluvial feature deposited by the Canadian River and its tributaries. **Qt** provides a record of fluvial activity during the wetter Pleistocene Epoch.	**Abandoned Mineral Lands and Borrow Site**—borrow site in Lake Meredith National Recreation Area may occur in **Qt**.; may need further investigation. **Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Canadian River Valley**—**Qt** provides a record of incision that has been active throughout the past few tens of thousands of years, including incision of the Canadian Breaks. Inclusion of much older gravel (e.g., *Gryphaea* fossils) provides evidence that a stream system incised into and flowed through Cretaceous rocks (deposited in the Western Interior Seaway) that are no longer present in the area.
QUATERNARY PERIOD Pleistocene Epoch (2.6–0.01)	Playa deposits (**Qp**)	Composed of clay and silt. Sandy, light-gray, deposits in shallow depressions. Mostly covered by thin deposit of Holocene sediment. Significant feature in the Texas Panhandle though not mapped within the parks.	**Aeolian Features and Processes**—**Qp** is a source of loess (**Ql**).	**Wind Erosion and Dust Storms**—wind likely erodes areas mapped as **Qp**, redepositing that material elsewhere.	**Canadian River Valley**—**Qp** developed in areas with poor drainage. Developed at the time of the most recent ice age ("Wisconsinan glaciation").
QUATERNARY PERIOD Pleistocene Epoch (2.6–0.01)	Loess (**Ql**)	Windblown silt. Derived primarily from material eroded during dry periods between ice ages. At scale 1:250,000, **Ql** was not mapped within the parks, but loess is known to occur there.	**Alibates Dolomite and Alibates Flint**—"chertification" or the replacement of dolomite by silica (possibly from windblown ash) resulted in the development of Alibates flint. **Aeolian Features and Processes**—one of three types of aeolian features in the GRI GIS data; the other two are sand dunes (**Qsd**) and sand sheets (**Qs**). Subsequent to prehistoric mining, the flint quarries have partially filled with windblown dust (**Ql**).	**Off-Road Vehicle Use and Disturbed Land Restoration**—blowing dust is a concern where ORV use has denuded vegetation and kicks up sand, making it available for aeolian transport. **Wind Erosion and Dust Storms**—high winds transport **Ql**, resulting in diminished visibility.	**Canadian River Valley**—**Ql** originated during the alternating cold-and-wet and warm-and-dry climates of the past 2.6 million years. Ongoing transport of loess, including dust storms and dust devils, continues to the present day.
QUATERNARY PERIOD Pleistocene Epoch (2.6–0.01)	Blackwater Draw Formation (**Qbd**)	Composed of sand. Fine to medium-grained quartz, silty, calcareous, caliche nodules, massive, pink to grayish red, reddish brown, olive gray. Thickness 8 m (25 ft), feathers out locally.	**Aeolian Features and Processes**—composed of "cover sands" in an aeolian mantle over the Ogallala Formation (**To**).	None reported.	**Ogallala Formation**—**Qbd** represents significant aeolian sedimentation and soil formation on the Southern High Plains following deposition of **To**.

Colored map units are mapped within Lake Meredith National Recreation Area and/or Alibates Flint Quarries National Monument (colors match those on GRI poster [in pocket]). Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
TERTIARY* PALEOGENE AND NEOGENE PERIODS (66.0–2.6)	Ogallala Formation (**To**)	Composed of sand, silt, clay, gravel, and caliche. Locally includes Ogallala sand that has moved downslope covering older formations. Sand—fine to coarse-grained quartz, silty in part, caliche nodules locally, cemented locally by calcite and by silica, locally cross-bedded, various shades of gray, brown, and red. Minor silt and clay with caliche nodules, sandy in places, massive, white, gray, olive-green, brown, red, and maroon. Gravel, not everywhere present, composed of pebbles and cobbles of quartz, quartzite, minor chert, igneous rock, metamorphic rock, limestone, clay balls in lower part, and abraded oyster (*Gryphaea*) fossils in channel deposits and in basal conglomerate. Caliche, not everywhere present, sandy, pisolitic, white, gray, pink, comprises four or five beds up to 4 m (12 ft) thick in upper part, forms ledges and caprock. Maximum thickness 170 m (550 ft), thins westward. Mapped in both parks. *Original source used "Tertiary." The Paleogene (66.0 million–23.0 million years ago) and Neogene (23.0 million–2.6 million years ago) periods are the formally designated terms that cover this segment of geologic time.	**Alibates Dolomite and Alibates Flint**—"chertification" or the replacement of dolomite by silica (from overlying rocks, possibly **To**) resulted in the development of Alibates flint. **Ogallala Formation**—contains Ogallala aquifer. **Paleontological Resources**—**To** yielded bones of turtles and other vertebrates in Alibates Flint Quarries National Monument. In Lake Meredith National Recreation Area, **To** yielded a proboscidean tooth, and a bonebed with unspecified remains; possibly also root casts, grass anthoecia, *Celtis* endocarps, gastropods, insect burrows, fish impressions, vertebrate material, and reworked Cretaceous oysters (*Gryphaea*) and fossiliferous limestone (provenance unclear). **Canadian River**—the river and tributaries cut into **To** and underlying Triassic (**Trdj** and **TRdv**) and Permian rocks (**Pqw**). **Canadian Breaks and Caprock Escarpment**—**To** forms the rim of the Canadian Breaks and Caprock Escarpment.	**Changes to Hydrology**—draw down of water table (in the Ogallala aquifer) impacts springs and base streamflow into Lake Meredith and the Canadian River. **Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Ogallala Formation**—**To** sediments distributed by rivers and winds across the western plains. Inclusion of much older gravels (e.g., *Gryphaea* fossils) provides evidence that a stream system incised into and flowed through Cretaceous rocks (deposited in the Western Interior Seaway) that are no longer present in the area.
TRIASSIC PERIOD (252.2–201.3)	Trujillo Formation (**TRdj**)	Composed of conglomerate, sandstone, and shale. Conglomerate—sandy, granules and pebbles of quartz, limestone, sandstone, siltstone, minor chert, and fragments of petrified wood, massive, gray and brown. Sandstone—conglomeratic, fine to coarse grains of quartz and limestone, micaceous, calcareous locally, cross-bedded to massive, gray, greenish gray, and brown. Shale—micaceous, occurs as thin beds, gray and red. Forms scarp. Thickness of formation 9 m (30 ft), truncated locally. **TRdj** is mapped only in the western part of Lake Meredith National Recreation Area.	**Geologic Structures**—**TRdj** is part of the sediment package that was deposited in the Anadarko and Palo Duro basins. Covers the now-buried Amarillo uplift. **Alibates Dolomite and Alibates Flint**—"chertification" or the replacement of dolomite by silica (from overlying rocks, possibly **TRdj**) resulted in the development of Alibates flint. **Paleontological Resources**—conglomerate contains fragments of petrified wood. **Dissolution of Red Beds**—**TRdj** collapses into dissolution voids, forming "chimneys." **Canadian River**—the river and tributaries cut through **To** and into **TRdj** (as well as **Trdv)** and underlying Permian rocks (**Pqw**). **Canadian Breaks and Caprock Escarpment**—**TRdj** is exposed in the Canadian Breaks.	**Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Terrestrial Rocks**—**TRdj** was deposited in continental environments such as lakes and streams before the breakup of the supercontinent Pangaea.

Colored map units are mapped within Lake Meredith National Recreation Area and/or Alibates Flint Quarries National Monument (colors match those on GRI poster [in pocket]). Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
TRIASSIC PERIOD (252.2–201.3)	Tecovas Formation (**TRdv**)	Composed of shale, clay, siltstone, and sand. Sandy in places, micaceous, calcareous locally, reddish brown, various shades of red, maroon, gray, greenish gray, yellow, and purple. Sand—fine to medium-grained quartz, unconsolidated, massive, lenticular, white and light gray. Thickness 84 m (275 ft), truncated eastward. **TRdv** is exposed only in the western part of Lake Meredith National Recreation Area.	**Geologic Structures**—**TRdv** is part of the sediment package that was deposited in the Anadarko and Palo Duro basins. Covers the now-buried Amarillo uplift. **Alibates Dolomite and Alibates Flint**—"chertification" or the replacement of dolomite by silica (from overlying rocks, possibly **TRdv**) resulted in the development of Alibates flint. **Triassic Rocks**—Tecovas jasper was a dominant tool-making material along the eastern Caprock Escarpment. **Paleontological Resources**—sand layer contains petrified logs. **Dissolution of Red Beds**—**TRdv** collapses into dissolution voids, forming "chimneys." **Canadian River**—the river and tributaries cut through **To** and into **TRdv** (as well as **Trdj)** and underlying Permian rocks (**Pqw**). **Canadian Breaks and Caprock Escarpment**—**TRdv** is exposed in the Canadian Breaks. Tecovas jasper occurs along the escarpment.	**Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance, as needed.	**Terrestrial Rocks**—**TRdv** was deposited in terrestrial (as opposed to marine or coastal) environments such as lakes and streams before the breakup of the supercontinent Pangaea.
PERMIAN PERIOD (298.9–252.2)	Alibates Dolomite (**Pqwa**)	An upper and lower dolomite separated by shale. Dolomite locally replaced by chert ("Alibates flint"), which is banded and mottled red, pink, pale blue, pale purple, gray, brown, and black. Lower dolomite forms ledges. Upper dolomite less resistant to weathering than lower dolomite and is locally absent. Average thickness of entire unit is 5 m (15 ft). Mapped as a linear geologic unit in GRI GIS data. Mapped in both parks.	**Geologic Structures**—**Pqwa** is part of the sediment package that was deposited in the Anadarko and Palo Duro basins. Covers the now-buried Amarillo uplift. **Permian Red Beds**—**Pqwa** contains red bed between upper and lower dolomite members. **Alibates Dolomite and Alibates Flint**—lower dolomite member forms local "capstone." Upper dolomite member locally removed by erosion. Flint is most abundant in the upper dolomite member but is not confined to any particular bed or stratigraphic horizon. Most exposures of **Pqwa** in the national monument yield flint. "Chertification" or the replacement of dolomite by silica resulted in the development of Alibates flint. The Canadian River has transported pieces of Alibates flint downstream into western Oklahoma. Ancient peoples carved petroglyphs onto boulders of **Pqwa**. **Paleontological Resources**—**Pqwa** contains algal mats. **Canadian Breaks and Caprock Escarpment**—**Pqwa** is exposed in the Canadian Breaks. **Aeolian Features and Processes**—subsequent to prehistoric mining, the flint quarries have partially filled with windblown dust (**Ql**).	**Slope Movement Hazards**—**Pqwa** breaks into dolomite boulders that may break away and fall from cliffs or travel in leaps and bounds down slopes. **Paleontological Resource Inventory, Monitoring, and Protection**—park staff should observe exposed rock and sedimentary deposits for fossil material while conducting usual duties; photo-document and monitor in situ fossils; document fossils in cultural contexts; and contact the NPS Geologic Resources Division for technical assistance as needed.	**Red Beds**—two members of dolomite separated by a red-bed member indicate a sequence of sea level rise when dolomite was deposited, followed by sea level fall when red beds were deposited, then rise (dolomite) again.

Colored map units are mapped within Lake Meredith National Recreation Area and/or Alibates Flint Quarries National Monument (colors match those on GRI poster [in pocket]). Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PERMIAN PERIOD (298.9–252.2)	Quartermaster Formation, Cloud Chief Gypsum, and Whitehorse Sandstone, undivided (**Pqw**)	Interbedded sandstone, sand, siltstone, shale, gypsum, and dolomite. Sandstone and sand—fine-grained quartz, scattered to locally abundant frosted and polished coarse quartz grains, silty, massive, friable to indurated, various shades of red and orange, orange brown, and grayish green. Siltstone and shale—sandy in part, indistinctly bedded to massive, indurated, thin beds and veins of satin spar in upper part, various shades of red and orange, reddish brown, and grayish green. Gypsum—white, gray, and pink. Dolomite—see description for Alibates Dolomite (**Pqwa**). Maximum thickness of formation 200 m (650 ft). Mapped in both parks.	**Geologic Structures**—**Pqw** is part of the sediment package that was deposited in the Anadarko and Palo Duro basins. Covers the now-buried Amarillo uplift. **Permian Red Beds**—exposures of **Pqw** form the dramatic red bed landscape of the parks. **Dissolution of Red Beds**—**Pqw** is the unit most susceptible to dissolution at the parks. **Karst**—parks are karst areas resulting from the dissolution of mostly gypsum in Permian rocks. **Rock Shelter**—Permian strata are the most likely to host the rock shelter at Rosita; needs further investigation. Rock shelter is thought to have formed as a result of erosion of a less resistant rock layer below a more resistant rock layer and not associated with dissolution typical of a karst area. **Canadian River**—after cutting through **To** and underlying Triassic rocks (**TRdj** and **TRdv**), the river and tributaries cut into **Pqw**. **Canadian Breaks and Caprock Escarpment**—**Pqw** is exposed in the Canadian Breaks.	**Accelerated Erosion and Sedimentation**—fine-grained sediment washed from slopes composed of **Pqw** creates slippery mud and poses a hazard for people and vehicles at Stilling Basin Road and the Sanford-Yake boat ramp. **Wind Erosion and Dust Storms**—when lake level is high, waves erode **Pqw** along the Lake Meredith shoreline. **Slope Movement Hazards**—slumping and rockfall occur in **Pqw**. **Sinkhole Collapse and Erosion**—sinkhole in the Plum Creek area is a result of dissolution of **Pqw**. **Cave Resource Management**—development of a park-specific cave management plan would evaluate the significance of the rock shelter and the need for monitoring and protection.	**Red Beds**—deposited about 260 million years ago in Panthalassa, a global ocean surrounding much of the supercontinent Pangaea. **Canadian River Valley**—heightened groundwater recharge during the Pleistocene Epoch accelerated dissolution of Permian evaporites, triggering widespread vertical collapse and the formation of "chimneys."