National Park Service
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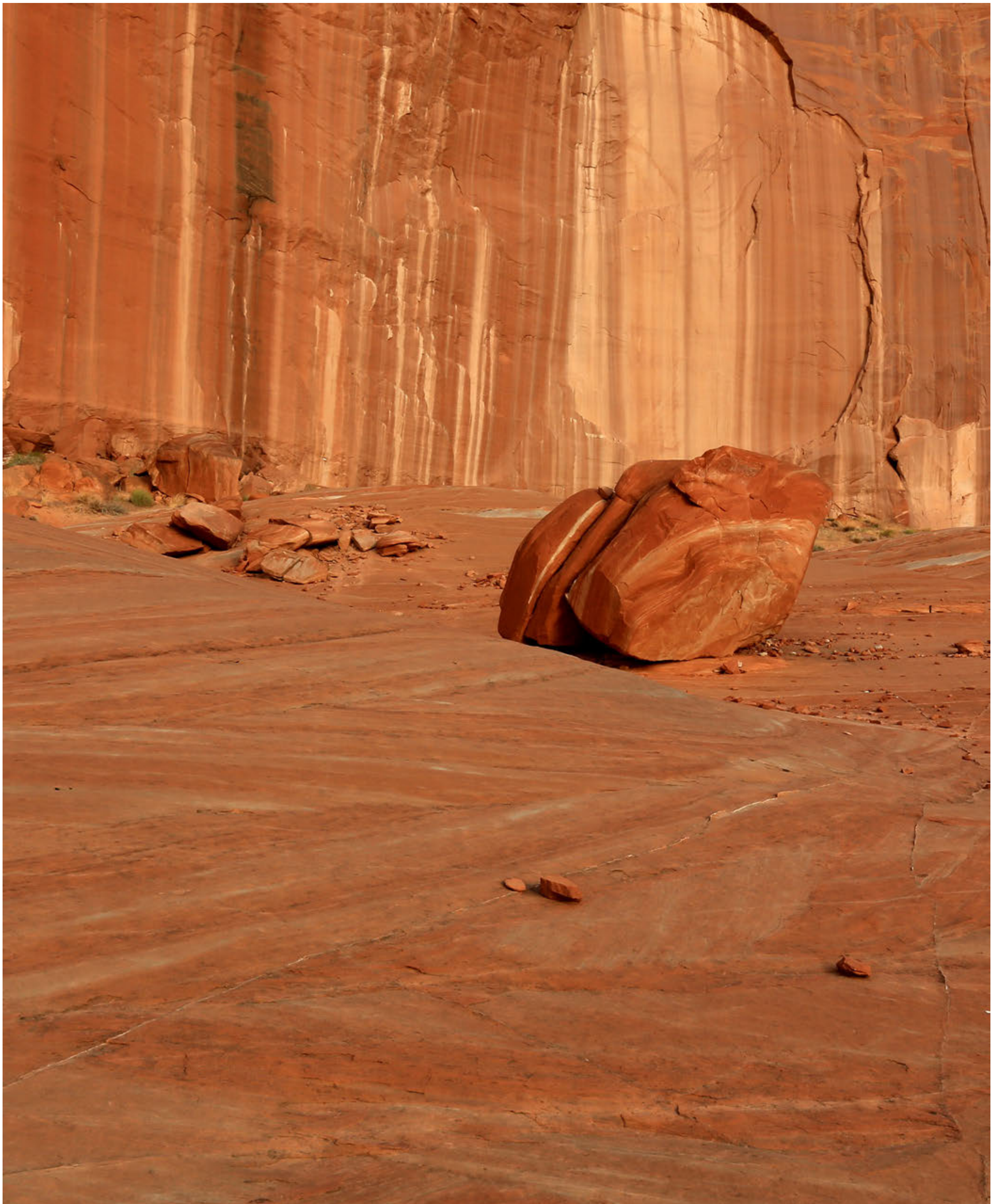
Natural Resource Stewardship and Science

Glen Canyon National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1264



ON THE COVER: Horseshoe Bend entrenched meander, Colorado River, Glen Canyon National Recreation Area. National Park Service photograph.

THIS PAGE: Slickrock sandstone cliff with desert varnish and cross-bedding. National Park Service photograph by Bob Moffit.

Glen Canyon National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1264

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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.

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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 Glen Canyon National Recreation Area (Arizona and Utah) on 23–25 September 1999 and a follow-up conference call on 5 March 2015, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI GIS data.

Glen Canyon National Recreation Area encompasses geologic features, landforms, and landscapes that are part of America's geologic heritage. Preservation of these features enriches a full range of values that contributed, and continue to contribute, to our country's history and culture. Glen Canyon National Recreation Area was established in 1972 to preserve the area's scenic, scientific, and historic features and to provide public use and enjoyment of Lake Powell. The recreation area's 506,000 ha (1.25 million ac) not only include Lake Powell but also sections of the Colorado and San Juan rivers. About 51% of Glen Canyon National Recreation Area consists of proposed and potential wilderness, considered to be a fundamental resource in the recreation area's Foundation Document.

Located on the Colorado Plateau, a physiographic province that spans roughly 34 million ha (84 million ac), Glen Canyon National Recreation Area shares a border with other national park system units including Grand Canyon National Park, Capitol Reef National Park, Canyonlands National Park, and Rainbow Bridge National Monument. In addition, the recreation area shares 800 km (500 mi) of its southern boundary with the Navajo Nation, and it adjoins public lands administered by the Bureau of Land Management, including the Grand Staircase-Escalante and Vermilion Cliffs National Monuments and the Paria Canyon-Vermilion cliffs Wilderness.

Lake Powell began filling behind Glen Canyon Dam in 1963. At full capacity, Lake Powell is 299 km (186 mi) long and contains 3,150 km (1,960 mi) of shoreline, which includes 96 major side canyons. The spectacular landscape includes over 3,000 m (10,000 ft) of sedimentary rocks that represent approximately 300 million years of Earth history. This geologic history includes several mountain–building events (orogenies), the formation of the supercontinent Pangea, multiple incursions of shallow seas onto the North American continent, vast deserts with Sahara-like sand dunes (ergs), the rise and demise of the dinosaurs, unique igneous intrusions known as laccoliths, and the carving of the Colorado River system. The recreation area has one of the most extensive exposures of Mesozoic Era rocks of any National Park Service unit, providing exceptional documentation of ecosystems and paleoclimates from approximately 252 million to 66 million years ago.

This dynamic history is expressed in the recreation area's myriad geologic features and associated processes, which include:

- **Landscape Features**. Mesas, buttes, cliffs, slickrock, slot canyons, alcoves, hanging gardens, arches, natural bridges, badlands, hoodoos, entrenched meanders, desert varnish, sandstone pipes, and weathering pits are just some of the features that record the processes that shaped the Glen Canyon National Recreation Area landscape.
- **Sedimentary Rocks and Sedimentary Rock Features**. The bedrock in Glen Canyon National Recreation Area consists of sedimentary rock, one of the three basic rock types. Features in the sedimentary rock strata document marine, nearshore marine, fluvial, and eolian environments that have transformed the landscape of southeastern Utah through geologic time.
- **Unusual Sedimentary Rock Features**. Oasis deposits, Moqui (Moki) marbles, soft sediment deformation, and tafoni record unusual environments and processes preserved in the sedimentary rock strata.
- **Paleontological Resources**. Marine fossils are common in Paleozoic limestones, while dinosaur

tracks are found in the terrestrial Mesozoic units. Pollen extracted from dung and packrat middens have provided evidence for the ecology and climate during the more recent Quaternary Period. Cultural sites contain artifacts fashioned from rocks and fossils, such as projectile points and scrapers fashioned from petrified wood.

- **Caves and Karst**. Numerous alcoves and caves have formed in the Navajo Sandstone and Cedar Mesa Sandstone cliffs. One of the more significant caves is Bechan ("big feces" in Navajo) Cave. The single-room cave, or alcove, contains 300 m^3 (10,600 ft^3) of fossil sloth and mammoth dung. Dung, hair, teeth, and bones found in Bechan Cave date back thousands of years. Paleozoic carbonate strata provide potential sites for solution caves, which are a characteristic of karst topography.
- **Paleosols**. These ancient soils, especially those found in the Chinle Formation, provide clues to past climates.
- **Unconformities**. Significant regional unconformities document millions of years of erosion or non-deposition during the Mesozoic Era.
- **Folds and Faults**. Faults, some reactivated throughout geologic time, and broad, asymmetrical, north- to northwest-trending folds, such as the regional Circle Cliffs anticline, resulted from tectonic events that deformed the Colorado Plateau.
- **Joints**. Near-vertical, inclined, and surficial joints fracture the bedrock in Glen Canyon National Recreation Area. The joints are partly responsible for the formation of slot canyons, rockfalls, and natural arches.
- **Laccoliths**. These mushroom-shaped igneous intrusions resulted from magma being forcefully injected along bedding planes, causing overlying strata to dome-upward. They form the dome-shaped Henry Mountains and Navajo Mountain, which are within the viewshed of Glen Canyon National Recreation Area.
- **Unconsolidated Surficial Deposits**. Surficial deposits in Glen Canyon National Recreation Area fall into seven categories: (1) alluvium, (2) eolian, (3) mass-wasting, (4) colluvium, (5) residuum, (6) lacustrine, and (7) tufa deposits. Each of these deposits represents specific processes that have been operating throughout geologic time.
- **Hite Delta Geomorphic Features**. The drought of 2000–2005 exposed domes, mud volcanoes, pockmarks, polygonal joints, slumps, and lateral spreads on the Hite delta. Analyses of these features may allow researchers to distinguish between seismic (earthquake) and non-seismic triggering mechanisms.
- **Economic Minerals**. Bitumen in the form of tar sands, gold, uranium, and coal occur in the recreation area. Tar sand deposits in the White Rim Sandstone intersect the northern portion of the recreation area. Gold dust, originating from the mountains of Colorado, mixes with river gravels in the recreation area. Uranium occurs in sandstones and conglomerates of Jurassic and Triassic strata. Coal beds are present in Cretaceous strata.
- **Geologic type sections**. Eleven of the mapped units have designated type sections (locations where a unit was first described) or other reference sections within or adjacent to Glen Canyon National Recreation Area.

Geologic resource management issues identified during the GRI scoping meeting in 1999 and follow-up conference call in 2015 include the following:

- **Landscape Safety Hazards**. Overlooks offer impressive views of the landscape, but they also present a potential hazard for visitors. Fatalities from falls have occurred at overlooks and along slick trails.
- **Slope Movement Hazards and Risk**. Landslides, slumps, slides, and rockfalls are common in the recreation area and can adversely impact park resources, infrastructure, and/or visitor safely. Erosion of less-resistant slopes, especially in the Chinle Formation, may undercut cliffs and lead to cliff collapse.
- **Flash Floods and Debris Flows**. Intense thunderstorms and sparse vegetation result in rapid runoff and flash floods through the narrow canyons in the recreation area. Debris carried by these floods may damage or destroy park infrastructure, as well as threaten visitor safety.
- **Paleontological Resource Inventory, Monitoring, and Protection**. In 2009, Glen Canyon National Recreation Area was selected as the prototype paleontological resource monitoring park for the National Park Service. The park maintains an inventory and monitoring database for the fossil

sites in the park. Natural degradation and fossil theft remain a concern for resource managers.

- **Cave and Alcove Management**. The caves and alcoves in Glen Canyon National Recreation Area contain a diverse assemblage of paleontological and cultural resources. A park-specific cave/alcove management plan should provide a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves.
- **Sediment Deposition in Lake Powell**. Because of Glen Canyon Dam, sediment is continuously deposited in Lake Powell. Sediment deposition has impacted several locations in the lake, including paleontological sites. Climate change models predict lower lake levels due to higher temperatures, decreased precipitation, and decreased runoff. As lake levels lower and sedimentation continues, storage in Lake Powell will be reduced.
- **Abandoned Mineral Lands and Potential Mining Activity**. Abandoned mineral lands in Glen Canyon National Recreation Area include mine adits, waste rock, abandoned oil and gas wells, surface mines, abandoned mining equipment, buildings, and roads. External and internal mining activities that may require remediation or impact the recreation area include past uranium mining, coal mining, burning coal beds in neighboring Grand Staircase-Escalante National Monument, external oil and gas exploration, and current tar sands exploration and development.
- **Potential Impacts from Global Climate Change**. A decline in winter precipitation may adversely impact the aquifers, springs, and seeps upon which the fragile ecosystems of the hanging gardens depend. A decline in precipitation may also lower the water level in Lake Powell, adversely impacting visitor access and increasing rockfall potential along the shoreline.
- **Earthquakes**. The probability of an earthquake with a magnitude >5 shaking the recreation area in the next 100 years is 0.04 to 0.30. The southern part of the recreation area, where Glen Canyon Dam was built, has a greater chance of an earthquake than the northern section.
- **Glen Canyon Dam and Downstream Impacts to the Colorado River**. With the closure of Glen Canyon Dam, average peak flows decreased and the downstream Colorado River channel narrowed and became dominated by cobbles and rocks. In the 1960s, flushing discharges scoured most of the sand out of the channel. Nonnative vegetation now stabilizes the banks.
- **Navajo Sandstone and Potential Glen Canyon Dam Failure**. The Glen Canyon Dam is anchored in the relatively porous Navajo Sandstone. The spillways have been engineered to prevent cavitation and eliminate the potential for water flowing over the dam. Should dam failure occur, the Colorado River channel would be scoured and downstream communities, archeological sites, and riparian ecosystems would be damaged or destroyed.

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, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Sections of the report discuss distinctive geologic features and processes within Glen Canyon National Recreation Area, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI GIS data. Posters (in pocket) illustrate these data. The Map Unit Properties Tables (in pocket) summarize report content for each geologic map unit.

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 ("source maps") 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

Additional thanks to: **Sarah Doyle** (Glen Canyon National Recreation Area) for her list of geohazards; **Grant Willis**, **Tyler Knudsen**, **Doug Sprinkel**, **John Spence**, and **Vincent Santucci** for their excellent reviews and photograph contributions; **John Burghardt** (NPS Geologic Resources Division) for his updated AML database; **Steve Simon**, **Julia Brunner**, and **Eric Bilderback** (NPS Geologic Resources Division) for their review comments and discussion regarding mineral leases, hazards, and risk; and **Trista Thornberry-Ehrlich** (Colorado State University) for producing many of the graphics in this report. Thanks to the Utah Geological Association (**Stephanie Carney** and **Jason Blake**) for permission to reproduce photographs from Netoff et al. (2010). **Betsy Scroggs** (Glen Canyon National Recreation Area) provided NPS photographs taken by **Bob Moffitt**.

The Utah Geological Survey completed mapping for Glen Canyon National Recreation Area (and other Utah NPS units) with funding from the GRI program.

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Geologic Setting and Significance

This chapter describes the concept of geologic heritage, park significance, fundamental resources, the regional geologic setting, and summarizes connections among geologic resources, other park resources, and park stories.

Geologic Heritage

America's geologic heritage (geoheritage) encompasses the geologic features, landforms, and landscapes integral to our country's history and culture. As in so many of our national parks, the geologic features in Glen Canyon National Recreation Area inspire a sense of awe and wonder, and the preservation of these features enriches a full range of values including scientific, aesthetic, cultural, ecosystem, educational, recreational, tourism, and many others.

> *Everybody needs beauty as well as bread, places to play in and pray in, where nature may heal and give strength to body and soul.*
> – John Muir, 1912

At the turn of the twentieth century, visionaries like John Muir recognized the value of our geoheritage. More than scenery, these iconic sites offered the opportunity to interact with a landscape shaped by the dynamic forces and interminable processes of nature and to reflect and grow as individuals and as a culture. The streams and rivers are as much a part of us as the blood that flows in our veins. The majestic mountains speak to the beauty of our souls just as the vast horizons of the prairies speak to the expansion of our consciousness. Today's visitor that looks out over the plateaus, mesas, narrow canyons, and buttes that collectively define Glen Canyon National Recreation area is as awestruck with the glory and power of nature as were the first visitors to the canyon more than 11,000 years ago. Our geoheritage reminds us that we are part of a much larger community, a community that includes not only those with whom we interact but the land, as well.

The American landscape of mountains, plateaus, plains, volcanoes, glaciers, canyons, and beaches is one of the most diverse on Earth. Much of the history of Earth is written in the geodiversity of Glen Canyon National Recreation Area. The ebb and flow of entire continents, the rise and erosion of mountain ranges, and the evolution of first organisms to today's ecosystems is documented in the rocks that grace the cliffs and canyon walls. Included in that history are the seeds of our own present-day culture, the hopes and dreams of all who have gone before, and the natural processes that are destined to shape the landscapes upon which future generations will stand and for a moment, pause and reflect.

> *Today, our open spaces are more precious than ever—and it's more important than ever that we come together to protect them for the next generation.* – President Barack Obama, 2011

Refer to http://go.nps.gov/americasgeoheritage and the publication *America's Geologic Heritage: An Invitation to Leadership* (National Park Service and American Geosciences Institute 2015) for details about geologic heritage and values.

Park Significance and Fundamental Resources

Glen Canyon National Recreation Area was established in order to preserve and protect this geodiversity and make it available for public enjoyment through both land- and water-based recreational activities. The recreation area "protects scenic, scientific, natural, and cultural resources on Lake Powell, the Colorado River, its tributaries, and surrounding lands" (National Park Service 2014a).

The significance of Glen Canyon National Recreation Area is stated as follows in the 2014 Foundation Document (National Park Service 2014a):

- The Colorado River and its many tributaries, including the Dirty Devil, Paria, Escalante, and San Juan rivers, carve through the Colorado Plateau to form a landscape of dynamic and complex desert and water environments.
- The vast, rugged landscapes of Glen Canyon National Recreation Area provide an unparalleled spectrum of diverse land- and water-based

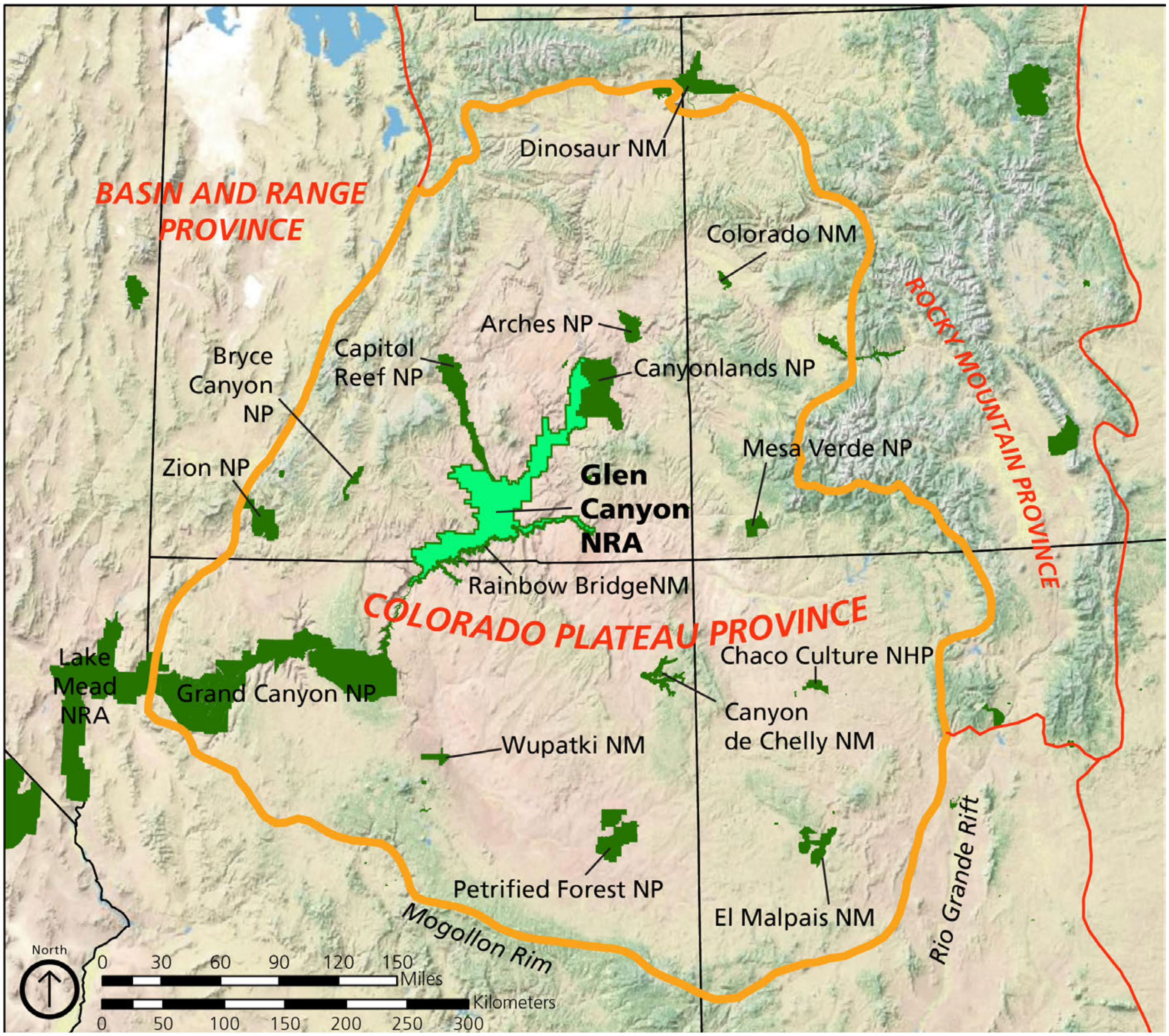

Figure 1. Physiographic provinces of the western United States. Glen Canyon National Recreation Area (bright green area) lies within the Colorado Plateau province. There are many other National Park System areas on the plateau, some of which are labelled. Compiled by Jason Kenworthy and Philip Reiker (NPS Geologic Resources Division) from ESRI Arc Image Service, National Geographic Society TOPO Imagery.

recreational opportunities for visitors of wide-ranging interests and abilities.

- Glen Canyon National Recreation Area preserves a record of more than 10,000 years of human presence, adaptation, and exploration. This place remains significant for many descendant communities, providing opportunities for people to connect with cultural values and associations that are both ancient and contemporary.
- The deep, 15-mile-long, narrow gorge below the dam provides a glimpse of the high canyon walls, ancient rock art, and a vestige of the riparian and beach terrace environments that were seen by John Wesley Powell's Colorado River expedition in 1869, providing a stark contrast to the impounded canyons of Lake Powell.

Heritage resources, Lake Powell, the landscape, paleontology, water, and wilderness are among the fundamental resources and values identified in Glen Canyon National Recreation Area (National Park Service 2014a). Heritage resources include archeological and historic sites, cultural landscapes,

Figure 2. Photograph of Reflection Canyon in Lake Powell, Glen Canyon National Recreation Area. Sedimentary rock forms the landscape surrounding Lake Powell. Many visitors explore the lake and side canyons via houseboat. National Park Service photograph by Gary Ladd, available at https://www.nps.gov/glca/learn/photosmultimedia/photogallery.htm (accessed 24 June 2016).

and traditional cultural properties that illustrate the connection of people with the landscape. By surface area, Lake Powell is the largest human-constructed reservoir in the United States. The rugged water- and wind-carved canyons, buttes, mesas, rivers, seeps, springs, and hanging gardens provide diverse habitats for a variety of endemic, rare, and relict plant and animal communities. Fossils found in Glen Canyon National Recreation Area continuously add to the scientific understanding of the past. Water quality and quantity is essential for public outdoor recreational use and enjoyment and for sustaining terrestrial and aquatic life in the high desert. The proposed and potential wilderness areas offer a variety of culturally and ecologically unique landscapes where visitors can experience that character and solitude of wilderness within a recreation area (National Park Service 2014a).

Geologic Setting

From northeast to southwest, Glen Canyon National Recreation Area extends from the Orange Cliffs in Utah to Lees Ferry in northernmost Arizona (plate 1; fig. 1). The San Juan Arm of the park follows the San Juan River eastward from Glen Canyon to Goosenecks State Park in southeastern Utah. The largest National Park Service unit in Utah, Glen Canyon National Recreation Area protects more than 506,000 ha (1.25 million ac) of sedimentary rocks that represent approximately 300 million years of Earth history (Anderson et al. 2010). Approximately 51% of the recreation area consists of 238,301 ha (588,855 ac) of proposed wilderness and 19,811 ha (48,955 ac) of potential wilderness.

Glen Canyon National Recreation Area shares its borders with public lands administered by the National Park Service and the Bureau of Land Management (BLM), as well as the Navajo Nation. National Park

Eon	Era	Period	Epoch	MYA	Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals: Extinction of large mammals and birds; Modern humans	Ice age glaciations; glacial outburst floods
			Pleistocene (PE)	2.6		Cascade volcanoes (W)
		Tertiary (T) Neogene (N)	Pliocene (PL)	5.3		Linking of North and South America (Isthmus of Panama)
			Miocene (MI)	23.0	Spread of grassy ecosystems	Columbia River Basalt eruptions (NW); Basin and Range extension (W)
		Tertiary (T) Paleogene (PG)	Oligocene (OL)	33.9		
			Eocene (E)	56.0		Laramide Orogeny ends (W)
			Paleocene (EP)	66.0	Early primates	
				66.0	Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles: Placental mammals; Early flowering plants	Laramide Orogeny (W); Western Interior Seaway (W); Sevier Orogeny (W)
		Jurassic (J)		201.3	Dinosaurs diverse and abundant	Nevadan Orogeny (W); Elko Orogeny (W)
		Triassic (TR)		252.2	Mass extinction; First dinosaurs; first mammals; Flying reptiles	Breakup of Pangaea begins; Sonoma Orogeny (W)
				252.2	Mass extinction	
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians	Supercontinent Pangaea intact
		Pennsylvanian (PN)		323.2	Coal-forming swamps; Sharks abundant; First reptiles	Ouachita Orogeny (S); Alleghany (Appalachian) Orogeny (E); Ancestral Rocky Mountains (W)
		Mississippian (M)		358.9		
		Devonian (D)		419.2	Fishes: Mass extinction; First amphibians; First forests (evergreens)	Antler Orogeny (W); Acadian Orogeny (E-NE)
		Silurian (S)		443.8	First land plants; Mass extinction	
		Ordovician (O)		485.4	Marine Invertebrates: Primitive fish; Trilobite maximum; Rise of corals	Taconic Orogeny (E-NE)
		Cambrian (C)		541.0	Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian (PC, W, X, Y, Z)		2500	Complex multicelled organisms; Simple multicelled organisms	Supercontinent rifted apart; Formation of early supercontinent; Grenville Orogeny (E); First iron deposits; Abundant carbonate rocks
Archean				4000	Early bacteria and algae (stromatolites)	Oldest known Earth rocks
Hadean				4600	Origin of life; Formation of the Earth	Formation of Earth's crust

Figure 3. 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. Time periods representing the strata mapped in Glen Canyon National Recreation Area are in green. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 7 May 2015).

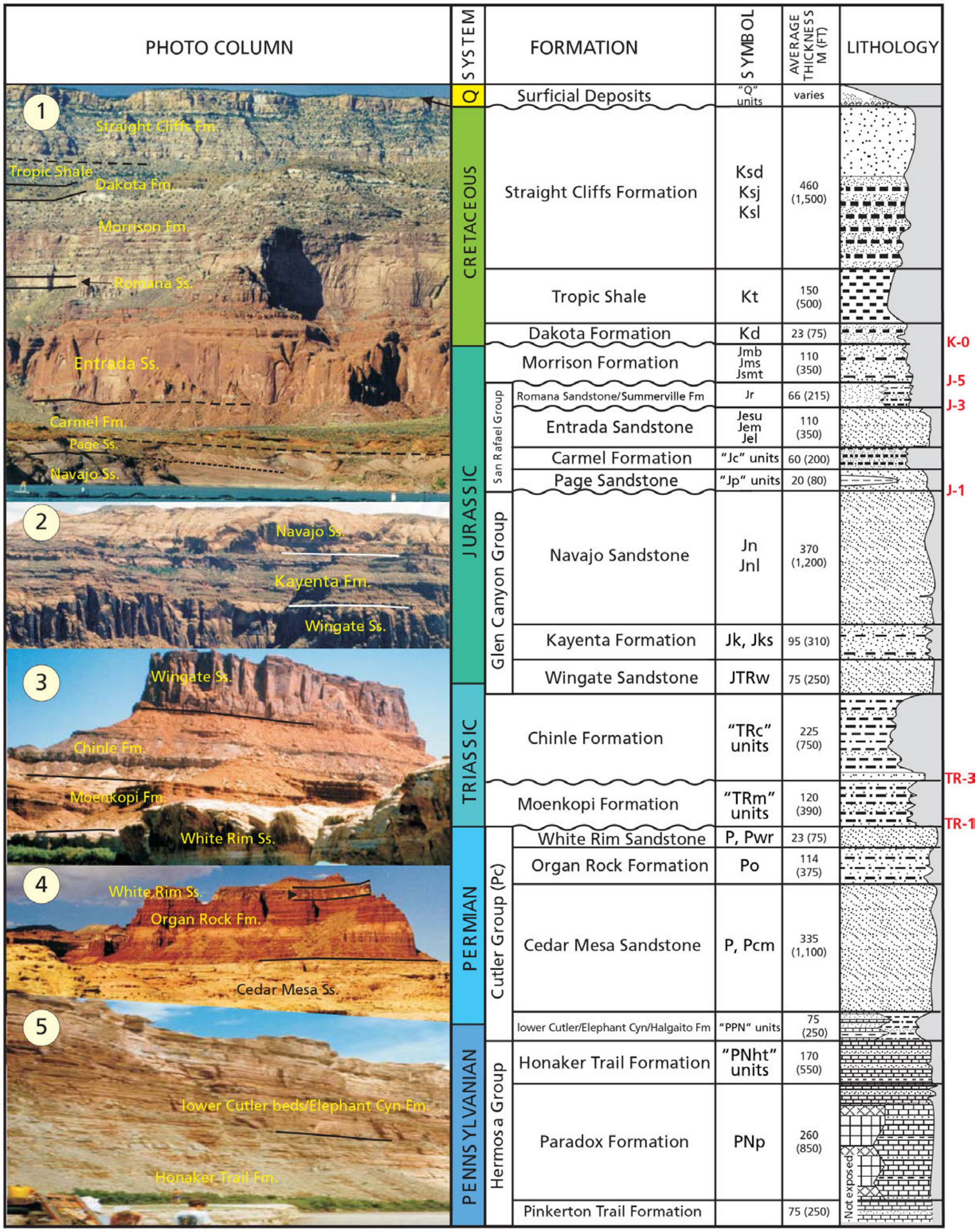

Figure 4. Stratigraphic column for Glen Canyon Recreation Area and vicinity. The lithology column includes sandstone (dots), shale (dashes), siltstone (dots and dashes) and limestones (brick-like pattern). It also indicates weathering patterns with coarser-grained, more erosion-resistant rocks (i.e., sandstone) to the right and less-resistant rocks (i.e., shale) to the left. The wavy lines represent regional unconformities (TR-1, TR-3, J-1, J-3, J-5, K-0), which are explained in the "Unconformities" section. Note: Many rocks mapped as Page Sandstone are now recognized as the Temple Cap Formation (see "Unconformities" section). Photographs: (1) View north from Dangling Rope Marina. (2) View east near Red Canyon. (3) Stillwater Canyon, Green River. (4) Junction of Dirty Devil and Colorado rivers, near Hite Crossing. (5) Confluence of the Green and Colorado rivers, view up Colorado River. Photographs and stratigraphic column are from Anderson et al. (2010, figure 4). Column redrafted by Trista Thornberry-Ehrlich (Colorado State University).

System units that border the recreation area include Grand Canyon National Park, Capitol Reef National Park, Canyonlands National Park, and Rainbow Bridge National Monument (plate 1; fig. 1). Geologic Resources Inventory reports are available for Capitol Reef and Canyonlands national parks and Rainbow Bridge National Monument, and the report for Grand Canyon National Park is in progress as of August 2016 (KellerLynn 2005; Graham 2006a, 2009). The reports are available on the National Park Service Geologic Resources Inventory publications website http://go.nps.gov/gripubs. BLM administered areas include the Grand Staircase-Escalante and Vermilion Cliffs national monuments and the Paria Canyon-Vermilion Cliffs Wilderness. The Navajo Indian Reservation borders the recreation area to the southeast (plate 1).

Lake Powell, by volume the second largest reservoir in the United States (plate 1), began filling when the gates of Glen Canyon Dam closed in 1963 and reached its full capacity (referred to as “full pool”) of 32.336 km^3 (7.7578 mi^3) of water in 1980. At full pool, the reservoir is 299 km (186 mi) long with 3,150 km (1,960 mi) of shoreline that wraps around 96 major side canyons (fig. 2). Lake Powell accounts for 14% of the total area of Glen Canyon National Recreation Area and 80% of the Colorado River Storage Project (US Department of the Interior 2008).

Glen Canyon National Recreation Area is part of the Colorado Plateau, a physiographic province that covers roughly 340,000 km^2 (130,000 mi^2) of Colorado, Utah, Arizona, and New Mexico (fig. 1). Climate on the Colorado Plateau varies from arid at its lowest elevations, semi-arid at intermediate elevations, and humid at higher elevations. The rugged topography of the region includes broad plateaus and mesas, steep narrow canyons, and the Navajo and Henry Mountains that range in elevation from 2,400 m (8,000 ft) to 3,540 m (11,600 ft) above sea level (Anderson et al. 2010; John Spence, Glen Canyon National Recreation Area, Chief Scientist and Terrestrial Natural Resources Branch Chief, written communication, 9 December 2015). These dome-shaped mountains owe their origin to world-renowned igneous intrusions known as laccoliths.

Glen Canyon National Recreation Area contains over 3,000 m (10,000 ft) of sedimentary rocks that were deposited during the Pennsylvanian and Permian periods of the Paleozoic Era and throughout the Mesozoic Era (figs. 3 and 4). Bedrock consists of both clastic and carbonate sedimentary rock types (fig. 4). Sediment transported into Lake Powell by the Colorado River and its tributaries comes primarily from the friable sandstone, shale, and mudstone of the sedimentary strata on the Colorado Plateau. Unconsolidated river gravels eroded from the Rocky Mountains include all three basic rock types: sedimentary, igneous, and metamorphic.

Geologic Significance and Connections

The extensive exposures of Mesozoic rocks in Glen Canyon National Recreation Area may represent the best overall Mesozoic stratigraphic section in the National Park Service.

The landscape of the Colorado Plateau transformed from a region of shallow seas in the Paleozoic Era more than 300 million years ago to terrestrial and coastal environments in the Mesozoic Era (~252 million–66 million years ago). The strata in Glen Canyon National Recreation Area document this transition from open marine and marginal marine environments to vast sand dune-covered deserts and river systems. Fossils preserved in the strata also illuminate this transition as abundant marine invertebrate fauna gave way to terrestrial plants, reptiles, and dinosaurs. These shifting environments were the result of tectonic plate movements that caused continents to collide and separate, climates to change, sea levels to rise and fall, and mountains to form.

Collisions between oceanic plates and the North American continent have deformed the western margin of North America since the Paleozoic, yet the Colorado Plateau has remained a relatively rigid lithospheric block during these millions of years of deformation. Tectonic activity folded and faulted the continental margin into a north–south-trending mountain range approximately 140 million years ago, deformed the continental interior into the Rocky Mountains about 70 million to 35 million years ago, and began pulling apart Earth’s crust to form the Basin-and-Range province about 35 million years ago. However, strata on the Colorado Plateau, including the bedrock in Glen Canyon National Recreation Area, sustained relatively mild deformation, being bent and folded into broadly warped anticlines (convex folds) and regional monoclines (one-limbed

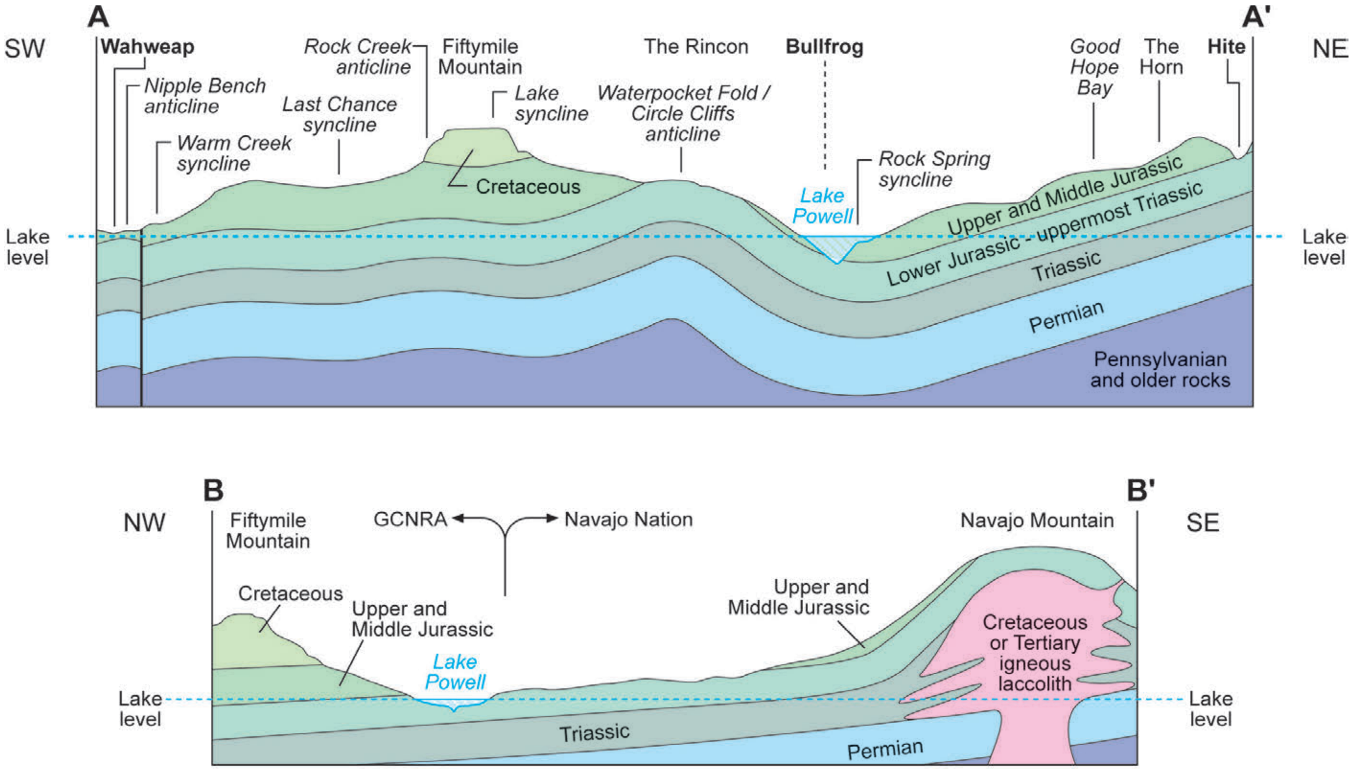

Figure 5. Exaggerated geologic cross-sections for Glen Canyon National Recreation Area. The cross-sections illustrate the relatively undeformed nature of the strata with broad anticlines (A-shaped folds) and synclines (U-shaped folds). The Navajo Mountain laccolith in cross-section B-B' cuts Lower Jurassic-Upper Triassic strata, indicating that emplacement of the igneous unit occurred after the Late Jurassic. Cross-sections from Anderson et al. (2010, figure 5).

folds in relatively flat-lying strata) (fig. 5). Glen Canyon National Recreation Area also contains a variety of unconsolidated Quaternary deposits that range in size from clay-size particles to house-size boulders (table 1). Millions of years are missing between bedrock in Glen Canyon National Recreation Area and the overlying unconsolidated sediments. This gap in time is known as an unconformity, which represents a period of non-deposition and/or erosion of previous strata (see the "Geologic Features and Processes" chapter).

Dating the Colorado River terrace deposits and the carving of the Grand Canyon and Glen Canyon has been the focus of spirited debate for many years (e.g., Willis 1992; Hanks et al. 2001; Willis and Biek 2001; Garvin et al. 2005; Karlstrom et al. 2007; Cook et al. 2009; Pederson 2009). The alluvial deposits and associated river terraces in Glen Canyon National Recreation Area have helped constrain the incision of Glen Canyon to the past one million years (Garvin et al. 2005; Anderson et al. 2010; tables 1 and 2 in Willis and Ehler, in preparation; see glca_geology.pdf in GRI GIS data).

Glen Canyon had been visited by humans for about 11,500 years before it was drowned by Lake Powell (table 2; National Park Service 2015a). Although not every cultural period is well-represented, prehistoric artifacts found in the recreation area document human occupation beginning with Clovis and Folsom nomads during the Paleoindian period (11,500 BCE–8,050 BCE) and extending to the first Spanish explorers in 1540 CE during the Protohistoric period (1500 CE–1850 CE) (table 2; Geib and Fairley 1997; Tweet et al. 2009; National Park Service 2015a).

The Historic period begins with the 1776 expedition of Spanish priests, Father Dominguez and Father Escalante, who provided the first written record of Glen Canyon (National Park Service 2015a). Their grueling expedition had bypassed the canyon country on their way from Santa Fe to California, but on their return trip, they arrived at the confluence of the Colorado and Paria rivers, downstream from the current Glen Canyon Dam. Unable to cross the Colorado at the mouth of the Paria River, they eventually chopped steps in the sandstone wall at Padre Creek, led their pack animals

Table 1. Summary of unconsolidated deposits mapped in Glen Canyon National Recreation Area.

Age	Unit (map symbol)		Description (see Unconsolidated Map Unit Properties Table for more detail)
Holocene	Artificial fill & disturbed areas (Qfd)		Gravel, sand, earth-fill, and large disturbed areas.
	Concrete fill in Glen Canyon Dam (Qfdm)		Concrete fill used in the construction of Glen Canyon Dam.
Pleistocene to Holocene	Alluvial deposits	Alluvial deposits (Qa, Qal, Qal1, Qat, Qaty, Qat2-13, Qag, Qagm, Qago)	Boulder to pebble gravel, sand, silt, and clay deposited in Colorado and San Juan rivers and their tributaries, on broad alluvial fan surfaces, and in terrace remnants. Clasts generally reflect local lithologies.
	Mixed environment deposits	Alluvial and colluvial deposits (Qac, Qaco)	Boulder to clay-sized sediment deposited in small ephemeral drainages. Moderately to poorly sorted. Includes colluvium.
		Alluvial and eolian deposits (Qae, Qae2, Qae3, Qaeo)	Boulder to clay-sized alluvial sediments and windblown sand and silt. Deposited by in streams, washes, and low slopes.
		Alluvial fan and stream, eolian, and colluvial deposits (Qaec)	Boulder to clay-sized deposits on low slopes below cliff- and ledge-forming units where stream gradients are reduced.
		Eolian and alluvial deposits (Qea, Qeao)	Sand, silt, clay deposited by wind mixed with stream-deposited pebbles and cobbles and capped by a thick calcic soil (caliche) that forms a resistant bench.
	Lacustrine deposits (Ql)		Thinly laminated silt, very fine-grained sand, peat, and clay partly covered by eolian silt.
	Spring tufa deposits (Qst)		Calcareous tufa deposited by springs. Tufa cements bedrock and talus rubble, colluvium, and other surficial deposits.
	Eolian sand (Qes)		Very well-sorted, well-rounded, fine- to medium-grained quartz sand. Deposited by wind in sheets, mounds, and dunes.
	Mass movement deposits	Landslide and slump deposits (Qms, Qmsh)	Extremely poorly sorted, angular, massive blocks to clay-size material that slumped or flowed down slopes.
		Slump blocks (Qmsb)	Intact to partially intact blocks of rock as much as 2.7 km (1.5 mi) long that have slumped downslope. Blocks commonly rotate backwards and dip toward the nearby cliff.
		Talus deposits (Qmt)	Broken, angular rockfall debris at the base of steep slopes.
		Landslide, slump, and talus deposits, undifferentiated (Qmst)	Undifferentiated Qms, Qmsh, Qmsp, Qmt, and Qmte deposits.
		Talus deposits with eolian sand mantle (Qmte)	Similar to Qmt deposits except commonly covered by moderate to large amounts of eolian sand.
Pleistocene	Alluvial deposits (Qatg8, Qatg9)		Older alluvial river terrace and locally derived gravel deposits.

to the banks of the Colorado, and crossed where the river was wide and shallow. Today, this Crossing of the Fathers lies beneath Padre Bay, but an inscription carved into the sandstone wall reads "paso por aqui" (passed by here) with the date 1776, which may have been left behind by Fathers Dominguez and Escalante (DesertUSA 2015; John Spence, written communication 9 December 2015).

About 100 years after the Dominguez-Escalante expedition, Major John Wesley Powell, the one-armed geologist and American Civil War veteran, led a crew of nine men on the first-ever scientific expedition through the Colorado and Green rivers. In May 1869, Powell left Green River, Wyoming, and on July 28, he and his men entered a canyon decorated with "carved walls, royal arches, glens, alcove gulches, mounts, and monuments" (Major John Wesley Powell quoted in Anderson et al. 2010, p. 309). The expedition named this canyon "Glen Cañon." Ironically, the reservoir that bears his name has drowned the rapids and canyons through which Powell navigated, as well as many of the natural features that Powell documented.

Railroad workers further explored the Colorado River in hopes of extending a line from Grand Junction, Colorado, to the Gulf of California, but funding for their project did not materialize. In 1873, the Church of Jesus Christ of Latter-day Saints (Mormon Church) sent John D. Lee to the confluence of the Colorado and Paria rivers with instructions to build and operate a ferry. Various operators (with a variety of ferryboats; fig. 6) maintained a ferry at Lees Ferry until Navajo Bridge was completed in 1929 to accommodate automobile traffic.

Table 2. American Indian history in Glen Canyon National Recreation Area.

Cultural Period	Time	Geologic Heritage Connection
Paleoindian	11,500 BCE – 8,050 BCE	Clovis and Folsom nomadic hunters left a few projectile points that had been fashioned from bedrock.
Archaic	8,050 BCE – 400 BCE	Broad-based hunting/gathering period. Many distinctive artifacts, such as sandals. Maize agriculture began about 2,600 years ago.
Preformative (Basketmaker II)	400 BCE – 500 BCE	Artifacts are sparse in Glen Canyon. Pottery has yet to be developed. The bow and arrow are introduced late in the period.
Formative	500 CE – 1300 CE	Fremont and Puebloan cultures. Plethora of artifacts from the recreation area. Period is characterized by agriculture, permanent or semi-permanent habitations, and pottery. The Fremont culture occupied the region north of the Colorado River, while the ancestral Puebloans, who include today's Hopi Indians, lived south of the river. The ancestral Puebloans leave the Four Corners area at the end of the period.
Late Prehistoric	1300 CE – 1500 CE	Paiute groups expanded into Glen Canyon, but this period is poorly understood within the recreation area.
Protohistoric	1500 CE – 1850 CE	Artifacts are sparse, but some evidence suggests that Navajo, who migrated into the area from northwestern Canada and eastern Alaska around 1400 CE, Paiute and Hopi visited Glen Canyon prior to the arrival of the Spanish in 1540 CE.

Information from Geib and Fairley (1997), Tweet et al. (2009), and National Park Service (2015a).

Settlers in the San Juan Valley continued to find more suitable ferry routes across the Colorado River. An early river crossing in Hole-In-The-Rock at the confluence of the Colorado and Escalante rivers was superseded by a better crossing found by Charles Hall about 56 km (35 miles) upstream. Travelers were ferried across Hall Crossing until Cass Hite found and developed another, still more accessible crossing. The town and ferry at Hite, Utah, remained operational until they were flooded by the rising waters of Lake Powell.

Figure 6. Historic photograph of ferryboat at Lees Ferry. John D. Lee established the first ferry at the confluence of the Colorado and Paria rivers in the 1870s. Ferries operated there until Navajo Bridge opened in 1929. National Park Service photograph available at https://www.nps.gov/glca/learn/photosmultimedia/photogallery.htm (accessed 24 June 2016).

In 1956, Congress authorized Glen Canyon Dam to provide water storage in the upper Colorado River Basin. The dam is managed by the Bureau of Reclamation. Several major tributaries such as the Green, Yampa, White, Dolores, Dirty Devil, and San Juan rivers provide water to Lake Powell. At full pool, the surface elevation of the reservoir is 1,128 m (3,700 ft) above mean sea level. Since 2000, the average annual surface elevation of the reservoir has fluctuated from a high of 1,121.09 m (3,678.11 ft) above sea level in 2000 to a low of 1,091.15 m (3,579.88 ft) in 2004 (Lake Powell Water Database 2016). The NASA Earth Observatory website includes a feature showing water levels of Lake Powell over time (http://earthobservatory.nasa.gov/Features/WorldOfChange/lake_powell.php). Most of the water (85%) from Lake Powell is dedicated to agricultural production. The rest goes to urban areas in California, Arizona, and Nevada.

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Glen Canyon National Recreation Area.

During the 1999 scoping meeting (NPS Geologic Resources Division and Natural Resources Information Division 1999) and 2015 conference call, participants (see Appendix A) identified geologic features and processes from the following categories:

- Landscape Features
- Sedimentary Rocks and Sedimentary Rock Features
- Unusual Sedimentary Rock Features
- Paleontological Resources
- Caves and Karst
- Paleosols
- Unconformities
- Folds and Faults
- Joints
- Laccoliths
- Unconsolidated Surficial Deposits
- Hite Delta Geomorphic Features
- Economic Minerals
- Geologic type sections

Features within these categories, and the processes responsible for them, capture the rich geodiversity of the recreation area.

The National Park Service Foundation Document (National Park Service 2014a) outlines the significance, fundamental resources, and other important resources within the recreation area. Many of these have connections to geology (see "Geologic Setting and Significance" chapter).

This chapter utilizes much information from, and follows the terminology of, the Glen Canyon National Recreation Area chapter (Anderson et al. 2010) in *Geology of Utah's Parks and Monuments* (Utah Geological Association, 3rd edition). A companion geologic field trip guide to the recreation area is available as Chidsey et al. (2012).

Resource management issues associated with these features and processes are discussed in the next chapter.

Landscape Features

Colorful bluffs, mesas, buttes, canyons, and a myriad of other spectacular landscape features dominate the viewshed in Glen Canyon National Recreation Area (table 3). These iconic features are some of the more accessible and popular features of their type in the world, and they were visited by 2.5 million visitors in 2015 (National Park Service 2015b). Fittingly, they are considered fundamental resources by the NPS and are summarized in the Foundation Document for the recreation area (National Park Service 2014a). A variety of resource management issues exist for these iconic features and are summarized in the following "Geologic Resource Management Issues" chapter.

Plateaus, Mesas, and Buttes

The plateaus, mesas, and buttes that characterize the Colorado Plateau differ from one another primarily in size. A plateau is usually higher and more extensive than a mesa, which is more extensive than a butte. Plateaus are generally at least 150 m (500 ft) above the adjacent countryside or sea level, relatively flat, and bordered on at least one side by an abrupt descent. Plateaus are often dissected by steep canyons or valleys. Glen Canyon National Recreation Area is bordered by the Kaiparowits Plateau to the northwest, the Rainbow Plateau to the southeast, and the Red Rock Plateau to the east (plate 1).

A mesa is an isolated flat-topped landmass bounded on all sides by steep scarps and capped by a layer of resistant rock. Some of the mesas in the recreation area are included in table 3. The erosion-resistant Navajo Sandstone (geologic map unit **Jn**) caps the majority of the mesas in the recreation area (table 3).

A butte is often an isolated remnant of an eroded mesa (fig. 7). Buttes have steep slopes or cliffs, a resistant caprock, and a summit that may be flat-topped, craggy, rounded, pointed, or otherwise irregular. Many of the buttes in Glen Canyon National Recreation Area are carved in the Kayenta (**Jk**), Chinle (**TRc**), and Moenkopi (**TRm**) formations (table 3). Persistent erosion whittled the original plateaus and mesas of less-resistant strata into buttes.

Table 3. Landscape features in Glen Canyon National Recreation Area.

Feature	Examples and/or Locations	Formations (map symbol)
Mesas	Dry Mesa (southern end of Cataract Canyon)	Cedar Mesa Sandstone (Pcm)
	Good Hope Mesa (Glen Canyon)	Navajo Sandstone (Jn)
	Hall Mesa (north of Bullfrog visitor center)	
	Iron Top Mesa (southwest of Halls Crossing)	
	Grey Mesa (east of Hole-in-the-Rock)	
	Wilson Mesa (east of Hole-in-the-Rock)	
	Grand Bench (borders of Last Chance Bay)	Morrison Formation, Salt Wash Member (Jms)
	Romana Mesa (east of Warm Creek Bay)	
Buttes (fig. 7)	Buttes of the Cross (Millard Canyon)	Kayenta Formation (Jk)
	Cleopatras Chair (Millard Canyon)	
	Ekker Butte (east of Panorama Pt Overlook)	
	Bagpipe Butte (Bagpipe Butte Overlook)	Chinle Formation, upper members (TRcu)
	Castle Butte (mouth of Blue Notch Canyon)	Chinle Formation, Church Rock Member (TRcc)
	Teapot Rock (south of Teapot Canyon)	Moenkopi Formation (TRm)
Cliffs (fig. 7)	Navajo Point	Straight Cliffs Formation (Ksj, Ksl)
	Bullfrog area; shoreline along Last Chance, Padre, and Wahweap Bays	Entrada Sandstone (Je)
	Dominates the shoreline of Lake Powell	Navajo Sandstone (Jn)
	Good Hope Bay, San Juan Arm, The Rincon	Wingate Sandstone (JTRw)
	Lees Ferry/Navajo Bridge area	Kaibab Formation (Pk), Coconino Sandstone (Pco)
	Northern part of recreation area	White Rim Sandstone (Pwr)
	San Juan River canyon; Colorado River canyon (east of Hite Crossing)	Cedar Mesa Sandstone (Pcm)
	The Horn limestone (San Juan River canyon)	Paradox Formation (PNp)
Ledges/Benches and Slopes (fig. 7)	Navajo Point	Tropic Shale (Kt)
	Between Wahweap Bay and Fiftymile Mountain	Dakota Formation (Kd)
	Between Wahweap Bay and Dangling Rope Marina; between West and Wetherill Canyons	Morrison Formation (Jmb, Jms, Jsmt)
	Bullfrog Bay, near Dangling Rope Marina, upper part of Rock Creek	Carmel Formation (Jc)
	Near Glen Canyon Dam	Page Sandstone (Jp)
	Good Hope Bay, San Juan Arm, The Rincon	Kayenta Formation (Jk), Chinle Formation (TRc)
	Lower Cataract Canyon	Cutler Group: lower Cutler beds (PPNcl)
	Near Hite, San Juan Arm, Escalante Canyons	Moenkopi Formation (TRm)
	San Juan River canyon (The Horn, Hite Crossing, Clay Hills)	Organ Rock Formation (Po), Halgaito Formation (PPNhg), Honaker Trail Formation (PNht, PNhtu, PNhtl)
	South of Navajo Bridge	Toroweap Formation (Pt)
Slickrock (fig. 8)	Associated with cliffs	Navajo Sandstone (Jn), Entrada Sandstone (Je), Cedar Mesa Sandstone (Pcm)
Slot Canyons	Many slot canyons branch from Lake Powell	Kayenta Formation (Jk), Navajo Sandstone (Jn)
Alcoves* (fig. 9)	Escalante Canyon*	Navajo Sandstone (Jn), Cedar Mesa Sandstone (Pcm)
	Main channel of Lake Powell*	
Hanging Gardens*	Side drainages of Colorado River (i.e., Ribbon Canyon and Knowles Canyon [fig. 9])	Contact of the Navajo Sandstone (Jn) and the Kayenta Formation (Jk)

* Indicates landscape features identified as "classic geologic sites" in Anderson et al. (2010).

Table 3. Landscape features in Glen Canyon National Recreation Area, continued.

Feature	Examples and/or Locations	Formations (map symbol)
Arches (fig. 10)	Annies Canyon Arch (Annies Canyon)	Navajo Sandstone (Jn)
	Bement Arch (Davis Gulch)	
	Bills Arch (Silver Falls Creek)	
	Broken Bow Arch (Willow Gulch)	
	Cliff Arch (Coyote Gulch)	
	Golden Cathedral Bridges (Choprock Bench)	
	Halls Creek Bridge (Halls Creek Bay)	
	Hole in the Rock Arch (Fiftymile Point)	
	Humdinger Arch (Rock Creek Bay)	
	Jacob Hamblin Arch (Coyote Gulch)	
	LaGorce Arch (Davis Gulch)	
	Natural Arch (east of Hans Flat)	
	Not Bills Arch (Silver Falls Creek)	
	Overlooked Arch (Rock Creek Bay)	
	Stevens Natural Arch (Stevens Canyon)	
	Stove Pipe Arch (East of Pollywog Bench)	
	Triple Arch (Cottonwood Canyon)	
	Zane Grey Arch (Explorer Canyon)	
	Skylight Arch (north of Stud Horse Point)	Entrada Sandstone (Je)
	Wahweap Window (Wahweap Bay) (Je)	
	Alcove Arch (Rock Creek Bay)	Morrison Formation, Salt Wash Member (Jms)
	Millard Canyon Arch (Millard Canyon)	Moenkopi Formation (TRm)
Natural Bridges (fig. 11)	Rainbow Bridge	Navajo Sandstone (Jn)
	Coyote Natural Bridge (Coyote Gulch)	
	Wiregrass Canyon Bridges	Entrada Sandstone (Je)
Badlands	Navajo Point area	Tropic Shale (Kt)
Hoodoos	Stud Horse Point (south of Skylight Arch)	Entrada Sandstone (Je), Carmel Formation (Jc)
Entrenched Meanders* (fig. 12; cover)	The Rincon*	Kayenta Formation (Jk), Navajo Sandstone (Jn)
	Horseshoe Bend (south of Glen Canyon Dam)	Navajo Sandstone (Jn)
	The Horn (south of Hite)	Kayenta Formation (Jk)
Desert Varnish (fig. 9)	Cliffs throughout the recreation area	Wingate Sandstone (JTRw), Navajo Sandstone (Jn)
Sandstone Pipes (fig. 13)	Rock Creek Bay	Entrada Sandstone, lower member (Jel)
	Cookie Jar Butte	
	Warm Creek Bay	
Weathering Pits* (fig. 13)	Cookie Jar Butte (Padre Bay)*	Entrada Sandstone, lower member (Jel)

* Indicates landscape features identified as "classic geologic sites" in Anderson et al. (2010).

Cliffs, Ledges, and Slopes

The strata in Glen Canyon National Recreation Area form a landscape of cliffs, ledges, and slopes as a result of their lithology and resistance to erosion (fig. 4). On the arid Colorado Plateau, sandstone and limestone are more resistant to weathering and erosion than siltstone and shale (table 3). Cliffs composed of 170–340 m- (550–1,100 ft-) thick Navajo Sandstone (**Jn**), for example, dominate the central part of Glen Canyon National Recreation Area. By comparison, the 150–230 m (500–750 ft) of less-resistant Tropic Shale (**Kt**) forms slopes along Fiftymile Mountain.

In units composed of alternating layers of sandstone, siltstone, and shale, the topography may take on a stair-step like appearance. These transitions may reflect a change in depositional environments as well

Figure 7. Photograph of buttes, alcoves, and outcrop patterns. Sandstones form cliffs; finer-grained siltstone of the Carmel Formation forms slopes. Alcoves have formed in the Entrada Sandstone. The photo shows Boundary and Dominguez buttes. Photograph from Anderson et al. (2010, figure 17).

as a change in lithology. For example, the cliffs in the Kayenta Formation (**Jk**) are composed of cross-bedded sandstone reflecting an eolian environment, but the overlying ledges of sandstone and slopes of mudstone reflect deposition in a fluvial-floodplain-lacustrine environment.

Within a single formation, changes in weathering and landscape patterns may differentiate individual members. In the Morrison Formation (**Jm**), for example, the resistant conglomerate and sandstone of the Salt Wash Member (**Jms**) form ledgy cliffs distinct from the overlying mudstone slopes of the Brushy Basin Member (**Jmb**).

Slickrock

Slickrock is an informal term for smooth cliffs and steep slopes of sandstone bedrock (fig. 8). Slickrock surfaces are not necessarily slick. Rather they are more like sandpaper, until they get wet. The term originated from early immigrants who found these sloping sandstone surfaces a challenge for their horses' metal shoes. In southeastern Utah and Glen Canyon National Recreation Area, slickrock surfaces are common in the Jurassic Navajo (**Jn**) and Entrada (**Je**) sandstones and in the Permian Cedar Mesa Sandstone (**Pcm**) (table 3). Slickrock in these three formations form in cross-bedded sandstone that represent preserved dune fields. As the eolian cross-beds weathered, they formed massive knobs and domes and slickrock.

The Navajo Sandstone (**Jn**) forms domes above vertical canyon cliffs. The unit covers about 85% of the central part of Glen Canyon National Recreation Area and about one-third of the entire surface area of the park (Anderson et al. 2010). It dominates the Lake Powell shoreline from Rainbow Bridge National Monument north to Good Hope Bay.

Abundant outcrops of Middle Jurassic Entrada Sandstone are present in the Bullfrog area, between Bullfrog and Hansen Creek, and surrounding Last Chance, Padre, and Wahweap bays on the western shoreline of Lake Powell. The formation has been divided into both informal and formal members:
(1) lower member (Gunsight Butte Member),
(2) middle member (Cannonville Member), and
(3) upper member (Escalante Member) (Doelling and Davis 1989; Anderson et al. 2010). The lower two members are preserved in the southern part of the recreation area, and all three have been mapped in the northern part (Anderson et al. 2010). Slickrock surfaces form primarily in the lower member (**Jel**; Gunsight Butte Member), which is characterized by smooth cliffs and rounded domes barren of vegetation.

In the northeastern part of the recreation area and along the upper reaches of the San Juan Arm, the Early Permian Cedar Mesa Sandstone (**Pcm**) forms an impressive slickrock landscape (Anderson et al. 2010). Numerous small drainages dissect the Cedar Mesa Sandstone, resulting in extensive slickrock canyons.

Figure 8. Photograph of slickrock in Glen Canyon National Recreation Area. Steep slopes of slickrock and cliffs are characteristic features in the recreation area. National Park Service photograph by Bob Moffitt, available online: https://www.nps.gov/media/photo/gallery.htm?id=14298A9B-155D-451F-676507C4A4BB767E (accessed 11 September 2015).

Slot Canyons

Southern Utah likely contains the highest density of slot canyons in the world. A slot canyon is a narrow canyon formed by the vertical incision of rushing water (table 3). Slot canyons are significantly deeper than they are wide. They may be as narrow as 1 m (3 ft) and as deep as 90 m (300 ft).

With the uplift of the Colorado Plateau and rapid incision by the Colorado River, beginning about 5.5 million years ago, numerous slot canyons developed as tributaries cut into bedrock. As with entrenched meanders, many of these canyons cut into the relatively soft Cretaceous, Jurassic, and Triassic strata (Anderson et al. 2010). Near-vertical and inclined joints contributed to the development of slot canyons in the recreation area (Anderson et al. 2010).

Many slot canyons branch away from Lake Powell. Kayakers can explore slot canyons, such as Cathedral, Cascade, Wetherill, and Face canyons, that have been flooded by Lake Powell but are too narrow for power boats to enter.

Debris flows and flash floods generated by sudden, intense rain storms may pose a threat to hikers in slot canyons throughout the Escalante watershed (see the "Geologic Resource Management Issues" chapter).

Alcoves and Hanging Gardens

Alcoves and hanging gardens, considered "classic geologic sites" by Anderson et al. (2010), are visible along the main channel of Lake Powell and in many side canyons, such as Escalante Canyon (table 3). The alcoves form as a result of groundwater flow, wind, fractures in the rock, and gravity, and most of them are

Figure 9. Photograph of Navajo Sandstone alcove with a hanging garden in Knowles Canyon, Glen Canyon National Recreation Area. Hanging gardens develop where groundwater seeps along an impermeable horizontal bed. Desert varnish above the hanging garden has stained some of the cliff a dark brown color. Cross-beds high on the cliff face tilt to the south-southeast, indicating paleowind direction in the Navajo erg. Photograph from Anderson et al. (2010, figure 26).

found at the contact between the relatively impermeable Kayenta Formation (**Jk**) and the overlying porous and permeable Navajo Sandstone (**Jn**).

The Kayenta Formation contains silt and clay that fill pore spaces in the rock and impede the downward flow of groundwater coming from the Navajo Sandstone. When groundwater encounters the Kayenta Formation, it begins to flow laterally, emerging from the canyon walls as seeps and springs. The water dissolves and removes the carbonate cement holding the Navajo sand grains together, and the loosened grains are blown away by the wind. Over time, slabs of rock weaken and break away from the cliff, forming a recess or alcove (fig. 9). Alcoves, especially those with a spring at the Navajo/Kayenta interface, attracted prehistoric visitors. Excellent examples of alcoves containing intact cliff dwellings dating to the late 13th century are preserved in Navajo National Monument, about 60 km (40 mi) southeast of Rainbow Bridge National Monument (see GRI report by Graham 2007).

Surface water also contributes to alcove formation. Vertical fractures or joints in the Navajo Sandstone serve as conduits for surface water. Localized pools of water in these fractures promote both plant growth and animal life (macroscopic and microscopic) which increases the acidity of the water and generates additional erosion.

The moisture and shade in the alcoves create an ideal environment for a variety of plants. These spring-fed plants cling to the vertical cliff walls to form hanging gardens (fig. 9). Some hanging gardens in Glen Canyon were drowned by Lake Powell, but many hanging gardens are found in the canyons and side drainages of the Colorado and San Juan rivers. The lush hanging gardens composed of algae, ferns, lilies, orchids, grasses, and sedges are in stark contrast to the surrounding desert landscape (Everhart 1983; Welsh 1989; Anderson et al. 2010). Roots from these plants also help to break down the surrounding rock. In addition to plants, the hanging gardens contain a rich biodiversity of invertebrates (terrestrial and aquatic), birds, mammals, and amphibians.

Although they cover less than 0.1% of Glen Canyon National Recreation Area, hanging gardens support at least 35 plant species endemic to the central-eastern Colorado Plateau (National Park Service 2015c; John Spence, Glen Canyon National Recreation Area, Chief Scientist and Terrestrial Natural Resources Branch Chief, written communication, 9 December 2015). These features are particularly susceptible to climate change (see the "Geologic Resource Management Issues" chapter).

Natural Arches

The greatest concentration of natural rock arches anywhere in the world dominates the landscape of Arches National Park, approximately 40 km (25 mi) northeast of the northern boundary of Glen Canyon National Recreation Area (see GRI report by Graham 2004). Over 2,000 arches have been documented in Arches National Park, and most of these formed in the Entrada Sandstone (National Park Service 2015d). In Glen Canyon National Recreation Area, many arches developed in the massive Navajo Sandstone (**Jn**), but they also occur in the Entrada Sandstone (**Je**), Salt Wash Member of the Morrison Formation (**Jms**), and the Moenkopi Formation (**TRm**) (table 3; fig. 10).

The Natural Arch and Bridge Society (NABS) may be the only organization dedicated to the study, interpretation, and preservation of natural arches and bridges (Grant Willis, Utah Geological Survey, geologist, written communication, 1 December 2015). The NABS defines a natural arch as any rock exposure, regardless of size, in which a hole has formed as a result of natural processes (NABS 2015). The natural processes that produce the hole are primarily processes of erosion, which operate on macroscopic and microscopic scales.

Figure 10. Photograph of Broken Bow arch, Glen Canyon National Recreation Area. Carved in Navajo Sandstone (Jn) and named for an Indian bow found beneath it in 1930, the Broken Bow arch is (2.3 mi) from the Willow Gulch Trailhead and stands 52 m (170 ft) tall. Its limbs are as much as 21 m (70 ft) thick. The opening is 29 m (94 ft) wide and 30 m (100 ft) high. Photograph courtesy of Tyler Knudsen, Utah Geological Survey.

Macroscopic erosion usually involves joints or fractures in the rock matrix that formed because of tectonic, or catastrophic, processes. Folding caused by the Laramide Orogeny, a mountain building event that shaped the Rocky Mountains between about 70 million and 40 million years ago, may have significantly contributed to arch formation in Glen Canyon National Recreation Area (Grant Willis, written communication, 1 December 2015). The laccolith intrusion of Navajo Mountain may have caused the joints associated with Rainbow Bridge.

Once fractures form, they widen through a variety of processes. Plant roots may physically enlarge the fracture. In winter, water in the cracks may freeze and expand and pry the rock apart. The end result consists of fragments of the original rock that are now susceptible to the forces of gravity.

On the microscopic scale of erosion, water dissolves the crystalline cement holding individual grains together. The Navajo and Entrada sandstones, which contain the majority of arches in Glen Canyon

National Recreation Area (table 3), represent ancient sand dunes. Sand dunes, ancient or modern, contain primarily well-sorted, nearly spherical sand grains and lack finer-grained silt and clay particles. Upon burial, calcium carbonate precipitated out of groundwater and cemented together the sand grains in the Navajo and Entrada sandstones. Most of the weathering that initially created the arches occurred when the porous and fractured sandstones were near the surface, where water lingered and had time to dissolve the cement (Grant Willis, written communication, 1 December 2015).

Every process involved in arch formation includes the action of water, gravity, temperature variation, or tectonic pressure on rock. Wind, however, is not a significant process in arch formation. Wind does not remove grains loosened by microscopic erosion, and while sandstorms may polish already existing arches, they cannot create arches. Detailed information regarding the process of erosion relevant to arch formation, the various classification schemes, and arch types is available on the NABS website (http://www.naturalarches.org/nabs.htm, accessed 4 January 2016).

Typical of low-humidity desert environments, weathering in the Glen Canyon region slowed once the rocks were elevated, exposed at the surface, and mostly surrounded by air (Grant Willis, written communication, 1 December 2015). Rain that falls on the arch, or other landscape feature such as a hoodoo, fin, or pedestal, is quickly evaporated in the arid climate, and in an ironic twist, the remaining salts are re-precipitated, hardening the surface.

Natural Bridges

A natural bridge is one of many types of natural arches (NABS 2015). Natural bridges are distinguished from arches by having one or more of the following attributes:

- Flowing water was a major factor in forming the hole.
- Flowing water currently flows through the opening.
- The bridge was, or still is, used by humans as part of a road.
- The bridge looks like a man-made bridge, e.g., it has a flat, level top over an arched opening.

A stream flows beneath the 15 m (50 ft) span of Coyote Natural Bridge in Coyote Gulch (table 3). The bridge formed in Navajo Sandstone (**Jn**) and is 2.7 km (1.7 mi) downstream from Jacob Hamblin Arch (table 3). Fremont Indian dwellings are on the north canyon wall upstream from the bridge, and Fremont Indian pictographs are found downstream (Wild Backpacker 2015).

The two natural bridges in Wiregrass Canyon formed in Entrada Sandstone (**Je**; table 3). Flood waters from a parallel canyon cut through the narrow canyon wall to form the natural bridge about 1.6 km (1 mi) south of the road. During floods, water still flows under this bridge and into Wiregrass Canyon. The second natural bridge in Wiregrass Canyon is found near Lake Powell.

The most famous natural bridge in the area is Rainbow Bridge in Rainbow Bridge National Monument (fig. 11). The national monument is adjacent to, and administered by staff from, Glen Canyon National Recreation Area (plate 1). Bridge Creek, fed by springs and runoff from Navajo Mountain, carved Rainbow Bridge by eroding through a thin wall of Navajo Sandstone (Chidsey et al. 2000a, 2000b; see GRI report by Graham 2009).

Streams also flow beneath the three exceptional natural bridges in Natural Bridges National Monument, approximately 48 km (30 mi) east of Hite and adjacent to highway 95. These bridges formed in the Cedar Mesa Sandstone (**Pcm**) (see GRI report by Thornberry-Ehrlich 2004)

Badlands and Hoodoos

Steep, unvegetated slopes of unconsolidated or poorly cemented clay or silt characterize badlands topography. The shale and mudstone of the Late Cretaceous Tropic Shale (**Kt**) forms stark badlands topography in Glen Canyon National Recreation Area (table 3). Exposed at the southern end of Fiftymile Mountain, the 150–230 m- (500–750 ft-) thick Tropic Shale underlies the sandstone and mudstone of the Straight Cliffs Formation (**Ksl**). Viewed from Dangling Rope Marina, these Cretaceous units cap Navajo Point. Many landslides occur along the escarpment of Fiftymile Mountain because the Tropic Shale is so easily eroded (Anderson et al. 2010).

Broad, gently sloped badlands characterize local exposures of the Triassic Chinle Formation (**TRc**) in Glen Canyon National Recreation Area and in the

Figure 11. Photograph of Rainbow Bridge, Rainbow Bridge National Monument. Carved in Navajo Sandstone, Rainbow Bridge towers over visitors (yellow arrow) hiking along the stream that flows under the opening. National Park Service photograph available: http://www.nps.gov/media/photo/gallery.htm?id=00D6226E-155D-451F-679D6F8C5886A244 (accessed 5 January 2016).

Tununk Shale Member of the Cretaceous Mancos Shale (**Kmt**). The Tununk Shale is roughly equivalent in age to the Tropic Shale (**Kt**), but it is only mapped northwest of Bullfrog in the Henry Mountains basin, outside the recreation area (see GRI GIS data; Anderson et al. 2010).

The bizarre columns, pinnacles, and pillars of rock in the recreation area are known as hoodoos. Hoodoos are the iconic geologic feature of Bryce Canyon National Park (see GRI report by Thornberry-Ehrlich 2005). Hoodoos result from differential weathering, a process in which rocks composed of relatively soft material, such as mudstone, erode more easily than harder rocks, such as sandstone. Sporadic intense rainfall in the high-desert regions of the Colorado Plateau drives the differential weathering in the recreation area. Joints in the rocks contribute to this differential erosion to produce such unusual shapes as the toadstool-shaped pinnacles and balanced rocks at Stud Horse Point, south of Skylight Arch.

Entrenched Meanders

A typical meandering stream migrates laterally back and forth across its floodplain, cutting sinuous curves and bends into easily erodible unconsolidated surface sediments. However, if a stream erodes downward more rapidly than laterally, its meanders may incise into bedrock and become entrenched, unable to migrate laterally. Entrenched meanders with tight, curling loops are known as goosenecks.

Vertical downcutting may exceed lateral migration across a floodplain as a result of rapid uplift or a lowering of a stream's base level, which is the lowest level to which a stream channel can erode (the ultimate

Figure 12. Photograph of Horseshoe Bend, Glen Canyon National Recreation Area. Horseshoe Bend is an entrenched meander south of Glen Canyon Dam. Near-vertical joints cut through the exposed sandstone and are easily visible in the rocks. National Park Service photograph.

base level is sea level). Uplift of the Colorado Plateau and rapid incision of the Colorado River beginning about 5.5 million years ago caused the Colorado River to carve narrow slot canyons and entrenched meanders into relatively soft Cretaceous, Jurassic, and Triassic strata (Anderson et al. 2010). Tributary drainages, such as the Escalante and Dirty Devil rivers, also became entrenched as their channels encountered bedrock and their canyons deepened in an attempt to keep pace with the incision of the Colorado River (Cook et al. 2009; Anderson et al. 2010).

Entrenched meanders in Glen Canyon National Recreation Area include The Rincon, Horseshoe Bend, the Horn, Georges Camp on the Escalante River, and many lesser meanders along the rivers (plate 1; fig. 12; table 3). Located on the southern plunging nose of the Circle Cliffs anticline on the east side of Lake Powell, The Rincon, one of the "classic geologic sites" of Anderson et al. (2010), stands 180–230 m (600–750 ft) above its now-abandoned channel. Stratigraphically, the Chinle Formation (**TRc**) anchors the butte at lake level followed by the Wingate Sandstone (**JTRw**), the Kayenta Formation (**Jk**) which caps the butte, and some local exposures of Navajo Sandstone (**Jn**) above the Kayenta (Anderson et al. 2010). Several thousand years ago, the Colorado River shortened its length by 10 km (6 mi) by carving its way through the Wingate Sandstone and cutting off The Rincon meander.

The Colorado River eroded vertically through the Upper Member of the Moenkopi Formation (**TRmu**) to form the entrenched meander of the Horn, south of Hite (plate 1). Like The Rincon, the Horn is capped by the Kayenta Formation and Navajo Sandstone.

About 8 km (5 mi) downstream from Glen Canyon Dam, the Colorado River carved the horseshoe-shaped Horseshoe Bend entrenched meander in Jurassic and upper Triassic strata (cover photograph). The butte rises 300 m (1,000 ft) above the Colorado River. Ledgy slopes of the Moenave Formation (**JTRmd**) at the base of the butte are overlain by the Kayenta Formation, and the butte is capped by jointed Navajo Sandstone. Hundreds of smaller entrenched meanders exist along tributaries such as the Escalante and San Juan rivers.

Desert Varnish

The thin, red-to-black coating known as desert varnish is found throughout arid regions, such as the Colorado Plateau. In Glen Canyon National Recreation Area, this surface stain often outlines the large-scale cross-beds in the Navajo Sandstone (**Jn**) and darkens the pale, massive sandstones in the Wingate Sandstone (**JTRw**) (fig. 9). The color of the varnish depends on the amount of iron relative to manganese. Varnish high in manganese appears black; an abundance of iron colors the varnish red to orange. Varnishes intermediate in composition are usually a shade of brown.

Desert varnish is the product of the interaction between microorganisms and rock surfaces. Microorganisms oxidize the manganese, which cements clays and other particles to rock surfaces. Most rock surfaces in desert environments contain these microorganisms, which may be able to use both organic and inorganic nutrition sources. Sources of manganese and iron originate from outside the exposed rock, probably from atmospheric dust and surface runoff. Black varnish often occurs where water slides over cliffs.

Because desert varnish takes thousands of years to form, it more commonly occurs on erosion-resistant strata, such as the Navajo Sandstone cliffs in Glen Canyon, rather than on easily eroded surfaces. The coating deteriorates under acidic conditions, such as acid rain, and may be chemically eroded by lichens.

Giant Sandstone Pipes and Weathering Pits

Giant sandstone pipes and associated weathering pits in Glen Canyon National Recreation Area are also "classic geologic sites" (table 3; Anderson et al. 2010). Occurring over a 20,000 km^2- (7,700 mi^2-) area of southeastern Utah, these landscape features are primarily in the lower part of the Entrada Sandstone (**Je**), but they also occur in the Carmel Formation (**Jc**) and the Navajo Sandstone (**Jn**) (Netoff 1999; Netoff and Shroba 1993; Netoff and Shroba 2001; Huuse et al. 2004; Netoff and Chan 2009; Anderson et al. 2010). In the recreation area, the features occur on barren exposures of the Entrada Sandstone at the north end of Rock Creek Bay, Cookie Jar Butte (north shore of Padre Bay), and Warm Creek Bay (Netoff and Shroba 2001; Anderson et al. 2010).

The cylindrical sandstone pipes generally form in clusters, and their contact with the cross-bedded host rock is sharp. The pipes are as much as 75 m (246 ft) wide and 100 m (330 ft) high (Netoff 1999). The pipes form the core of cone-shaped landforms that vary in size from broad domes less than 5 m (16 ft) high to narrow, steep-sided cones as high as 70 m (230 ft) (Netoff and Shroba 2001). Some of the Entrada pipes extend well into the underlying redbeds of the Carmel Formation (Wheatley et al. 2014). Small-scale ring faults, which are circular or elliptical in plan view, may be present at the contact between the pipes and the host rock. Local displacement on the ring faults may be as much as 5 m (16 ft; Netoff 1999).

The homogeneous sandstone pipes suggest the injection of fluidized sand into the host rock, as do the irregular, finger-like projections that also occur in the surrounding Entrada Sandstone (fig. 13; Netoff 1999). Fluidization probably occurred in a water-saturated environment prior to the Entrada Sandstone becoming completely lithified. The abundance of these sandstone masses along with evidence of liquefaction extending to depths exceeding 100 m (330 ft) suggests the occurrence of one or more major earthquakes on the Colorado Plateau during the Middle Jurassic (Phoenix 1958; Davidson 1967; Alvarez et al. 1998; Netoff and Shroba 1995; Netoff 1999; Huuse et al. 2004; Wheatley et al. 2014). Potential triggering mechanisms for such a major seismic event include a possible meteor impact approximately 60 million years ago that may also be responsible for Upheaval Dome in Canyonlands National Park, changes in the regional stress field, Jurassic movement along the Mojave-Sonora megashear, and explosive volcanism (Netoff 1999; Huuse et al. 2004).

Once exposed by erosion, the conical landforms evolved because of differential weathering. Differences in pipe material versus the enclosing host rock, clay content, type and abundance of microorganisms on the rock surface, and distribution of carbonate cement

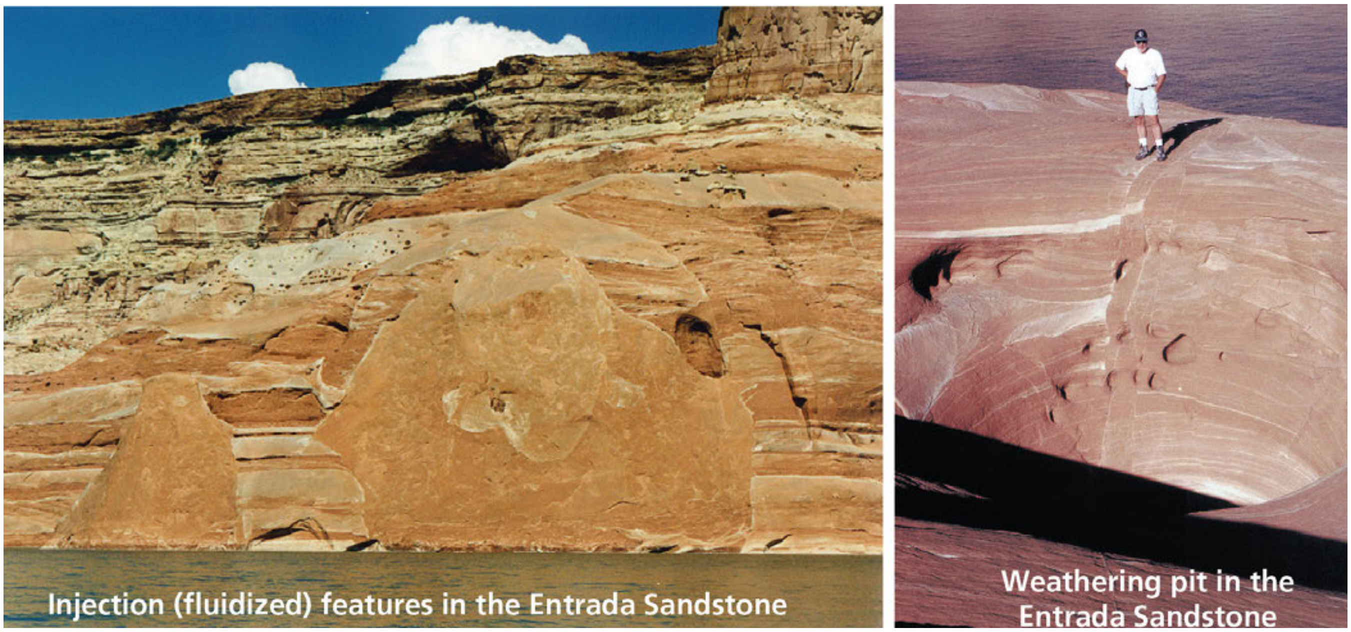

Figure 13. Photographs of fluidized injections of sandstone into Entrada Sandstone and a weathering pit that formed on a sandstone pipe. This pit is one of many that are clustered near Cookie Jar Butte along Padre Bay. Photographs from Anderson et al. (2010, figures 29 and 33).

all contributed to variations in the erosion rates and subsequent topographic relief of the cones (Netoff and Shroba 2001).

Some of the cones have relatively soft cores, allowing weathering pits to form on their summits. The pits range from shallow [< 5 m (< 16 ft)] doughnut-shaped pits to deep, circular pits as much as 35 m (115 ft) deep and 37 m (120 ft) wide (fig. 13). The walls of some of these deeper pits have been breached, creating an armchair-like shape (Netoff and Shroba 2001). The exceptional pits at Cookie Jar Butte are likely among the deepest weathering pits on Earth (Netoff et al. 1993; Netoff and Shroba 1997; Anderson et al. 2010). Some of the pits contain several meters of water, which may remain for months or years.

The pits are probably no older than early Pleistocene (about 2 million years old), and may be the result of several weathering processes including the growth of salt crystals from moisture collected in the pits, expansion and desiccation of smectite clay, and dissolution of calcite cement (Netoff et al. 1994; Netoff and Shroba, 1995; Anderson et al. 2010). These processes, even today, dislodge and destabilize weakly cemented sandstone grains exposed on the surface.

The relatively flat floors of the deeper, cylindrical pits may contain a thin [< 1 m (< 3.3 ft)] mantle of sandy sediment (Netoff and Shroba 2001). Questions still remain as to how sediment is removed from these deep pits. Wind deflation may be one answer. Abrasional, depositional, and deflational features in a giant sandstone pit in the Navajo Sandstone in Grand Staircase-Escalante National Monument suggest exceptionally strong winds removed the sediment from this pit (Netoff and Chan 2009). Evidence of strong winds swirling in some of the Entrada Sandstone pits includes pit-floor sand dunes and abrasional features such as grooves, flutes, ventifacts, and yardangs (streamlined protuberances carved from bedrock by wind). Abrasional features indicate two distinct types of wind patterns: (1) rotary patterns in which the wind rotates around a horizontal axis within the pit, and (2) corkscrew-like patterns in which strong vortices rotate on a vertical axis (Netoff and Shroba 2001).

Wind deflation certainly can remove loose, dry sand from shallow pits, but whether wind can remove sand-size grains from the deep, narrow cylindrical depressions at Cookie Jar Butte remains debatable (Netoff et al. 1993; Anderson et al. 2010). Wind gusts as strong as 130 km/h (80 mi/h) occur on Lake Powell, and Pleistocene winds may have had an even greater velocity as a result of high-pressure gradients between the warm, low canyon floors and the ice-capped, high plateaus north of Glen Canyon (Netoff et al. 1993). However, some of the deep pits at Cookie Jar Butte lack wind scour features on the walls, floors, and bedrock surfaces. Some pits have even formed on the leeward slopes where wind would not have an impact (Netoff et al. 1993).

Recently, Jim Davis of the University of Utah proposed a novel idea suggesting that diatoms play a pivotal role in the weathering and erosion of potholes (Davis 2013). Studying the physical-chemical-biological relationship in pits near Moab, Utah, Davis found that silica concentrations are consistently low in these desert geomorphic features and the abundance of benthic diatoms is quite high. When the potholes contain water, kelp and bacteria etch the sandstone surface and diatoms absorb the released silica to form their tests. Photosynthetic organisms, such as diatoms, also affect the daily pH and oxygen concentrations in the potholes and along with fluctuations in water temperature, affect the solubility of the surrounding sandstone (Davis 2013). Diatoms, which have the aerodynamic properties of dried leaves, are easily removed from potholes even by light winds during dry pothole phases.

Although the diatom hypothesis requires further research, the bio-geologic association may prove to be a significant factor in giant pothole formation on the Colorado Plateau. Questions remain as to whether or not diatoms may directly dissolve sand grains, the age of the pits, and the removal of sediment from the deep pits in Glen Canyon National Recreation Area. The distribution of the pits also presents a conundrum. In this vast expanse of exposed friable Navajo and Entrada sandstones with similar characteristics, these giant weathering pits are clustered in areas that do not appear to be exceptionally different from the rest of the Colorado Plateau.

Sedimentary Rocks and Sedimentary Rock Features

The bedrock in Glen Canyon National Recreation Area consists entirely of sedimentary rock, one of the three basic rock types (metamorphic and igneous rocks are the other two). Sedimentary rocks are classified as clastic, chemical, or organic (table 4). Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock or fossil fragments called "clasts." Chemical sedimentary rocks form when ions precipitate out of water. Organic sedimentary rocks are composed of organic remains, such as the decomposition of plants to form peat and coal.

Sedimentary rock features in the strata in Glen Canyon National Recreation Area help define the various depositional environments that occupied southeastern Utah during the Mesozoic and Paleozoic Eras (see the "Geologic History" chapter). These features commonly form from both marine and terrestrial processes and can be divided into three general categories: (1) marine and nearshore marine features, (2) fluvial and floodplain features, and (3) eolian and associated features (table 5). Fossils are important resources in many sedimentary rocks within the recreation area. They are further described in the "Paleontological Resources" section.

Marine and Nearshore Marine Features

Beds of limestone, sandstone, and mudstone containing fossils of marine organisms are the primary sedimentary features that characterize marine depositional environments (table 5). Most of the marine limestone in Glen Canyon National Recreation Area is found in Paleozoic Era strata. Contorted beds of the upper part of the Middle Pennsylvanian Paradox Formation (**PNp**) are exposed in the deepest parts of Cataract and San Juan River canyons. The formation contains cyclic layers of black organic shale, siltstone, gypsum, lime mudstone, wackestone, packstone, ooid grainstone, and algal boundstone. Fossils include a variety of marine invertebrates including crinoids, bryozoans, brachiopods, fusulinids, corals, foraminifers, conodonts, and fish fragments.

Exposed in the northern part of the park along the Colorado River and into neighboring Canyonlands National Park, the Late Pennsylvanian Honaker Trail Formation (**PNht**), which averages 170 m (550 ft) thick in the park, contains fossils of marine invertebrates including foraminifera, bryozoans, gastropods, crinoids, and conodonts (Ritter et al. 2002; Tweet et al. 2009).

Limestone in the Halgaito Formation (**PPNhg**) contains fossils of sharks and fish near Cedar Point in Glen Canyon National Recreation Area and in John's Canyon just outside of the park boundaries (table 7; Tweet et al. 2009). Fossils of marine invertebrates occur in both the Halgaito and Elephant Canyon (**PPNe**) formations and include foraminifera, corals, crinoids, conodonts, bryozoans, brachiopods, cephalopods, trilobites, and

Table 4. Sedimentary rock classification and characteristics.

Sedimentary Rock Type	Rock Name	Texture	Depositional Environment
Inorganic Clastic*	Conglomerate (rounded clasts)	Clast size: >2 mm (0.08 in)	Ranges from higher energy (swift river currents; strong winds) for larger grain sizes to lower energy (floodplains, lagoons, lakes) for smaller grain sizes
	Breccia (angular clasts)		
	Sandstone	Clast size: 1/16–2 mm (0.0025–0.08 in)	
	Siltstone	Clast size: 1/256–1/16 mm (0.00015–0.0025 in)	
	Claystone	Clast size: <1/256 mm (0.00015 in)	
Carbonate Clastic**	Fossiliferous Limestone	Generic name for carbonate rock containing fossils	Primarily marine
	Crystalline	Crystal supported; no fossil fragments, carbonate grains, or carbonate mud	No depositional features can be recognized
	Boundstone	Composed entirely of fossils, fossil fragments, or carbonate mud fragments cemented together	Higher energy setting. Bound together during deposition (e.g., reefs)
	Grainstone	Grain (i.e., fossil fragments) supported with no carbonate mud	Original components bound together following deposition; depositional settings range from higher energy (grainstone) to lower energy (mudstone)
	Packstone	Grain (i.e., fossil fragments) supported with some carbonate mud	
	Wackestone	Carbonate mud supported with more than 10% grains and less than 90% carbonate mud	
	Mudstone	Carbonate mud supported with less than 10% grains and more than 90% carbonate mud	
Chemical	Limestone (Carbonate Mud)	Generic name. Formed by the precipitation of calcium (Ca) and carbonate (CO_3^{2-}) ions from water	Freshwater (lakes) or marine environments
	Travertine	Precipitation of calcium (Ca) and carbonate (CO_3^{2-}) ions from freshwater	Terrestrial springs
	Dolomite	Precipitation of calcium (Ca), magnesium (Mg), and carbonate (CO_3^{2-}) ions from water	Post-depositional alteration of limestone by Mg-rich ground-water or direct precipitation in shallow marine environments
	Evaporites (e.g., gypsum)	Precipitation of salts to form evaporite minerals	Hot, dry environment
	Oolite	Precipitation of calcium carbonate in thin spherical layers around an original particle (i.e., fossil fragment)	Shallow marine environment; particles are rolled back and forth by the constant motion of tides or waves
Organic	Coal	Peat (partly decomposed plant matter) is buried, heated, and altered over time	Lagoon, swamp, marsh

* Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

**Carbonate classification is based on Dunham's textural classification scheme (Dunham 1962).

Refer to the Map Unit Properties Tables (in pocket) and glca_geology.pdf (in GRI GIS data) to identify formations comprised of these rock types in Glen Canyon National Recreation Area.

echinoderms (Tweet et al. 2009). Like the Honaker Trail Formation, the Halgaito-Elephant Canyon interval is restricted to the northern portion of the recreation area and the San Juan Arm (Anderson et al. 2010). The two units are age-equivalent and interfinger (fig. 14).

Cyclic interbeds of fossiliferous limestone, siltstone, sandstone, black organic shale, dolomite, and/or gypsum in the Paradox (**PNp**), Honaker Trail (**PNht**), Halgaito (**PPNhg**), and Elephant Canyon (**PPNe**) formations characterize marginal marine or nearshore depositional environments and represent episodes of sea level rise (transgression) followed by sea level lowering (regression) (Langford and Chan 1987; Langford et al. 2007; Tweet et al. 2009; Anderson et al. 2010). The cycles in the Paradox Formation (**PNp**) that are exposed throughout the Colorado Plateau provide a textbook example of fluctuating sea levels during the Middle Pennsylvanian in western North America (Wengerd 1962; Rueger 1996). The Halgaito-Elephant Canyon interval averages 75 m (250 ft) thick in the park,

Table 5. Sedimentary rock features identified in Glen Canyon National Recreation Area.

Feature Type	Feature	Process/Depositional Environment	Formation (map symbol)
Eolian and Associated Features	Well-sorted, frosted sandstone grains	Eolian (wind) processes; grains colliding against each other results in a translucent (frosted) coating	Entrada Sandstone (Je), Page Sandstone (Jpj, Jpt), Navajo Sandstone (Jn), Wingate Sandstone (JTRw)
	Local high-angle cross-bedding	Eolian processes that produce local sand dunes in a nearshore, coastal environment, which may contain sabkhas	Straight Cliffs Formation (Ksj), Romana Sandstone (Jr), Coconino Sandstone (Pco), Organ Rock Formation (Po)
	Extensive high-angle cross-bedding	Eolian processes that form vast Sahara-like deserts (ergs) with migrating sand dunes	Entrada Sandstone (Je), Page Sandstone (Jpj, Jpt), Navajo Sandstone (Jn), Wingate Sandstone (JTRw), White Rim Sandstone (Pwr), Cedar Mesa Sandstone (Pcm)
	Limestone lenses with algae, ripple marks, and mudcracks	Oases or lakes in interdune areas of the erg	Navajo Sandstone (Jn)
Fluvial and Floodplain Features	Trough cross-bedding	Sandstones deposited in fluvial channels	Kayenta Formation (Jk), Chinle Formation (TRcc, TRcs), Organ Rock Formation (Po)
	Mottled red and gray clay layers; root zones	Paleosol (fossil soil) development; preserved on floodplains	Chinle Formation (TRcc, TRcop, TRcmn)
	Combination of interbedded or fining upward sequences of conglomerate, sandstone, siltstone, and mudstone; reddish-brown color; ripple laminations; mudcracks; and/or small-scale cross-beds	Fluvial processes; floodplain and overbank deposits; paleosol development	Straight Cliffs Formation (Ksl, Ksj), Dakota Formation (lower) (Kd), Morrison Formation (Jm), Kayenta Formation (Jk), Moenave Formation (JTRmd), Chinle Formation (TRcc, TRcms, TRcmn), Moenkopi Formation (TRm), Organ Rock Formation (Po), Cedar Mesa Sandstone (Pcm)
	Dinosaur and reptile bones and/or tracks	Terrestrial animal remains	Morrison Formation (Jm), Navajo Sandstone (Jn), Kayenta Formation (Jk), Chinle Formation (TRc), Moenkopi Formation (TRm)
	Petrified wood	Wood fragments transported by fluvial processes	Chinle Formation (TRcop)
	Coal beds	Deposition under anaerobic conditions followed by burial in coastal lagoons	Straight Cliffs Formation (Ksl, Ksj), Dakota Formation (middle) (Kd)
Marine and Nearshore Marine Features	Planar beds of calcareous sandy siltstone with local gypsum	Tidal flat, nearshore, shallow marine deposition and evaporite deposits (gypsum)	Romana Sandstone (Jr), Carmel Formation (Jcu)
	Cyclic interbeds of fossiliferous limestone, cherty limestone, dolomite, siltstone, organic shale, and/or gypsum	Alternating nearshore, marine environments caused by a fluctuating sea level in an arid climate	Halgaito Formation (PPNhg), Elephant Canyon Formation (PPNe), Honaker Trail Formation (PNht), Paradox Formation (PNp)
	Shallow marine invertebrate fossils and burrows	Beach and shallow marine	Straight Cliffs Formation (Ksl)
	Marine invertebrate fossils in sandstone or mudstone	Marine environments	Tropic Shale (Kt), Dakota Formation (upper) (Kd)

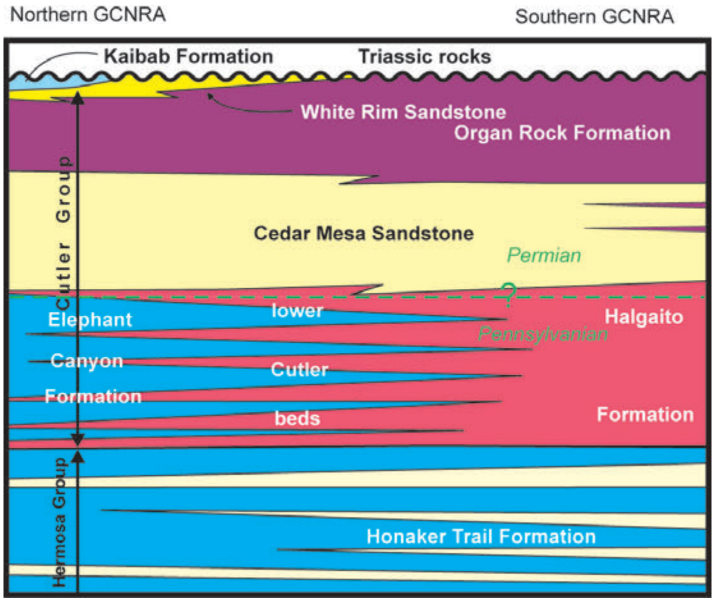

Figure 14. Schematic illustrating the Interfingering of the Elephant Canyon and the Halgaito Formations, Glen Canyon National Recreation Area. Yellow and red colors represent clastic, primarily terrestrial rocks; blue colors are dominantly carbonate, marine rocks. Schematic from Anderson et al. (2010, figure 10).

and the cyclic stratigraphic relationships suggest that transgressions occurred every 300,000 to 400,000 years (Langford and Chan 1987; Tweet et al. 2009; Anderson et al. 2010).

The layers of calcareous sandstone, siltstone, local gypsum, and limestone found in the Middle Jurassic Carmel Formation (**Jcu**) and Upper Jurassic Romana Sandstone (**Jr**), which bracket the eolian sand dunes of the Entrada Sandstone (**Je**), document nearshore, tidal flat, or shallow marine depositional environments (table 5). Good exposures of the Carmel Formation occur along Bullfrog Bay, near Dangling Rope Marina, and in upper Rock Creek. Romana Sandstone strata are exposed south of the Circle Cliffs uplift (Anderson et al. 2010).

In the Glen Canyon region, sandstone and mudstone, rather than limestone, characterize marine and nearshore marine environments during the Late Cretaceous (table 5). Oysters and clams, indicative of marine to brackish environments, occupy a 5–50 m- (20–170 ft-) thick band in the upper part of the Dakota Formation (**Kd**) between Wahweap Bay and Fiftymile Mountain and near Last Chance Bay (Anderson et al. 2010). The Dakota Formation is an extensive heterogeneous rock unit which formed in a variety of depositional environments. On the Colorado Plateau, the Dakota Formation has been divided into three informal members: (1) a lower member reflecting fluvial channels, (2) a middle member representing coastal plain environments, and (3) an upper member deposited in coastal, transgressive marine environments. Plant material deposited in anoxic coastal lagoons became coal beds in the Dakota (**Kd**) and Straight Cliffs (**Ks**) formations.

Marine fossils are also found in the overlying, poorly exposed Tropic Shale (**Kt**). The Tropic Shale represents the maximum transgression of the Western Interior Seaway into the area (see the "Geologic History" chapter).

The thick Straight Cliffs Formation (**Ks**) has been divided into four members, and the sedimentary features in these members represent fluctuating Late Cretaceous sea levels (Peterson 1969). In Glen Canyon National Recreation Area, the lower two members, the basal Tibbet Canyon Member and overlying Smoky Hollow Member, are mapped as one unit (**Ksl**). The cliff-forming sandstone of the Tibbet Canyon Member contains pelecypods, gastropods, cephalopods, shark teeth and trace fossils from beach and shallow marine environments (table 5; Tweet et al. 2009). The Tibbet Canyon Member transitions into the Smoky Hollow Member, a heterogeneous unit with features reflecting fluvial, floodplain, lagoonal, and marsh settings. Coastal features and marine fossils mark a rise in sea level and a marine transgression in the slope- and ledge-forming John Henry Member (**Ksj**), but only the lower part of this rock unit is present within Glen Canyon National Recreation Area (Tweet et al. 2009). The uppermost member, the cliff- and bench-forming Drip Tank Member (**Ksd**), is present in the westernmost part of the enclosed posters (in pocket), but it is outside the recreation area.

Fluvial and Floodplain Features

Sedimentary features in this category represent processes associated with fluvial systems (table 5). Grain size is an indicator of depositional environment. For example, lenses of conglomerate in the upper part of the Organ Rock Formation (**Po**) represent high energy stream channel deposits, while trough-shaped cross-bedded sandstone and asymmetrical ripple marks, such

Figure 15. Photograph of cross-section of mudcracks, Red Canyon, Glen Canyon National Recreation Area. These mudcracks formed in the Moenkopi Formation. Light-colored silt filled the cracks after they formed in the reddish-brown shale. Photograph from Anderson et al. (2010, figure 23).

as those in the Lower Triassic Moenkopi Formation (**TRm**) and Upper Triassic Chinle Formation (**TRc**), characterize lower velocity flow regimes. Because higher channel velocities are required to transport larger clasts compared to finer grained sand and silt grain size becomes an important indicator of the energy level during deposition.

Fluvial and floodplain ecosystems dominated the region in the Triassic Period (see the "Geologic History" chapter). Petrified wood, dinosaur tracks (see "Paleontological Resources" section), and mudcracks (fig. 15) that formed when overbank floodwaters evaporated are common sedimentary features in the Early–Middle Triassic Moenkopi Formation (Anderson et al. 2010). Periodic flooding deposited silt and clay on the floodplain, and mottled, reddish-brown and gray layers record the development of paleosols (old soils) (table 5). Mudcracks are not unique to the Moenkopi Formation, but those found in Red Canyon offer a rare view of mudcracks shown in profile (fig. 15) and are one of the "classic geologic sites" of Anderson et al. (2010). The v-shaped cracks formed in red siltstone, and they were filled by light-gray sandstone, making them easy to identify.

The Moenkopi Formation in Glen Canyon National Recreation Area is not as thick as exposures to the northeast and west where it is subdivided into several members (Blakey 1974; Anderson et al. 2010; Billingsley and Priest 2010; Doelling et al. 2010; Morris et al. 2010). In the park, the unit ranges from 80 to 150 m (270–500 ft) thick and has been subdivided into a basal Hoskinnini Member (**TRmh**) and upper and lower members (**TRmu**, **TRml**), which have similar lithology.

Sedimentary features in the six members of the Upper Triassic Chinle Formation include cross-bedding, ripple marks, thin coal or shale beds, uranium-bearing logs, paleosols, mottled limestone, smectitic clay layers, and dinosaur bones and tracks, which characterize a complex interlayering of fluvial, lacustrine, floodplain, and eolian deposits (table 5). Conglomerate and sandstone of the basal Shinarump Conglomerate Member (**TRcs**) fill channels and paleovalleys incised into the underlying Moenkopi Formation (Anderson et al. 2010).

Cross-bedded sandstone interbedded with reddish-brown siltstone and shale in the Early Jurassic Kayenta Formation (**Jk**) represent shifting freshwater braided and meandering streams that flowed across the area between 197 million and 190 million years ago (Colbert 1974; Lucas et al. 2005; Tweet et al. 2009). The formation is exposed in the Good Hope Bay area, between The Rincon and a few miles south of the Escalante-Colorado River junction, and in the western San Juan Arm (Anderson et al. 2010). A 55–68 m-(180–223 ft-) thick basal Springdale Sandstone Member (**Jks**) is mapped in the Lees Ferry area. The upper part of the formation contains more sandstone than siltstone and intertongues with the overlying Navajo Sandstone, documenting a time when the Navajo Sandstone sand dunes advanced into the area and smothered the rivers of the Kayenta Formation (Harshbarger et al. 1957; Kocurek and Dott 1983).

Fluvial systems are also represented by the conglomerate, sandstone, sandy mudstone, and shale in the basal part of the Dakota Formation (**Kd**).

Conglomerates and sandstone were deposited in channels while the finer-grained sediments (mudstone and shale) were deposited on the floodplain. The upper sandstone and marine fossils in the upper Dakota Formation reflect a transition from this fluvial landscape to coastal and marine environments as the Western Interior Seaway advanced into the region.

The interbedded sandstone, siltstone, carbonaceous mudstone, and coal in the ledge- and slope-forming Smoky Hollow Member (**Ksl**) of the Upper Cretaceous Straight Cliffs Formation record the reintroduction of fluvial and floodplain environments to the region. The member is 7–40 m (24–132 ft) thick and was deposited about 91 million years ago (Kirkland and Eaton 2002).

Eolian and Associated Features

As they do today, eolian processes in the past transported available sand grains and shaped them into sand dunes with gentle windward slopes and high-angle slopes (foreset beds) approaching the angle of repose on the dune slipface (fig. 16). Ancient sand dunes with high-angle cross-beds of well-sorted sand grains are preserved in a variety of formations in Glen Canyon National Recreation Area (table 5). High velocity winds created a natural sandblasting affect that "frosted" the sand grains with a translucent coating. Today, this process may be experienced by travelers crossing the deserts of the southwest during a wind storm. Vehicle windshields become pitted and frosted due to the impact of the sand grains on glass.

Localized high-angle cross-bedded sandstone preserved in Permian, Jurassic, and Cretaceous strata represents ancient coastal dune fields (table 5). Excellent exposures of coastal sand dunes in the Early Permian Period Cedar Mesa Sandstone (**Pcm**), Organ Rock Formation (**Po**), and overlying White Rim Sandstone (**Pwr**) occur in the northern part and the San Juan section of the recreation area (Anderson et al. 2010). The dunes that compose the 210–425 m- (700–1,400 ft-) thick Cedar Mesa Sandstone are separated by erosion surfaces that may represent episodes of marine transgressions (sea level rise) which occurred on the order of every 300,000 to 400,000 years, similar to the timing of marine transgressions in the Halgaito-Elephant Canyon interval (Langford and Chan 1987; Langford et al. 2007; Tweet et al. 2009).

The presence of horizontally bedded sandstone, algal limestone, and gypsum indicate that these sand dunes were part of a coastal environment that included eolian dunes and sabkhas. Sabkhas are relatively flat surfaces that form when sea water evaporates. Early Permian marine environments north of Glen Canyon National Recreation Area support this coastal interpretation (Anderson et al. 2010; Baars 2010; Huntoon et al. 2010).

In the Late Triassic and Jurassic Periods, vast inland dune fields (ergs) similar to those in today's Sahara Desert swept across the Colorado Plateau (see the "Geologic History" chapter). These extensive dune fields are preserved in the cross-bedded sandstone that forms the massive cliffs and rounded domes of Wingate (**JTRw**), Navajo (**Jn**), and Entrada (**Je**) sandstones (fig. 17).

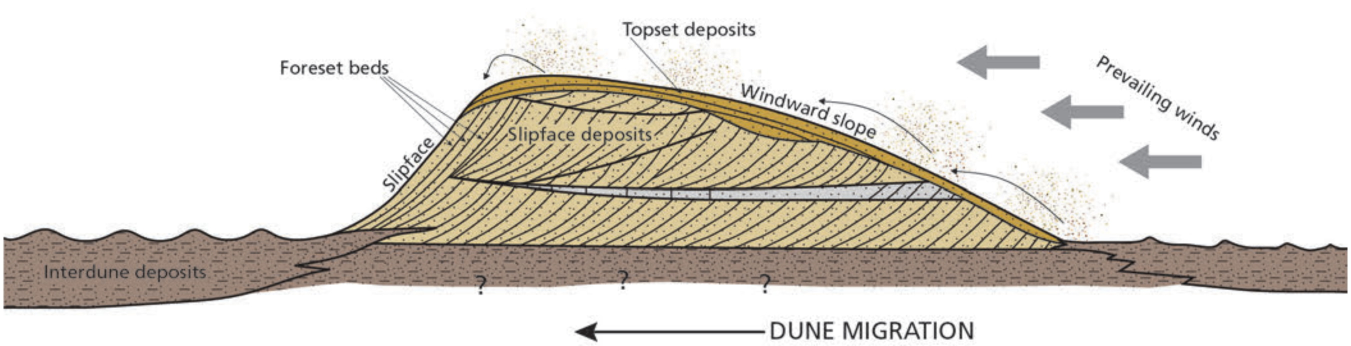

Figure 16. Schematic cross-section of a sand dune. Foreset beds form on the slipface and are preserved in the eolian deposits exposed in Glen Canyon National Recreation Area. Graphic by Trista Thornberry-Ehrlich (Colorado State University), modified from Ahlbrandt and Fryberger (1982, figure 3).

Figure 17. Photograph of cross-bedding in Jurassic Navajo Sandstone sand dunes. The "petrified" foreset beds on the slipface of these ancient dunes capture the shifting nature of modern sand dunes. National Park Service photograph by Bob Moffitt, taken in 2013, available online: http://www.nps.gov/glca/learn/photosmultimedia/photogallery.htm (accessed 11 September 2015).

The Navajo Sandstone is one of the largest preserved eolian systems in the stratigraphic record, and represents the most widespread eolian deposit in North America (Blakey 1994; Peterson 1994). In the Navajo Sandstone, cross-bed sets are up to 23 m (75 ft) thick. Weathering has etched out the cross-beds, and they are often outlined by desert varnish (Anderson et al. 2010). Excellent exposures of cross-bedded Navajo Sandstone occur across the Colorado Plateau and are preserved in a number of national parks including Navajo National Monument (see GRI report by Graham 2007), Capitol Reef National Park (see GRI report by Graham 2006a; Morris et al. 2010), Arches National Park (see GRI report by Graham 2004; Doelling 2010), and Zion National Park (see GRI report by Graham 2006b; Biek et al. 2010).

Unusual Sedimentary Rock Features

Unusual processes often produce unusual features. Oasis deposits, Moqui marbles, soft sediment deformation, and tafoni are some of the unusual features preserved in Glen Canyon National Recreation Area.

Oasis Deposits

Thinly bedded, 1.5–3 m- (5–10 ft-) thick limestone in the Navajo Sandstone (**Jn**) represents oases that formed between dunes within a vast Jurassic desert, similar to the vegetated oases in the Sahara (table 5). Sedimentary features in the limestone include oscillation ripples (formed by water moving back and forth), mudcracks, fossil plants, possible algal layers (stromatolites), and dinosaur tracks (fig. 18; Stokes 1991; Anderson et al. 2010; Santucci and Kirkland 2010). Flood velocities can erode river beds, ripping up pieces of the underlying mud and shale and transporting them downstream. The oasis deposits contain rip-up clasts of underlying interdune sediments within overlying stromatolites (algal laminations), indicating that large quantities of water sometimes inundated the Navajo desert (Loope et al. 2004; Irmis 2005).

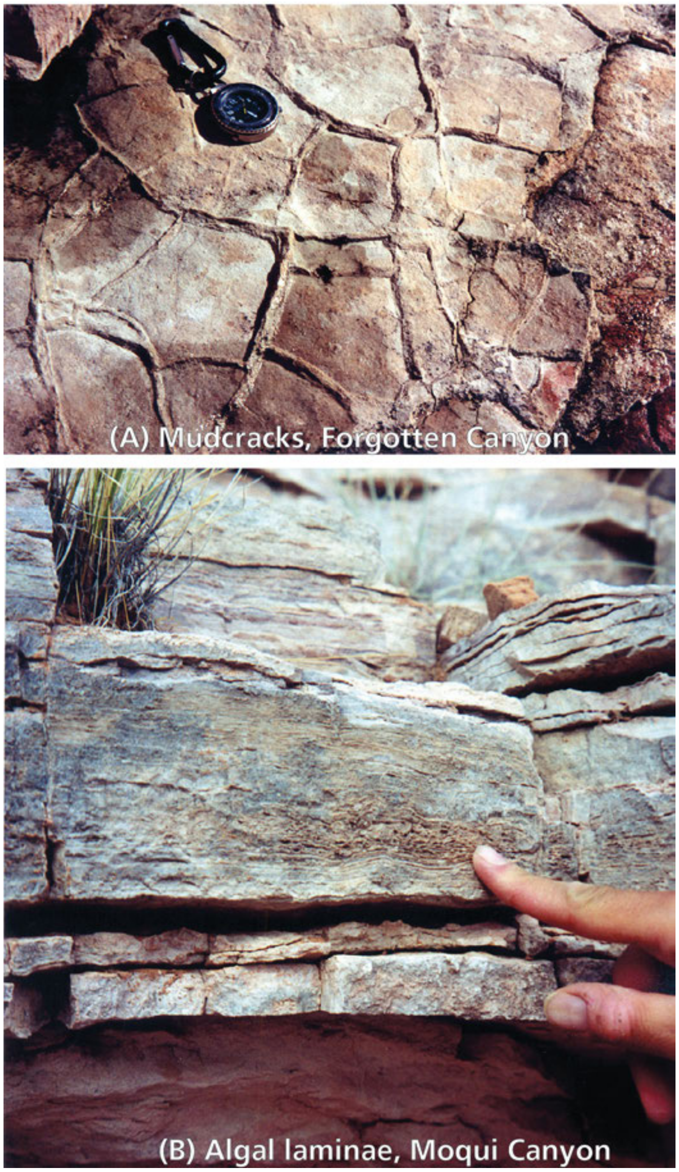

Figure 18. Photographs of features typically found in the "oasis" deposits in the Navajo Sandstone. (A) Mudcracks (desiccation cracks) formed in oasis limestone above a bed containing ripple marks; Forgotten Canyon. (B) Algal laminae within limestone oasis beds; Moqui Canyon. Photographs from Anderson et al. (2010, figure 25).

The Jurassic oases were quite extraordinary and represent enigmatic sedimentary depositional environments that contrasted sharply with the surrounding desert. They are included in the "classic geologic sites" of Anderson et al. (2010) and can be found along the main channel of Lake Powell and in Forgotten, Moqui, Annies, Slickrock, Iceberg, and Escalante canyons.

Freshwater lakes or ponds also formed in these vast deserts (Gilland 1979; Anderson et al. 2010). For lakes to develop, shallow groundwater had to persist for extended periods of time, perhaps for thousands of years (Stokes 1991; Anderson et al. 2010). Lake deposits are preserved in Canyonlands National Park (Gilland 1979).

Moqui Marbles and the Mars Connection

Moqui marbles, also referred to as "Navajo berries," are nearly spherical concretions of friable (loosely cemented) sandstone surrounded by an ironstone shell of densely cemented hematite (Fe_2O_3) (Doelling 1968, 1975; Chan et al. 2004; Downs and Wronkiewicz 2007; Anderson et al. 2010). They are common in the Navajo Sandstone (**Jn**) throughout southern Utah, and are found eroding from the spectacular white cliffs in Zion National Park and Grand Staircase-Escalante National Monument (see GRI report by Graham 2006b). The concretions, which range from pea size to as much as 10 cm (4 in) in diameter, are more resistant to erosion than the surrounding sandstone, thus they stand out on bedding planes or weather out to form aprons of loose concretions at the base of an outcrop (fig. 19). Moqui marbles are generously scattered on the surface of the Navajo Sandstone along the popular Horseshoe Bend trail, downstream from Glen Canyon Dam, and are considered to be one of the "classic geologic sites" in Anderson et al. (2010).

To form, the berries require a porous and permeable host rock, groundwater flow, and a chemical reaction between groundwater and iron-rich fluids (Chan et al. 2004). The Navajo Sandstone is one of the more porous and permeable formations in southern Utah. It serves as both a reservoir for hydrocarbons and groundwater. Meteoric groundwater and weathering processes disseminate iron films in the sandstone, resulting in the sandstone's familiar pinkish to orange-red color. Reducing fluids, such as hydrocarbons or acidic water, mobilize the iron-oxide films, and when these iron-rich fluids interact with oxygenated groundwater, hematite precipitates, usually as spherical balls (Chan and Parry 2002; Chan et al. 2004; Anderson et al. 2010). The lack of central nuclei in these Moqui marbles suggests that hematite precipitation and the spacing between each marble may be controlled by several factors such as characteristics of the sandstone, fluid chemistry, oxidation potential, pH, flow paths, timing, and possibly the presence of bacteria (Chan et al. 2004).

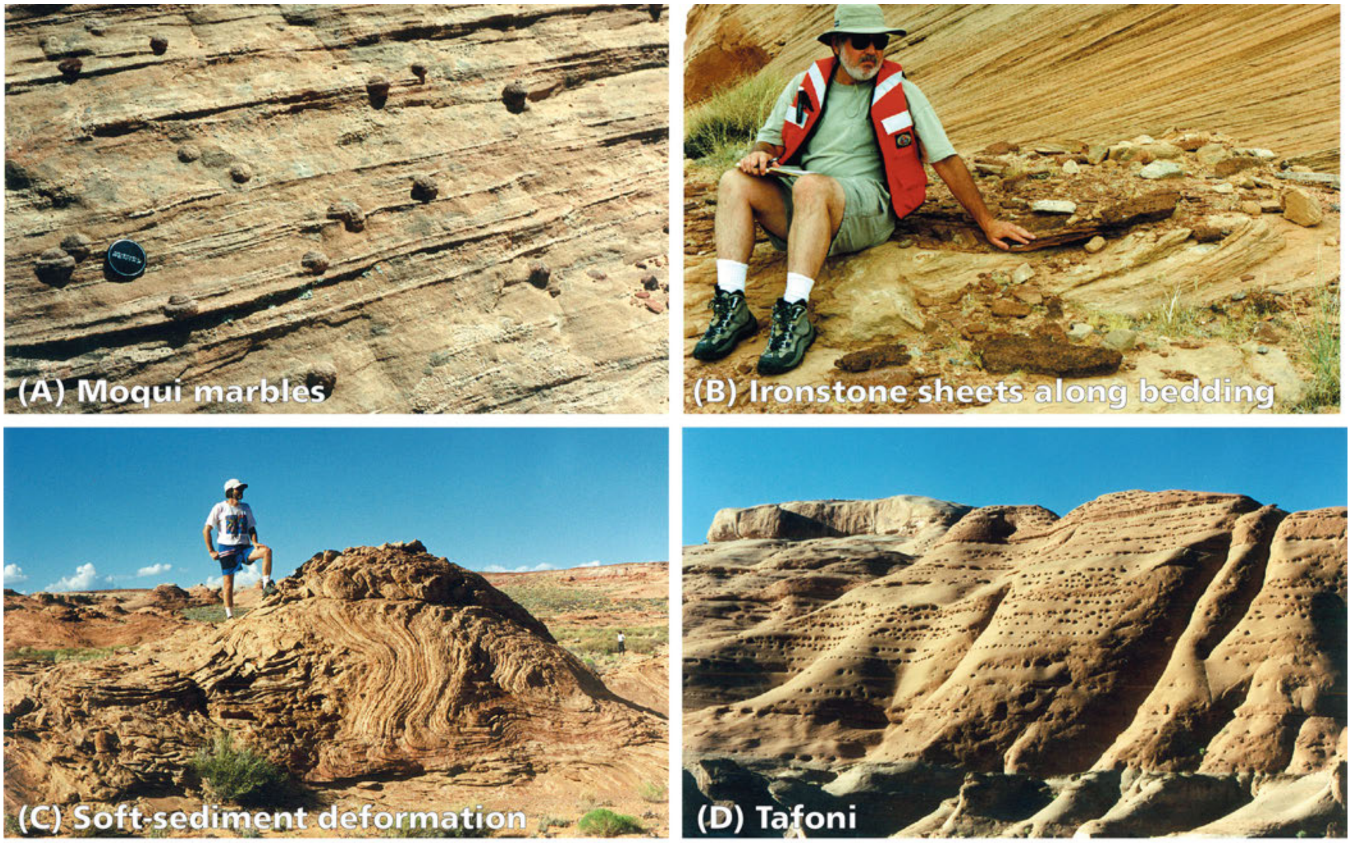

Figure 19. Unusual sedimentary features in the Navajo and Entrada sandstones, Glen Canyon National Recreation Area. (A) Moqui marbles in the Navajo Sandstone, east shore of the main channel west of Crossing of the Fathers. (B) Ironstone sheets along Navajo Sandstone bedding planes, west shore of Bullfrog Marina. (C) Soft-sediment deformation in Navajo Sandstone, south side of Antelope Island. (D) Tafoni (holes) in Entrada Sandstone, Dry Rock Creek Canyon. (E) Small-displacement faults within the Entrada Sandstone, Last Chance Bay. The faults do not penetrate the stratigraphic layers above and below the deformed bed. Photographs from Anderson et al. (2010, figures 27 and 31).

Hematite precipitation may form a variety of unusual shapes in addition to spherical concretions, such as bulbous nodules, pipes, and sheets (Chan et al. 2004). In Glen Canyon National Recreation Area, thin sheets of iron have precipitated along the surface of Navajo cross-beds and in highly contorted beds, such as those on Antelope Island (fig. 19).

Iron concretions are not unique to the Navajo Sandstone. They have been documented from a variety of rock types and geologic settings. However, the Moqui marbles in the Navajo Sandstone, including those identified in Glen Canyon National Recreation Area, bear a strong resemblance to iron concretions found on Mars by NASA's twin *Spirit* and *Opportunity* rovers. Both Moqui and Martian concretions are spherical, composed of hematite, and form loose, weathered accumulations. Merely the presence of hematite suggests that large volumes of subsurface fluids flowed through porous rock (Chan et al. 2004). Research continues into the comparison between the concretions, the source of iron, and the driving force of fluid flow, but for now, the Moqui marbles provide a significant terrestrial analogue for the Martian marbles (Chan et al. 2004; Downs and Wronkiewicz 2007).

Soft-sediment Deformation in Navajo Sandstone

When sediments are still unconsolidated, they can be deformed by gravity- or seismic-induced movements. This type of deformation is known as “soft-sediment” deformation. The resulting slides or slumps can produce faults, folds, and breccias that are unrelated to any tectonic deformation process. Soft-sediment deformation usually bears no relation to larger structures or regional tectonic patterns. The faults and folds produced by soft-sediment deformation are small scale, and the deformed beds are often truncated by a bedding plane (fig. 19).

In Glen Canyon National Recreation Area, spectacular soft-sediment deformation occurs in the Navajo Sandstone (**Jn**). On Antelope Island, Navajo sandstone beds have been contorted and deformed into tight, recumbent (overturned) folds (fig. 19). Because the folds tend to trap fluids, ironstone has formed in sheets along the bedding surfaces (Anderson et al. 2010).

Tafoni

Tafoni, one of the “classic geologic sites” of Anderson et al. (2010), are small holes that are found in the Entrada (**Je**), Page (**Jp**), Navajo (**Jn**), Wingate (**JTRw**), White Rim (**Pwr**), and Cedar Mesa (**Pcm**) sandstones (fig. 19). Tafoni forms when groundwater weakens the mineral cement between sand grains, usually around small variations in the cement, and weathering removes the loose grains, creating holes. Water accumulates in the holes, which shelter the water from evaporation. The water further weakens the rock cement and the holes grow (Anderson et al. 2010).

A hardened crust may form around tafoni, a process known as “case hardening.” The dry, arid climate of the southwestern US draws groundwater in porous sandstones toward the surface of the rock. When fresh water evaporates, mineral cement is left behind that hardens the rock “case.”

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are nonrenewable, and collecting is prohibited in the recreation area. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of June 2016, 262 parks, including Glen Canyon National Recreation Area, had documented paleontological resources in at least one of these contexts. The NPS Fossils and Paleontology website provides more information http://go.nps.gov/fossils_and_paleo; accessed 20 June 2016).

Fossils play a significant role in determining the environment and climate at the time they were deposited, and greatly contribute to understanding the geologic history at Glen Canyon National Recreation Area. The recreation area contains a myriad of paleontological resources and preserves one of the most complete sections of Mesozoic strata in the world (National Park Service 2014a). Fossils may potentially be found in every formation present within the recreation area (table 6). Kirkland et al. (2010) completed a paleontological resource inventory and monitoring report for Glen Canyon Recreation Area. During their field investigation, they discovered undocumented tracksites and other fossil localities.

Fossils discovered in Glen Canyon Recreation Area are housed in several locations, including the recreation area, the Western Archeological and Conservation Center (WACC), museums, and academic institutions (Tweet et al. 2009). The recreation area’s collections include the Kayenta Formation tracks discovered in Explorer’s Canyon. The WACC natural history catalog contains 39,461 paleontological objects arranged under 1,668 catalog numbers (Tweet et al. 2009). Almost all of these came from packrat middens or various caves in the recreation area.

The fossils summarized in this GRI report (tables 6, 7, 8, 9) only reflect those found within the park or in the immediate vicinity of the park. However, a complete list of fossils found on the Colorado Plateau and references associated with those discoveries may be found in Tweet et al. (2009). Currently, the recreation area has about 350 documented sites, although some lack sufficient coordinate data (John Spence, written communication, 9 December 2015). The Utah Geological Survey maintains an unpublished database of fossil localities

Table 6. Relative distribution of tracks and bones found in the stratigraphic units along the shoreline of Lake Powell, Glen Canyon National Recreation Area.

Period and Epoch	Geologic Unit (map symbol)	Distribution of Tracks	Distribution of Bones
Middle Jurassic	Carmel Formation: Paria River and Winsor members (Jcu, Jcw, Jcp)	Rare	Rare
Middle Jurassic	Page Sandstone (Jpj, Jpt)	Present	Present
Lower Jurassic	Glen Canyon Group: Navajo Sandstone (Jn, Jnl)	Present	Rare
Lower Jurassic	Glen Canyon Group: Kayenta Formation (Jk, Jks)	Present	Present
Lower Jurassic–Upper Triassic	Glen Canyon Group: Wingate Sandstone (JTRw)	Present	Rare
Upper Triassic	Chinle Formation: Church Rock Member (TRcc, TRcu)	Common	Common
Upper Triassic	Chinle Formation: Owl Rock and Petrified Forest members (TRcop, TRcu)	Present	Common
Upper Triassic	Chinle Formation: Moss Back Member (TRcu, TRcms)	Present	Common
Upper Triassic	Chinle Formation: Monitor Butte Member (TRcmn)	Present	Common
Upper Triassic	Chinle Formation: Shinarump Conglomerate Member (TRcs)	Present	Present
Lower Triassic	Moenkopi Formation: Upper member (TRmu)	Rare	Rare
Lower Triassic	Moenkopi Formation: Hoskinnini Sandstone Member (TRmh)	Rare	Rare
Lower Permian	Cutler Group: White Rim Sandstone (P, Pc, Pwr)	Rare	Rare
Lower Permian	Cutler Group: Organ Rock Formation (Pc, Po)	Present	Present
Lower Permian	Cutler Group: Cedar Mesa Sandstone (P, Pc, Pcm)	Rare	Rare
Lower Permian–Upper Pennsylvanian	Cutler Group: Lower Cutler beds/Halgaito Formation (Pc, PPNcl, PPNhgu, PPNhgl)	Present	Present
Upper Pennsylvanian	Hermosa Group: Honaker Trail Formation (PNht, PNhtu, PNhtl)	Rare	Rare

Information from Kirkland et al. (2010, figure 1).
Colors in Period and Epoch column correspond to US Geological Survey colors for geologic time periods. Colors in distribution columns correspond to relative abundance of fossil tracks or bones: Rare (yellow), Present (orange), or Common (green).

in Glen Canyon National Recreation Area (Tweet et al. 2009). Servicewide summaries of types of paleontological resources also include information on the scope and significance of fossil vertebrate trackways (Santucci et al. 2006), Mesozoic mammals (Tweet and Santucci 2015), packrat middens (Tweet et al. 2012), coprolites, and bromalites (urine deposits; Hunt et al. 2012) from Glen Canyon National Recreation Area.

Resource management issues associated with Glen Canyon paleontological resources are described in the "Paleontological Resource Inventory, Monitoring, and Protection" section.

Paleozoic Era Fossils: Pennsylvanian and Permian Periods

Marine and Nearshore Environments

In general, fossils from Paleozoic Era strata in Glen Canyon National Recreation Area represent a transition from marine to nearshore, coastal conditions (table 7). Fauna that lived in normal, well-circulated marine environments populate the Honaker Trail Formation (PHht), and these are joined by fossils common to nearshore marine environments in the overlying Late Pennsylvanian and Early Permian Halgaito (**PPNhgu**, **PPNhgl**) and Elephant Canyon Formations (**PPNe**; table 7). The rare "sail back" *Platyhystrix*, an extinct early amphibian, was discovered in a conglomeratic stream channel in the Halgaito Formation (Sumida et al. 1999; Kirkland et al. 2010; Santucci and Kirkland 2010).

The Cedar Mesa Sandstone (**Pcm**) contains three published tracksites in Glen Canyon National Recreation Area: Dirty Devil, Grand Gulch, and Steer Gulch (Tweet et al. 2009). The Dirty Devil tracksite was the first Permian tracksite known from the Glen Canyon area and documented the skink *Anomalopus* attacking its prey, the beetle *Stenichus* (Lockley and Madsen 1993; Kirkland et al. 2010). The tracks at the other two Cedar Mesa Sandstone sites were mostly made by synapsids (mammal-like reptiles) and tracks that are similar to *Anomalopus* and tetrapod fossil track genus *Chelichnus*.

Table 7. Paleozoic Era fossils found in Glen Canyon National Recreation Area or its immediate vicinity.

Period and Epoch	Geologic Unit (map symbol)	Fossils*	Depositional Environment
Lower Permian	Cutler Group: Cedar Mesa Sandstone (P, Pc, Pcm)	Three published tracksites. (1) Dirty Devil. *Anomalopus* (skink), *Stenichus* (beetle). (2) Grand Gulch tracksite. Mostly synapsids (pelycosaurs, other mammal relatives, and true mammals) with tracks similar to *Anomalopus* (skink) and *Chelichnus* (reptile). (3) Steer Gulch tracksite. Similar tracks to those found at Grand Gulch.	Coastal sand dunes and evaporative sabkha environments.
Lower Permian–Upper Pennsylvanian	Cutler Group: Lower Cutler beds (Pc, PPNcl) (old Rico Formation)	Marine invertebrate fossils (foraminifera, brachiopods, bivalves, gastropods, crinoids), elasmobranch teeth (including petalodont, bradyodont, and cladodont sharks).	Fluctuating sea levels in southeastern Utah. Repetitive cycles of coastal dunes, channels, mudflats, tidal flats, supratidal areas, deltas, bays, bars, and open marine environments (Terrell 1972; Tweet et al. 2009).
Lower Permian–Upper Pennsylvanian	Cutler Group: Halgaito Formation (PPNhgl)	Extinct early amphibian *Platyhystrix* ("sail back" temnospondyl), sharks, crossopterygian fish (lobe fins), early ray-finned fish, amphibians, early tetrapods, early diapsid reptiles (includes lizards, snakes, and crocodilians), pelycosaurs, synapsids ("mammal-like reptiles").	
Lower Permian–Upper Pennsylvanian	Cutler Group: Elephant Canyon Formation (PPNe)	Marine invertebrate fossils (foraminifera, corals, bryozoans, brachiopods, bivalves, gastropods, cephalopods, trilobites, echinoderms), invertebrate burrows, palaeoniscid fish, algal mats, wood fragments.	
Middle and Upper Pennsylvanian	Hermosa Group: Honaker Trail Formation (PNht, PNhtu, PNhtl) and Paradox Formation (PNp)	Marine invertebrate fossils (foraminifera, bryozoans, gastropods, crinoids, conodonts), algae, pellets, root traces (rhizoliths), borings in marine rocks.	Normal, well-circulated marine environments. In Arches National Park, 37 km (23 mi) north, fossils are from a variety of coastal settings, including delta lobes and tidal flats, as well as open marine environments (Wengerd 1962; Melton 1972; Millberry 1983; Tweet et al. 2009; Doelling 2010).

* Fossils from Tweet et al. (2009) and descriptions compiled in Willis and Ehler (in preparation; see glca_geology.pdf in GRI GIS data).

Lizard-like tracks are also known from Oljeto Wash (Lockley et al. 1998).

Discovered in 1973, the Dirty Devil tracksite consists of a large sandstone block tilted vertically. In 1973, the average annual lake level was 1,104.94 m (3,625.13 ft) above sea level, but from 1974 to 2003, lake level was higher and the tracksite was submerged below the surface of Lake Powell except for one year, 1992. An unsuccessful attempt was made to find the tracksite in 1992, but silt had accumulated in the lower reaches of the Dirty Devil River and the site could no longer be reached by either boat or from the precipitous canyon walls (Lockley and Madsen 1993). It appeared that the tracksite would only exist in photographs and replicas of the tracks taken in 1973. Since 2003, however, lake levels have often been lower than the 1973 mark, exposing the Dirty Devil tracksite (Lake Powell Water Database 2016; Vincent Santucci, NPS Geologic Resources Division, paleontologist, written communication 20 December 2015). Global climate change models predict increased temperatures and decreased precipitation for the region, which may result in lower lake levels and exposure of other previously submerged fossil sites.

Outside of the park, nonmarine and marine fossils have been found near the top of the Cedar Mesa Sandstone. These fossils include leaf impressions, root casts, vertebrate tracks, and invertebrate marine fossils such as stromatolites, algae, fusulinids, bryozoans, brachiopods, gastropods, and crinoids. This fossil association has been interpreted to represent tidal inlets or estuaries (Loope 1984; Tweet et al. 2009).

Mesozoic Era Fossils: Triassic Period

<u>Terrestrial Trace Fossils and Plants</u>

Terrestrial tracksites dominate the fossil resources in the Triassic and Jurassic Periods (table 8). The Early–Middle Triassic Moenkopi Formation in Glen Canyon

Figure 20. Photograph of dinosaur tracks in the Powell Fossil Track Block tracksite, Glen Canyon National Recreation Area. The tracks are in a house-size block of Jurassic Navajo Sandstone (see table 7). National Park Service photograph by Vincent Santucci (NPS Geologic Resources Division).

National Recreation Area, deposited approximately 250 million to 240 million years ago, contains at least five tracksites (Mickelson et al. 2005, 2006; Kirkland et al. 2010). The Farley Canyon and Trachyte Point sites have been published and their tracks are listed in table 8 (Lockley et al. 1998; Tweet et al. 2009). The formation also has vertebrate and invertebrate trace fossils similar to those found in Capitol Reef National Park and on the San Rafael Swell. Most of these are reptile traces, but there are also horsetail molds, millipede and horseshoe crab tracks, and fish bones that suggest the depositional setting was a broad flat coastal delta plain influenced by tidal and fluvial processes (Mickelson et al. 2006).

Stromatolites are the only fossils found in the Moenkopi Formation's Hoskinnini Member in the recreation area (Tweet et al. 2009). These accretionary sedimentary structures grow in shallow marine water by trapping and binding fine-grained sediment in microbial mats. Exceptional living stromatolites are found today in the warm, relatively shallow waters of Australia's Shark Bay, Utah's Great Salt Lake, and a few other extreme environments around the world. Elsewhere on the Colorado Plateau, the lower members of the Moenkopi Formation contain marine invertebrates that indicate episodic incursion of shallow seas into the region during the earliest part of the Triassic (Tweet et al. 2009).

Table 8. Mesozoic Era fossils found in Glen Canyon National Recreation Area.

Period and Epoch	Geologic Unit (map symbol)	Fossils*	Depositional Environment
Upper Cretaceous	Straight Cliffs Formation (Ksl, Ksj, Ksd)	Abundant fossils in the nearby Grand Staircase-Escalante National Monument.	Broad coastal plain that formed with sea level fall.
Upper Cretaceous	Tropic Shale (Kt)	Ammonites, bivalves, sharks, rays, turtles (*Desmatochelys* and *Naomichelys*), and plesiosaurs from two short-necked lineages (pliosaurid *Brachauchenius lucasi* and polycotylids *Eopolycotylus rankini*, *Palmulasaurus quadratus*, and *Trinacromerum*? *bentonianum*). The polycotylid plesiosaur *Dolichorhynchops* with associated gastroliths ("stomach stones") was found in an undesignated location.	Deposited during sea level rise and transgression of the Western Interior Seaway. Water depth in the area was less than 100 m (330 ft).
Upper Cretaceous	Dakota Formation (Kd)	Clams (*Exogyra*), oysters, plant fossils (especially angiosperm leaves), vertebrate tracks, and a dragonfly nymph.	Shifting environments from floodplains to coastal settings.
Upper Jurassic	Morrison Formation: Salt Wash Member (Jms)	Sauropod tracks (Lost Spring Wash area).	Semiarid seasonal savanna-like environment.
Upper Jurassic	Morrison Formation: Tidwell Member (Jsmt)	Track of a small sauropod dinosaur (first sauropod track with skin impressions). Bone fragments. Termite nests. Pterosaur (*Pteraichnus*) tracks (Del Monte Mines area).	
Middle Jurassic	Entrada Sandstone (Je)	Some theropod and sauropod tracks.	Semiarid to arid dune field.
Lower Jurassic	Navajo Sandstone (Jn)	Unionid clams **Dam tracksite**: *Eubrontes*. **Crossing of the Fathers tracksite**: in situ tracks of *Otozoum* (large prosauropod); *Grallator* tracks. **West Canyon tracksite**: multiple *Otozoum* and *Grallator*-like tracks. **Last Chance Bay tracksite**: *Eubrontes*-like biped. **Driftwood Canyon tracksite**: small and large tridactyl tracks. **Hole in the Rock tracksite**: three levels of tridactyl dinosaur tracks. **Slickrock Canyon tracksite**: tracks on four fallen blocks of *Eubrontes*, *Grallator*, *Anomoepus*-like ornithopods, and *Brasilichnium* (mammal-like reptile). **Annie's Canyon tracksite**: two levels of tracks from *Eubrontes*, *Grallator*, and *Otozoum*. **Tapestry Wall**: overhang site with *Eubrontes*-like tracks. **Orange Cliffs area**: tridactyl tracks. **Onion Dome tracksite**: *Grallator* and *Anchisauripus*. **Sand Hills *Otozoum* tracksite**: *Otozoum*. **Powell Fossil Track Block**: *Grallator*, *Anchisauripus*, and unknown tracks.	Tropical arid climate with seasonal monsoons. Eolian, playa, sabkha (salt flats), and lake (unionid clams) environments. Sahara-like desert with sand dunes moving west-to-east, advancing over rivers of the Kayenta Formation. Water in interdunes formed oases. Fossils are mostly associated with oasis, interdune environments.
Lower Jurassic	Kayenta Formation (Jk) Springdale Sandstone Member (Jks)	Dinosaur tracks from multiple sites (6 described). **Explorer's Canyon tracksite**: *Eubrontes* dinosaur tracks (on display at the Page Visitor Center). **Long Canyon tracksite**: elongate tracks. **Mike's Mesa tracksite**: *Eubrontes* tracks. **Slickrock Canyon tracksites** (2 sites): *Eubrontes* and *Grallator* tracks. **Rainbow Bridge National Monument tracksite**: *Eubrontes* tracks.	Shifting braided and meandering streams on a broad floodplain in a more humid climate than JTRw.
Lower Jurassic–Upper Triassic	Wingate Sandstone (JTRw)	**Lees Ferry and North Wash tracksites**: *Grallator* tracks from the small theropod dinosaur. **The Rincon tracksite**: tridactyl biped tracks.	First of several giant ergs in area. Also, playas.

* Fossils from Tweet et al. (2009) and Kirkland et al. (2010).

Table 8. Mesozoic Era fossils found in Glen Canyon National Recreation Area, continued.

Period and Epoch	Geologic Unit (map symbol)	Fossils*	Depositional Environment
Upper Triassic	Chinle Formation, undivided	Variety of fossils including fossil wood, carbonaceous debris, gastropods, crayfish burrows, bones, coprolites, and dinosaur tracks. **Fourmile Canyon tracksite**: tracks of the dinosaur-like *Atreipus milfordensis* and lizard-like *Rhynchosauroides* (removed in 1992 and now part of the NPS collection). **Mike's Mesa tracksite**: tridactyl (three-toed) tracks.	Transition over time from braided streams in TRcs to a monsoonal climate in TRcmn and TRcms to an arid climate in the upper part of the unit.
Upper Triassic	Chinle Formation: Church Rock Member (TRcc)	Petrified wood. Fish bones at The Rincon. Isolated ganoid (fish) scales in a block of sandstone, west side of The Rincon.	Aridification continues.
Upper Triassic	Chinle Formation: Owl Rock and Petrified Forest Members (TRcop)	**Owl Rock Member**: permineralized wood, root traces. **Petrified Forest Member**: petrified logs. Bone fragments of archosaurs and metoposaurs and unionid clam shell fragments from sites on north side of San Juan Arm.	**Owl Rock**: arid climate with carbonate soil horizons and small ponds on a floodplain. **Petrified Forest**: deposited by streams.
Upper Triassic	Chinle Formation: Moss Back Member (TRcms)	Petrified logs, plant debris, possible tracks of *Pentasauropus*, a dicynodont (large mammal-like reptile).	Streams, crevasse splays, and floodplain settings.
Upper Triassic	Chinle Formation: Monitor Butte Member (TRcmn)	Red Canyon site has unionids (freshwater mussels), a small crocodile relative, coprolites, and lake fossils that include plants, insects, crustaceans, conchostracans, and fish fossils. Unit also contains logs.	Braided and meandering stream systems, lakes, and swamps in a monsoonal climate.
Upper Triassic	Chinle Formation: Shinarump Conglomerate Member (TRcs)	Fossils found in the vicinity of the recreation area are most commonly plants, including petrified wood, logs, pith casts, leaf compressions, pollen and spores, fragments of carbonized wood. Plant types include horsetails, ferns, fern-like plants, cycads, conifers, cycad-like bennettitaleans, and other gymnosperms. Other fossils from this unit include bone fragments, some of metoposaurs (extinct salamander-like aquatic amphibians) or phytosaurs (extinct crocodile-like aquatic reptiles, tetrapod footprints, swim traces, and coprolites. Invertebrates include polychaete worm Spirorbis shells, two types of insect eggs, possible beetle feeding traces.	Braided streams filling valleys eroded into underlying strata.
Lower–Middle Triassic	Moenkopi Formation (TRm): Upper and Lower Members, undivided (TRmu, TRml)	Two published tracksites. **Farley Canyon site**: horseshoe crab tracks, swim traces, lizard-like tracks. **Trachyte Point site**: horseshoe crab tracks, swim marks.	Broad floodplain leading to a sea to the west and northwest.
Lower–Middle Triassic	Moenkopi Formation (TRm): Hoskinnini Member (TRmn)	Stromatolites.	Periodically wet sabkha.

* Fossils from Tweet et al. (2009) and Kirkland et al. (2010).

The Chinle Formation (**TRc**) contains abundant petrified wood and other plant fossils (table 8; Finnell et al. 1963; Tweet et al. 2009). In fact, the Chinle Formation's Wolverine Petrified Forest that ranges into the northern part of Glen Canyon National Recreation Area represents an extensive fossil forest second only to the one preserved at Petrified Forest National Park (Tweet et al. 2009; Kirkland et al. 2010; see GRI report by KellerLynn 2010). Many localities in the park contain petrified wood (Santucci 2000). In 1985, a 9 m- (30 ft-) long petrified log was removed from Trachyte Canyon (Tweet et al. 2009). In 2009, a petrified log jam was documented in the Shinarump Member of the Chinle Formation in the San Juan arm (Vincent Santucci, written communication, 20 December 2015). Petrified wood in the Owl Rock/Petrified Forest Member is often black and more solidly petrified than in the other members. Large logs have been known to roll down slopes, remaining relatively intact (Kirkland et al. 2010).

In addition to plant material, fossils in the Chinle Formation at Glen Canyon National Recreation Area include gastropods, crayfish burrows, bones, coprolites, and dinosaur tracks (table 8; Anderson et al. 2010). Dinosaur tracks have been reported from three sites, two of which have been published and are listed in table 8 (Tweet et al. 2009). According to Kirkland et al. (2010), the plants, insects, crustaceans, conchostracans, and fish fossils discovered in the Monitor Butte Member (**TRcmn**) in Red Canyon may be the most significant collection of lake fossils ever discovered in the Triassic of western North America (table 8).

Of all the Chinle Formation members, the Petrified Forest Member (**TRcop**) contains the most diverse assemblage of fossil vertebrates (Tweet et al. 2009). Vertebrate fossil sites are known in the recreation area, but they have not received serious attention yet (John Spence, written communication, 9 December 2015). At a site northwest of the recreation area, a diverse assemblage of fossil vertebrates has been found in the Petrified Forest Member (**TRcop**). The assemblage includes bones from lungfish, phytosaurs, and theropod dinosaurs ("beast-footed" bipeds), and an ornithischian (herbivorous bird-hipped dinosaur) like jaw (Parrish 1999).

Chinle Formation fossils discovered in the nearby Grand Staircase-Escalante National Monument include carbonaceous debris, petrified logs, palynomorphs (organic microfossils like pollen and spores), bivalves, gastropods, ostracods, insects, horseshoe crabs, fish, reptiles, and tracks of phytosaurs, theropods, lepidosauromorphs (lizards, snakes, tuataras, and relatives), and prosauropods (herbivorous dinosaurs related to sauropods) (Foster 2002; Tweet et al. 2009).

In Canyonlands National Park, the Petrified Forest, Owl Rock, and Church Rock Members (**TRcop**, **TRcc**) have yielded leaves, stems, needles, cones, wood, bivalves, gastropods, crayfish, conchostracans (clam shrimp), traces from crayfish and horseshoe crabs, metoposaurs (an extinct lizard), aetosaurs (an extinct order of armored herbivorous archosaurs), and phytosaurs (an extinct semi-aquatic reptile) (Hasiotis 1992; Tweet et al. 2009).

Mesozoic Era Fossils: Jurassic Period

Significant Reptile Tracks

Fossils of the Jurassic Period in Glen Canyon National Recreation Area are dominated by dinosaur and reptile tracksites (table 8). Of the five tracksites in the Wingate Sandstone (**JTRw**), three have been documented (table 8; Tweet et al. 2009). In addition to the tracks, a skull of the Triassic-age phytosaur *Redondasaurus* was found at the base of the Wingate Sandstone, outside of the park. Prior to this discovery, the Wingate Sandstone was thought to be entirely Jurassic in age. The skull, however, indicates that at least some of this formation was deposited in the Late Triassic (Lucas et al. 1997; Tweet et al. 2009). This discovery emphasizes the importance of documenting not only the fossil but also the stratigraphic level in which the fossil is found.

The overlying Kayenta Formation contains dinosaur tracks in many locations at Glen Canyon National Recreation Area and the immediate vicinity (Tweet et al. 2009). *Eubrontes* tracks represent the first large theropod tracks in the fossil record (Kirkland et al. 2010). Large theropod tracks (*Eubrontes*) and small theropod tracks (*Grallator*) dominate the six described sites from the recreation area (table 8). While lake levels were still low, the *Eubrontes* tracks at the Explorer's Canyon site were removed and are on display at the Page Visitor Center (Santucci and Kirkland 2010; Kirkland et al. 2010). *Eubrontes* tracks can also be found at Rainbow Bridge National Monument, but they are badly weathered.

An in situ *Eubrontes* track and a fallen slab containing more than 30 *Grallator* tracks were found in Slickrock Canyon (Tweet et al. 2009). The *Grallator* tracks in Slickrock Canyon are typical of the many tracks found in the transition zone between the Kayenta Formation and Navajo Sandstone (Tweet et al. 2009). Low water levels in Lake Powell have revealed even more tracks in this transition zone. Impressions of theropod heels and tracks from an animal moving at 22.4 km/hr (13.9 mph) were found in Chaol Canyon and 150 tracks were found at four sites in Slickrock Canyon. These tracks were left by small theropods, large theropods, and ornithischians (Lockley et al. 2005; Tweet et al. 2009).

The Kayenta Formation on the Colorado Plateau also contains a diverse collection of vertebrate body fossils, which are summarized in Tweet et al. (2009). These body fossils are primarily found in the upper, siltier part of the Kayenta Formation, which is not widely exposed in Glen Canyon National Recreation Area. At the base of the Kayenta Formation, fossils are limited to semionotid (ray-finned) fish and dinosaur tracks in the medium-to-coarse sandstone and conglomerate of the Springdale Sandstone Member (table 8; Harshbarger et al. 1957; Smith and Santucci 1999). Coprolites, fish scales, and body fossils from crocodylomorphs, and tritylodontids (non-mammalian cynodonts) such as *Kayentatherium* may occur in the recreation area (Tweet et al. 2009).

Kayenta Formation fossils also include petrified wood, algal limestone, invertebrate trails and burrows, unionid bivalves, freshwater gastropods, and ostracods. As with the vertebrate fossils, these fossils are more prevalent in the upper, silty part of the formation (Tweet et al. 2009).

Most of the fossils from the Navajo Sandstone are associated with oasis deposits (Loope et al. 2004; Irmis 2005; Tweet et al. 2009). These limestone deposits primarily yield plants and invertebrates. Body fossils are rare in the Navajo Sandstone, but in the last decade, important vertebrate body and trace fossils have been discovered (Irmis 2005; Vincent Santucci, written communication, 20 December 2015). They include specimens of tritylodonts, crocodylomorphs, sauropodomorphs, and theropods (Irmis 2005). *Eubrontes*, *Anchisauripus*, and *Otozoum* tracks are only known from interdune oases (Loope 2006). Tracks (identified as *Batrachopus*, *Brasilichnium*, and *Grallator*) of smaller dinosaurs are found in preserved sand dune deposits (Loope 2006). Irmis (2005) pointed out that this differentiation may reflect how the tracks were preserved in interdune compared to sand dune environments rather than the habitat range of the different species.

The first ten Navajo Sandstone tracksites in table 8 had been documented in Glen Canyon National Recreation Area prior to the 2009 paleontological resources inventory field study (Kirkland et al. 2010). Twenty-eight trackways from prosauropods (*Otozoum*) and small theropods (*Grallator*) found at the most extensive in situ tracksite at the recreation area (Tweet et al. 2009). The Dam tracksite, which had a single *Eubrontes* track, was destroyed during construction of Glen Canyon Dam.

The 2009 field inventory discovered several undocumented tracksites (Kirkland et al. 2010). Many of these new sites were small, but the Onion Dome tracksite near the base of the Navajo Sandstone contained about 100 m (330 ft) of Grallator and *Anchisauripus* tracks in a playa deposit. The Sand Hills *Otozoum* and Powell Fossil Track Block tracksites have been recommended as paleontological interpretive sites (table 8; Kirkland et al. 2010). The Sand Hills tracksite contains excellent *Otozoum* tracks, which were likely from a long-necked herbivorous dinosaur (prosauropod) that was the precursor to the gigantic sauropods of the Late Jurassic. *Otozoum* is also an index fossil for the Early Jurassic, which means it is used to define and identify this geologic epoch.

The Powell Fossil Track Block tracksite was first reported in the summer of 2009 (fig. 20; Kirkland et al. 2010). Located near the base of the Navajo Sandstone, the tracksite preserves isolated theropod tracks and trackways (*Grallator* and *Anchisauripus*), and an unusual trackway of a large slow-moving bipedal dinosaur with tracks similar to iguanodontian ornithopods that do not show up in the geologic record for another 30 million–40 million years (Kirkland et al. 2010).

As with the Kayenta Formation, additional trackways in the Navajo Sandstone were exposed when the lake level dropped (Lockley et al. 2005). As of 2016, researchers and park staff had documented approximately 100 tracksites in Glen Canyon National Recreation Area (John Spence, written communication, 9 December 2015). In addition to dinosaur tracks, termite mounds, petrified wood, possible mammal-like tracks, and a reptile skeleton have been found in the vicinity of the recreation area (Hamblin 1998; Santucci 2000; Tweet et al. 2009; Santucci and Kirkland 2010).

A unionid clam bed discovered in the Navajo Sandstone preserves a unique environment that existed among the Jurassic dunes (Kirkland et al. 2010). The bed, which is often submerged by Lake Powell, preserves molds of hundreds (perhaps thousands) of these freshwater bivalves. The unionid clam has a parasitic relation with fish, in that all unionid larvae spend part of their life cycle in the gill filaments of fish. The abundance of unionid clams suggests that fish were also present in this area during the Early Jurassic. In contrast to playas that formed in interdune sites when the water table impinged on the surface, this clam bed represents an environment with relatively permanent surface water within the Navajo Sandstone erg, which may be among the largest sand deserts in Earth's history (Loope et al. 2004; Kirkland et al. 2010; Milligan 2012).

Although the Navajo Sandstone represents an immense, arid, active dune field, Early Jurassic tropical monsoons also impacted the western interior of the United States. Evidence of abundant rainfall can be found in the petrified trees found near Page, Arizona, at the southern tip of Glen Canyon National Recreation Area (Thomas 2000). In situ fossil tree stumps, abundant dinosaur tracks, bioturbated strata as much as 20 m (66 ft) thick, and layers of stromatolites discovered outside of the park also suggest vibrant plant communities grew within this Sahara-like desert (Loope 1979; Loope et al. 2004). Some trees had diameters of almost 1 m (3 ft) while others lacked growth rings, indicating continuous growth. Thick-trunked cycadeoids, which first appeared in the Triassic Period and became extinct at the end of the Cretaceous Period, grew during times of increased precipitation. Araucarian conifers, whose living relatives include the hardy monkey puzzle tree (*Araucaria araucana*), grew along lake margins (Parrish et al. 2002; Wilkens et al. 2005, 2007; Parrish and Falcon-Lang 2007; Tweet et al. 2009).

Trace fossils are the main fossils found in the Middle Jurassic Entrada Sandstone, the last major erg to cover the area. Some theropod tracks in the Entrada Sandstone have been found at Glen Canyon National Recreation Area, and in nearby Grand Staircase-Escalante National Monument, the Entrada Sandstone has yielded insect burrows, large vertebrate burrows, dinosaur tracks, and sand-swimming traces (Loope 2004; Lockley et al. 2005; Graversen et al. 2007).

The Upper Jurassic Morrison Formation is famous for its dinosaur fossils, many of which are spectacularly displayed at Dinosaur National Monument (see GRI report by Graham 2006c; Gregson et al. 2010). As of 2009, however, few Morrison Formation fossils had been reported from Glen Canyon National Recreation Area (table 8; Tweet et al. 2009). The most notable dinosaur fossil discovery has been several sauropod footprints with preserved skin impressions that were found in the Tidwell Member of the Morrison Formation (**Jsmt**) near Bullfrog (Tweet et al. 2009; Kirkland et al. 2010). This track proved to be the first sauropod track with skin impressions.

In addition to dinosaur traces, termite nests in the Tidwell Member have been preserved in an unspecified location in the park (Engelmann 1999; Santucci 2000; Kirkland et al. 2010). The nests form cylindrical concretions 20 cm (8in) in diameter and 30–40 cm (12–16 in) tall.

Morrison Formation fossils have been found in nearby areas and include pterosaur tracks (*Pteraichnus*) from the Tidwell Member and sauropod tracks in the Salt Wash Member (**Jms**). Bone fragments and petrified wood have been found in Salt Wash Member paleochannels in Capitol Reef National Park, and fossils of plants, non-dinosaurian reptiles, and dinosaurs have been discovered in Grand Staircase-Escalante National Monument (Tweet et al. 2009).

Mesozoic Era Fossils: Cretaceous Period

Fossils Within and Surrounding the Western Interior Seaway

During the Cretaceous, a major sea level rise drowned the terrestrial environments of southeastern Utah and created the Western Interior Seaway that bisected the North American continent (see the "Geologic History" chapter). The fossil diversity in the Upper Cretaceous Dakota Formation (**Kd**) records the transition from fluvial to coastal to shallow marine settings as sea level rose. Tweet et al. (2009) summarized the extensive paleobotanical fossils, dinosaur tracks, nonmarine fauna, and marine invertebrates common to the Dakota Formation. In Glen Canyon National Recreation Area, coal beds are found in the middle part of the formation, and fossils of clams (*Exogyra*) and oysters that lived in brackish to open marine environments are abundant in the upper sandstone (Anderson et al. 2010).

Potential Dakota Formation fossils that may be found in Glen Canyon National Recreation Area include those found in the adjacent Grand Staircase-Escalante National Monument and Kaiparowits Plateau. These fossils include palynomorphs, petrified wood, algae, foraminifera, bivalves, gastropods, ostracodes, ammonites, invertebrate traces, sharks, rays, ray-finned fish, lungfish, lizards amphibians, turtles, crocodilians and crocodile relatives, small theropods (dromaeosaurids and troodontids), tyrannosaurids, armored dinosaurs, hypsilophodonts (small bipedal herbivorous dinosaurs), hadrosaurids (duckbills), and mammals (marsupials, multituberculates, and non-marsupial therian) (see Tweet et al. 2009 for references).

The myriad marine fossils found in the Upper Cretaceous Tropic Shale (**Kt**) reflect deposition in the shallow waters of the Western Interior Seaway in this area (Tweet et al. 2009). Published sites in Glen Canyon National Recreation Area are from the southwestern part of the park and include ammonites, bivalves, sharks, rays, turtles, and plesiosaurs (table 8; Santucci 2000; Albright et al. 2007a, 2007b).

When sea level fell later in the Cretaceous and the Western Interior Seaway shrank in size, coastal plain environments developed, and these environments are reflected in the fauna from each member of the Upper Cretaceous Straight Cliffs Formation. Only coal is known from the formation in Glen Canyon National Recreation Area, but exposures in Grand Staircase-Escalante National Monument have yielded abundant fossils, which may eventually be found in the recreation area (Tweet et al. 2009). The Tibbet Canyon Member (**Ksl**) yields marine invertebrates, sharks, rays, gars, crocodilians, and marsupials. The Smoky Hollow Member (**Ksl**) has dicotyledonous leaf compressions, sharks, rays, ray-finned fish such as bowfins and gars, the unusual amphibian *Albanerpeton*, frogs, turtles, lizards, crocodilians, small theropods (such as dromaeosaurids and troodontids), tyrannosaurids, armored dinosaurs, hypsilophodonts, hadrosaurids, and symmetrodont, marsupial, and possible eutherian mammals. Fossils from the John Henry Member (**Ksj**) include ammonites, bivalves, footprints, sharks, rays, ray-finned fish like bowfin and gars, *Albanerpeton*, frogs, turtles, lizards, crocodilians, dromaeosaurids, armored dinosaurs, hadrosaurids, and multituberculate, symmetrodont, and marsupial mammals. The Drip Tank Member (**Ksd**) in Grand Staircase-Escalante National Monument yields turtle and crocodilian fragments (Tweet et al. 2009).

Cenozoic Era Fossils: Quaternary Period

Pollen, Dung, Bromalites, and Bones

Quaternary fossils found in Glen Canyon National Recreation Area and its immediate vicinity have proven useful for both paleoecological and paleoclimatological reconstructions. Fossil pollen is especially valuable in these reconstructions as are the many fossils found in packrat middens (table 9; Tweet et al. 2009). For example, pollen analyzed from the dung in Bechan Cave indicated that the predominant plant community away from the riparian zone may have been sagebrush steppe rather the blackbrush (*Coleogyne* sp.), which is the dominant shrub today (Mead et al. 1984; Kirkland et al. 2010). Bones of large mammals such as sloths, proboscideans, equids, bison, and camelids are typical of Quaternary fossils found in the southern Colorado Plateau, and large mammal bones have been found in the recreation area (Tweet et al. 2009). A mammoth tracksite was discovered in Glen Canyon National Recreation Area near Forty-Mile drainage.

Alcoves are important Quaternary fossil sites in Glen Canyon National Recreation Area (table 9). Most of the fossils found in the alcoves are associated with fossil dung. The best-known Quaternary site is Bechan Cave (fig. 21). This single-room cavern formed by spalling of cross-bedded sandstone and was aided by seepage and calcite crystal growth (Agenbroad and Mead 1989). The recessed alcove is 53 m (170 ft) deep, 32 m (100 ft) wide, and up to 9 m (30 ft) high. Containing 300 m^3 (10,600 ft^3) of fossil dung, Bechan Cave lives up to its name, which means "big feces" in Navajo (Santucci et al. 2001).

Located on BLM land adjacent to Canyonlands National Park, Cowboy Cave, contains extensive archeological resources and Pleistocene dung deposits (Mead and Agenbroad 1992; Santucci et al. 2001). This large, one-room grotto provided the first radiocarbon dates (ranging from 13,040 to 11,020 years before present) for *Mammuthus* remains from the Colorado Plateau (Agenbroad and Mead 1989).

Microfossils, plant matter, and freshwater invertebrates have also been found in Quaternary fluvial sediments. Pleistocene bivalves and Holocene plant debris are present in the canyon near Bechan Cave (Agenbroad and Mead 1990). In Grand Staircase-Escalante National Monument, pollen and gastropods in Upper Valley Creek on the Escalante River date from the last 2,000 to 200 years (Webb and Hasbargen 1997). Pollen, peat, and insects that provide paleoclimate information have been retrieved from the Lake Pagahrit site in the Lake Canyon area (Phillips 1995; Anderson et al. 2000).

Formations with Potential for Fossils in Glen Canyon National Recreation Area

As of 2009, the following formations had yet to yield fossils in Glen Canyon National Recreation Area, but fossils have been recovered from them elsewhere on the Colorado Plateau (Tweet et al. 2009).

- Middle Pennsylvanian Paradox Formation (**PNp**). Fossil fish fragments and abundant marine invertebrates represent well-circulated, open

Figure 21. Photograph of Bechan Cave, Glen Canyon National Recreation Area. The alcove formed in Navajo Sandstone. Note the people for scale. Photograph courtesy of Tyler Knudsen (Utah Geological Survey).

marine systems (Wengerd 1962; Rueger 1996; Tweet et al. 2009).

- Lower Permian Organ Rock Formation (**Po**). In the Monument Valley area, fossils in stream channel deposits about 11 m (35 ft) from the base of the unit include sharks, fish, amphibians, reptile-like tetrapods, pelycosaurs, and tetrapod tracks (Tweet et al. 2009).
- Lower Permian Kaibab Formation (**Pk**). Abundant marine invertebrate fossils have been documented from the Fossil Mountain Member on the Colorado Plateau. About 72 m (235 ft) of the Kaibab is mapped in the Lees Ferry area where it consists of the Fossil Mountain Member overlain by the Harrisburg Member (Phoenix 1963; Anderson et al. 2010).
- Lower Permian De Chelly Sandstone. Although not highly fossiliferous, this eolian unit contains trace fossils from invertebrates, such as spiders, scorpions, and beetles, and vertebrate tracks from pelycosaurs and *Dromopus* tracks from a lizard-like animal (Tweet et al. 2009).
- Lower Permian White Rim Sandstone (**Pwr**). Although rare, trace fossils have been reported from Canyonlands National Park (Baars and Seager 1967).
- Middle Jurassic Carmel Formation (**Jc**). The lower Carmel Formation contains marine invertebrate fossils, and terrestrial trace fossils are found in the upper part of the formation (Tweet et al. 2009).
- Middle Jurassic Summerville Formation (**Jesu**). Plant debris, a single sauropod tail vertebra, invertebrate traces, and a variety of vertebrate tracks are known from the Summerville Formation at Moab, Utah (Tweet et al. 2009).

Table 9. Quaternary Period fossils found in Glen Canyon National Recreation Area.

Epoch	Site*	Calibrated Radiocarbon Age* (years before present)	Fossils
Holocene	Near Lake Pagahrit	Unknown	Pollen, peat, and insects
Holocene	Bechan Cave (packrat midden)	1,523–1,306	Nine beetle taxa and a reduviid (assassin bug)
Holocene	Cow Perfect (packrat midden)	1,952–1,528	Two beetle taxa
Holocene	Bowns (packrat midden)	10,160–9,423	Two beetle taxa
Holocene–Pleistocene	Oak Haven Alcove	From 13,776 to 13,301 and 10,588 to 10,184	Plant material; mammoth, bison, and shrubox dung
Pleistocene	Withers Wallow Alcove	14,272–13,433	Plant material; mammoth, bison, bighorn sheep dung
Pleistocene	BF Alcove	From 14,728 to 13,632 and 14,023 to 13,270	Douglas fir needles, maple material, and two dung pellets possibly from a camel (*Camelops*)
Pleistocene	Cottonwood Alcove	From 15,188 to 14,018	Large dung pellets, some of which are from shrubox.
Pleistocene	Hooper's Hollow Alcove	Oak twigs: 14,114–13,652 Middens: 15,926–15,132 Bison dung: 23,472–21,369	Plant material; a packrat midden; bison, shrubox, and bighorn sheep dung; bones from marmot, horse, and mountain goat
Pleistocene	Bechan Cave	From between 17,775 and 14,229 to between 13,781 and 13,221	Fungal spores, seeds, plant fragments, insects, charcoal, wood **Dung** of packrats (*Neotoma*), cottontail rabbits (*Sylvilagus*), Shasta ground sloths (*Nothrotheriops shastensis*), mammoths (*Mammuthus*), ?horses (*Equus*), shrubox (*Euceratherium collinum*), bighorn sheep (*Ovis canadensis*), and mountain goats (*Oreamnos harringtoni*) **Hair** from shrews, packrats (*Neotoma*), deer mice (*Peromyscus*), olive-backed mice (*Perognathus*), Abert's squirrel (*Sciurus aberti*), small-footed bats (*Myotis*), coyotes (*Canis latrans*), bear (*Ursus*), horses, ground and mylodont sloths (*Glossotherium* and *Nothrotheriops*), mammoths, bison (*Bison*), bighorn sheep, and deer (*Odocoileus*) **Bones** from toads (*Scaphiopus intermontanus* and *S. cf. bombifrons*), snakes (*Crotalus* and *Pituophis*), grouse-sized birds, marmots (*Marmota*), ground squirrels (*Spermophilus*), pocket gophers (*Thomomys*), voles (*Microtus*), packrats, rabbits (*Brachylagus*), and the extinct shrubox *Euceratherium collinum* (a tooth) **Packrat middens** spanning the past 12,000 years
Pleistocene	Mammoth Alcove	From 20,341 to 19,218	Dung from mammoth, bison, and bighorn sheep; mammoth bones; gastropods from a nearby site
Pleistocene	Shrubox Alcove	From 23,100 ± 660 to between 10,299 and 9,482	Oak twigs and dung from mammoth, shrubox, bison, mountain goat, and bighorn sheep
Pleistocene	Oakleaf Alcove	24,600 ± 1,400	Dung (probably horse)
Pleistocene	Grobot Grotto	From 28,290 ± 2,100 to 18,866–18,460	Plant material and mammoth, bison, shrubox, bighorn sheep, and mountain goat dung

* From Santucci et al. (2001) and Tweet et al. (2009).
Radiocarbon ages have been calibrated to yield calendar years before present (see Tweet et al. 2009).

Paleontological Resources in a Cultural Resource Context

Because the archeological record at Glen Canyon National Recreation Area spans over ten thousand years, human artifacts found in archeological sites are commonly associated with paleontological resources (Geib and Fairley 1997; Agenbroad et al. 1989). For example, at least five cultural horizons dating from 7,795 to 570 years BP have been recovered with fossils from the dung heaps in Bechan Cave (Agenbroad et al. 1989; Tweet et al. 2009). Remains of beans, corn, and squash were found along with artifacts such as sandals, bone beads, and a snare that were crafted from contemporaneous flora and fauna (Agenbroad et al. 1989; Tweet et al. 2009). Cultural artifacts also include flake tools, projectile points, and scrapers fashioned from chalcedony and/or petrified wood.

In 1989, Agenbroad et al. correlated the cave data to alluvial deposits in the adjacent canyons in order to determine the relationship between episodes of human occupation and changing fluvial and environmental conditions. The canyon alluvial and cave sequences suggest that humans occupied the canyon and Bechan Cave during periods of floodplain stability and abandoned the region during periods when the floodplain was actively eroding (Agenbroad et al. 1989).

Although not yet known at Glen Canyon National Recreation Area, pictographs and petroglyphs of dinosaur tracks have been found in the surrounding region. Petroglyphs of dinosaur tracks carved into Kayenta Formation rocks occur in Grand Staircase-Escalante National Monument and near Zion National Park (Staker 2006; Tweet et al. 2009).

Caves and Karst

Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, "losing streams," springs, and internal drainage are characteristic features of karst landscapes. As of June 2016, cave or karst resources are documented in at least 159 parks, including Glen Canyon National Recreation Area. More information is available on the NPS Cave and Karst website, http://go.nps.gov/cavesandkarst (accessed 20 June 2016).

Land et al. (2013) reported that Glen Canyon National Recreation Area could potentially contain karst landscape on about 23% of the recreation area. This figure was based on GIS analysis of a US Geological Survey national karst map (later published as Weary and Doctor 2014) which classified some of the sedimentary rocks in the park as "evaporite rocks at or near the land surface in a dry climate." Such conditions are known to produce karst features in some areas. However, John Spence (Chief Scientist and Terrestrial Natural Resources Branch Chief at Glen Canyon National Recreation Area, written communication, 9 December 2015) is not aware of any karst topography in the park, with the exception of possible karst features in the Kaibab Limestone in the Lees Ferry area.

Paleozoic carbonate strata, especially in the Honaker Trail (**PNht**), Elephant Canyon (**PPNe**), and the Kaibab Formations (**Pk**) are potential sites for solution caves in Glen Canyon National Recreation Area. As mentioned in the "Alcoves and Hanging Gardens" section, numerous alcoves and caves have formed in the Navajo Sandstone and Cedar Mesa Sandstone cliffs (tables 3 and 9).

Paleosols

As they do today, soils in the geologic past (paleosols) result from five major soil-forming factors: (1) parent material, (2) climate, (3) living organisms, especially vegetation, (4) topography, and (5) time. Study of paleosols, therefore, may provide evidence of paleoclimates. Many of the Mesozoic Era formations contain evidence of paleosol development, but typical paleosol characteristics, such as mottled reddish, greenish, and gray mudstone and siltstone, are especially abundant in the Owl Creek Member of the Chinle Formation (**TRcop**; fig. 22). Chinle paleosols exposed at the base of a channel sandstone between

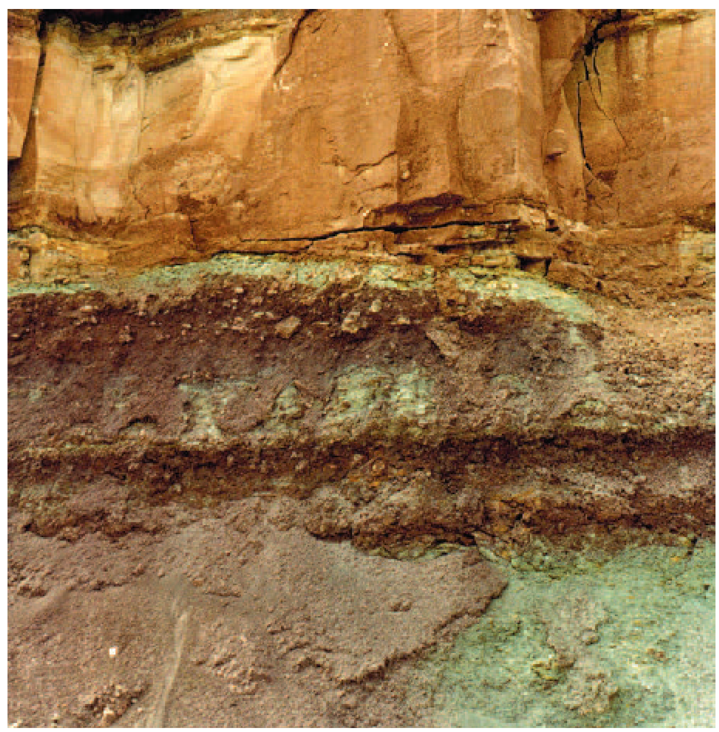

Figure 22. Photograph of paleosols in the Chinle Formation, between Twomile and Fourmile Canyons, Glen Canyon National Recreation Area. These paleosols formed on a floodplain and were then incised by a river that deposited the overlying, thick-bedded sandstone. Photograph from Anderson et al. (2010, figure 12).

Twomile and Fourmile Canyons are one of the "classic geologic sites" in Glen Canyon National Recreation Area (Anderson et al. 2010). The lighter-colored beds are typically carbonate (caliche) zones that, like today, formed near the ancient ground surface. Vegetation that grew in these developing soils is documented by light-colored, steeply inclined veinlets of carbonate rock that represent root zones (Anderson et al. 2010).

Unconformities

An unconformity represents a substantial break or gap in the stratigraphic record, which results from either non-deposition over an extended period of time or erosion of previously formed strata. Unconformities often separate rock units representing different depositional environments. In Glen Canyon National Recreation Area, six regional unconformities mark major hiatuses (missing time) in the Mesozoic Era's geologic record and are shown on the stratigraphic column for the recreation area (fig. 4). Unconformities have been identified in rocks of Triassic (**TR**), Jurassic (**J**), and Cretaceous (**K**) periods. Documenting unconformities is important to understanding the expanse of time represented by rocks and fossils in the area. Paleontologists and geologists do not always agree on the location and/or duration of unconformities. Continued scientific investigation may be able to further refine the interpretation of geologic history recorded in the rocks of the Colorado Plateau in general and Glen Canyon National Recreation Area in particular.

Triassic Unconformities

There are five unconformities in strata of the Triassic Period, and all of them except TR-2 have been recognized in Glen Canyon National Recreation Area (Pipiringos and O'Sullivan 1978; Dubiel 1994; Anderson et al. 2010). Two, TR-1 and TR-3, are regional unconformities that represent major episodes of erosion and/or non-deposition (fig. 4). All of the Triassic unconformities are associated with significant regressive (sea level fall) episodes (Dubiel 1994).

The regional TR-1 unconformity marks the boundary between the Paleozoic and Mesozoic eras, a time when all the land masses were coming together to form the supercontinent Pangea. In the northern part of Glen Canyon National Recreation Area, the TR-1 unconformity separates the White Rim Sandstone (**Pwr**) from the overlying Early Triassic Moenkopi Formation (**TRm**), and where the White Rim Sandstone is absent in the San Juan Arm, TR-1 separates the Moenkopi Formation from the Early Permian Organ Rock Formation (Stewart et al. 1972a). The unconformity represents several million years of elapsed time during which paleochannels were eroded into the Permian strata in southeastern Utah. The basal Hoskinnini Member (**TRmh**) of the Moenkopi Formation filled these paleochannels (Pipiringos and O'Sullivan 1978; Dubiel 1994).

Nearly all of the Middle Triassic rocks were eroded from southeastern Utah during a regression that occurred after deposition of the upper part of the Moenkopi Formation. TR-3 represents those millions of missing Middle Triassic years prior to the deposition of the basal Shinarump Conglomerate Member (**TRcs**) of the Late Triassic Chinle Formation (fig. 4; Stewart et al. 1972b; Pipiringos and O'Sullivan 1978; Dubiel 1994).

The TR-4 and TR-5 unconformities occur within the Chinle Formation and mark shorter intervals of missing time. The TR-4 unconformity separates the fluvial-lacustrine environment of the Monitor Butte Member (**TRcmn**) from the overlying fluvial system of the Moss Back Member (**TRcms**). The TR-5 unconformity separates the cliff-forming Church Rock Member (**TRcc**) from the underlying ledgy slopes of the Owl Rock and Petrified Forest Members (**TRcop**) (Lucas et al. 1997; Anderson et al. 2010).

Jurassic Unconformities

The contact represented by the J-1 unconformity, which separates the Lower Jurassic Navajo Sandstone (**Jn**) from the Middle Jurassic Temple Cap Formation, is one of the "classic geologic sites" referred to in Anderson et al. (2010). Features at the contact of the two formations include a lag of angular pebble- to cobble-size fragments of chert, breccia zones, large polygonal shrinkage (desiccation) cracks filled with sand from the overlying Temple Cap, carbonate nodules, extensive bioturbation, and weathering or bleaching that forms alteration zones up to 9 m (30 ft) thick. The J-1 surface also undulates over long distances, effectively reducing the thickness of the Navajo Sandstone by 60 m (200 ft). These features suggest that the surface was exposed to erosion for a long period of time prior to deposition of the Temple Cap (Anderson et al. 2010; Doelling et al. 2013).

Correlating stratigraphic units and unconformities over great distances on the Colorado Plateau is challenging, and the relationship between the J-1 and J-2 unconformities remained a conundrum for many years. In Zion National Park, the J-1 unconformity separates the Lower Jurassic Navajo Sandstone (**Jn**) from the Middle Jurassic Temple Cap Formation, and the J-2 unconformity separates the Temple Cap Formation from the overlying Carmel Formation (**Jc**) (Pipiringos and O'Sullivan 1978; GRI report by Graham 2006b; Doelling et al. 2013). East of Zion National Park, the Temple Cap pinches out, and previous reports suggested that the J-2 unconformity continued across southern Utah and cut out both the Temple Cap Formation and the J-1 unconformity (Pipiringos and O'Sullivan 1978; Peterson and Pipiringos 1979; Anderson et al. 2010).

Recent field and isotopic age data collected in a regional study of the Jurassic in Utah, however, tell a different story. The study documents north–south trending paleotopographic highs in southern Utah and the eastward thinning of the Temple Cap Formation against these paleotopographic highs (Doelling et al. 2013). The Temple Cap Formation consists of sediments that were originally deposited on both sides of the paleotopographic highs. Isotopic ages indicate relatively little time separates Temple Cap from Carmel Formation deposition. In other words, the J-2 unconformity is a relatively minor, local unconformity. The J-1 and Temple Cap Formation in Zion National Park are interrupted by paleotopographic highs, but they continue to the east into Glen Canyon National Recreation Area (Doelling et al. 2013).

Isotopic age data from the Face Canyon area of Lake Powell indicate that Temple Cap sediments were deposited approximately 173 million to 170 million years ago. In the recreation area, the Temple Cap Formation is conformable with the overlying Carmel Formation (**Jc**) (fig. 4; Sprinkel et al. 2009; Anderson et al. 2010; Doelling et al. 2013). The GRI GIS data includes the Page Sandstone (**Jp**). Now, the Page Sandstone is restricted to areas south-southeast of Page, Arizona (Doelling et al. 2013), and many of the mapped areas of "Page Sandstone" should be considered Temple Cap Formation. Research continues on validating the regional significance of Jurassic unconformities in the recreation area (Anderson et al. 2010).

The regional J-3 unconformity is at the top of the Entrada Sandstone (**Je**) (fig. 4). The contact between the cliff-forming Entrada Sandstone and slope-forming Summerville Formation (**Jesu**) is easy to identify, but the J-3 unconformity becomes less obvious where the Romana Sandstone overlies the Entrada Sandstone (Anderson et al. 2010). The Entrada Sandstone is generally tannish-orange and rounded compared to the more reddish-brown, blocky sandstone of the Romana Sandstone.

The Romana Sandstone and Summerville Formation are considered equivalent in age because they are bounded by the J-3 and J-5 regional unconformities (the J-4 unconformity is not found in southeastern Utah) (Pipiringos and O'Sullivan 1978). The exact stratigraphic relationship between these formations is uncertain because erosion has removed these rocks from the Circle Cliffs uplift (figs. 4 and 23).

Erosion at the top of the Jurassic Morrison Formation (**Jmb**, **Jms**, and **Jsmt**) accounts for its varying thickness in southeastern Utah and resulted in the K-0 (also known as the sub-Cretaceous) unconformity (fig. 4). This regional unconformity represents a long gap in the rock record separating the Morrison Formation from the Late Cretaceous Dakota Formation (**Kd**).

Folds and Faults

The Laramide Orogeny folded and faulted the strata in the Glen Canyon area. Folds and faults are included as layers in the GRI GIS data. The folds are broad, north- to northwest-oriented anticlines (convex, A-shaped folds) and synclines (concave, U-shaped folds). In general, the anticlines that intersect Glen Canyon National Recreation Area are asymmetrical, with steep eastern limbs and more gently dipping western limbs. The Circle Cliffs anticline is the most prominent fold in Glen Canyon National Recreation Area (fig. 23). The nearly 160-km- (100-mi-) long steep eastern limb of the fold is referred to as the Waterpocket Fold. The Waterpocket Fold is also referred to (and mapped) as a monocline, which is a one-limb, step-like fold in otherwise relatively horizontal or gently dipping strata. The Waterpocket Fold forms the principal geologic structural feature in Capitol Reef National Park (see GRI report by Graham 2006a). In Glen Canyon National Recreation Area, dips on the Waterpocket Fold are up to 15°, but north of the recreation area, dips can be greater than 60° (Doelling and Willis 2006, 2008;

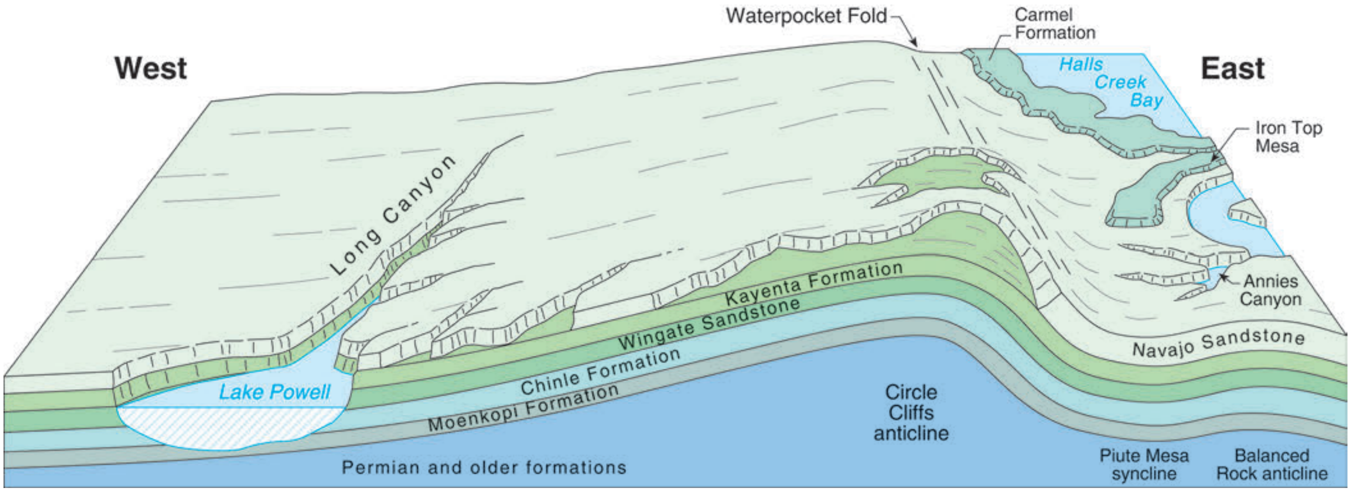

Figure 23. Schematic diagram across the Circle Cliffs anticline, which trends north–south to northwest–southeast through Glen Canyon National Recreation Area. The Waterpocket Fold defines the steep eastern limb and is the dominant structural feature in Capitol Reef National Park (plate 1). Diagram from Anderson et al. (2010, figure 22).

Morris et al. 2010). The west limb of the Circle Cliffs anticline, on the other hand, has dips of 4° or less. The anticline tilts to the south and crosses Lake Powell in The Rincon area (Willis 2004).

In Glen Canyon National Recreation Area, the crest of the Circle Cliffs anticline is composed primarily of Navajo Sandstone (**Jn**). Near Iceberg Canyon, the Kayenta Formation (**Jk**) forms the steep slope of the Waterpocket Fold. A series of normal faults (fig. 24) extends north from Lake Powell for 20 km (12 mi) along the Waterpocket Fold. Rocks on the east side of these faults have moved down relative to the strata across the faults.

Pennsylvanian and Permian formations are exposed on the Monument uplift, a broad, north–south-trending, asymmetrical monocline in southeastern Utah and northeastern Arizona. The eastern limb of the Waterpocket Fold is the gently dipping west flank of the Monument uplift, a portion of which lies within the eastern part of the recreation area (Anderson et al. 2010). North–south-trending secondary folds wrinkle the monocline along the San Juan Arm and include, from east to west, the Halgaito anticline, Cedar Mesa anticline, Slick Horn anticline, Moonlight syncline, North Organ Rock anticline, and South Organ Rock anticline (Anderson et al. 2010).

Laramide deformation also produced the Kaiparowits and Henry Mountains basins. The axis of the Henry Mountains basin trends north-northwest between the Henry Mountains and the Circle Cliffs, and the southeastern part of the basin lies within the north-central section of Glen Canyon National Recreation Area. The steeply dipping Waterpocket Fold forms the western limb of the basin (Anderson et al. 2010).

North of Bullfrog Bay, the relatively small, northwest-trending Mule Creek anticline lies between the axis of the Henry Mountains basin and the Rock Spring syncline (Anderson et al. 2010). In the recreation area, the Salt Wash Member (**Jms**) of the Jurassic Morrison Formation forms the crest of the anticline, indicating that deformation occurred after Late Jurassic time. North of Bullfrog Bay, the axes of the Mule Creek anticline and the Rock Spring syncline merge with the central axis of the Henry Mountains basin, which proceeds to curve to the southwest, eventually merging with the axis of the Circle Cliffs anticline (see geologic map posters [in pocket]).

Several northwest-trending anticlines and synclines deform the Kaiparowits basin, which extends into the southern part of Glen Canyon National Recreation Area. From Fiftymile Mountain southwest to Marble Canyon, these folds include:

- Fiftymile Creek syncline
- Bridge anticline
- Hurricane Wash syncline
- Willow Tank anticline
- Lake Creek syncline

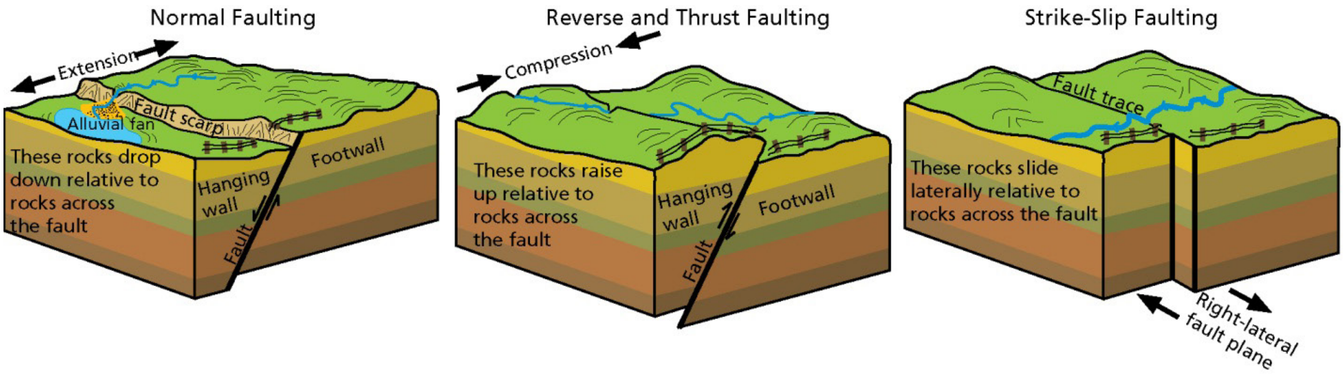

Figure 24. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, such as those associated with the Waterpocket Fold, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. Reverse faults are associated with deeply buried Precambrian basement rocks beneath Glen Canyon National Recreation Area. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

- Rock Creek anticline
- Croton Canyon syncline
- Rees Canyon anticline
- Last Chance Creek syncline
- Smoky Mountain anticline
- Warm Creek syncline
- Nipple Bench anticline
- Wahweap syncline
- Cedar Mountain anticline

These secondary folds developed over reverse-faulted (compressional setting) (fig. 24), deeply buried Precambrian basement rocks (Anderson et al. 2010). The folds extend for tens of kilometers (miles). Minor, high-angled normal faults (extensional setting) (fig. 24) with less than 30 m (100 ft) of displacement parallel the axes of some anticlines (Anderson et al. 2010). The strata have dropped down on the west side of the fault relative to the east side.

Folds and faults create geologic structures that can trap oil, gas, or groundwater. According to Anderson et al. (2010), several unsuccessful oil exploration wells were drilled on the Mule Creek anticline and the secondary folds in the Kaiparowits basin. Folds and faults can also weaken the strata, which may then be more easily exploited by natural erosion or human activity. In 1880, Mormons took advantage of the weak, fractured rock in the Hole-in-the-Rock fault zone and built a primitive road through the canyon wall that dropped almost 600 m (2,000 ft) to the Colorado River (Anderson et al. 2010).

Joints

Joints are fractures or breaks in bedrock surfaces, but unlike faults, they do not displace rock strata. Large joint sets, especially in the sandstones of the Wingate Sandstone (**JTRw**), Kayenta Formation (**Jk**), and Navajo Sandstone (**Jn**), are some of the more prominent features in Glen Canyon National Recreation Area. More than 4,100 joints are mapped in the GRI GIS data. Joint spacing depends on bed thickness and lithology, and in some areas, such as in the Navajo Sandstone south of Glen Canyon dam, the joints are closely spaced.

Three types of joints occur in Glen Canyon National Recreation Area: (1) near-vertical, (2) inclined, and (3) surficial (Anderson et al. 2010). Near-vertical and inclined joints were partly responsible for the development of slot canyons, rockfalls, and many natural arches in the recreation area. Many joints parallel the vertical canyon walls. Processes responsible for the near-vertical and inclined joints in these brittle sandstones include: (1) regional deformation of the Colorado Plateau during the Laramide Orogeny, (2) regional uplift throughout the Cenozoic Era that led to the removal of thousands of feet of overlying rock by erosion, and (3) local stresses such as laccolith intrusions (Anderson et al. 2010).

Surficial joints, also known as exfoliation or sheeting joints, form concentric, sheet-like layers that are roughly parallel to the surface topography. The origin of exfoliation joints has fascinated geologists for more than a century. Dense bedrock forms under great pressure deep within the Earth, and perhaps the most widely held hypothesis, included in textbooks for decades, suggests that exfoliation joints form when this confining pressure is released by erosion of overlying rock and sediment (Anderson et al. 2010). Another popular explanation for local surficial fractures involves the vertical grooves in Checkerboard Mesa, one of the "classic geologic sites" in Zion National Park. These shallow fractures may have formed as a result of freeze-thaw weathering where water in grooves freezes and expands in winter and thaws in summer, similar to freeze-thaw processes involved in the formation of natural arches (Biek et al. 2010).

Recent studies have shown, however, that simple relief of confining pressure will not open large fractures in massive rock bodies, such as those in the Navajo Sandstone (Martel 2004, 2006, 2011). Most eroded terrains contain no sheeting joints, and erosion typically does not produce the pull-apart stress perpendicular to Earth's surface required to open such joints. Martel (2006, 2011) explained that surficial joints occur primarily in strong, dense rocks that have convex surfaces and are under strong horizontal compression. Greg Stock, Yosemite National Park geologist, and Allen Glazner, a professor at the University of North Carolina–Chapel Hill, illustrated how horizontal compression could open joints parallel to a convex surface if the curvature was sufficient and horizontal compression overcame both the force of gravity and the strength of the rock (Glazner and Stock 2010).

Questions about surficial joint formation persist, including the nature of their interaction and propagation (Stock et al. 2012), the distances they extend, and their presence in slopes that are now concave (Martel 2006). Regardless of how they form, surficial joints have contributed to the impressive dome-like structures above vertical canyon cliffs in the Navajo Sandstone (Anderson et al. 2010).

Laccoliths

The dome-shaped laccoliths of the Henry Mountains and Navajo Mountain contribute to the dramatic landscape and viewshed surrounding Glen Canyon National Recreation Area (fig. 25). Laccoliths,

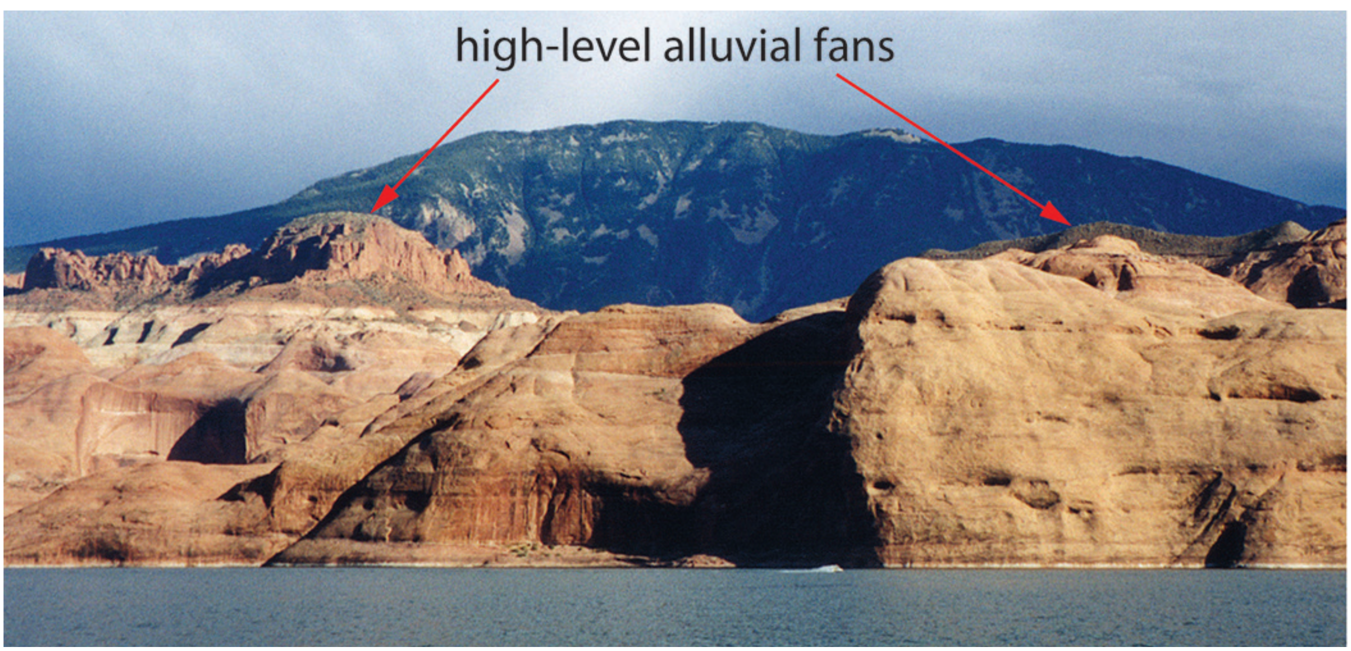

Figure 25. Photograph of Navajo Mountain. The domed shape of Navajo Mountain was caused by an igneous intrusion known as a laccolith. The Carmel and Entrada Formations overlie the cliffs of Navajo Sandstone that rise from lake level. High-level alluvial fans shed off Navajo Mountain cap outcrops of Entrada Sandstone. These fans are about 500,000 years old. Photograph from Anderson et al. (2010, figure 19).

composed of intrusive igneous rock, form when magma is injected between bedding planes, causing the overlying sedimentary rock strata to dome or bow upward (fig. 5). Renowned geologist Grove Karl Gilbert first described laccoliths and designated the Henry Mountains as their "type locality" in 1877 (Gilbert 1877).

Five laccoliths form the five dome-shaped mountains that are collectively known as the Henry Mountains. These mountains include Mounts Ellen, Pennell, Hillers, Holmes, and Ellsworth, and they define the skyline north of Bullfrog and west of the northern part of the recreation area (plate 1). Each mountain consists of a "stock" (an igneous intrusion that cuts through strata) that provided a conduit for the laccolith's magma. In the Henry Mountains, radiometric ages of the exposed igneous rock indicate that the laccoliths formed between 31.2 million and 23.3 million years ago, during the late Oligocene Epoch (Doelling 1975; Hunt 1980; Nelson et al. 1992). Cretaceous formations, exposed on the flanks of the Henry Mountains, are the youngest strata intruded by the magma. In the northern part of Lake Powell, Permian and Triassic formations dip gently west into a subtle syncline oriented parallel to Mounts Ellsworth and Holmes (Anderson et al. 2010).

The broad dome of Navajo Mountain outlines the eastern skyline in southern Glen Canyon National Recreation Area (fig. 25). However, in contrast to the laccoliths in the Henry Mountains and elsewhere on the Colorado Plateau, the igneous rock beneath Navajo Mountain is not exposed at the surface, and so very little is known about the laccolith's formation (Anderson et al. 2010). At 3,166 m (10,388 ft) above sea level, Navajo Mountain is similar in elevation to the Henry Mountains. It has a diameter of 10 km (6 mi). The Cretaceous Dakota Formation, which was deposited approximately 95 million to 100 million years ago, shapes the dome of Navajo Mountain, and like the Henry Mountains, it is the youngest exposed unit deformed by the laccolith (Anderson et al. 2010). The Navajo Mountain laccolith may have been emplaced at the same time as the Henry Mountains laccoliths or it may be age-equivalent to the Carrizo Mountains laccoliths in northeastern Arizona, which formed approximately 71 million to 74 million years ago in the Late Cretaceous (Semken and McIntosh 1997).

Unconsolidated Surficial Deposits

Although best known for the stark beauty of its bedrock landscape, Glen Canyon National Recreation Area contains a variety of unconsolidated surficial deposits dating from the middle Quaternary, about 1 million years ago, to the present (Anderson et al. 2010). The surficial deposits are in seven categories based on their depositional process: (1) alluvium (stream-deposited), (2) eolian (wind deposited), (3) slope movement (mass-wasting), (4) colluvium (water-, wind-, or gravity-deposited), (5) residuum (weathered in place), (6) lacustrine (lake-deposited), and (7) tufa (evaporation).

Alluvium

Thirty-three alluvial and mixed alluvial units are in the GRI GIS data ("**Qa**" units), making alluvial deposits the most diverse group of surficial deposits in the recreation area (table 1). Anderson et al. (2010) categorized these deposits into three general types: (1) alluvium deposited by the large rivers, (2) alluvium deposited by local streams and washes, and (3) alluvial fans deposited at the mouths of washes and canyons and on large pediment-like benches (gently sloping bedrock surfaces at the base of mountains). The Unconsolidated Map Unit Properties Table (in pocket) contains a detailed description of all 33 units.

Clasts in the large river alluvium run the gamut of sizes from clay to large boulders (fig. 26). Constant grinding and knocking into one another resulted in well-sorted

Figure 26. Photograph of clasts of river alluvium south of Antelope Island. The clasts consist of a variety of rock types, including quartzite, chert, metamorphic, and volcanic rocks. Photograph from Anderson et al. (2010, figure 18).

and well-rounded cobbles and pebbles. Some of the cobbles transported by the Colorado and San Juan rivers have their origins in Precambrian and Paleozoic rocks exposed in central and western Colorado, more than 240 km (150 mi) away (Anderson et al. 2010). These clasts are a mixture of all three general rock types: sedimentary, igneous, and metamorphic.

In contrast to the clasts found in large rivers, the clasts common along small streams and washes were locally derived, angular, and more poorly sorted because transport distance and transport velocity was less than in the Colorado and San Juan rivers. The boulders and cobbles consist of fragments of local sandstone, siltstone, and other rock types found in the recreation area. Volcanic and quartzite clasts derived from the high plateaus to the west are part of the alluvium in washes in the western part of the recreation area (Anderson et al. 2010).

Alluvial fan deposits reflect a decrease in stream gradient and range in size from small fans at the mouths of small washes to large coalesced fans and fan remnants found on benches and mesas associated with the Henry Mountains, Navajo Mountain, the Kaiparowits Plateau, and other mesas in the area (fig. 25). Clasts in the alluvial fans are generally poorly sorted and may contain large boulders transported by debris flows from intense summer afternoon thunderstorms (Anderson et al. 2010).

Alluvial deposits in Glen Canyon National Recreation Area are found in active channels and as erosional remnants (terraces) as much as 490 m (1,600 ft) above modern river level (Hunt 1969; Willis 2004, 2010a, 2010b). These erosional remnants represent past river levels that were abandoned when the Colorado River and its tributaries vertically incised bedrock (fig. 27). Anderson et al. (2010) summarized the various methods that have been used to date these river terraces in order to calculate incision rates of the Colorado River and its tributaries (tables 1 and 2 in Willis and Ehler, in prep.). In central Glen Canyon National Recreation Area, the Colorado River incised bedrock at a rate of over 0.6 m (2 ft) per thousand years, which is one of the highest incision rates in any part of the Colorado River system. Between 500,000 and 250,000 years ago, the incision rate was 0.40 m (1.3 ft) per thousand years, and from 250,000 years ago to the present, the incision rate has been 0.70 m (2.3 ft) per thousand years (Garvin et al. 2005). These incision rates suggest that most of the canyon visible today was carved in the last one million years. This exceptionally high incision rate may have been aided by isostatic rebound (crustal unloading) following the rapid erosion of relatively nonresistant strata when the Grand Canyon was carved about 5.5 million years ago (Pederson 2009; Lucchitta 1989).

Figure 27. Photograph of river-cut terrace near Oak Canyon, Glen Canyon National Recreation Area. Alluvial cobbles carried in by the Colorado and San Juan rivers and large boulders derived from old, high-level alluvial fans associated with Navajo Mountain cover this terrace. Photograph from Anderson et al. (2010, figure 20).

Features in Holocene alluvium (**Qal1**) include small-scale trough cross-bedding, climbing ripple laminations, and imbricated cobbles. Similar features are found in terrestrial bedrock strata, indicating that the same fluvial processes acting today have occurred throughout geologic time. Holocene flooding has deposited human-made debris up to 12 m (40 ft) above the modern river (Willis and Ehler, in preparation). If preserved in the rock record, these deposits will indicate the flow paths the rivers took on their way to the sea.

Eolian Deposits

Wind-blown sand (**Qes**), primarily derived from the easily weathered sand dunes preserved in the Navajo and Entrada Sandstones, accumulates in wind shadows and areas not affected by runoff during intense thunderstorms (Anderson et al. 2010). The deposits generally consist of well-sorted, rounded, fine- to medium-grained quartz sand (table 1). Eolian sand is also found associated with alluvial deposits (**Qae**, **Qaeo**, **Qaec**, **Qea**, **Qeao**). Wind-blown silt (loess) and clay commonly form dark-reddish-brown deposits found at higher elevations on the Kaiparowits Plateau.

Water may leach wind-blown calcium-carbonate dust into the subsurface where it can accumulate to form caliche (calcic soil) deposits. These deposits are known as "hardpan," a calcium-carbonate layer that ranges from a few inches to several feet thick (Anderson et al. 2010). Because caliche takes time to accumulate, it can be a valuable age indicator (Birkeland et al. 1991).

Slope Movement (Mass-Wasting) Deposits

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, debris flows, and avalanches are common types of slope movements. These processes and the resultant deposits are also known as "mass wasting" and commonly grouped as "landslides" (table 1). Slope movements occur on time scales ranging from seconds to years, and most landslides continue to move, or have the potential to move, long after they are considered to be stable (Ashland 2003). The landslides in the recreation area record an ongoing process that has been active since the late Pleistocene (Willis and Ehler, in preparation). As is the case in many other parks, slope movements create geologic hazards and associated risks in Glen Canyon National Recreation Area. These hazards are addressed in the "Geologic Resource Management Issues" chapter of this report.

Landslides are common in the Triassic Chinle Formation (**TRc**), Triassic-Jurassic Wingate Sandstone (**JTRw**), and the Cretaceous Tropic Shale (**Kt**), but they also occur in the Morrison (**Jm**), Carmel (**Jc**), Kayenta (**Jk**), Moenkopi (**TRm**), Organ Rock (**Po**), Honaker Trail (**PNht**), and Paradox (**PNp**) Formations. The categories of slope movement deposits mapped in the Glen Canyon National Recreation Area include:

- Landslide and slump deposits (**Qms**): chaotic, extremely poorly sorted, massive blocks to clay-size material, some with obvious historic movement (**Qmsh**).
- Slump blocks (**Qmsb**): blocks that may be as much as 2.7 km (1.5 mi) long and typically rotate backwards and tilt toward the nearby cliff. The most common slump blocks are those of Wingate Sandstone that have slid onto the Chinle Formation.
- Talus deposits (**Qmt**): extremely poorly sorted, angular rubble deposited at the base of steep slopes. Some piles have an eolian sand mantle (**Qmte**).

The massive landslides and slumps that involve the Chinle Formation and the Wingate Sandstone are considered to be "classic geologic sites" by Anderson et al. (2010). Although the cliff-forming Shinarump Conglomerate Member (**TRcs**) of the Chinle Formation produces few landslides, the variegated claystones in the Monitor Butte Member (**TRcmn**) and Petrified Forest Member (**TRcop**, **TRcu**) trigger enormous landslides. These units contain abundant bentonite, a clay composed primarily of the mineral montmorillonite. Montmorillonite is one of the smectite group of minerals that form by the chemical alteration of volcanic ash in contact with water. The resulting chemical structure of smectitic minerals allows them to expand with the absorption of water and shrink upon desiccation, resulting in unstable slopes that give rise to abundant landslides.

The stratigraphic juxtaposition of the highly erodible Chinle Formation below the cliff-forming Wingate Sandstone contributes to spectacular rockfalls and landslides. Erosion of the weaker Chinle Formation undercuts the Wingate Sandstone, and as a result of the lack of support, huge blocks detach from the cliff. The detached blocks may be quite large, up to several hundred meters across. Abundant vertical joints in the Wingate Sandstone help define the rock slabs that detach from the cliffs. Landslide deposits in the Chinle Formation often result in fresh landslide scarps and hummocky topography with blocks of Wingate Sandstone resting on the Chinle slopes (fig. 28). Extensive landslide deposits may be found in the Good Hope Bay area, the San Juan Arm, and at The Rincon (Anderson et al. 2010).

According to Anderson et al. (2010), mass wasting has significantly increased along the Lake Powell shoreline as a result of three interrelated processes: (1) destabilization of clay minerals by water that constantly soaks deep into the bedrock, (2) dissolution of mineral cements, and (3) erosion of less resistant rocks by constant wave action, resulting in undercutting and destabilizing overlying cliffs and ledges. Landslides, rockfalls, and slumps (**Qms**) are especially common nearly everywhere the Chinle Formation is exposed above or just below the water line of Lake Powell (fig. 29). Lake water destabilizes the bentonite-rich members of the Chinle Formation. Spring runoff and water releases associated with power generation cause fluctuations in lake levels, which aggravate an already unstable position along the shoreline.

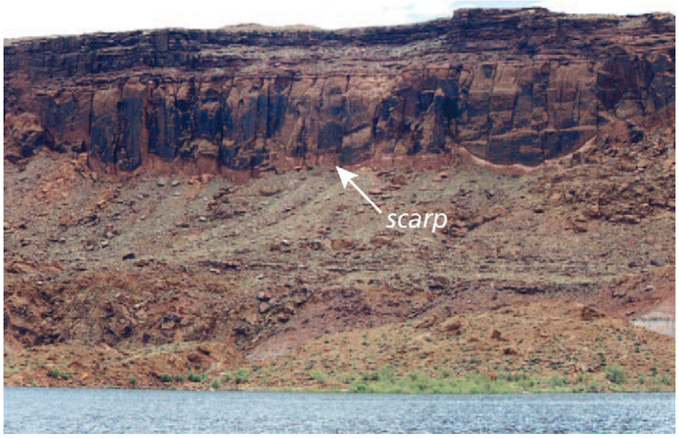

Figure 28. Photograph of landslide scarp along the east shore of Good Hope Bay, Glen Canyon National Recreation Area. The landslide developed in the Chinle Formation, and 6–9 m (20–30 ft) of downward movement exposed a fresh surface (no desert varnish) of Wingate Sandstone. The talus blocks that mantle the Chinle slope are Wingate Sandstone and are not involved in the development of the landslide (they are just "along for the ride") (Tyler Knudsen, Utah Geological Survey, geologist, written communication, 5 December 2015). Note the vertical jointing in the Wingate Sandstone. Photograph from Anderson et al. (2010, figure 13).

Figure 29. Photograph of cliff along the west shore between Twomile and Fourmile Canyons, Glen Canyon National Recreation Area. Erosion of the Chinle Formation (dark brown) undercuts the Wingate Sandstone, resulting in cliff collapse (note large boulders along water's edge). Photograph from Anderson et al. (2010, figure 12).

Mass wasting due to undercutting of overlying cliff- and ledge-forming units also occurs where the Straight Cliffs Formation (**Ks**) overlies the bentonite-rich claystones, mudstones, and shale in the Tropic Shale (**Kt**). Water percolates along joints to the base of the resistant sandstone where it perches on less porous clay and silt layers. The trapped water weakens cement, decreases friction, increases the load on the rocks, and can eventually cause bedrock to fail and slide down slope (Anderson et al. 2010).

In addition to triggering landslides, erosion in the Tropic Shale impacts paleontological resources (see "Paleontological Resource Inventory, Monitoring, and Protection" section). As of December 2016, monitoring protocols for measuring erosion in the Tropic Shale were being developed. In the interim, average erosion rates from available, albeit flawed, data range from 0.14 cm/yr (0.06 in/yr) to 0.26 cm/yr (0.10 in/yr), which are relatively rapid compared with other units on the Colorado Plateau (Miller no date; available from John Spence, written communication, 9 December 2015). These erosion rates, which Miller considers to be conservative, suggest that 1.0 m (3.3 ft) of Tropic Shale will erode within either 715 years or 385 years. Large landslides of Tropic Shale scar the outcrops along the Straight Cliffs section of the Fiftymile Mountain escarpment (Anderson et al. 2010).

Talus deposits (**Qmt**) are mapped in the Hite Crossing, Bullfrog, Lees Ferry, and San Juan Canyon areas, but they also occur in other areas (Willis and Ehler, in preparation). Eolian sand (**Qmte**) that mantles some talus deposits may be as much as 9 m (30 ft) thick.

Colluvium

Colluvium consists of a mixture of unconsolidated sediments derived from alluvial, eolian, minor mass-wasting, and residual deposits (Anderson et al. 2010). Colluvium accumulates on moderate slopes in Glen Canyon National Recreation Area and is mapped with alluvial deposits (**Qac**, **Qaco**, **Qaec**).

Residuum

Residuum consists of rock debris and sediment formed by weathering and essentially left in place after all but the least soluble constituents have been removed. Because sandstone is the most common rock type in Glen Canyon National Recreation Area, residuum primarily consists of sand weathered from these exposures. The residuum sand deposits often resemble wind-blown sand piles. Residuum is not mapped as a separate unit in the GRI GIS data for Glen Canyon National Recreation Area.

Lacustrine Deposits

Lake deposits (**Ql**) in Glen Canyon National Recreation Area consist of thin, poorly consolidated silt, very fine-grained sand, peat, and clay (table 1). They are estimated to be as much as 10 m (30 ft) thick, but could be thicker. Middle Pleistocene lake deposits occur in an abandoned meander channel of the Colorado River in the Good Hope Bay area (Willis and Ehler, in preparation).

Unusually thick lake deposits consisting of sand, silt, clay, and peat in Lake Canyon near Halls Crossing resulted from a lake called Pagahrit by the Piute Indians (Lyman 1963). The deposit records several lake cycles, with the oldest cycle dated at 5,180 radiocarbon years before present (Graf 1989; Pederson 2000). Lake Pagahrit formed behind a natural dam as much as 30 m (100 ft) high consisting of cottonwood, black willow, sand, and other debris flow deposits. The natural dam also served as a bridge until it was breached by an intense cloudburst in CE 1915 (Lyman 1963).

Tufa Deposits

Tufa is a chemical sedimentary rock composed of calcium carbonate and formed by evaporation. In Glen Canyon National Recreation Area, calcareous tufa (**Qst**) is associated with seeps and springs (table 1). The tufa cements bedrock and talus rubble, colluvium, and other surficial deposits. Tufa found below seeps and springs in many canyons in the recreation area may be 1–2 m (3–6 ft) thick. Extensive deposits of tufa are mapped in a small area in lower Red Canyon.

Questions remain to be answered regarding the age of the tufa deposits, the rate at which they formed, the effect of climate on the rate of tufa formation, and their potential to cover fossil resources (Kirkland et al. 2010). Kirkland et al. (2010) suggest that tufa deposits may also represent future fossil localities because the deposits contain plant and possibly animal remains.

Hite Delta Geomorphic Features

When Lake Powell reached full capacity in 1980, a delta immediately began forming in the lower reaches of Cataract Canyon, near the old town of Hite. The Hite delta grew rapidly because of the abundant sediment load of the Colorado River, which averaged ~24.7 x 10^6 m^3/year (~20,000 acre feet/year), and the narrowness of Cataract Canyon (Netoff et al. 2010).

Delta growth accelerated during the drought of 2000–2005. Lake Powell lowered by more than 40 m (131 ft) and large volumes of delta sediment were remobilized in addition to the normal load of sediment from the Colorado and Dirty Devil rivers. Incision by the Colorado River exceeded 10 m (30 ft) (Netoff et al. 2005, 2010). From 1999 to 2005, the delta advanced at a rate of almost 2.7 km/yr (1.7 mi/yr), growing to 60 km (37 mi) long and extending almost to the mouth of White Canyon, ~6 km (3.7 mi) below the Hite marina.

Near-normal runoff returned in 2006, and by 2011, lake levels had risen by ~15 m (~50 ft) and again inundated much of the Hite delta (Netoff et al. 2010; Lake Powell Water Database 2016). Since 2011, average yearly lake levels have fallen by ~11 m (~37 ft). As of January 20, 2016, the shoreline of Lake Powell was 14 m (47 ft) below the former Hite marina (Lake Powell Water Database 2016).

Exposure of the Hite delta offered researchers an opportunity to study the evolution of fluvial and lacustrine features and processes that are either rarely exposed or result from a non-seismic origin. Features include fluid/gas escape features (domes, mud volcanoes, and pockmarks), slumps and lateral spreads, and polygonal joint patterns (Netoff et al. 2010). These dynamic bio-geomorphic features and their transformations have analogs in marine sedimentary deposits, methane-dependent life forms, and methane contributions to global warming.

Domes, Mud Volcanoes, and Pockmarks

When lake levels started dropping in 2000, hundreds of closely-spaced, meter-decameter diameter domes were observed in the shallowing water. The domes had summit depressions from which a mixture of water, methane gas, and suspended sediment erupted. Rapid entrenchment of the Hite delta by the Colorado River exposed the domes, and many of them remained active, erupting muddy slurry that transformed the domes into steeper-sided cones known as mud volcanoes (fig. 30; Netoff et al. 2005, 2010). As their name suggests, mud volcanoes are surficial, volcano-shaped features that eject mud or silt (instead of lava) from a central vent (Dionne 1973; Reineck and Singh 1980).

By December 2004, many of the volcanoes had collapsed, leaving shallow depressions on the surface of the Hite delta (fig. 31). The pockmarks ranged in size

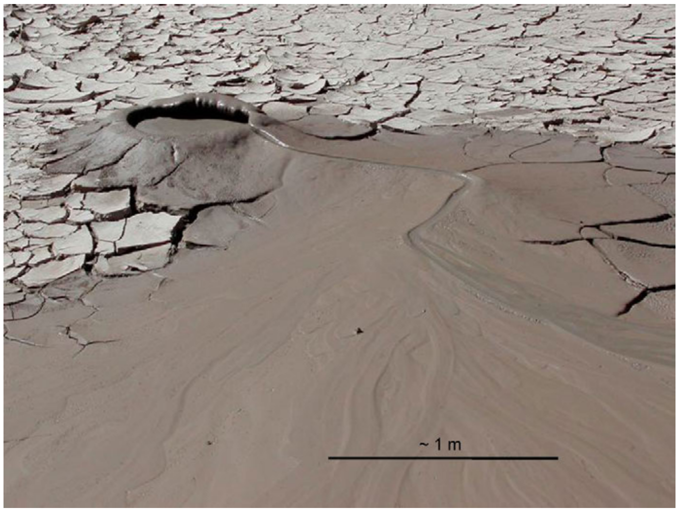

Figure 30. Photograph of a mud volcano on the Hite delta, Glen Canyon National Recreation Area. Viscous, muddy sediment erupts long after subaerial exposure. Radial cracks form on the flanks of the mud volcano, probably from desiccation. Photograph from Netoff et al. (2010, figure 11). Used with permission from Utah Geological Association.

Figure 31. Photograph of a collapsed mud volcano on the Hite delta, Glen Canyon National Recreation Area. Many of the collapsed mud domes and mud volcanoes remained active following subaerial exposure, emitting clear gasses and fluids or a turbulent slurry. Radial joints formed, which may be a result of desiccation or stresses related to collapse. Photograph from Netoff et al. (2010, figure 12). Used with permission from Utah Geological Association.

from 0.5 m (1.6 ft) to 7 m (23 ft) in diameter and 0.1 m (0.3 ft) to 0.5 m (1.6 ft) deep (Netoff et al. 2005, 2010; Livingston et al. 2014). Some of them remained active, emitting clear gases and fluids or a turbulent mixture of gases, fluids, and sediment. Once exposed, the viscosity of the extruded muds increased, resulting in the transformation of domes to mud volcanoes.

Lateral Spreads and Slumps

Incision by the Colorado and Dirty Devil rivers caused slumping and lateral spreading in the delta sediments. The slump blocks associated with the Colorado River are broadly arcuate, sub-parallel, and slightly tilted backward (Netoff et al. 2010). Direction of slumping has been towards the incised channel. The slump scarps range from 1 m (3 ft) to 5 m (16 ft) high and from 300 m (984 ft) to 530 m (1,739 ft) long. A nested series of semi-circular, concentric scarps extends up the Dirty Devil delta beginning about 200 m (656 ft) from the mouth of the Dirty Devil River. The scarps extend up-stream for over 525 m (1,722 ft) (Netoff et al. 2010). The slight back-tilting and back-stepping of the slumps, combined with the drawdowns and incision of the Colorado River, suggest that the curved rupture surfaces become nearly horizontal (listric) at a relatively shallow depth.

Away from the incised channel, the slumps transform into lateral spreads on the Hite delta. The rupture surface and movement associated with lateral spreads is essentially horizontal (Netoff et al. 2010). Horizontal separation ranges from just a few meters to as much as 40 m (131 ft). Surface ruptures resulting from slumping or lateral spreading do not appear to be related to domes and mud volcanoes.

Polygonal Joint Patterns

When lake levels dropped and the clay-rich delta beds were exposed, desiccation and shrinkage of the clays resulted in orthogonal, hexagonal, and radial joint patterns on the delta surface. Orthogonal joints (joints intersecting at right angles) dominate the joint patterns and are 5–15 cm (2–6 in) wide and can be over 0.7 m (2.3 ft) deep, indicating the clay-rich beds lost a large amount of volume during joint formation (Netoff et al. 2010). Columns bordered by the joints are typically 20–35 cm (8–14 in) across. Hexagonal joint patterns occur locally, but they are often a mix of polygons with anywhere from 4 to 7 sides.

Mud volcanoes and pockmarks are dominated by radial joint patterns, which may be connected by orthogonal joints (fig. 31). Some radial joints formed prior to collapse, while others may have formed during subsidence and collapse.

Non-Seismic Triggering Mechanisms
Vibrations, especially from large earthquakes, often trigger fluid escape structures, slumps, and lateral spreads. These features in the sedimentary record indicate past or potential future seismic hazards. However, the features on the Hite and Dirty Devil deltas resulted from the release of methanogenic gas, channel incision, and loss of lateral support, rather than from seismic (earthquake) activity. Although several faults cut Permian strata in the vicinity of Hite, offset along these faults is small, and the faults do not cut Quaternary deposits, suggesting that any earthquake activity associated with the faulting was minimal (Netoff et al. 2010). In addition, only a few minor faults have been recorded in the region between 1990 and 2006 (US Geological Survey 2014). Documenting the geomorphic changes of these delta features may help researchers identify similar features in the rock record and to distinguish between seismic and non-seismic origins.

Decaying organic matter buried in the sediment brought in by the Colorado and Dirty Devil rivers produced the methane gas that escaped through the central vents of the domes and mud volcanoes (Netoff et al. 2010; Livingston et al. 2014). Localized conduits probably formed in the delta sediments as fine-grained, low porosity and low permeability clay and mud accumulated on top of the more porous sediments. Increased pore water pressure may have resulted from dewatering of the delta sediments and also from leakage of the Cedar Mesa Sandstone. Pressure gradients resulting from methanogenic decay or organic material, pore water pressure from locally perched water bodies upslope on the delta surface, and underlying and adjacent water-saturated Cedar Mesa Sandstone were enough to fluidize and entrain unconsolidated subsurface silts, clay, and fine-grained sands as the gas escaped to the surface (Netoff et al. 2005).

With subaerial exposure, pore water pressure decreased, causing the domes and mud volcanoes to collapse and leaving pockmarks on the delta surface (Netoff et al. 2010). The porous and permeable Cedar Mesa Sandstone lines the lower portion of Cataract Canyon and the narrow gorge of the Dirty Devil River. When lake levels are high, water seeps into the Cedar Mesa Sandstone. Dewatering of the sandstone when lake levels dropped provided at least some of the water pressure that enabled the exposed mud volcanoes and pockmarks to continue to erupt (Netoff et al. 2010).

Most of the clay minerals deposited on the deltas are derived from the montmorillonite-rich shale and mudstone of such Colorado Plateau units as the Chinle (**TRc**), Morrison (**Jm**), Mancos (**Kmt**), and Tropic (**Kt**) formations (Potter and Drake 1989; Netoff et al. 2010). Shrinkage of the clays upon exposure resulted in the polygonal jointing on the delta surface. The radial joint pattern on domes and mud volcanoes may be strictly desiccation features, or they may have been influenced by stresses created during doming.

Removal of lateral support as the Colorado River entrenched its channel triggered slumping and lateral spreading on the delta. Lateral spreads tend to occur where a somewhat competent surficial unit, in this case the partially dried mud, overlies water-saturated, non-cohesive sediments under hydrostatic pressure, such as the coarser silts and sands that had previously been deposited.

Further research is needed to provide detailed morphological analyses of these features, the subsurface sediments and underground ‘plumbing’ associated with the pockmarks and mud volcanoes, the types of organic matter and microbes involved with the fluid/gas escape structures, the similarity with features associated with seismic events, the potential for Martian analogues, and a comparison with similar features on other deltas, such as the San Juan delta (Netoff et al. 2010). Furthermore, relatively new techniques such as ground penetrating radar (GPR) may be used to identify buried slump blocks and fluid escape conduits as lake levels rise. For example, in 2009 when lake levels rose to cover the Hite Delta and sediments infilled the incised channel, GPR recognized slump blocks, previously exposed topographic profiles, and large vertical fluid escape conduits (Degenhardt et al. 2009). Recognizing the geomorphic character of these modern features provides a guide for interpreting similar features preserved in ancient environments.

Economic Minerals

Tar Sands
Tar sands are a mixture of sand, clay, water, and bitumen, which is a black, syrupy, viscous oil. Tar sands near the surface are extracted from open-pit mines, such as those in northern Canada. Buried tar sands can be mined by injecting super-heated steam or igniting pockets of oxygen gas. Surface tar sands are transported to processing plants where the bitumen is separated

from the sand using vibration and hot water. Subsurface bitumen is usually upgraded to synthetic-grade oil at a refinery.

Utah contains between 19.4 billion and 29.2 billion barrels of oil in tar sands, which is more than any other state in the United States (Bishop and Tripp 1993). For comparison, the much larger tar sand deposits in Alberta, Canada, contain an estimated 1.2 trillion barrels of oil (Huntoon et al. 1999). Most of the tar sands are located in the Uinta basin (northeastern Utah) and in southeastern-central Utah, where tar sands accumulated in three areas: the San Rafael Swell, Circle Cliffs, and Tar Sand Triangle (Bishop and Tripp 1993).

The Tar Sand Triangle in southeastern Utah is the

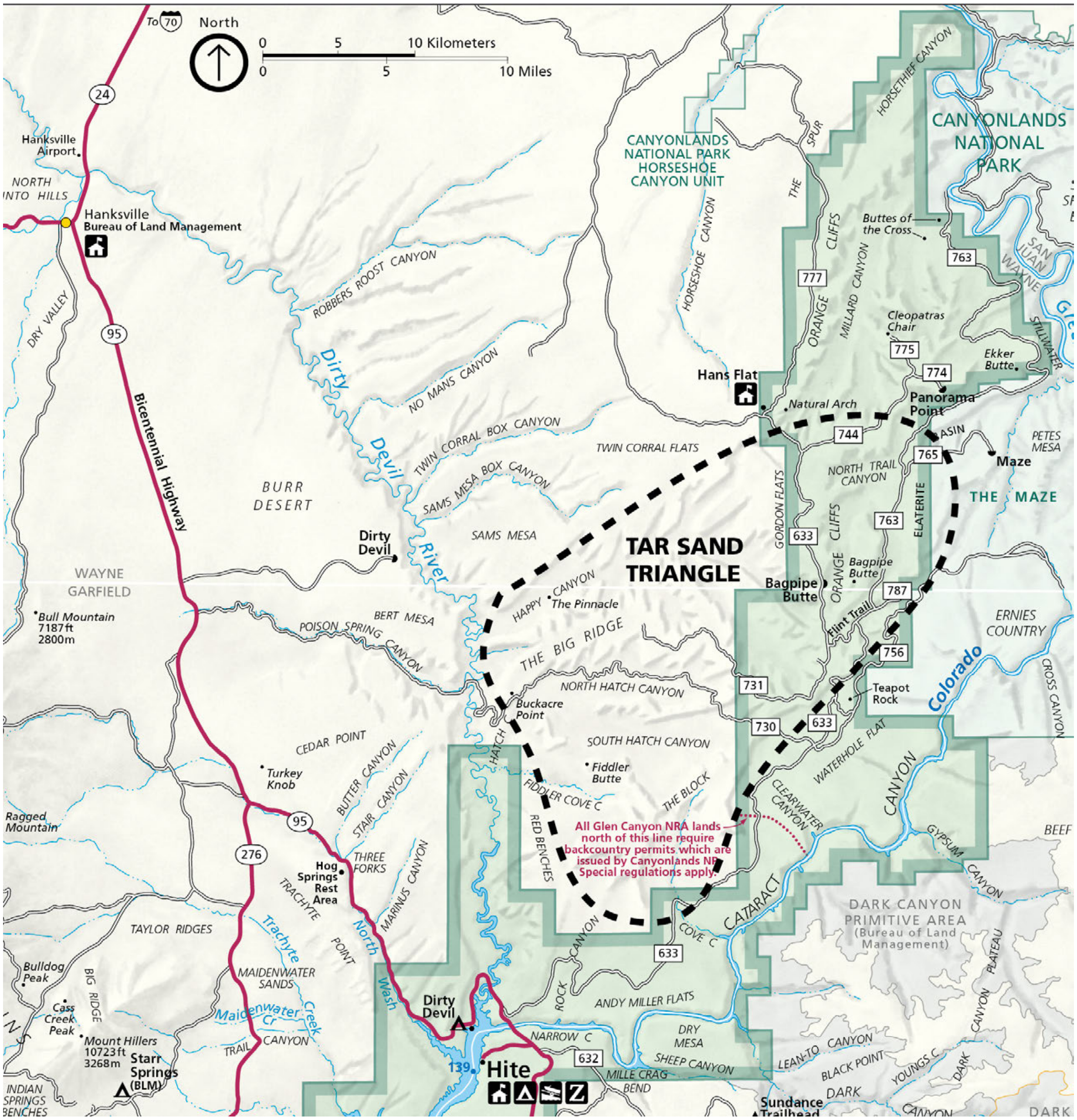

Figure 32. Map showing the location of the Tar Sand Triangle and road access. Road access to the bitumen deposit and the boundaries of Glen Canyon National Recreation Area are also shown. The dashed black line marks the approximate zero pinch-out boundary of bitumen-impregnated sandstones. Unpaved roads provide only limited access to the deposit. Tar Sand Triangle extent from Schamel (2013, figure 3) added to NPS map of Glen Canyon National Recreation Area.

largest known tar sands deposit in the United States and intersects the northeastern portion of Glen Canyon National Recreation Area (fig. 32). The triangle is located on a deeply dissected plateau bounded on three sides by deep canyons formed by the Green River to the northeast, the Colorado River to the southeast, and the Dirty Devil River to the west. Bitumen-saturated sandstone at least 30 m (100 ft) thick covers an area of 218 km^2 (84 mi^2) (Dana et al. 1984; Huntoon et al. 1999; Schamel 2013). A recent rigorous analysis of the Tar Sand Triangle estimated a total of 4.7 billion–5.6 billion barrels of in-place oil in a deposit exceeding 520 km^2 (200 mi^2) in size (Schamel 2013).

Tar sand in the Tar Sand Triangle occurs primarily in the eolian sandstones of the White Rim Sandstone (**Pwr**), although tar sands have also been found in the upper Cedar Mesa Sandstone (**Pcm**) and the sandy basal part of the Moenkopi Formation (**TRml**). Although the White Rim Sandstone is only as much as 26 m (85 ft) thick in the Hite area, it thickens rapidly to over 60 m (200 ft) to the north and northwest. Average porosity (15–20%) and permeability (200–500 millidarcies) values for the White Rim Sandstone are relatively high, but oil saturation averages 30–35%, which is considered to be low (Schamel 2013). Beds in the Tar Sand Triangle gradually tilt to the west-southwest at about 37 m (120 ft) per mile (fig. 33; Huntoon et al. 1999; Schamel 2013).

Processes involved with oil migration into the White Rim Sandstone took advantage of tectonic plate collisions and the stratigraphic relationship between the porous White Rim Sandstone and relatively non-porous overlying strata. The collision of an oceanic plate with the western margin of North American during the Late Jurassic to the Eocene (Sevier and Laramide orogenies) caused west-to-east thrusting that stacked large thrust sheets on top of one another. Prior to tectonic deformation, many of the Pennsylvanian and Permian aquifers were hydrologically connected (Sanford 1995). Thrusting shortened central Utah by about 120 km (190 mi), and the huge thrust sheets may have acted, as Oliver suggested, like "giant squeegees" to hydrodynamically force long-distance oil migration into southeastern Utah (Oliver 1986, p. 99).

Thermal modeling of the White Rim Sandstone's burial history indicates that oil migrated into the Tar Sand Triangle when the unit was at maximum burial depth and temperature, near the end of the Laramide Orogeny approximately 35 million to 40 million years ago (Huntoon et al. 1999; Whidden et al. 2014).

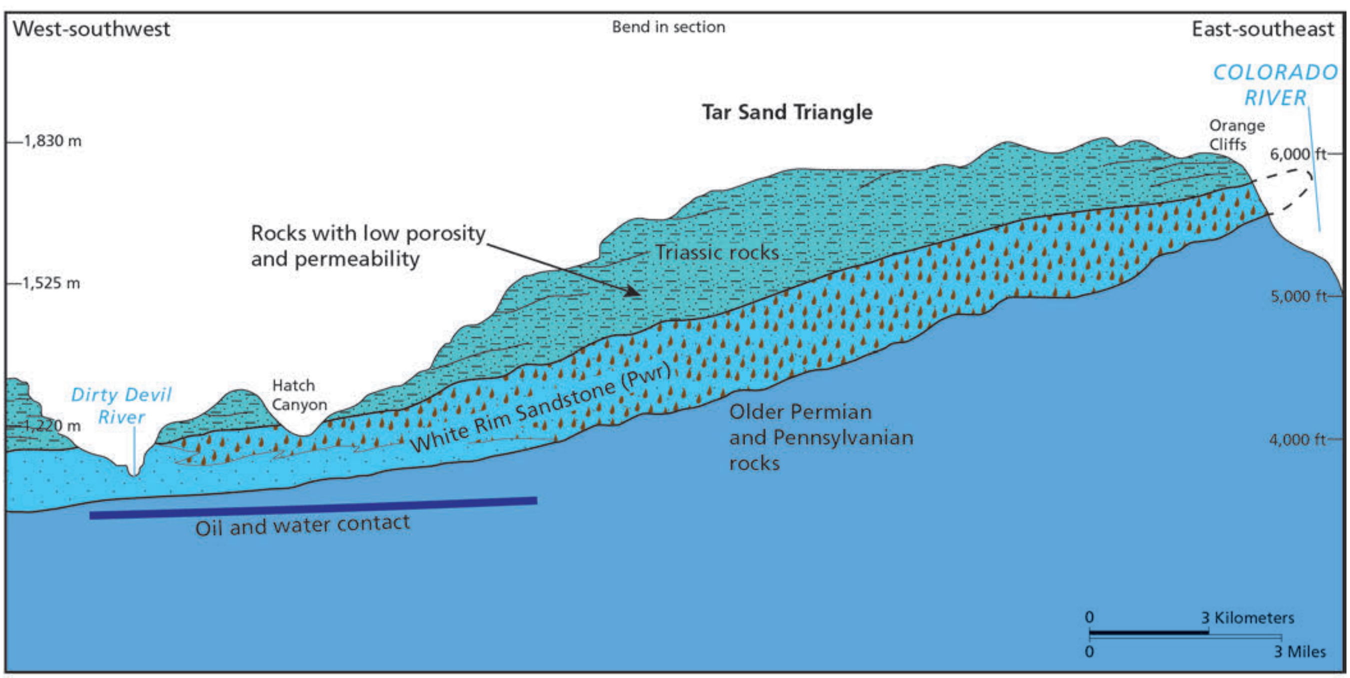

Figure 33. Schematic geologic cross-section through the Tar Sand Triangle. The "drop pattern" represents the thickness of the bitumen deposit in the White Rim Sandstone (Pwr). The blue line marks the oil/water contact. Vertical scales are elevations above mean sea level. Diagram modified from Schamel (2013, figure 5).

Oil migration was aided by vertical faults that offset formations below the White Rim Sandstone and by regional unconformities, which may provide excellent conduits for migrating fluids (Huntoon et al. 1994, 1999). Rocks in contact with Laramide faults on the eastern side of the Paradox Basin are often lighter colored than strata away from the faults. This bleaching effect resulted from migrating reducing fluids, such as petroleum (Breit and Meunier 1990).

Oil migrated into gently dipping, porous sandstones in the Tar Sand Triangle and was trapped by the up-dip unconformable contact with non-porous Triassic strata (Dana et al. 1984; Huntoon et al. 1999; Schamel 2013). Down-dip, the oil floats above an oil-water contact at elevations of 1,280–1,420 m (4,200–4,650 ft) above sea level (fig. 33).

Basin-and-Range faulting in the Miocene Epoch disrupted oil migration by severing and fragmenting the permeable strata and unconformities in western Utah (Huntoon et al. 1999). Uplift of the Colorado Plateau eventually exhumed the White Rim Sandstone. Dead oil (crude oil containing very little dissolved gas) is found in the White Rim Sandstone on both sides of the Colorado and Green rivers in the Canyonlands area, suggesting that migration took place before the Green River dissected the White Rim Sandstone in the Oligocene–Miocene epochs (Gardner 1975; Huntoon et al. 1999).

Neither the direction of migration nor the source of the oil in the White Rim Sandstone is well defined. The black shales in the Paradox Formation (**PNp**) and the Honaker Trail Formation (**PNht**) are the primary source rocks for the Paradox Basin, east of the Tar Sands Triangle (Whidden et al. 2014). To the north, in central Utah, geochemical analyses have identified Permian and Cretaceous oil sources in the Uinta Basin, Sanpete-Sevier Valley area, and the Wasatch Plateau (Sprinkel et al. 1997). Discovered in 2004 after more than 50 years of unsuccessful exploration in the area, the Covenant oil field in north-central Utah produces Pennsylvanian-sourced oil from Navajo Sandstone reservoirs (Chidsey et al. 2007). None of these sources, however, are a geochemical match for the heavy oil found in the White Rim Sandstone. Rather, geochemical analyses suggest that the oil in the Tar Sand Triangle migrated from Mississippian and/or Permian age source rocks found to the distant west and northwest. To reach the tar sands, the oil had to migrate over 100 km (60 mi) eastward (Sandberg and Gutschick 1984; Huntoon et al. 1999; Whidden et al. 2014).

Development of tar sands in southeastern Utah poses a potential resource management issue, which is discussed in the "Abandoned Mineral Lands and Potential Mining Activity" section.

Gold

Much of the river gravel in Glen Canyon National Recreation Area eroded from the mountains of Colorado. Along with gravel, gold was transported downstream from Colorado's many gold deposits. Early prospectors found gold in most gravel bars, but the gold is "flour gold," which occurs as tiny specks about the size of finely sifted flour. Placer gold mines were developed in the region, including in the recreation area, but these very fine gold particles proved very difficult to separate from silt and clay and none of the mines were profitable (Anderson et al. 2010). Currently, gold mining is not a resource management issue for the recreation area.

Uranium

On the Colorado Plateau, uranium occurs in sandstones and conglomerates of the Shinarump Conglomerate Member (**TRcs**) of the Triassic Chinle Formation and in the Jurassic Morrison Formation (Jm). The Morrison Formation is famous for both uranium and dinosaur bones, although only uranium has been found in Glen Canyon National Recreation Area (Anderson et al. 2010). Uranium-bearing fossil logs are present in the Chinle Formation. Past uranium mining has resulted in geologic resource management issues for the recreation area (see the "Geologic Resource Management Issues" chapter).

Coal

Coal beds are found throughout the Colorado Plateau, especially in the Late Cretaceous Straight Cliffs (**Ks**) and Dakota (**Kd**) formations (Anderson et al. 2010). The John Henry Member of the Straight Cliffs Formation (**Ksj**) contains the major coal resources on the Kaiparowits Plateau, northwest of Glen Canyon National Recreation Area (Hettinger 2000; Anderson et al. 2010; Doelling et al. 2010). The Kaiparowits coalfield lies within Grand Staircase-Escalante National Monument, and as of 2010, it contained 60.7% of Utah's estimated recoverable coal (Vanden Berg 2011).

Locally, coal beds in the John Henry Member can be 6 m (20 ft) or more thick.

Coal beds in the Dakota Formation are thinner and discontinuous. Most of the beds occur in the sandstone, mudstone, and bentonitic claystone of the middle unit (Anderson et al. 2010). Coal beds formed in the Dakota Formation during the Late Cretaceous rapid transgression that produced the Western Interior Seaway. Because regression of the seaway occurred more slowly, thick peat beds formed in swamps and lagoons. Upon burial, which was accompanied by heat and pressure, these peat beds became the coal beds of the Straight Cliffs Formation. The Surface Mining Control and Reclamation Act of 1977 (30 USC § 1201 et. seq.) (SMCRA) prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights. See the "Mineral Leasing" and "Coal Mining" sections.

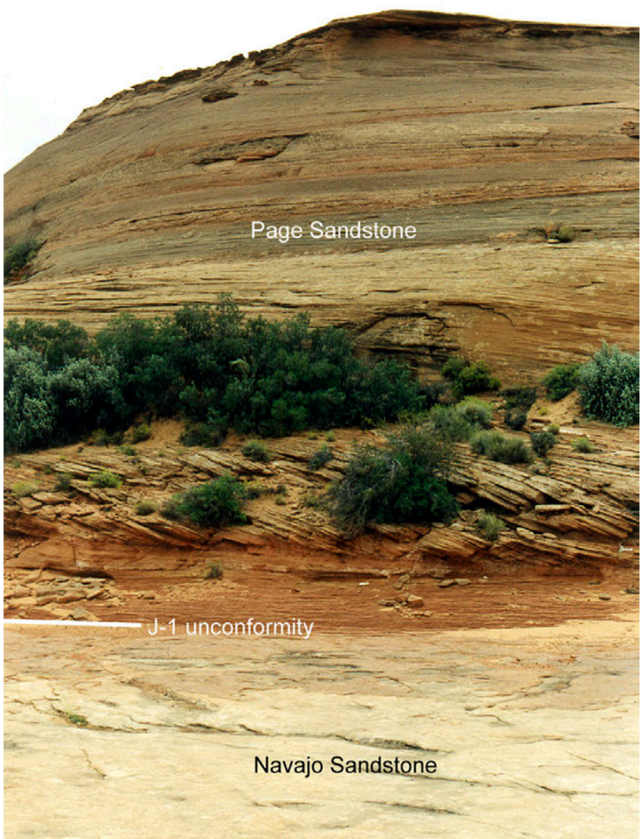

Figure 34. Photograph of the Page Sandstone at its type locality on Manson Mesa, Arizona. The Page Sandstone is separated from the Navajo Sandstone by the J-1 unconformity. Photograph from Anderson et al. (2010, figure 28A).

Geologic Type Sections

A type section is an area where a sequence of strata was originally described. The type section serves as an objective standard with which to compare spatially separated strata (fig. 34). Preferably, a type section is designated in an area where the unit shows maximum thickness and both the top and bottom of the unit are exposed. Designated ("official") and undesignated (a specific location is not designated, but general area is known) type sections of 11 formations occur in Glen Canyon National Recreation Area or its immediate vicinity (table 10). The US Geological Survey "GEOLEX" website provides location information and nomenclatural summaries for geologic map units across the country and is a source of additional information: http://ngmdb.usgs.gov/Geolex/search (accessed 25 August 2015).

Type sections are typically selected for layers of sedimentary rocks which share similar characteristics, such as rock type (e.g., sandstone, shale, siltstone), color, or distinctive features. Such a rock unit is called a "formation." Geologists usually name formations to reflect a geographic feature such as a river, mountain, or city where the layers are best seen (e.g., Wahweap Formation). Formations can be lumped together into "groups" (e.g., Hermosa Group) or subdivided into "members" (e.g., Moss Back Member of Chinle Formation).

Table 10. Designated and unofficial type sections for formations within or in the vicinity of Glen Canyon National Recreation Area.

Period and Epoch	Geologic Unit (map symbol)	Type Location(s)	Official Designation	Reference
Upper Cretaceous	Wahweap Formation (Kw)	Probably named for exposures along Wahweap Creek that drains into Wahweap Bay, northwest of Antelope Island.	No	Gregory and Moore (1931)
Upper Cretaceous	Straight Cliffs Formation (Ks)	Straight Cliffs in Escalante Valley.	Yes	Gregory and Moore (1931)
Upper Jurassic	Romana Sandstone (Jr)	Romana Mesa in the southern part of the recreation area north of The Sand Hills (north side of Lake Powell).	Yes	Peterson (1988)
Middle Jurassic	Page Sandstone (Jpt)	Northwest side of Manson Mesa near Page, AZ (fig. 35). Thins from 90 m (300 ft) at its type section to 27–60 m (90–200 ft) in the recreation area.	Yes	Peterson and Pipiringos (1979)
Lower Jurassic	Navajo Sandstone (Jn)	Named from the "Navajo Country" of AZ, UT, and NM.	Yes	Gregory and Stone (1917)
Lower Permian	White Rim Sandstone (Pwr)	Topographic bench called White Rim, between the Green and Colorado rivers, Canyonlands National Park.	No	Baker (1929)
Lower Permian	Organ Rock Formation (Po)	Natural monument known as Organ Rock, south of the San Juan Arm in San Juan County, UT.	No	Baker (1929)
Lower Permian	Cedar Mesa Sandstone (Pcm)	Cedar Mesa, north of the eastern end of the San Juan Arm.	Yes	Baker (1929)
Lower Permian–Upper Pennsylvanian	Halgaito Formation (PPNhg)	Halgaito Spring, southwest of Mexican Hat.	Yes	Baker (1929)
Upper Pennsylvanian	Elephant Canyon Formation (PPNe)	Elephant Canyon in Canyonlands National Park.	Yes	Baars (1962)
Upper Pennsylvanian	Honaker Trail Formation (PNht)	Honaker Trail, about 0.8 km (0.5 mi) east of the recreation area near the Goosenecks of the San Juan River.	Yes	Wengerd and Matheny (1958)

Refer to US Geological Survey GEOLEX for additional information about type sections: http://ngmdb.usgs.gov/Geolex/search (accessed 21 June 2016).

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 Glen Canyon National Recreation Area. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 1999 scoping meeting (Geologic Resources Division and Natural Resources Information Division 1999) and 2015 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Landscape Safety Hazards
- Slope Movement Hazards and Risk
- Flash Floods and Debris Flows
- Paleontological Resource Inventory, Monitoring, and Protection
- Cave and Alcove Management
- Sediment Deposition in Lake Powell
- Abandoned Mineral Lands and Potential Mining Activity
- Potential Impacts from Global Climate Change
- Earthquakes
- Glen Canyon Dam and Downstream Impacts to the Colorado River
- Navajo Sandstone and Potential Glen Canyon Dam Failure

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these 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, suggested methods of monitoring, and case studies.

The Foundation Document for Glen Canyon National Recreation Area (National Park Service 2014a) identified current conditions and trends, challenges and opportunities, existing data and plans, data or GIS needs, planning needs, and applicable laws, executive orders, regulations, and policies associated with fundamental resources in the recreation area. Those resources are heritage resources, Lake Powell, landscape, paleontology, and water. Information is provided here for geologic resources, many of which contribute to the fundamental resources of the recreation area.

Landscape Safety Hazards

As with any canyon environment, the landscape poses safety hazards for hikers, climbers, and unwary sightseers (fig. 35). In spring 2014, Sarah Doyle, physical scientist at Glen Canyon National Recreation Area, compiled a list of geohazards, primarily from incident reports. Her list included detailed descriptions of each event, whether the incident was natural or human-caused, the rock type associated with the incident, and the date, time, and locality of each incident. Eighteen of the thirty-one reported incidents resulted in fatalities and were caused by rockfalls, landslides, flash floods, rock climbing, slipping on trails, or falls from the cliffs in the Kaibab Formation (**Pk**), Navajo Sandstone (**Jn**), and Salt Wash Member of the Morrison Formation (**Jms**) (Sarah Doyle, Glen Canyon National Recreation Area, physical scientist, written communication, 4 May 2015).

Moqui marbles contribute to potential slipping on trails that traverse the Navajo Sandstone (**Jn**). These iron-coated concretions, for example, are scattered on the friable sandstone surface of the popular Horseshoe Bend Trail (fig. 36). The National Park Service sign at the trailhead advises caution because the rocks may be unstable, the terrain uneven, and the viewpoint has no railing (fig. 35).

The Foundation Document for Glen Canyon National Recreation Area considers identifying landscape hazards and high-risk zones to be a medium priority for the park (National Park Service 2014a). Visitors approach the edge of cliffs in the recreation area to get a better look at the impressive landscape, but unstable conditions may lead to landslides, rockfalls, and other slope movement hazards discussed in the following section.

Figure 35. Photograph of visitors overlooking the popular Horseshoe Bend, Glen Canyon National Recreation Area. Much of the lighter-colored, cross-bedded sandstone that is supporting the darker ledge upon which the photographer is standing has fallen away, and what remains is nearly detached from the cliff face. Some visitors set up tripods on this ledge to get a photograph of the entire meander. Signs at the overlook and the trailhead (inset photos) include warnings to “not stand on the edge” and to “be aware of where you are standing.” Overlook photograph courtesy of Tyler Knudsen, Utah Geological Survey. Sign photographs by Eric Bilderback (NPS Geologic Resources Division) in February 2014.

Slope Movement Hazards and Risk

As described in the “Unconsolidated Surficial Deposits” section, slope processes are common throughout Glen Canyon National Recreation Area (fig. 37). Although they may appear to be inactive, landslides and other slope movements may continue to move by slow creep, may be reactivated, and continue to pose a risk (Ashland 2003). Slumps and slides (**Qms** and **Qmsb**) are common where erosion of less resistant strata oversteepens slopes and undercuts the more resistant sandstone cliffs and ledges (fig. 29). These natural processes become issues when visitors or boaters travel or camp near the base of the cliffs or atop overhanging ledges. Potentially hazardous areas include those with visible cracks, loose material, or overhangs. Fatal rockfalls have occurred where people were standing on ledges that collapsed or were struck by rocks falling from above.

Rockfalls from overhanging alcoves and cliffs may occur without warning, making camping or boating beneath the overhangs potentially dangerous. Slabs of rock have fallen onto boats and caused fatalities in the recreation area.

Figure 36. Photograph of moqui marbles. These lose concretions on the surface of the friable Navajo Sandstone cover the trail to Horseshoe Bend Overlook and may lead to slippery conditions. Squares on scale bar are 1 cm to a side. National Park Service photograph.

Ten of the 16 rockfalls documented by Sarah Doyle occurred in the Navajo Sandstone (**Jn**), including the impressive 1983 rockfall at Rainbow Bridge National Monument (see GRI report by Graham 2009; Sarah Doyle, written communication, 4 May 2015). Rockfalls were also reported from the Chinle Formation (3), Entrada Sandstone (2), Wingate Sandstone (1), Kayenta Formation (1), and Morrison Formation (1).

The Chinle Formation (**TRc**) is especially susceptible to slope movements because of its abundant bentonite content. The shrink-swell property of bentonite produces nearly impassable slippery roads and trails and slippery slopes that easily give way to landslides and slumps.

Hiking on talus landslides (**Qmt**) may be potentially dangerous. Talus deposits may become dangerously unstable during periods of increased precipitation. Water tends to decrease friction and eventually the piles of talus begin to slide down slope.

Figure 37. Photograph of a cloud of dust from a rockfall. This rockfall occurred in the jointed Wingate Sandstone just east of Bald Rock Canyon near the crest of the Circle Cliffs anticline, San Juan Arm, Glen Canyon National Recreation Area. Photograph from Anderson et al. (2010, figure 21).

There are many options that park managers can consider to reduce risk associated with slope movement hazards. One is visitor and staff education regarding the potential risks. Verbal warnings by park rangers, or signs and other written notices posted at visitor centers, trailheads (fig. 35), and/or websites is one option to educate visitors. Another option is limiting access to potentially hazardous sites via fencing, ropes, or other barriers. These options should be assessed by NPS staff with regards to impacts to the natural experience, fiscal limitations, visitor access, and maintenance requirements.

One resource management tool that is expected to be completed in 2016 is a map folio consisting of nine or ten GIS-based geologic-hazard maps (Tyler Knudsen, Utah Geological Survey, geologist, written communication, 5 December 2015). The 1:24,000-scale maps will cover approximately 750 km^2 (290 mi^2) near high-use areas at Wahweap/Lees Ferry and Bullfrog/Hall's Crossing. Each map will cover a different hazard including rockfall, landslides, flooding, faulting, and problematic soils. The mapped hazard will be ranked on a relative high, medium, or low index.

If funding permits, resource managers could consider obtaining quantitative information to assess the frequency and magnitude of rockfall and other slope movements in high visitation areas. A photomonitoring program is one possibility. The Geoscientist-in-the-Parks program (http://go.nps.gov/gip) is an option to support such a project. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of how photographic techniques support structural analysis of rockfall areas.

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (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. Additional information regarding slope movements, monitoring, and mitigation options may be found in Highland and Bobrowsky (2008) and the following websites: the US Geological Survey landslides website(http://landslides.usgs.gov/), the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards), and the NPS slope movement monitoring website (http://go.nps.gov/monitor_slopes).

Flash Floods and Debris Flows

During the summer monsoon season in southern Utah, intense thunderstorms cause flash floods and debris flows. Flash floods are common in this region of the Colorado Plateau because the arid, sparsely vegetated terrain does not have the capacity to absorb abundant precipitation that falls over a short time period. Runoff flows rapidly through the narrow slot canyons carved in the Kayenta Formation (**Jk**) and Navajo Sandstone (**Jn**). Even small storms can turn normally dry arroyos into raging torrents of water and mud in minutes.

Flash floods can transport clasts the size of boulders, along with vegetation and other debris, and these debris flows can quickly overwhelm hikers in slot canyons with little time to escape and no place to go. Fatal flash floods have occurred within the recreation area.

Debris flows may originate kilometers away from the slot canyons in Glen Canyon National Recreation Area. For example, a fatal Antelope Canyon debris flow in 1997 originated from a cloudburst 24 km (15 mi) southeast of the canyon. At the trailhead, the skies were clear. National Park Service staff recommend that hikers seek weather information before hiking the slot canyons in the recreation area. The Glen Canyon National Recreation Area website provides safety information (https://www.nps.gov/glca/planyourvisit/safety.htm) and a podcast about flash floods (https://www.nps.gov/glca/learn/photosmultimedia/podcasts.htm). The Grand Canyon National Park website(http://www.nps.gov/grca/planyourvisit/weather-dangers.htm) provides a list of safety factors regarding hiking safely in canyon country and being aware of flash floods.

Floods can also damage or destroy park infrastructure. On September 12, 2013, flood waters washed out a newly paved road to Lees Ferry (fig. 38). According to park staff, the flood waters deposited a "VW-van-sized rock" in the center of the road (National Park Service 2015f).

Flash floods also shape the landscape of Glen Canyon National Recreation Area. These natural processes form alluvial-fan deposits (**Qaec**) at the mouth of canyons where debris flow velocity dramatically decreases. Clasts in the alluvial fans may be as large as boulders.

Figure 38. Photograph of boulders and mud covering the road to Lees Ferry following the September 2013 flood. Person for scale. National Park Service photograph available at http://www.nps.gov/glca/learn/photosmultimedia/photogallery.htm (accessed 30 April 2015).

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of June 2016, regulations associated with the Act were awaiting surnaming by the National Park Service (Julia Brunner, Policy and Regulatory Specialist, NPS Geologic Resources Division, written communication, 20 June 2016). The fossils of Glen Canyon National Recreation Area are diverse and significant. See "Paleontological Resources" section.

In 2009, Glen Canyon National Recreation Area was selected as the prototype Paleontological Monitoring Park for the National Park Service. According to the Glen Canyon National Recreation Area Foundation Document, approximately 350 paleontology sites have been located, but only about 10% of these sites have condition and trend assessments (National Park Service 2014a). The Foundation Document identified the following challenges:

- Fluctuating lake levels (wetting and drying cycles) that may damage sites.
- Vandalism and illegal collecting, especially petrified wood in the Chinle Formation and fossils in easily accessible sites.
- Lack of staff or funds to survey and monitor sites.
- Effects from climate change, including severe flooding, storms, and accelerated erosion rates.

Fossils associated with the clay-rich Tropic Shale (**Kt**; table 8) have also been impacted by erosion and theft (Miller no date). These fossils are distinct

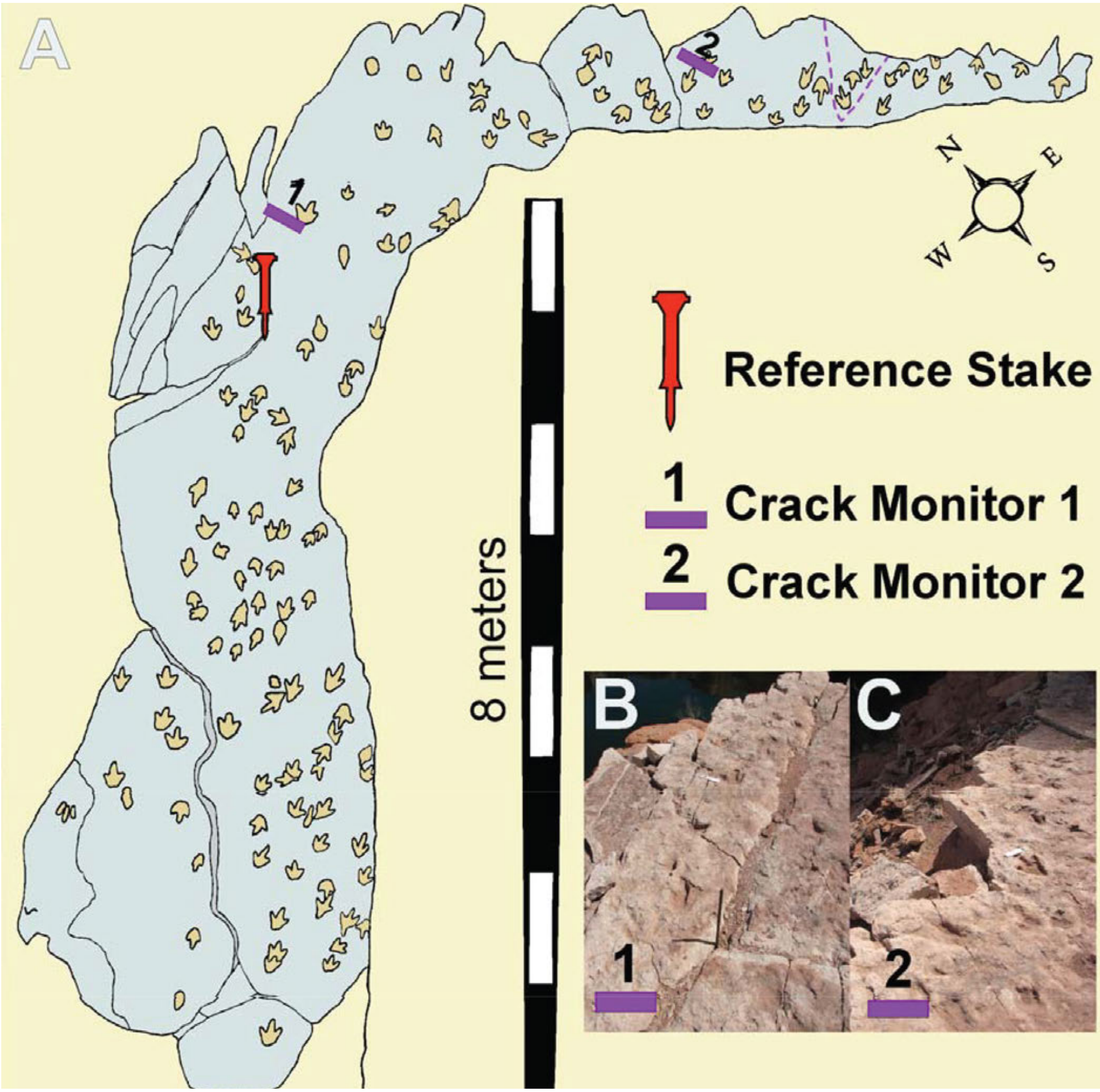

Figure 39. Map of Slick George Dinosaur Tracksite, Glen Canyon National Recreation Area. (A) Distribution of dinosaur tracks showing the position of the reference stake and crack monitors for future site monitoring. (B) Overview of crack monitor 1 looking north. (C) Overview of crack monitor 2 looking east. Diagram and photographs from Kirkland et al. (2010, figure 23).

paleontological resources, offering an insight into the organisms and environment of the Cretaceous Western Interior Seaway. Continued inventory, monitoring, and preservation are critical for maintaining this scientific resource and mitigating damage to these fossils.

Kirkland et al.'s (2010) *Final Report for Paleontological Resources Inventory and Monitoring at Glen Canyon National Recreation Area* recognized seven paleontological sites in Lockley's Cove, an informal name for the recreation area's first identified Paleontological Site Complex (PSC). A PSC is defined as "an area of restricted geographic and temporal extent that preserves an abundance of important fossil localities" (Kirkland et al. 2010, p. 28). Slick George's

Dinosaur Tracksite, an exceptional tracksite within Lockley's Cove PSC, was established as the first official monitoring site in Glen Canyon National Recreation Area (fig. 39). The site is about 8 m (26 ft) below the high waterline on the east side of Lake Powell.

The 2010 report recommended specific monitoring protocol for the site and any future monitoring sites inventoried within the recreation area. This protocol included using NPS locality data forms, developing hard-copy "Paleontological Locality Files," and developing a detailed monitoring database (Kirkland et al. 2010). Since 2010, the following significant developments have been made towards implementing these recommendations (John Spence, written communication, 9 December 2015):

- A GIS-rational database that contains site-specific spatial and scientific baseline data. The site information includes whatever was available and may range from a simple location to more detailed information about monitoring and significance, photos, and any additional information.
- Hard-copy files that include assessment and monitoring forms. These are kept for all sites and include any information based on site visits and monitoring.
- On-going training of personnel who monitor sites.
- Systematic files for many, but not all, paleontological sites. Files on the majority of older sites may contain only basic information, such as location and fossil type.

Santucci et al. (2009) present a guide to collecting and recording monitoring site data, especially important indicators, or "Vital Signs." Kirkland et al. (2010) identified critical data that applied to the following Vital Signs.

- Vital Sign 1—Rates of Natural Erosion I (Geologic Variables). Erosion measurements using calibrated stakes and repeat photography of pre-determined reference points.
- Vital Sign 2—Rates of Natural Erosion II (Climatic Variables). Measuring short- and long-term effects of climatic fluctuations and their impact on fossil resources by noting new cracks or widening of old cracks due to freeze-thaw cycles; new vegetation growing in cracks; encroaching vegetation or roots; proliferation of lichen or algae; spalling of rock; and evidence of secondary mineral encrustation that obscures or obliterates the fossil.
- Vital Sign 3— "Catastrophic" Geologic Processes or Geohazards. Documenting slope movements that may cover or expose fossil sites.
- Vital Sign 4—Hydrology and Bathymetry. Documenting the spatial relationship of fossil sites with lake levels of Lake Powell, groundwater seeps, and wave action. Also, documenting the association of fossil sites with tufa deposits.
- Vital Sign 5—Human Impacts. Monitoring adverse human impacts on fossil resources by recording a fossil site's proximity to roads, trails, shoreline, marines, beaches, fire circles, old anchors, trash, and toilet paper. Also, documenting footprints and trampling, whether by humans or wild or domestic animals. Monitoring vandalism and theft by documenting stacked piles of petrified wood or body fossils and slabs of tracks turned on end.

Many of the fossil localities identified in the recreation area were submerged as lake levels rose. In the course of their research, Kirkland et al. (2010) found a number of new sites. Developing an inventory of fossil sites will be an ongoing process. Each of the documented sites at Glen Canyon National Recreation Area will need to be evaluated to determine the frequency and nature of future monitoring (Kirkland et al. 2010).

As suggested by Kirkland et al. (2010), resource managers may wish to implement protocols previously developed by Milner et al. (2006), Spears et al. (2009), and Santucci et al. (2009). Some of the methods in these references include:

- Repeat photography using recognizable natural or human-made landmarks (e.g., stakes).
- Using stakes (rebar) to provide reference points.
- Developing site-specific data packets for site monitors.
- Careful documentation of field notes and observations.
- Mapping and photogrammetric documentation of select sites (labor intensive and requires special techniques).
- Monitoring cracks in the rock by using clear resin plates following the technique used at Dinosaur National Monument.
- Sampling rocks to determine the effect of water on the rock's minerals, mineral cement, and changes, if any, in the rock's porosity and permeability.

Obviously, developing a detailed inventory and systematically monitoring the paleontological resources at Glen Canyon National Recreation Area will be a substantial undertaking. To develop a proper paleontological database for Glen Canyon National Recreation Area, previous fieldwork conducted by other institutions, such as the Museum of Northern Arizona, Denver Museum of Nature and Science, and the US Geological Survey, should be assembled and checked for duplication or omission of site data, although locating sites from old field data may prove problematic (Kirkland et al. 2010). Hard-copy data need to be maintained in digital form for use in the field. Each identified fossil locality needs to be visited to determine if the site is "at risk" and should be monitored. Protocols, methodology, and schedules for monitoring each site need to be formalized. Paleontological sensitivity maps could be made that include fossiliferous formations and members that are susceptible to chemical weathering, dissolution, spalling, wave action, and human activity.

In addition, Glen Canyon National Recreation Area can support ongoing research and educational opportunities related to paleontological resources (National Park Service 2014a). To survey the expanse of the recreation area, cooperative relationships should be developed with the Utah Geological Survey and other research groups with paleontological expertise. According to the Foundation Document, an interdisciplinary team consisting of personnel from Visitor and Resource Protection, Science and Resource Management, and Interpretation and Education could be assembled to monitor, conserve, and interpret paleontological sites (National Park Service 2014a). A paleontologist position shared among Glen Canyon National Recreation Area, other national parks, and Grand Staircase-Escalante National Monument is one possibility (John Spence, written communication, 9 December 2015).

Cave and Alcove Management

Cave features are non-renewable 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 act 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). A park-specific cave management plan has not yet been completed for Glen Canyon National Recreation Area. Such plans include a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves. The NPS Geologic Resources Division can facilitate the development of such a plan.

The caves and alcoves listed in table 9 contain a diverse assemblage of paleontological and cultural resources that the park currently manages. Research of the thick organic layer in Bechan Cave began in 1983, and it is the only cave from which skeletal evidence of a large mammal was discovered (a tooth from the shrubox *Euceratherium collinum*, see table 9) (Santucci et al. 2001). Oakleaf Alcove was the site of numerous archaeological excavations in the 1960s, but it was submerged under Lake Powell in 2001 (Santucci et al. 2001). Prior to its submergence, Oakleaf Alcove had been vandalized.

In the *Geological Monitoring* chapter about caves and associated landscapes, Toomey (2009) described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers.

Sediment Deposition in Lake Powell

Lake Powell is, of course, one of the fundamental resources in the recreation area (National Park Service 2014a). Reservoirs, however, are temporary and eventually fill with sediment. Abundant sediment enters Lake Powell from the Colorado River, one of the most sediment-laden rivers in North America, and sediment accumulation, along with low water levels, has impacted several locations in the lake. Visitor access to Hite marina, for example, has been lost due to low water levels and the growth of the Hite delta. The absolute minimum usable elevation at the Hite marina is 1,111 m (3,645 ft) above sea level, which has not been reached since 2001 (Lake Powell Water Database 2016).

Climate change models predict higher temperatures, decreased precipitation, and decreased runoff by 10%–30% by 2100 (see "Potential Impacts from Global Climate Change" section; National Park Service 2014a). As lake levels lower, continued sedimentation into the lake will reduce storage in Lake Powell, potentially by 50% by 2021. Currently, silt accumulates behind the dam and fills the reservoir at an average rate of 0.046 km^3 (0.011 mi^3) per year. As lake levels fluctuate and sedimentation eliminates or complicates access to locations within the recreation area, resource managers will need an updated strategy to provide and maintain visitor and commercial access (National Park Service 2014a).

Abandoned Mineral Lands and Potential Mining Activity

Abandoned mineral lands (AML) are 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. The NPS takes action under various authorities to mitigate, reclaim, or restore AML in order to reduce hazards and impacts to resources.

According to the NPS AML database (updated 28 October 2014) and Burghardt et al. (2014), Glen Canyon National Recreation Area contains 99 AML features at 39 sites. Features at the sites include mine adits, waste rock, abandoned oil and gas wells, surface mines, abandoned mining equipment, buildings, and roads. Features that require mitigation are associated with the abandoned Jomac and El Pequito underground mines. As mentioned in the "Uranium Mining" section, high levels of radiation may require additional monitoring and mitigation of some AML features as documented in the database.

Sixteen of the sites are abandoned oil and gas wells. Nine of the sites are associated with the five abandoned underground uranium mines mentioned in the "Uranium Mining" section. Six of the sites are surface mines. The remaining sites include a placer mine, and abandoned access roads.

As Burghardt et al. (2014) discuss, 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 managers at Glen Canyon National Recreation Area inventory and report on the AML features in the park. Data should be recorded in the Servicewide AML Database (the NPS Geologic Resources Division may be able to provide assistance). The NPS AML website, http://go.nps.gov/aml, provides further information.

Mineral Leasing

Generally, units of the National Park System are not open to federal mineral leasing under the Mineral Leasing Act (30 USC § 181 et seq.) and the Mineral Leasing Act for Acquired Lands (30 USC § 351 et seq.). However, Glen Canyon National Recreation Area is one of three units in the National Park System which has specific statutory authority to allow federal mineral leasing. See also NPS Management Policies 2006 § 8.7.2 and Appendix B. The Glen Canyon enabling legislation authorizes the removal of nonleasable or leasable minerals in accordance with BLM regulations at 43 CFR Part 3109.2, only if mineral removal does not have a significant adverse effect on the administration of the unit.

Approximately 32,000 ha (80,000 ac) in Glen Canyon National Recreation Area are designated as the "Special Tar Sands Area (STSA)" (see "Tar Sands Exploration" section).

Uranium Mining

Mining for uranium occurred mostly in the 1950s through 1970s, but only sporadic, small operations were conducted within or near what is now Glen Canyon National Recreation Area. Uranium mine openings at the following four abandoned uranium mine adits have been closed to prevent public access and to reduce health and safety risks: Jomac Mine, Blue Notch, White Canyon, and Whirlwind. In 1992, three adits in the Monitor Butte Member (**TRcmn**) of the Chinle Formation at the Jomac Mine were sealed, but routine monitoring in 2008 discovered the backfill had been breached. Portals to adits were patched and again backfilled (fig. 40). The adits at the Jomac Mine will receive additional attention in 2016 (John Spence, written communication, 9 December 2015). Adits from White Canyon, Blue Notch, and Whirlwind were backfilled in 2002 and 2003.

Waste rock from mining operations at the White Canyon, Blue Notch, and Whirlwind mines do not pose a potential hazard. However, ore piles associated with the abandoned Jomac Mine are considered a high radiation risk and may require remediation.

Removal or encapsulation of the spoils piles has not been done at these abandoned sites because radiation exposure to reclamation crews could be much greater than the inconsequential exposure to occasional visitors passing by the sites. Furthermore, far more contamination would be released into the environment in any type of reclamation attempt than if the piles were left alone in their current condition. Detailed site investigations conducted by the National Park Service in collaboration with US Environmental Protection Agency and the State of Utah on similar abandoned uranium sites in Canyonlands and Capitol Reef National Parks showed that there is virtually no environmental signature of uranium mining much beyond 10 m (30 ft) from the sampled waste rock piles, at which point radionuclide and heavy metals values return to essentially background levels. (John Burghardt and Phil Cloues, Geologic Resources Division, geologists, personal communications 19 April 2005).

In October, 2015, the recreation area finished the evaluation of the El Pequito mine. In 2016, the main entrance of the El Pequito mine will be closed (John Spence, written communication, 9 December 2015).

Coal Mining

In the early 1900s, Charles H. Spencer's American Placer Company began mining for gold near Lees Ferry, and Spencer needed coal to run his equipment. The nearest coal seam was 45 km (28 mi) upstream in Warm Creek. Initially, Spencer built a trail and used mules to haul the coal. Finding mules to be inefficient, Spencer built a 28-m (92-ft) steamboat, named the *Charles H. Spencer*, in 1912. The steamboat used most of the coal it transported, and by the end of 1912, Spencer's investors had pulled out. Spencer left the area and the *Charles H. Spencer* sank to the bottom of the Colorado River. The

Figure 40. Photographs of mitigation work at the Jomac Mine, Glen Canyon National Recreation Area. Top: Native rock and masonry are used to seal the adit. Bottom: Backfill in progress at the mine entrance using the mine's waste rock. National Park Service photographs from Burghardt et al. (2014, figure 11).

steamboat is now on the National Register of Historic Places. The Spencer mine was small, and in 1993, five adits were backfilled (Geologic Resources Division AML database). The Spencer Trail remains today, with its trailhead near the launch ramp for the Colorado River at Lees Ferry.

Unlike other federal minerals (see "Mineral Leasing"), coal leases cannot be issued in Glen Canyon National Recreation Area, or any other area of the National Park System, under the Federal Coal Leasing Amendments Act of 1975 (30 USC § 201). Likewise the Surface Mining Control and Reclamation Act of 1977 (SMCRA; 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. See Appendix B.

Under SMCRA Section 522(e), the NPS also has a role in surface coal mine operations outside park boundaries. If NPS can show that an operation will adversely affect park resources, then the NPS becomes a joint permitting agency with the appropriate lead agency (Office of Surface Mining Reclamation and Enforcement (OSMRE) or state agency). The NPS can then require mitigation measures designed to reduce the impacts to park resources or if mitigation measures cannot be sufficiently designed to avoid those impacts, the NPS can decline to approve the operation's permit. Another alternative is for the NPS and/or other interested parties to petition OSMRE to declare the lands proposed for the surface mine unsuitable for surface coal mining.

Burning Coal Beds

Strata containing coal, such as the coal beds in the John Henry Member of the Straight Cliffs Formation (**Ksj**) and discontinuous seams in the Dakota Sandstone (**Kd**), can spontaneously combust. Participants at the 1999 scoping workshop for Glen Canyon National Recreation Area and Rainbow Bridge National Monument noted that burning coal beds may occur in the recreation area (NPS Geologic Resources Division and Natural Resources Information Division 1999). However, the only burning coal beds in the region occur in Grand Staircase-Escalante National Monument, and they do not impact Glen Canyon National Recreation Area (John Spence, written communication, 9 December 2015).

Oil and Gas Exploration

The National Park Service works with adjacent land managers and other permitting entities to help ensure that National Park System resources and values are not adversely impacted by external mineral exploration and development. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction 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. The NPS Geologic Resources Division Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information.

In 1969, a petroleum exploration company acquired the rights to explore for petroleum on 3,940 ha (9.730 ac) in southern Utah. At that time, the BLM administered the land. Some of this land is now part of either Glen Canyon National Recreation Area or Capitol Reef National Park. In 1990, the company submitted an application to drill an exploratory well in the Circle Cliffs area in Glen Canyon National Recreation Area. Exploratory wells had previously been drilled on the Circle Cliffs in 1921 and 1947. Those wells were eventually plugged and abandoned. The company's lease expired in 2007 prior to any drilling (National Park Service 2015g).

Most of the oil and gas in Utah is concentrated in Duchesne and Uintah Counties in the north and San Juan County in the south (Vanden Berg 2011). San Juan County produces 15.8% of Utah's crude oil, primarily from the Greater Aneth oil field in the southeastern corner of Utah approximately 65 km (41 mi) from the eastern end of the San Juan Arm. The Greater Aneth oil field, discovered in 1956, is a giant oil field that originally contained an estimated 1.5 billion barrels of oil in place. As of 2012, 430 million barrels of oil had been produced primarily from the shallow marine limestone and dolomite in the Pennsylvanian Paradox Formation (**PNp**). This volume accounts for about 30% of the field's estimated recoverable oil (Resolute Energy Corporation 2013; Utah Geological Survey 2013). Other potential hydrocarbon reservoirs in southeastern Utah include the beach and deltaic sandstones in the Pennsylvanian Honaker Trail Formation (**PNht**) and the eolian sandstones of the Permian Coconino Sandstone (**Pco**) (Utah Geological Survey 2013).

Tar Sands Exploration

About 130 km^2 (50 mi^2) of land in the Book Cliffs, north of Glen Canyon National Recreation Area, has been leased for tar sand production. An estimated 180 million barrels of oil could be produced from what would be the first tar sands mine in the United States (Fessenden 2015; McCombs 2015).

Approximately 32,000 ha (80,000 ac) in Glen Canyon National Recreation Area are designated as the "Special Tar Sands Area (STSA)." Any new leases in the STSA are issued as combined hydrocarbon leases because of the Combined Hydrocarbon Leasing Act of 1981 (30 USC § 181), which provided for the conversion of existing oil and gas leases and oil and gas mining claims in the STSA to combined hydrocarbon leases.

Tar sand mining presents a direct threat to air and water quality, as well as an impact to the viewshed. The permitted mine site lies within the upper reaches of the Colorado River watershed. Any contaminants may eventually be transported to Lake Powell and to water users in the lower Colorado River basin. Utah officials have approved three more tar sands operations in the same area. In the recent past, Utah officials have attempted to exchange state lands for potentially more economically productive federal lands, and similar attempts could potentially occur in the Tar Sand Triangle.

Development of White Rim Sandstone (**Pwr**) tar sand deposits in the Tar Sand Triangle faces the following hurdles that will make commercial bitumen recovery difficult and expensive, but not impossible (Vanden Berg 2011; Schamel 2013):

- Low oil saturations and low quality of bitumen.
- High sulfur content of the oil and high viscosity at reservoir temperatures.
- Difficult access over unimproved roads, all of which pass through Glen Canyon National Recreation Area.
- Potentially expensive access to water.
- Lack of infrastructure, including petroleum service vendors and other support services in southeast Utah.
- Problems with reservoir sand heterogeneity.
- Proximity of environmentally protected public lands containing exceptional landscapes.

The Combined Hydrocarbon Leasing Act specifies that the conversion of leases within National Park Service units is prohibited without a finding by the Secretary of the Interior that there would be no significant adverse impacts. Draft Environmental Impact Statements (DEISs) completed in the 1980s for the Tar Sand Triangle and Circle Cliffs deposits discussed the adverse environmental impacts that would result from developing tar sands in Utah (Baxter 2008). The same environmental, economic, socio-economic, and technical concerns that existed in the 1980s exist today (Baxter 2008).

Impacts from External Mining Activities

The accidental spill of contaminated water from the Gold King Mine near Silverton, Colorado, on 5 August 2015 highlighted the potential impacts of past and present mining activities on Lake Powell and the Colorado River watershed. As many as 3 million gallons of wastewater contaminated with heavy metals, including arsenic, cadmium, lead, and mercury, were released into a tributary to the Animas River, which flows into the San Juan River. These rivers are part of the upper Colorado River basin watershed and supply water for drinking, recreation, livestock, and irrigation in Colorado, New Mexico, and Utah.

By mid-August 2015, the contaminated water had flowed into Lake Powell, but the Environmental Protection Agency (EPA) did not expect any significant impacts to the lake (Romboy 2015). According to Richard Hepworth, state Division of Wildlife Resources aquatics manager in southern Utah, much of the contamination dissipated before reaching Lake Powell. Storms and runoff events may transport the contaminants into the lake in the future. Wildlife resource managers already check Lake Powell fish for mercury and will now test for other heavy metals, as well.

Heavy metal contamination, however, is not new to the surface waters in Glen Canyon National Recreation Area. In 1994, the Water Resources Division of the National Park Service conducted a baseline water quality inventory for the recreation area and found that several heavy metals exceeded their respective EPA water quality criteria at least once within the study area. Arsenic, cadmium, chromium, copper, lead, silver, zinc, selenium, and mercury exceeded the acute or chronic criteria for the protection of freshwater aquatic life, and arsenic, cadmium, chromium, lead, nickel, mercury, and natural uranium exceeded the EPA drinking water criteria (Water Resources Division 1994).

At least twelve Superfund sites exist in the Colorado Rocky Mountains, and eight of these have been identified as among the 79 most polluted sites in the country (Environmental Protection Agency 2015). The Gold King Mine is one of the mines identified within the Upper Animas Mining District. Soil and water contamination at many of these sites is being successfully addressed by the combined efforts of the local communities and the EPA. In contrast, the Silverton community in the 1990s elected to decline the EPA's help to construct an on-site water treatment plant, so the EPA agreed to postpone adding the Gold King Mine to the Superfund National Priorities List. However, the community-based efforts to remediate contamination to the Animas River began to fail in 2005 when water quality began to significantly decrease in the river (Environmental Protection Agency 2015).

The closed mine sites also include potential uranium contamination from the Uravan Uranium Project near Montrose, Colorado. Uranium mining is part of the rich mining history of Utah. In southeastern Utah, the number of abandoned uranium mines on BLM land ranges from 8,000 to 11,000, including those within Glen Canyon National Recreation Area (BLM 2015). These abandoned uranium mines are within the Colorado River watershed, and their waste dumps often contain elevated levels of heavy metals, such as cadmium, lead, arsenic, and zinc. An estimated 5%–10% of the abandoned mine sites may have water quality problems (BLM 2015).

With uranium prices increasing, a new uranium mining boom is occurring in Utah (BLM 2015). Hard-rock mining for gold and other precious metals continues in Colorado. The prospect of tar sand mining in Utah adds an additional external threat to the water quality in Glen Canyon National Recreation Area.

Potential Impacts from Global Climate Change

As climate continues to change, national parks across the country, including Glen Canyon National Recreation Area, will face many challenges. The NPS Climate Change website, http://go.nps.gov/climatechange, provides background information and NPS context and actions. Primary concerns for the national recreation area include lower amounts of precipitation which will affect water availability for users of water stored in Lake Powell, as well as water-dependent ecosystems such as hanging gardens.

On the Colorado Plateau, elevation strongly controls temperature, precipitation and evapotranspiration (Spence 2001). In general, precipitation increases and potential evaporation decreases as elevation increases. The arid-humid climate boundary occurs at approximately 2,730 m (8,957 ft) (Spence 2001). The Glen Canyon region includes some of the lowest elevations on the Colorado Plateau and some of the highest temperatures. Elevations along the Colorado River range from 1,219 m (4,000 ft) at Moab to 978 m (3,209 ft) at Lees Ferry, a drop of only 241 m (791 ft) in 450 km (276 mi). The hot, arid climate at the elevation of Lake Powell accounts for an average annual evaporation of 2.6% of the lake's volume, or roughly 0.8 km3 (0.2 mi3) of water.

Over an 82-year period (1916–1998), the average annual temperature at Lees Ferry was 16.9°C (62.4°F). In contrast, the average annual temperature at Bryce Canyon National Park, where the weather station is 2,412 m (7,914 ft) above sea level, was 5.1°C (41.2°F) through the second half of the twentieth century (Spence 2001). The yearly average potential evapotranspiration at Lees Ferry was 99.3 cm (39.1 in) over the same period, approximately double the average annual evapotranspiration at Bryce Canyon National Park.

Glen Canyon National Recreation Area lies in a rain shadow. Rainfall is reduced because of the high Wasatch and Kaibab Plateaus to the north, west, and southwest. Over the 82-year period from 1916 to 1998, Lees Ferry received an annual average precipitation of 15.3 cm (6.0 in) (Spence 2001). For comparison, Phoenix receives an average of 20.4 cm (8.04 in) of annual rainfall.

Dynamic weather patterns in the region fluctuate between cool wet phases and dry warm phases based on the 20-year cyclic Pacific Decadal Oscillation (PDO), the Atlantic Multi-decadal Oscillation (AMO), which has a 50–80 year cycle, and El Niño-La Niña (EL-LN) events. The 1983 flood that almost overtopped Glen Canyon Dam, for example, corresponded to the 1983 El Niño event (National Park Service 2007). The extremely complex interactions between the PDO, AMO, and EL-LN are not well understood, but these interactions have a significant effect on the region's water supply and the organisms that depend on this water supply.

Water Resources

In general, precipitation is projected to decrease in the southwestern United States, and drought and increased warming are predicted to increase competition among agricultural, municipal, industrial, and ecological uses for scarce water resources, which are already overallocated (Bates et al. 2008; Karl et al. 2009; Intergovernmental Panel on Climate Change 2014; Melillo et al. 2014). Already known for its mega-droughts, the Southwest is expected to sustain substantially hotter droughts that will become more frequent, intense, and longer lasting than historical droughts in the Colorado River Basin (Karl et al. 2009; Intergovernmental Panel on Climate Change 2014; Melillo et al. 2014; Cook et al. 2015). Demand for freshwater may impact Lake Powell lake levels.

Over the past century, the duration and extent of snow cover, mountain snow equivalent, and annual precipitation has decreased in the southwestern US, and winter and spring precipitation is predicted to decrease even further by 2100, although a trend towards a slight increase in winter precipitation on the Colorado Plateau has occurred over the last 30–40 years (Spence 2001; Bates et al. 2008; Melillo et al. 2014). There has also been a shift toward earlier peak runoff because more precipitation is falling as rain rather than snow (Knowles et al. 2006; Loehman 2009). In addition, dust and soot transported by winds from lowland regions will accumulate on the surface of snowpack, increasing the amount of the sun's energy absorbed by the snow and resulting in an earlier snowmelt and evaporation. Already lower than 20th century average flows, streamflow in the Colorado River basin is projected to decline because of decreased snowpack and subsequent reduced spring runoff and soil moisture (Bates et al. 2008; Intergovernmental Panel on Climate Change 2014; Melillo et al. 2014).

At Lees Ferry, the minimum average temperature has significantly increased since 1944, although no significant changes have affected the average annual or maximum temperatures (Spence 2001). Increasing temperatures, even with no or minor changes in precipitation, will increase the rates of potential evapotranspiration in the Glen Canyon National Recreation Area (Spence 2001). Considering the general trend of increasing temperature at Lees Ferry, the annual potential evapotranspiration rate will increase from 99.3 cm (39.1 in) to 113.6 cm (44.8 in). By comparison, the potential evapotranspiration rate from 1982–2005 for Tucson in the Sonoran Desert averaged 110.0 cm/year (43.3 in/yr).

Ecosystems and irrigation demands are projected to be significantly stressed due to a combination of climate change, growing water demand, and water transfers to urban and industrial users (Bates et al. 2008; International Panel on Climate Change 2014). Increased minimum temperatures at lower elevations may encourage the growth of cool season plants and the subsequent depletion of soil moisture prior to the germination of warm season species (Spence 2001). Long-term models predict that grasslands and woodlands will increase on the Colorado Plateau at the expense of arid scrub vegetation.

Hundreds of reservoirs, irrigation projects and groundwater withdrawals have been developed in the semi-arid Colorado River basin in order to supply freshwater to a westward expanding population. The Colorado River Compact, negotiated in the 1920s, allocated the Colorado River's water to seven US states, two Mexican states, and thirty-four American Indian tribes. However, the water was allocated based on the wettest period in over 400 years (Pulwarty et al. 2005; Bates et al. 2008; Karl et al. 2009). About 30–40% of the region has been under severe drought conditions since 1999, and the flow of the Colorado River was at a 5-year low from 2000 to 2004 (Bates et al. 2008). With increased population growth, increased climatic warming, increased evaporation, increased surface and groundwater withdrawals, and decreased runoff, the Colorado River Compact may meet its requirements only 60–75% of the time by 2025 (Christensen et al. 2004). Discharge of the Colorado River at Lees Ferry, which separates the upper from the lower Colorado River basin, may be insufficient to meet current water demands within 20 years (Pulwarty et al. 2005; Bates et al. 2008).

In addition, hydropower production is predicted to decrease as total runoff decreases within the Colorado River basin (Christensen et al. 2004; Bates et al. 2008). Changes in precipitation and river discharge significantly affect hydroelectric generation. For example, a 1% decrease in streamflow in the Colorado

River basin results in a 3% drop in power generation (Karl et al. 2009).

Increasing development and climate variability may intensify conflicts among water users in the Colorado River basin. Lake Powell levels may continue to decline in order to meet the needs of the Colorado River Compact. Declining lake levels may impact recreational activities and expose fossil sites to erosion. Increased erosion from wave activity in Lake Powell and flash floods in tributary streams and slot canyons will increase the amount of silt deposited in the reservoir, as well. Climate change will not only impact average conditions but also accelerate specific climatic events such as intense storms, floods, and drought. These extreme events can significantly cause fundamental and widespread shifts in the condition of park resources (National Park Service 2014b).

Hanging Gardens

Hanging gardens and other spring systems in Glen Canyon National Recreation Area and throughout the Colorado Plateau are fragile ecosystems (fig. 9). In addition to foot traffic, livestock, and the invasion of exotic species that already threaten the delicate vegetation in the hanging gardens, global climate warming threatens the hanging gardens in Glen Canyon National Recreation Area (National Park Service 2015c).

If precipitation decreases and groundwater levels lower, seeps and springs along the contact of the Kayenta Formation (**Jk**) and the Navajo Sandstone (**Jn**) may also decrease. Many animals and plants living in the hanging gardens depend on this water for survival. Global climate change may significantly jeopardize the water resources and survival of organisms that are dependent

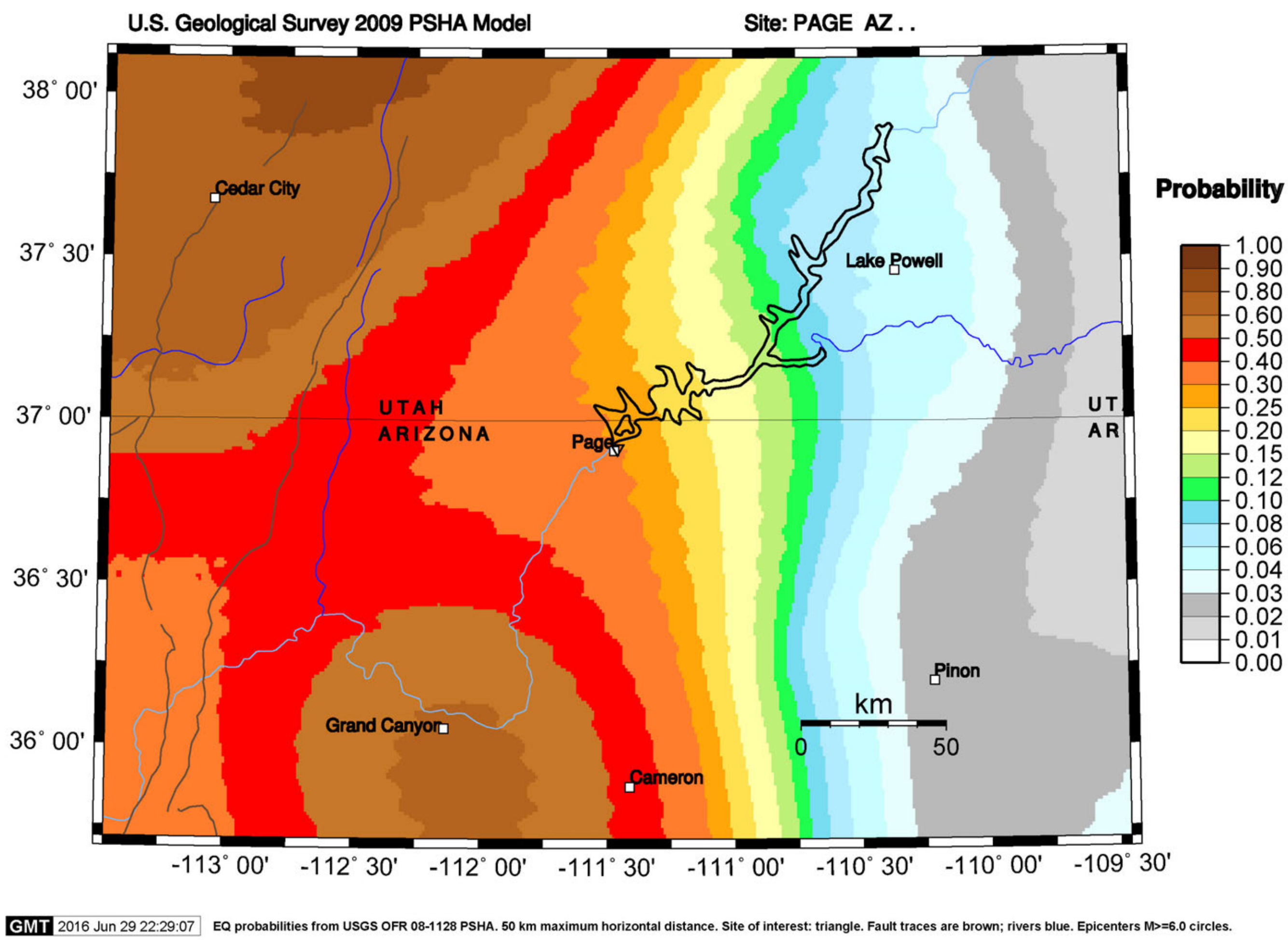

Figure 41. Map of earthquake probability for Glen Canyon National Recreation Area. The map shows the probability of an earthquake with a magnitude >5.0 occurring within 100 years. Brown lines are fault traces. Blue lines are rivers. The black outline is the approximate extent of Lake Powell. Map created using the US Geological Survey 2009 Earthquake Probability Mapping tool, available at http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 29 June 2016).

on the hanging gardens in Glen Canyon National Recreation Area (National Park Service 2007).

Earthquakes

Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. Earthquakes can directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety.

Until 1979, earthquakes were measured using the Richter magnitude scale which is based on a logarithmic scale from 1 to 10. Seismologists now measure earthquake magnitude using the moment magnitude (energy released) scale, which is more precise than the Richter scale but retains the same continuum of magnitude values. The Modified Mercalli Intensity Scale is a measure of the effect of an earthquake on Earth's surface. It consists of a series of key responses such as sleeping people awakening, furniture moving, chimneys damaged, and finally, total destruction.

All of Utah's earthquakes are associated with Basin-and-Range Province extension (Grant Willis, Utah Geological Survey, geologist, written communication, 2 December 2015). Extension began about 17 million years ago and continues today. The Hurricane fault, west of Zion National Park, marks the eastern boundary of the Basin-and-Range Province, but the Paunsaugunt fault, which is responsible for the cliffs of Bryce Canyon National Park, is a potentially active fault in the transition zone between the Basin-and-Range and the Colorado Plateau. The Paunsaugunt fault is only about 56 km (35 mi) away from Glen Canyon National Recreation Area, and the even more active Sevier fault, west of Kanab, is only about 97 km (60 mi) away.

Since 1973, no earthquakes of magnitude 4.5 or greater have occurred in southeastern Utah (US Geological Survey 2014). Nevertheless, the probability that an earthquake of magnitude >5 (considered a "moderate" earthquake) will occur in the Glen Canyon National Recreation Area in the next 100 years ranges from 0.04 to 0.30 (fig. 41; US Geological Survey 2010). The southern part of the recreation area where Glen Canyon Dam is located has a higher probability of an earthquake of this magnitude than does the area north of the San Juan Arm (fig. 41).

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. Braile (2009), 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 more information. The University of Utah Seismograph Stations (UUSS) provides real-time data and maps of the most recent earthquakes (http://quake.utah.edu/index.shtml).

Glen Canyon Dam and Downstream Impacts to the Colorado River

Typical of all large dams and their reservoirs, Glen Canyon Dam has trapped upstream sediment and significantly altered downstream flow regimes. Since the dam closed in 1963, average peak flows in Glen Canyon have decreased by 63% and the fine sediment supply has been essentially eliminated. The average daily legal range of outflow from Glen Canyon Dam is 140–570 m^3/s (5,000–20,000 ft^3/s), but flood events have produced a maximum flow of 9,120 m^3/s (322,000 ft^3/s) (Anderson et al. 2010). After the dam closed, the downstream Colorado River channel narrowed and was transformed from a sand-dominated channel to a gravel-dominated river channel. Bed incision, which occurred primarily in 1965, has scoured an average of 2.6 m (8. 5 ft) of sediment from the center of the channel. Sandbars and pre-dam flood deposits have been eroded and once active sand and gravel bars have been abandoned and stabilized by vegetation (Grams et al. 2005, 2007, 2010). On the enclosed map, thin point bars consisting of alluvial deposits (**Qal1**) have formed at meander bends along the downstream reach of the Colorado River south of the Glen Canyon Dam.

The physical changes to the Colorado River have led to an artificial ecosystem dominated by nonnative species. According to Grams et al. (2007, p. 556), models for the response of the Colorado River downstream from Glen Canyon dam should consider "(1) possibility of variable responses among different channel elements, and (2) the potential importance of exceptional flows resulting from management decisions," along with the usual factors such as the pre-dam and post-dam sediment load, grain size, and average flows.

In analyzing the bed degradation and channel adjustment of the Colorado River, Grams et al. (2005, 2007, 2010) used many of the techniques described in *Geological Monitoring* chapter on fluvial geomorphology (Lord et al. 2009). Glen Canyon National Recreation Area resource managers may wish to review this chapter in which Lord et al. (2009) present an overview of stream dynamics, describe factors that may lead to channel instability, and provide guidelines on monitoring rivers and streams in the Glen Canyon National Recreation Area. Taking an integrated system approach, Lord et al. (2009) present vital signs, or critical factors, that can be monitored in order to establish the overall condition of the river system. These vital signs include: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile (Lord et al. 2009).

Navajo Sandstone and Potential Glen Canyon Dam Failure

Participants at the 1999 scoping workshop expressed concern that the Glen Canyon Dam could fail because it was anchored in the porous Navajo Sandstone (NPS Geologic Resources Division and Natural Resources Information Division 1999). The two original internal spillways were first used during an impressive flood in May 1983, three years after Lake Powell had filled. Noticeable vibrations and rumblings occurred, and an inspection of the spillways found pieces of concrete and sandstone in the water. Cavitation had damaged and eroded the concrete lining at bends in the spillway tunnels. In places, erosion had exposed the relatively soft Navajo Sandstone (**Jn**).

Following the 1983 flood, the spillways were redesigned to reduce or eliminate cavitation and eliminate the possibility of the reservoir rising and flowing over the crest of the dam. Erosion of the Navajo Sandstone around the dam abutments, damage to the power plant at the base of the dam, and subsequent failure would probably occur if the dam were overtopped by the reservoir.

If Glen Canyon Dam were to fail, approximately 33 km^3 (7.9 mi^3) of water would surge out of Lake Powell. In addition to severely scouring the downstream Colorado River channel, damage would occur to every downstream community, every downstream dam (except possibly Hoover Dam), and every riparian ecosystem. Dam failure would also destroy up to 964 known archaeological sites, including 264 in the Grand Canyon (Colorado Riverkeep 2005). Glen Canyon Dam is the central part of the Colorado River Storage Project, and a dam failure would impact the water supply to residences and farmland dependent on Colorado River water.

Geologic History

This chapter describes the geologic events that formed the present landscape of Glen Canyon National Recreation Area.

The rock units in Glen Canyon National Recreation Area span approximately 300 million years and record the dynamic transition from shallow marine environments on the North American continent to the carving of the Colorado River through layers of bedrock on the Colorado Plateau. As an overview, from the Late Pennsylvanian Period to the mid-Triassic Period, southeastern Utah became part of the supercontinent Pangea. Expansive sand deserts (ergs) inundated the region in the Jurassic Period, and tracks of dinosaurs can be followed to their abrupt end in the Late Cretaceous. During the Late Cretaceous–Eocene Laramide Orogeny (between about 70 million and 40 million years ago), the strata on the Colorado Plateau were bent into broad folds, such as the Circle Cliffs anticline that trends through the recreation area. In the late Paleogene Period, approximately 31 million to 23 million years ago, magma flowed through the crust and solidified to form the laccoliths that core the Henry and Navajo Mountains. Drainage systems developed and approximately 5.5 million years ago, the modern Colorado River began carving the Grand Canyon. Within about the last 1 million years, the river carved the part of Glen Canyon that we see today (it had been carving the older, now-missing, Glen Canyon for about 5.5 million years). Today, these many millions of years of Earth history are on display along the shores of Lake Powell.

Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea

Aggressive tectonism in the Pennsylvanian Period built mountains in Colorado with as much as 3,000 m (10,000 ft) of relief (De Voto 1980). Compression from the southwest caused a northwest–southeast trending, shallow, subsiding trough called the Paradox Basin to form across the Four-Corners area (fig. 42; Stone 1986).

The Hermosa Group (**PNp** and **PNht**) records episodes of marine incursions from the south during the Pennsylvanian Period. The climate was quite arid in Glen Canyon National Recreation Area, and during times of sea level fall (regression), seawater evaporated and salt deposits formed (Rueger 1996). When relative sea level rose during subsequent transgressions, normal marine waters returned, salinity fell, and salt deposits (anhydrite) were overlain by silty dolomite, limestone, and black shale (Hite 1970; Rueger 1996; Doelling 2010). The Paradox Formation (**PNp**) offers textbook examples of these cycles of salt, dolomite, porous limestones, and black shales. These deposits in the Paradox Basin would later become economically important when the salt, reacting to overburden pressure in the subsurface, flowed upward to form anticlines that trapped oil migrating from the black shale into porous limestone reservoirs.

By Late Pennsylvanian time, barriers in the Paradox Basin that restricted open marine conditions were eliminated and unimpeded marine conditions returned to the area. The Honaker Trail Formation (**PNht**) records deposition in shallow marine, beach, lagoon, and deltaic environments (Rueger 1996; Anderson et al. 2010). The interlayered sandstones, mudstones, and fossiliferous limestones of the Permian–Pennsylvanian Elephant Canyon (**PPNe**) and Halgaito (**PPNhg**) formations and the lower Cutler beds (**PPNcl**) were deposited in tidal flat, delta, coastal sand dune, fluvial, and shallow-marine shelf environments (Loope 1984; Condon 1997; Huntoon et al. 2010).

Approximately 275 million years ago (Early Permian), most of Utah was located near 10° north latitude in a dry, high pressure climatic belt, analogous to that of the Sahara Desert today (fig. 42; Morris et al. 2010). An extensive dune field that would become the Cedar Mesa Sandstone (**Pcm**) formed along the sea coast, and most of southeastern Utah became covered by an extensive coastal dune field. Periodically, sea level rise would produce shallow marine incursions, resulting in the tidal mud-flat and beach environments preserved in parts of the Organ Rock Formation (**Po**) and White Rim Sandstone (**Pwr**) (Doelling and Davis 1989; Anderson et al. 2010).

At the end of the Paleozoic Era, the global landmasses sutured together to form the supercontinent Pangea. Collisions between these landmasses generated the Appalachian mountain chain, the Ouachita Mountains of Arkansas and Oklahoma, and the northwest–

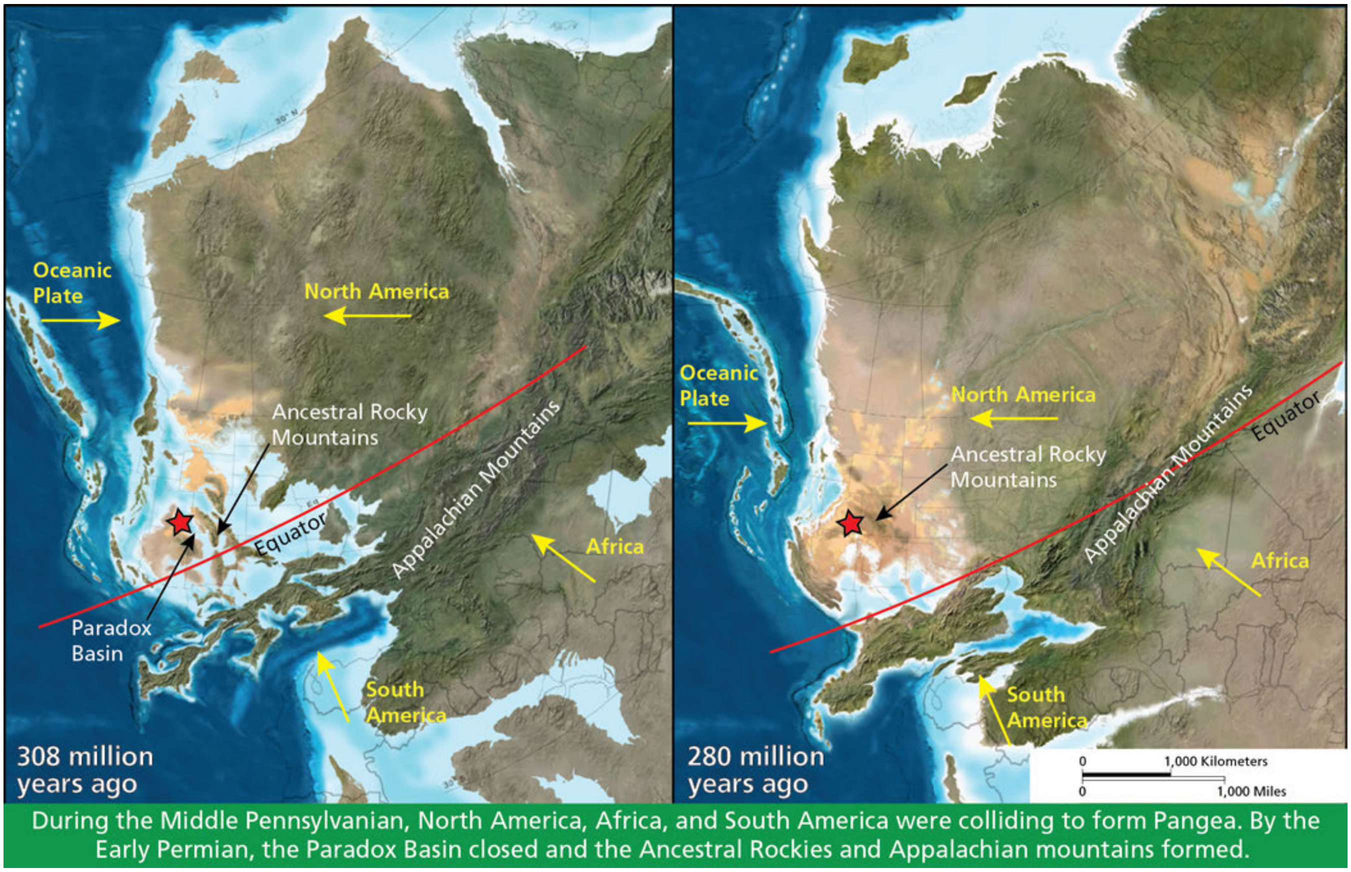

Figure 42. Middle Pennsylvanian (308 million years ago) and Early Permian (280 million years ago) paleogeographic maps of North America. As the Paleozoic Era came to a close, subduction zones along the western, southern, and eastern margins of present-day North America sutured together North America, South America, and Africa to form the supercontinent Pangea. By the Early Permian, the Paradox Basin had closed. The continent-continent collisions resulted in the Appalachian Mountain chain as well as the Ancestral Rocky Mountains. The red star approximates the location of Glen Canyon National Recreation Area. Yellow arrows represent the direction of plate movement. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/index.html (accessed 12 January 2016).

southeast trending Ancestral Rocky Mountains in Colorado.

Much of the Permian strata has been eroded from the Glen Canyon region, leaving a gap in the rock record. The boundary between the Early Permian Period and the Early Triassic Period is marked by the regional TR-1 unconformity (fig. 4).

Triassic Period: Fluvial Systems in a Tropical Climate

In the Early Triassic (251 million to 245 million years ago), Pangea was more-or-less centered on the equator (fig. 43; Dubiel 1994). To the west, explosive volcanoes arose from the sea and formed a north-south trending arc of islands along the present-day border of California and Nevada (Christiansen et al. 1994; Dubiel 1994; Lawton 1994). The western Colorado Plateau region consisted of a broad continental shelf that accumulated shallow marine to coastal marine sediments while a fluvial and floodplain system developed in the eastern part of the Colorado Plateau from the erosion of Colorado's Ancestral Rocky Mountains. These deposits became the Moenkopi Formation (**TRm**) (Stewart et al. 1972a; Christiansen et al. 1994; Doelling 2010; Anderson et al. 2010; Huntoon et al. 2010). Plant and animal fossils in the Moenkopi Formation (table 8) suggest a shift to a warm tropical climate with likely monsoonal, wet-dry conditions (Stewart et al. 1972a; Huntoon et al. 2010; Morris et al. 2010).

In the Late Triassic, streams cut valleys into the underlying Moenkopi Formation. Paleovalley geometry and channel sandstones in Glen Canyon National

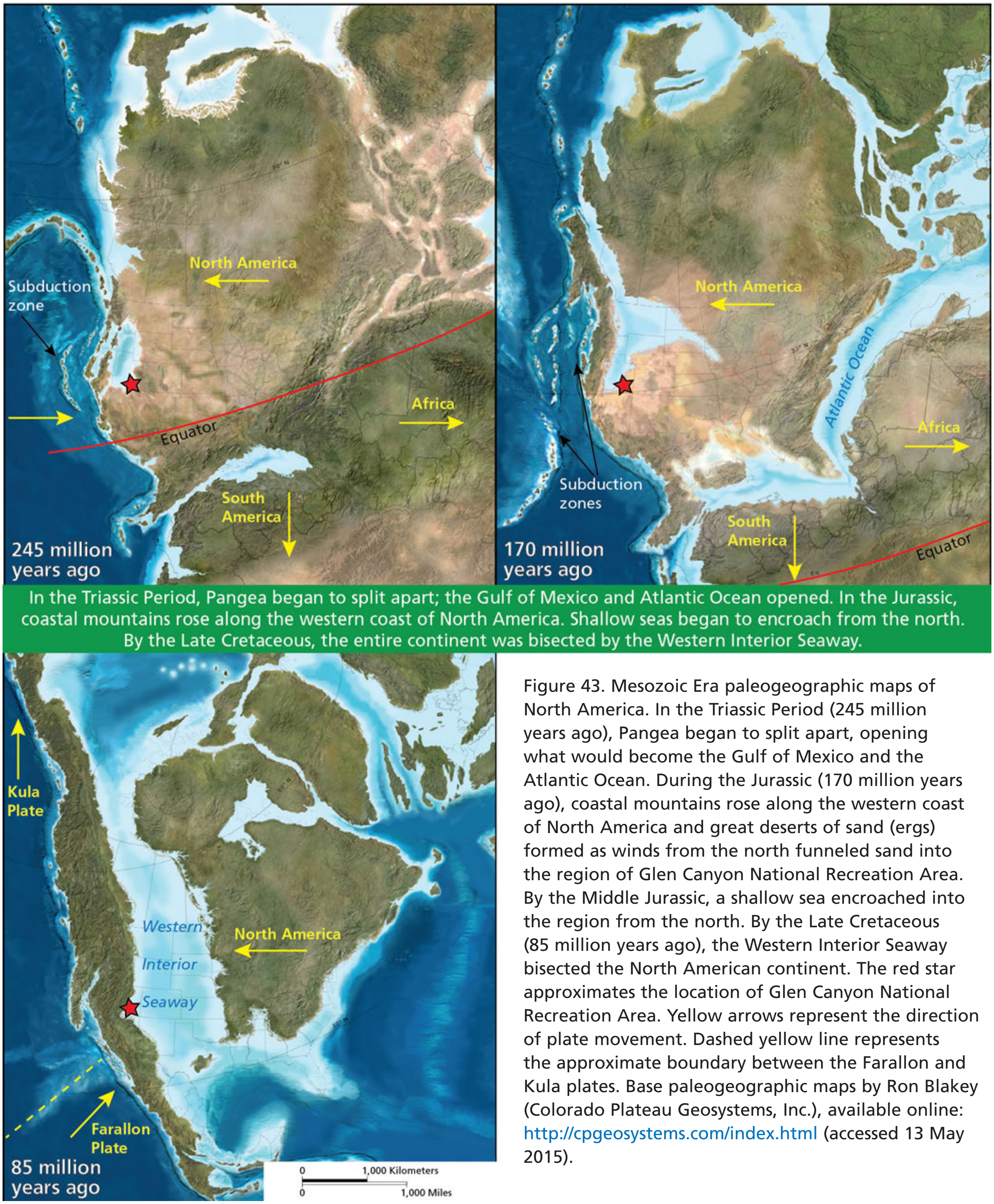

Figure 43. Mesozoic Era paleogeographic maps of North America. In the Triassic Period (245 million years ago), Pangea began to split apart, opening what would become the Gulf of Mexico and the Atlantic Ocean. During the Jurassic (170 million years ago), coastal mountains rose along the western coast of North America and great deserts of sand (ergs) formed as winds from the north funneled sand into the region of Glen Canyon National Recreation Area. By the Middle Jurassic, a shallow sea encroached into the region from the north. By the Late Cretaceous (85 million years ago), the Western Interior Seaway bisected the North American continent. The red star approximates the location of Glen Canyon National Recreation Area. Yellow arrows represent the direction of plate movement. Dashed yellow line represents the approximate boundary between the Farallon and Kula plates. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/index.html (accessed 13 May 2015).

Recreation Area, Capitol Reef National Park, and other exposures on the Colorado Plateau provide evidence for the development of a dendritic (tree-like) fluvial system in southeastern Utah. The main trunk river flowed to the northwest, and tributaries drained highlands that had risen to the west, southwest, south, and southeast (see GRI report by Graham 2006a; Lucas 1993; Dubiel 1994; Lucas et al. 1997; Morris et al. 2010). The complex assemblage of alluvial, marsh, lacustrine, playa, and eolian deposits became the Chinle Formation (**TRc**) (Stewart et al. 1972b; Anderson et al. 2010). Interlayered with the clastic sediments are beds of bentonite, altered volcanic ash that had blown into the area from volcanic activity in present-day Arizona and California (Christiansen et al. 1994; Anderson et al. 2010).

Jurassic Period: Extensive Dune Fields

The Jurassic western margin of North America was associated with an Andean-type margin where the eastward subduction of the seafloor gave rise to volcanism similar to that found in the modern Andes of South America. Volcanoes formed an arcuate north–south chain of mountains off the coast in what is now central Nevada. The northwest–southeast-trending Uncompahgre Uplift, that part of the Ancestral Rocky Mountains in western Colorado, and the Monument Upwarp in eastern Utah, east of present-day Glen Canyon National Recreation Area, remained slightly topographically high during the Jurassic.

The Four-Corners area of Arizona, New Mexico, Colorado, and Utah during the Early Jurassic was covered by extensive ergs, similar to the modern Sahara/Sahel regions (fig. 43). Southeastern Utah was located about 18° north latitude at the beginning of the Jurassic (about 199 million years ago) and moved to 30°–35° north latitude by the end of the Jurassic (about 145 million years ago) (Kocurek and Dott 1983; Peterson 1994). This is the latitude of the present day northeast trade wind belt where cool, dry air descends from the upper atmosphere and sweeps back to the equator in a northeast–southwest direction. The cool, dry air warms and expands and sucks up any additional moisture from the land's surface.

The Jurassic deserts that inundated the Colorado Plateau for roughly 40 million years (not counting the time represented by erosion) contained sand dunes that may be the largest recorded in the history of Earth (Kocurek and Dott 1983). Like the Sahara, these were ergs that formed on a coastal and inland dune field, and they affected the present areas of southern Montana, western Wyoming, eastern Idaho, eastern Utah, westernmost Colorado, southwest Colorado, northeastern Arizona, and northwestern New Mexico (Kocurek and Dott 1983; Peterson 1994).

During the Latest Triassic to Early Jurassic, wind transported abundant quantities of sand eroded from Paleozoic sandstones exposed from as far north as Montana and Alberta to the Colorado Plateau (Kocurek and Dott 1983). These dunes became the Wingate Sandstone (**JTRw**). Sinuous rivers meandered in a general westward to southwestward direction across a broad floodplain in southeastern Utah, depositing fluvial and floodplain sediments that formed the Kayenta Formation (**Jk**) (Anderson et al. 2010; Morris et al. 2010).

Extensive ergs returned to the Colorado Plateau as the region became increasingly arid. Lower Jurassic Navajo Sandstone (**Jn**) dune deposits are as much as 340 m (1,100 ft) thick below the dam in Glen Canyon. The sand dunes gradually overtook the fluvial systems of the Kayenta Formation. In contrast to the Wingate Sandstone, most of the sand that formed the Navajo dunes originated from the ancestral Appalachian Mountains (Dickinson and Gehrels 2003, 2009; Rahl et al. 2003; Biek et al. 2010). A continental-scale river system transported the sand grains to the western shore of the Jurassic margin of North America. Winds from the north and northwest blew the sand southward to be incorporated into the vast dune field represented by the regional Navajo, Nugget, and Aztec sandstones. Broad shallow lakes formed in interdunal desert oases that were scattered throughout the coastal Navajo dune field (Anderson et al. 2010).

Early Jurassic compressional deformation along the western margin of North America preserved this tremendous thickness of eolian sand (Allen et al. 2000). As North America collided with the oceanic plate, the continental interior flexed downward, providing space for sediment to accumulate. Along the continental margin, west of the Glen Canyon region, mountains rose and blocked any moisture blowing in from the western ocean, increasing aridity.

The regional J-1 unconformity separates the Navajo Sandstone from the eolian and fluvial sandstones of the Middle Jurassic Temple Cap Formation, which is mapped as the Page Sandstone (**Jp**) in the GRI GIS data (fig. 4; see posters [in pocket]). Interbedded sandstones and siltstones, fossil-bearing limestone, and gypsum record episodes of intermittent marine flooding and evaporation in the Glen Canyon area (Anderson et al. 2010; Morris et al. 2010). A broad depression called the Utah-Idaho trough was inundated by a sea encroaching onto the continent from the north. Associated with the advancing sea were shallow marine, marginal marine, and sabkha environments.

The members of the overlying Carmel Formation (**Jc**) represent two transgressive-regressive cycles. In Glen Canyon National Recreation Area, the first cycle is represented by the transgressive Judd Hollow Member (**Jcj**) and the regressive Thousand Pockets Member (**Jpt**) (Doelling et al. 2013). The transgressive Paria River Member (**Jcp**) marks the rise in sea level that initiated the second cycle, and the Winsor Member (**Jcw**) was deposited as the shoreline regressed to the northwest. During regressions, northward-flowing streams carried sand eroded from highlands covered with Navajo Sandstone, and wind reworked the sand into coastal dunes. These fluvial-eolian deposits were inundated by the sea during transgressive episodes (Blakey 1994; Anderson et al. 2010; Doelling et al. 2013).

The Entrada dunes formed following the final regression of the Carmel sea from the region. The Entrada Sandstone (**Je**) dune fields became the most widespread of the preserved late Paleozoic and Mesozoic wind-blown deposits on the Colorado Plateau (Peterson 1994).

Mudcracks, ripple marks, and inch-scale cross-bedding in the overlying Summerville Formation (**Jesu**) represent tidal flat deposition. These marginal marine conditions resulted from a major transgression of the inland seaway from the north at the end of the Middle Jurassic and beginning of the Late Jurassic (about 157 million years ago). Deposits from fluctuating sea levels mark the end of the vast ergs that once covered the Colorado Plateau (Kocurek and Dott 1983). Shallow marine, tidal flat, and eolian deposits of the Romana Sandstone (**Jr**) spread over the region. In the Late Jurassic, sea level fell, and the extensive Morrison Formation (**Jm**) was deposited in river floodplains across western North America (Lawton 1994; Anderson et al. 2010).

Cretaceous Period: Western Interior Seaway

No Early Cretaceous deposits are known from southeastern Utah, probably because the area was undergoing erosion rather than deposition. From approximately 155 million years to 50 million years ago, the western margin of North America became a subduction zone and tectonic forces compressed, folded, and faulted rocks from Alaska to northern Mexico and thrust them eastward as if a giant accordion was being squeezed. Older Paleozoic rocks were thrust over younger strata, thickening the crust until the sedimentary layers at the bottom of these kilometer-scale thrust stacks were metamorphosed (Oldow et al. 1989; Lageson and Schmitt 1994; Lawton 1994; DeCelles 2004).

The Sevier Orogeny, a mountain-building event that occurred between 140 million and 50 million years ago, generated a rugged north–south trending fold-and-thrust belt in central Utah. Rivers flowing from the early Sevier highlands deposited the sediments found in the lower Dakota Sandstone (**Kd**). As thrust sheets stacked atop one another, the crust parallel to the Sevier mountain range began to subside, and marine incursions produced the lagoons, beaches, and swamps documented in the upper Dakota Sandstone.

With subsidence, sea water began to fill the basin from the Arctic region and the Gulf of Mexico. Episodic fluctuations in sea level occurred throughout the Cretaceous, culminating in the formation of the most extensive interior seaway ever to bisect the North American continent (fig. 43). The Western Interior Seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4,800 km (3,000 mi; Kauffman 1977; Steidtmann 1993). At maximum sea level rise, the width of the basin reached 1,600 km (1,000 mi). The Mancos Shale (**Km**) and Tropic Shale (**Kt**) in Glen Canyon National Recreation Area accumulated in this seaway (Elder and Kirkland 1994; Anderson et al. 2010). When sea level fell, the shoreface, beach, lagoon, and paludal environments of the Straight Cliffs Formation (**Ks**) were deposited (Anderson et al. 2010). Peat beds in the swamps and lagoons were buried and eventually transformed into thick coal deposits.

Cretaceous–Paleogene Periods: The Laramide Orogeny

The Western Interior Seaway receded from the continental interior with the onset of the Laramide

Orogeny. The Laramide Orogeny occurred from about 70 million years ago (latest Cretaceous Period) to 40 million years ago (Eocene Epoch of the Paleogene Period) and overlaps the Sevier Orogeny by about 25 million years (Hintze and Kowallis 2009; Biek et al. 2009; Grant Willis, Utah Geological Survey, geologist, written communication, 1 December 2015). The Drip Tank Member (**Ksd**) of the Straight Cliffs Formation and the Dakota Formation (**Kd**) form the crest of the Smoky Mountain anticline in the southern part of the recreation area. Deformation of these strata indicates that the initiation of the Laramide Orogeny in this region had to have occurred after deposition of these Late Cretaceous units.

The Laramide Orogeny resulted from a profound eastward shift in tectonic activity along the western margin of North America. The angle of the subducting plate flattened and compressive forces were felt far inland. Rather than generating volcanic mountain ranges on the west coast as in previous orogenies, the Laramide Orogeny displaced deeply buried Precambrian plutonic and metamorphic rocks along reverse faults and folded the strata on the Colorado Plateau into asymmetric, north- to northwest-trending anticlines and synclines, such as the Circle Cliffs anticline, the associated Waterpocket Fold, and the secondary folds of the Kaiparowits basin (fig. 23). During folding of the Echo Cliffs monocline southeast of the southern end of the recreation area, the Navajo Sandstone was intensely brecciated (**TKb**). The broad, asymmetrical, north–south-trending Monument monocline formed in southeastern Utah and northeastern Arizona at this time. Its gently dipping western flank exposes Pennsylvanian and Permian rocks in the eastern part of the recreation area.

The regional increase in heat flow from the Laramide Orogeny also affected oil migration. The thermal history of the White Rim Sandstone (**Pwr**) in the Hite area constrains oil migration into the Tar Sand Triangle to sometime between the latest Cretaceous to the earliest Paleogene (Oligocene Epoch) (Huntoon et al. 1999).

Paleogene Period (Oligocene Epoch): Laccolith Emplacement

From about 31.2 million to 23.3 million years ago (Oligocene Epoch), laccoliths domed up the five steep-sided mountains in the Henry Mountains (Anderson et al. 2010). These igneous intrusions injected along bedding planes in Cretaceous and Permian sedimentary rocks that are now exposed on the Colorado Plateau, and probably in older still buried rocks as well.

The laccolith that formed the broad dome of Navajo Mountain is not exposed, so its age has not been determined as accurately as the laccoliths in the Henry Mountains. The intrusion deformed Jurassic and Triassic strata and is capped by the Cretaceous Dakota Sandstone (Anderson et al. 2010). Field relations suggest that the Navajo Mountain laccolith may be correlative with the Henry Mountains laccoliths, or it may be related to the 71 million to 74 million year old laccoliths that core the Carrizo Mountains in northeastern Arizona (Semken and McIntosh 1997; Anderson et al. 2010).

Paleogene–Quaternary Periods: Colorado River System and Carving Glen Canyon

The Colorado Plateau uplifted and the landscape transformed from one of deposition to one of erosion beginning in the Paleogene Period, which began about 66 million years ago (Anderson et al. 2010). Running water, wind, and mass wasting removed several thousand meters of sedimentary rock. Rivers flowed north to northeast, draining into lake basins in central and northeastern Utah (Blakey and Ranney 2008; Anderson et al. 2010). Erosion has removed most of the evidence of this drainage pattern.

About 5.5 million years ago, these northern drainages were captured by lower drainages in the Lake Mead area that flowed to the Gulf of California. The integration of these drainages resulted in the modern southwest-flowing Colorado River and led to the dramatic carving of Glen Canyon and the Grand Canyon in only a few million years (Karlstrom et al. 2008; Anderson et al. 2010). As the Colorado Plateau continued to rise, the Colorado River incised rapidly into relatively soft Cretaceous, Jurassic, and Triassic strata. Narrow slot canyons were carved into more resistant strata and wide valleys formed in softer strata (Anderson et al. 2010; Huntoon et al. 2010). Vertical incision entrenched the meanders of tributary channels as they attempted to keep pace with the downcutting of the Colorado River.

Erosion may have accelerated during the wet Pleistocene Epoch (2.6 million to 11,700 years ago). Glacial ice scoured the top of Boulder Mountain and the Aquarius Plateau, west of Capitol Reef National

Park, and a broad tongue of ice extended into the lowlands near Grover, southwest of Fruita, the best-known settlement in Capitol Reef National Park (see GRI report by Graham 2006a; Smith et al. 1963; Morris et al. 2010). Although erosion may have accelerated during the Pleistocene, incision of the Colorado River probably did not. Incision is controlled by the base level of the river, which is controlled by tectonic activity.

Meltwater from the glaciers flowed down valleys and spread outwash gravels along the drainage routes. Steep, rain-saturated slopes collapsed, resulting in some of the landslide and other mass movement deposits (**Qm**) in the recreation area. Some of the unconsolidated alluvial gravel deposits (**Qa**) in Glen Canyon National Recreation Area may have originated as glacial outwash. Today, the gravels cap terraces that were once floodplains before the Colorado River and its tributaries incised farther into the underlying bedrock.

Glen Canyon National Recreation Area And Other NPS Areas Along The Colorado River

Until 1963 when Glen Canyon Dam closed, the Colorado River flowed freely through Glen Canyon, continuing its natural incision of bedrock and depositing fresh sediments in the canyons. Today, silt accumulates at the sites of inflow deltas, such as the Hite delta, and the natural processes that produced the dynamic landscape of Glen Canyon National Recreation Area have been altered and subdued. Visitors with boats can easily access many geologic wonders.

Glen Canyon National Recreation Area is one in a series of National Park Service units that preserve and protect the exceptional landscape and expansive vistas of the Colorado Plateau along its namesake river. To the north, Canyonlands National Park protects the canyons, mesas, buttes, and spires that formed adjacent to the confluence of the Colorado and Green rivers (plate 1; National Park Service 2013). The expansive vistas include the La Sal, Abajo, Henry, and Navajo mountains. The Canyonlands landscape formed over hundreds of millions of years and preserves geologic processes such as sedimentation, erosion, salt dissolution and tectonics, and meteorite impact. As with the other parks along the Colorado River, Canyonlands preserves extensive fossil evidence of prehistoric life. Primarily a backcountry park, Canyonlands National Park offers visitors the opportunity to experience remote wilderness and solitude.

South of Glen Canyon National Recreation Area, the Colorado River flows through Grand Canyon National Park, established to preserve and protect the canyon's world renown vistas and unique geologic, paleontologic, and natural and cultural features (National Park Service 2010). One of the planet's most iconic geologic landscapes, Grand Canyon was carved by the Colorado River over the last six million years by the same erosional and tectonic processes that continue to shape the canyon today. The exposed layers of rock in the Grand Canyon provide scientific evidence of depositional environments and tectonic processes that spans more than one third of Earth's history. Geologic features, geologic processes, paleontological resources, and cave resources are included among the park's fundamental resources and values (National Park Service 2010).

Lake Mead National Recreation Area shares a border with Grand Canyon National Park. Like Lake Powell, Lake Mead offers recreational opportunities, but the area also includes fundamental geologic resources such as deep canyons, dry washes, sheer cliffs, vistas of mountain ranges, and a variety of rock formations. The rugged desert landscape contrasts vividly with the vast water bodies. The landscape reflects the diverse array of geologic, geomorphic, and hydrogeologic features and processes. As in the other parks, fossil resources, wilderness, and desert ecosystems are considered valuable fundamental resources in Lake Mead National Recreation Area (National Park Service 2015h).

Geologic Map Data

This chapter summarizes the geologic map data available for Glen Canyon National Recreation Area. Posters (in pocket) display the map GIS data draped over imagery of the park and surrounding area. The Map Unit Properties Tables (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also 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 digital geologic map 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 a compiled map (Willis and Ehler in prep.) as the primary source map. That compiled map incorporated geologic information from many published maps listed below. These sources also provided information for this report.

Billingsley, G. H., P. W. Huntoon, and W. J. Breed. 1987. Geologic map of Capitol Reef National Park and vicinity, Emery, Garfield, Kane, and Wayne Counties, Utah (scale 1:62,500). Map 87. Utah Geological and Mineral Survey, Salt Lake City, Utah.

Doelling, H. H. 2004. Geologic map of the La Sal 30'x60' quadrangle, San Juan County, Utah (scale 1:100,000). Map 205. Utah Geological Survey, Salt Lake City, Utah.

Doelling, H. H., and F. D. Davis. 1989. The geology of Kane County, Utah, geology, mineral resources, geologic hazards (scale 1:100,000). Bulletin 124 (also published separately as Map 121). Utah Geological and Mineral Survey, Salt Lake City, Utah.

Doelling, H. H., and G. C. Willis. 1999. Interim geologic map of the Escalante and parts of the Loa and Hite Crossing 30'x60' quadrangles, Garfield and Kane Counties, Utah (scale 1:100,000). Open-File Report 368. Utah Geological Survey, Salt Lake City, Utah.

Doelling, H. H., and G. C. Willis. 2006. Geologic map of the Smoky Mountain 30'x60' quadrangle, Kane and San Juan Counties, Utah, and Coconino County, Arizona (scale 1:100,000). Map 213, 2 plates. Utah Geological Survey, Salt Lake City, Utah.

Doelling, H. H., and G. C. Willis. 2007. Geologic map of the lower Escalante River area, Glen Canyon National Recreation Area, eastern Kane County, Utah (scale 1:100,000). Miscellaneous Publications 06-3DM (GIS data). Utah Geological Survey, Salt Lake City, Utah.

Huntoon, P. W., G. H. Billingsley, Jr., and W. J. Breed. 1982. Geologic map of Canyonlands National Park and vicinity, Utah (scale 1:62,500). Canyonlands Natural History Association, Moab, Utah.

Phoenix, D. A. 2009. Geologic map of part of the Lees Ferry area, Coconino County, Arizona (scale 1:24,000). Miscellaneous Publication 09-2DM (digitized and modified from plate 1 of US Geological Survey Bulletin 1137, scale 1;24,000, published in 1963). Utah Geological Survey, Salt Lake City, Utah.

Thaden, R. E., A. F. Trites, Jr., T. L. Finnell, and G. C. Willis. 2008. Geologic map of the White Canyon-Good Hope Bay area, San Juan and Garfield Counties, Utah (scale 1:100,000). Miscellaneous Publication 08-3DM (digitized and modified from plate 1 of US Geological Survey Bulletin 1125, scale 1:24,000, published in 1964). Utah Geological Survey, Salt Lake City, Utah.

Willis, G. C. 2004. Interim geologic map of the lower San Juan River area, eastern Glen Canyon National Recreation Area and vicinity, San Juan County, Utah (scale 1:50,000). Open-File Report 443DM (GIS data). Utah Geological Survey, Salt Lake City, Utah.

Willis, G. C. 2009a. Geologic map of the Hite Crossing–lower Dirty Devil River area, Glen Canyon National Recreation Area, Garfield and San Juan Counties, Utah (scale 1:100,000). GIS data. Utah Geological Survey, Salt Lake City, Utah.

Willis, G. C. 2009b. Interim geologic maps of the Bullfrog, Halls Crossing, Halls Crossing NE, Ticaboo Mesa, and Knowles Canyon quadrangles, Glen Canyon National Recreation Area, Garfield and San Juan Counties, Utah (scale 1:24,000). Open-File Report. Utah Geological Survey, Salt Lake City, Utah.

Willis, G. C. 2009c. Geologic map of the Glen Canyon Dam area, Glen Canyon National Recreation Area, Arizona and Utah (scale 1:24,000). GIS data. Utah Geological Survey, Salt Lake City, Utah.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is 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 the park 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 publically 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 (glca_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 (table 11);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- an ancillary map information document (glca_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures; and
- an ESRI map document (glca_geology.mxd) that displays the GRI GIS data.
- a version of the data viewable in Google Earth (glca_geology.kmz) (table 11).

GRI Posters

Three posters of the GRI GIS data, draped over a shaded relief image of the park and surrounding area, are included with this report (in pocket). Not all GIS feature classes are included on the poster (table 11). 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 set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Tables

The Bedrock and Unconsolidated Map Unit Properties Tables (in pocket) list the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the tables summarize 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 GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scale (1:24,000 to 1:100,000) and US National Map Accuracy Standards, geologic features represented in the geologic map (GRI GIS) data are expected to be horizontally within 12 m (40 ft) to 51 m (167 ft) of their true locations.

Table 11. Geology data layers in the Glen Canyon National Recreation Area GRI GIS data.

Data Layer	On GRI Posters?	Google Earth Layer?
Geologic Attitude Observation Localities (strike, dip, trend data)	No	No
Mine Point Features (NPS access only)	No	No
Geologic Point Features (natural arches and springs)	Yes	No
Structure Contours Showing Base of the Navajo Sandstone	No	No
Structure Contours Showing Base of the Carmel Formation	No	No
Structure Contours Showing Top of the Navajo Sandstone	No	No
Structure Contours Showing Top of the Permian	No	No
Structure Contours Showing Top of the Morrison Formation	No	No
Structure Contours Showing Top of the Wingate Sandstone	No	No
Structure Contours Showing Top of the Permian and the Hoskinnini Member of the Moenkopi Formation	No	No
Structure Contours Showing Top of the White Rim Sandstone	No	No
Geologic Line Features (mineralized veins)	No	No
Map Symbology	Yes	No
Linear Joints	Yes	Yes
Folds	Yes	Yes
Faults	Yes	Yes
Major Water Body Extent (approximate extent of Lake Powell)	Yes	No
Geologic Contacts	No	Yes
Geologic Units	Yes	Yes

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.

abandoned mineral lands (AML) feature. An individual element of an AML site, such as vertical shaft, adit, open stope, open pit, highwall, prospect, or associated structures.

abandoned mineral lands (AML) site. An area composed of AML features associated with past mineral exploration, extraction, processing, and transportation operations.

absolute age. The geologic age (in years) of a fossil, rock, feature, or event. The term is now in disfavor as it implies a certainty or exactness that may not be possible by present dating methods. See "isotopic age" and "radiometric age."

accretion (sedimentary). The gradual addition of new land to an existing landmass by the deposition of sediment, for example, on a beach by the washing up of sand from the sea.

active margin. A tectonically active plate boundary where lithospheric plates are converging, diverging, or sliding past one another.

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

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

aggradation. The building up of Earth's surface by depositional processes.

allochem. A collective term for one of several varieties of discrete and organized carbonate aggregates that serves as the coarser framework grains in most mechanically deposited limestones, as distinguished from sparry calcite (usually cement) and carbonate-mud matrix (micrite).

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.

alluvium. Stream-deposited sediment.

anhydrite. A sulfate (sulfur + oxygen) mineral composed of anhydrous calcium sulfate, $CaSO_4$; readily alters to gypsum (hydrous calcium sulfate).

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks.

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.

aragonite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; the second most abundant cave mineral after calcite, differing from calcite in its crystal structure.

argillaceous. Pertaining to, largely composed of, or containing clay-size particles or clay minerals.

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

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

axis. A straight-line approximation of the trend of a fold along the boundary between its two limbs. "Hinge line" is a preferred term.

badlands. Eroded topography characterized by steep slopes and surfaces with little or no vegetative cover; composed of unconsolidated or poorly cemented clays or silts.

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.

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

bathymetry. The measurement of ocean or lake depths and the charting of the topography of the ocean or lake floor.

beach. The unconsolidated material at the shoreline that covers a gently sloping zone, typically with a concave profile, extending landward from the low-water line to the place where there is a definite change in material or physiographic form (e.g., a cliff), or to the line of permanent vegetation (usually the effective limit of the highest storm waves).

beach face. The section of the beach normally exposed to the action of wave uprush.

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.

benthic. Pertaining to the ocean bottom or organisms living on or in substrate; also, referring to that environment.

bentonite. Soft clay or greasy claystone composed mostly of the clay mineral smectite, formed by the chemical alteration of glassy volcanic ash in contact with water.

bioherm. A moundlike, domelike, lenslike, or reeflike mass of rock built up by sedentary organisms, composed almost exclusively of their calcareous remains, and enclosed or surrounded by rock of different lithology.

bioturbation. The reworking of sediments by organisms.

body fossil. Evidence of past organisms such as bones, teeth, shells, or leaf imprints.

boundstone. A term used for a sedimentary carbonate rock whose original components were bound together during deposition and remained substantially in the position of growth (as shown by such features as intergrown skeletal matter and lamination contrary to gravity).

brachiopod. Any marine invertebrate belonging to the phylum Brachiopoda, characterized by two bilaterally symmetrical valves that are commonly attached to a substratum but may also be free. Range: Lower Cambrian to Holocene.

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

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

brecciation. Formation of a breccia, as by crushing or breaking a rock into angular fragments.

bryozoan. Any invertebrate belonging to the phylum Bryozoa; characterized by colonial growth and a calcareous skeleton. Range: Ordovician (and possibly Upper Cambrian) to Holocene.

burrow. A tubular or cylindrical hole or opening, made in originally soft or loose sediment by a mud-eating worm, mollusk, or other invertebrate; may be later filled with clay or sand and preserved.

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

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

calcic. Describes a mineral or igneous rock containing a significant amount of calcium.

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

calcrete. A deposit of calcium carbonate that forms a cemented layers within a soil profile. Synonymous with "caliche," especially used in the southwestern United States.

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

carbonaceous. Describes a rock or sediment with considerable carbon, especially organic material, hydrocarbon, or coal.

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.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of a sedimentary rock, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

cephalopod. A marine mollusk of the class Cephalopoda, characterized by a head surrounded by tentacles and, in most fossil forms, a straight, curved, or coiled calcareous shell divided into chambers. Range: Cambrian to Holocene.

chalcedony. A cryptocrystalline variety of quartz.

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.

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition providing more stability in the current environment.

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

chronology. The arrangement of events in their proper sequence in time.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

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.

claystone (sedimentary). An indurated rock with more than 67% clay-sized minerals.

coal. An organic sedimentary rock consisting of carbon, hydrogen, and oxygen, with some sulfur and nitrogen. Formed by the destructive distillation of plant remains under anaerobic and progressively rising pressures and temperatures.

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).

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

compaction. The process whereby fine-grained sediment is converted to consolidated rock.

compression. A decrease in volume of material (including Earth's crust) as it is pressed or squeezed together.

concordant. Describes a stratum with contacts parallel to the orientation of adjacent strata.

concretion. A hard, compact aggregate of mineral matter, rounded to irregularly shaped; composition generally differs from that of the rock in which it occurs.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in) in diameter.

conodont. One of a number of small fossil elements assigned to the order Conodontophorida; commonly toothlike in form but not necessarily in function.

contact. The surface between two types or ages of rocks.

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

coprolite. Fossilized feces.

coral. Any of a large group of bottom-dwelling, sessile, marine invertebrate organisms (polyps) that belong to the class Anthozoa (phylum Cnidaria), characterized by production of an external skeletons of calcium carbonate; may exist as solitary individuals or grow in colonies. Range: Abundant in the fossil record in all periods later than the Cambrian.

craton. The relatively old and geologically stable interior of a continent.

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate; "arms" are used to capture food. Range: Paleozoic to Holocene, through very common in the Paleozoic and rare today.

cross-bed. A single bed, inclined at an angle to the main planes of stratification; the term is commonly restricted to a bed that is more than 1 cm (0.4 in) thick.

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

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).

cross-stratification. Arrangement of strata inclined at an angle to the main stratification. This is a general term that is commonly divided into cross-bed, which is cross-strata thicker than 1 cm (0.4 in); and cross-lamination, which is cross-strata thinner than 1 cm (0.4 in).

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.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

cycad. A member of a group of seed-bearing plants (Cycadales) with pinnately compound leaves, poorly developed wood, and ovules borne on loosely or compactly arranged spore-bearing leaves in terminal cones. Range: late Carboniferous (?) to Holocene.

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less than 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

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.

delta plain. The level or nearly level surface composing the landward part of a large or compound delta; strictly, an alluvial plain characterized by repeated channel bifurcation and divergence, multiple distributary channels, and interdistributary flood basins.

dendritic. Describes a branching pattern.

desiccation. A complete or nearly complete drying-out or drying-up.

detrital. Pertaining to or formed from detritus.

detrital mineral. Any mineral grain resulting from mechanical disintegration of parent rock, especially a heavy mineral found in a sediment, or weathered and transported from a vein or lode and found in a placer or alluvial deposit.

detritus. Loose rock and mineral material that is worn off or removed by mechanical processes.

differential erosion. Erosion that occurs at irregular or varying rates due to differences in the resistance and hardness of surface material: softer and weaker rocks are rapidly worn away; harder and more resistant rocks remain to form ridges, hills, or mountains.

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

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

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

discordant. Describes an igneous intrusion having contacts that are not parallel to foliation or bedding in the country rock.

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

dolomite (rock). A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a rock containing dolomite, especially one that contains 5%–50% of the mineral dolomite in the form of cement and/or grains or crystals.

dome. Any smoothly rounded landform or rock mass; more specifically, an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion in which cutting is directed primarily downward, as opposed to laterally.

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.

dune field. Extensive deposits of sand in an area where the supply is abundant; individual dunes resemble barchans dunes but are highly irregular in shape and crowded.

emergence. A change in the levels of water and land such that the land is relatively higher and areas formerly under water are exposed; results from either an uplift of land or fall of water level.

entrenched meander. An incised meander carved downward into the surface of the valley in which the meander originally formed; preserves its original pattern with little modification, suggesting rejuvenation of a meandering stream as a result of rapid vertical uplift or a lowering of base level; exhibits a symmetric cross profile in a gorge or canyon setting.

ephemeral lake. A short-lived lake.

ephemeral stream. A stream that flows briefly, only in direct response to precipitation, and whose channel is always above the water table.

erg. A regionally extensive tract of sandy desert.

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."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix.

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).

exfoliation. The spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by a change in heat or a reduction in pressure when overlying rocks erode away.

extension. Deformation of Earth's crust whereby rocks are pulled apart.

extrusive. Describes an igneous rock that has been erupted onto the surface of the Earth. Extrusive rocks include lava flows and pyroclastic material such as volcanic ash.

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

fenestral. Having openings or transparent areas in a rock.

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).

fissile. Capable of being easily split along closely spaced planes.

flat slab subduction. Refers to the subduction of one tectonic plate beneath another at a relatively shallow angle.

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.

fluvial channel. A natural passageway or depression produced by the action of a stream or river.

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

foliation. A preferred arrangement of crystal planes in minerals. Primary foliation develops during the formation of a rock and includes bedding in sedimentary rocks and flow layering in igneous rocks. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas. Secondary foliation develops during deformation and/or metamorphism and includes cleavage, schistosity, and gneissic banding.

footwall. The lower wall of a fault.

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.

freeze-thaw. The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing water in pores, cracks, and other openings of rock and unconsolidated deposits, usually at the surface.

friable. Describes a rock or mineral that is easily crumbled.

frost wedging. A type of mechanical disintegration, splitting, or breakup of a rock by which jointed rock is pried and dislodged by ice acting as a wedge.

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.

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).

grainstone. A mud-free (less than 1% of material with diameter less than 20 micrometers), grain-supported, carbonate sedimentary rock.

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.

groundmass. The finer grained and/or glassy material between the large crystals of an igneous rock. Also, sometimes used for the matrix of a sedimentary rock.

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

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

hanging wall. The upper wall of a fault.

hematite. An oxide mineral composed of oxygen and iron, Fe_2O_3.

heterogeneous. Consisting of dissimilar or diverse ingredients or constituents.

homogeneous. Of uniform structure or composition throughout.

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.

ichnofossil. A trace fossil such as a fossil footprint, track, or burrow.

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.

imbrication. Consistent orientation of rocks or their clasts; commonly displayed by pebbles on a stream bed that have been tilted by flowing water so that their flat surfaces dip upstream.

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.

induration. Hardening by heat, pressure, or the introduction of cementing material, especially the process by which relatively consolidated rock is made harder or more compact.

interdune. The relatively flat surface between dunes, commonly a long, troughlike, wind-swept passage between parallel dunes; may be covered with sand or sand free.

intrusion. The process of emplacement of magma into preexisting rock. Also, the igneous rock mass formed.

intrusive. Pertaining to intrusion, both the process and the rock body.

island arc. A offshore, generally curved belt of volcanoes above a subduction zone.

isotopic age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products.

isotopic dating. Calculating an age in years for geologic materials by measuring the presence of a short-lived radioactive element (e.g., carbon-14) or by measuring the presence of a long-lived radioactive element plus its decay product (e.g., potassium-40/argon-40). The term applies to all methods of age determination based on nuclear decay of naturally occurring radioactive isotopes.

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

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.

laccolith. A mushroom-shaped pluton that has intruded sedimentary strata and domed up the overlying sedimentary layers.

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

lag gravel. An accumulation of coarse material remaining on a surface after finer material has been blown or washed away.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

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.

left-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the left. Synonymous with "sinistral fault."

lens. A sedimentary deposit that resembles a convex lens and is characterized by converging surfaces, thick in the middle and thinning out toward the edges.

lenticular. Resembling in shape the cross section of a lens.

limb. One side of a structural fold.

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

lithification. The conversion of sediment into solid rock.

lithify. To change to stone, especially to consolidate from a loose sediment to a solid rock.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit distinguished from adjacent subdivisions on the basis of lithology.

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.

losing stream. A stream that loses water or disappears as it flows downstream. The water infiltrates into the ground or into underground void spaces.

lower flow regime. A condition of stream flow that is characterized by a unidirectional current and relatively low sediment transport rates.

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

marker bed. A well-defined, easily identifiable stratum or body of strata that has sufficiently distinctive characteristics (such as lithology or fossil content) to facilitate correlation in field mapping or subsurface work. Also, a geologic formation that serves as a marker.

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to "erosion," the debris removed is not carried within, on, or under another medium. Synonymous with "slope movement."

meander. One of a series of sinuous curves, bends, or turns in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

mechanical weathering. The physical breakup of rocks without change in composition.

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

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

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

metamorphic rock. Any rock derived from preexisting rocks that was altered in response to marked changes in temperature, pressure, shearing stress, and chemical environment. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

micrite. A descriptive term for the semiopaque crystalline matrix of limestones, consisting of carbonate mud and interpreted as a lithified ooze.

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

mold. An impression made in the surrounding earth by the exterior or interior of a fossil shell or other organic structure and then preserved. Also, a cast of the inner surface of a fossil shell.

monocline. A one-limbed fold in strata that are otherwise flat-lying.

monument. An isolated pinnacle, column, or pillar of rock resulting from erosion that resembles a human-made monument or obelisk.

montmorillonite. A clay mineral of the smectite group, which is common in soils, sedimentary rocks, and some mineral deposits. Smectite minerals are derived from the alteration of volcanic glass and the weathering of primary silicates.

mud crack. A crack formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

mudstone (carbonate sedimentary rock). A carbonate mud-supported sedimentary rock containing less than 10% grains (particles with diameters greater than 20 micrometers).

mudstone (clastic sedimentary rock). An indurated mud having the texture and composition of shale, but lacking its fine lamination or fissility.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

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

ooid. An individual spherite or an oolitic rock; an oolith.

oolite. A sedimentary rock, usually a limestone, made up chiefly of ooliths cemented together.

oolith. One of the small round or ovate accretionary bodies in a sedimentary rock, resembling the roe of fish, and having diameters of 0.25–2 mm (0.01–0.08 in).

orogeny. A mountain-building event.

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

outwash. Glacial sediment transported and deposited by meltwater streams.

packstone. A sedimentary carbonate rock whose granular material is arranged in a self-supporting framework, yet also contains some matrix of calcareous mud.

paleogeography. The study, description, and reconstruction of the physical landscape in past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

paleosol. An soil layer preserved in the geologic record.

Pangea. A supercontinent that existed from about 300 million to about 200 million years ago and included most of the continental crust of the Earth, from which the present continents were derived by fragmentation and continental drift. During an intermediate stage of the fragmentation—between the existence of Pangea and that of the present continents—Pangea split into two large fragments, Laurasia in the Northern Hemisphere and Gondwana in the Southern Hemisphere.

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

parent rock. Rock from which soil, sediment, or other rock is derived.

passive margin. A continental plate boundary where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another.

peat. An accumulation of partly decomposed plant remains in swampy lowlands. It is an early stage or rank in the development of coal.

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

pediment. A gently sloping, erosional bedrock surface at the foot of a mountain or plateau escarpment.

pelecypod. Any benthic aquatic mollusk belonging to the class Pelecypoda, characterized by a bilaterally symmetrical bivalve shell, a hatchet-shaped foot, and sheetlike gills. Range: Ordovician to Holocene.

peloid. An allochem composed of micrite (carbonate mud), irrespective of size or origin, for which exact origin is unknown.

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.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or unconsolidated deposit.

pictograph. A picture painted on a rock by primitive peoples.

piedmont. A gently sloping area at the base of a mountain front. Synonymous with "bajada." Also, describes a feature (e.g., plain, slope, or glacier) that lies or formed at the base of a mountain or mountain range.

piping. Erosion or solution by percolating water in a layer of subsoil, resulting in the formation of narrow conduits, tunnels, or "pipes" through which soluble or granular soil material is removed.

placer. A concentrated deposit of minerals, usually heavy, such as gold, cassiterite, or rutile, in a beach or stream deposit.

placer mining. The extraction of metals or minerals from placers, usually involves running water.

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

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

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.

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

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."

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

radiometric age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. The preferred term is "isotopic age."

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.

regolith. From the Greek "rhegos" (blanket) + "lithos" (stone), the layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and eolian deposits, vegetal accumulations, and soil.

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

relative dating. The chronological placement and ordering of rocks, events, or fossils with respect to the geologic time scale and without reference to numerical ages.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall.

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right.

rincon. Meaning "inside corner or nook" in Spanish and used in the southwestern United States for a square-cut recess or hollow in a cliff or a reentrant in the borders of a mesa or plateau. Also used for a small, secluded valley, and for a bend in a stream.

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

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.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sabkha. Any flat area, either coastal or interior, where saline minerals crystallize near or at the surface as a result of deflation or evaporation.

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."

scour. The powerful and concentrated clearing and digging action of flowing water, air, or ice.

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.

siliciclastic. Describes noncarbonate clastic rocks.

siliceous. Describes a rock or other substance containing abundant silica.

sill. An igneous intrusion that parallels the bedding of preexisting sedimentary rock or the foliation of preexisting metamorphic rock.

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.

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

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."

slope wash. Soil and rock material that is or has been transported down a slope under the force of gravity and assisted by running water not confined to channels; also, the process by which slope-wash material is moved.

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

smectite. A group of expanding-lattice clay minerals derived from the alteration of volcanic glass and from the weathering of primary silicates.

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

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

spalling. The process by which scales, plates, or flakes of rock, from less than a centimeter to several meters thick, successively fall from the bare surface of a large rock mass; a form of exfoliation.

spicules. One of the numerous minute calcareous or siliceous bodies, having highly varied and often characteristic forms, occurring in and serving to stiffen and support the tissues of various invertebrates, and frequently found in marine-sediment samples and in Paleozoic and Cretaceous chert. Example: a discrete, needle-like skeletal element of a sponge.

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.

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

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

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

stream capture. The natural diversion of the headwaters of one stream into the channel of another stream having greater erosional activity. Synonymous with “stream piracy.”

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.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

stromatolite. An sedimentary structure produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes (blue-green algae); occurs in a variety of forms, from nearly horizontal to markedly columnar, domal, or subspherical.

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.

subduction. The process of one lithospheric plate descending beneath another.

subduction zone. A long, narrow belt in which subduction takes place.

submarine. Something situated or living under the surface of the sea.

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

suture. The linear zone where two continental landmasses become joined via obduction.

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks.

system (stratigraphy). The fundamental unit of chronostratigraphic classification of Phanerozoic rocks; each unit represents a time span and an episode of Earth history sufficiently great to serve as a worldwide reference unit. It is the temporal equivalent of a period.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have fallen.

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

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

terrace. 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.

terrigenous. Describes material or a feature derived from the land or a continent.

thrust fault. A dip-slip fault with a shallowly dipping (less than 45°) fault surface where the hanging wall moves up and over relative to the footwall.

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."

transform fault. A strike-slip fault that links two other faults or plate boundaries such as two segments of a mid-ocean ridge.

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

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

trilobite. Any marine arthropod belonging to the class Trilobita, characterized by a three-lobed ovoid outer skeleton, divided lengthwise into axial and side regions and transversely into cephalon ("head"), thorax (middle), and pygidium ("tail"). Range: Lower Cambrian to Permian.

tufa. A chemical sedimentary rock composed of calcium carbonate, formed by evaporation commonly as an incrustation around the mouth of a spring, along a stream, or less commonly as a thick, concretionary deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. The hard, dense variety of travertine.

type locality. The place where a geologic feature such as an ore occurrence, a particular kind of igneous rock, or the type specimen of a fossil species was first recognized and described.

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.

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.

undercutting. The removal of material at the base of a steep slope by the erosive action of water (such as a meandering stream), sand-laden wind in a desert, or waves along a coast.

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

upper flow regime. A condition of stream flow that is characterized by a unidirectional current and relatively high sediment transport rates.

vesicle. A cavity of variable shape formed by the entrapment of a gas bubble during solidification of lava.

vesicular. Describes the texture of a rock, especially lava, characterized by abundant vesicles formed as a result of the expansion of gases during the fluid stage of a lava.

volcanic. Pertaining to the activities, structures, or rock types of a volcano. A synonym of extrusive.

wackestone. A term for a mud-supported carbonate sedimentary rock containing more than 10% grains (particles with diameters greater than 20 micrometers).

wash. A broad, gravelly, dry stream bed, generally in the bottom of a canyon that is periodically swept by a torrent of water. The term is used especially in the southwestern United States.

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.

Agenbroad, L. D., and J. I. Mead. 1989. Quaternary geochronology and distribution of Mammuthus on the Colorado Plateau. Geology 17(9):861–864.

Agenbroad, L.D., and J. I. Mead. 1990. Investigations of a newly discovered Pleistocene megafaunal dung bed and alluvial sequences in S. E. Utah. Pages 58–69 in L. Agenbroad, J. Mead, R. Hevly, S. Clay-Poole, and G. Judges-Edwards, editors. Quaternary studies: Canyonlands National Park and Glen Canyon Recreational Area. USDI-NPS Contract CX-1200-4-AO62. Northern Arizona University, Flagstaff, Arizona.

Agenbroad, L. D., J. I. Mead, E. M. Mead, and D. Elder. 1989. Archaeology, alluvium, and cave stratigraphy: the record from Bechan Cave, Utah. Kiva 54(4): 336–351.

Ahlbrandt, T. S., and S. G. Fryberger. 1982. Introduction to eolian deposits. Pages 11–49 in P. A. Scholle and D. Spearing, editors. Sandstone depositional environments. American Association of Petroleum Geologists, Tulsa, Oklahoma.

Albright, L. B. III, D. D. Gillette, and A. L. Titus. 2007a. Plesiosaurs from the Upper Cretaceous (Cenomanian-Turonian) Tropic Shale of southern Utah: Part 1, new records of the pliosaur *Brachauchenius lucasi*. Journal of Vertebrate Paleontology 27(1):31–40.

Albright, L. B. III, D. D. Gillette, and A. L. Titus. 2007b. Plesiosaurs from the Upper Cretaceous (Cenomanian-Turonian) Tropic Shale of southern Utah: Part 2, Polycotylidae. Journal of Vertebrate Paleontology 27(1):41–58.

Allen, P. A., J. E. Verlander, P. M. Burgess, and D. M. Audet. 2000. Jurassic giant erg deposits, flexure of the United States continental interior, and timing of the onset of Cordilleran shortening. Geology 28(2):159–162.

Alvarez, W., E. Staley, D. O'Connor, and M. A. Chan. 1998. Synsedimentary deformation in the Jurassic of southeastern Utah—a case of impact shaking? Geology 26:579–582.

Anderson, P. B., G. C. Willis, T. C. Chidsey, Jr., and D. A. Sprinkel. 2010. Geology of Glen Canyon National Recreation Area, Utah-Arizona. Pages 309–347 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Anderson, R. S., J. L. Betancourt, J. I. Mead, R. H. Hevly, and D. P. Adam. 2000. Middle-and late-Wisconsin paleobotanic and paleoclimatic records from the southern Colorado Plateau, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 155(1–2):31–57.

Ashland, F. X. 2003. Characteristics, causes, and implications of the 1998 Wasatch Front landslides, Utah. Special Study 105. Utah Geological Survey, Salt Lake City, Utah.

Baars, D. L. 1962. Permian system of Colorado Plateau. American Association of Petroleum Geologists Bulletin 46(2):149–218.

Baars, D. L. 2010. Geology of Canyonlands National Park, Utah. Pages 61–85 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Baars, D. L., and W. R. Seager. 1967. Depositional environments of White Rim Sandstone (Permian), Canyonlands National Park, Utah. Bulletin 51. The American Association of Petroleum Geologists, Tulsa, Oklahoma.

Baker, A. A. 1929. Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado. American Association of Petroleum Geologists Bulletin 13(11):1413–1448.

Bates, B. C., Z. W. Kundzewicz, S. Wu and J. P. Palutikof, editors. 2008. Climate Change and Water. Technical Paper VI. Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, Switzerland. http://ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf (accessed 21 September 2015).

Baxter, S. 2008. Tar sands: worth the energy? An analysis of the future of Utah's tar sands. Utah Environmental Law Review 27(3):323–344. http://epubs.utah.edu/index.php/jlrel/article/view/54/47 (accessed 5 May 2015).

Biek, R. F., P. D. Rowley, J. M. Hayden, D. B. Hacker, G. C. Willis, L. F. Hintze, R. E. Anderson, and K. D. Brown. 2009. Geologic map of the St. George and east part of the Clover Mountains 30'x60' quadrangles, Washington and Iron Counties, Utah (scale 1:100,000). Map 242. Utah Geological Survey, Salt Lake City, Utah.

Biek, R. F., G. C. Willis, M. D. Hylland, and H. H. Doelling. 2010. Geology of Zion National Park, Utah. Pages 109–145 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Billingsley, G. H., and S S. Priest. 2010. Geologic map of the House Rock Valley area, Coconino County, northern Arizona (scale 1:50,000). Scientific Investigations Map 3108. US Geological Survey, Washington, DC.

Birkeland, P. W., M. N. Machette, and K. M. Haller. 1991. Soils as a tool for applied Quaternary geology. Miscellaneous Publication 91-3. Utah Geological Survey, Salt Lake City, Utah.

Bishop, C. E., and B. T. Tripp. 1993. An overview of the Tar Sand resources of Utah. American Association of Petroleum Geologists Bulletin 77(8):1443.

Blakey, R. C. 1974. Stratigraphic and depositional analysis of the Moenkopi Formation, southeastern Utah. Bulletin 104. Utah Geological and Mineral Survey, Salt Lake City, Utah.

Blakey, R. C. 1994. Paleogeographic and tectonic controls on some Lower and Middle Jurassic erg deposits, Colorado Plateau. Pages 273–298 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, Colorado.

Blakey, R., and W. Ranney. 2008. Ancient landscapes of the Colorado Plateau: Grand Canyon, Arizona. Grand Canyon Association, Grand Canyon, Arizona.

Breit, G. N., and J. D. Meunier. 1990. Fluid inclusion, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ evidence for the origin of fault-controlled copper mineralization, Lisbon Valley, Utah, and Slick Rock district, Colorado. Economic Geology 85:884–891.

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://go.nps.gov/seismic_monitoring (accessed 13 April 2015).

Bureau of Land Management. 2015. Abandoned mine lands: Utah. http://www.blm.gov/ut/st/en/prog/more/Abandoned_Mine_Lands.html (accessed 22 September 2015).

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. https://www.nps.gov/subjects/abandonedminerallands/publications.htm (accessed 4 May 2015).

Chan, M. A., and W. T. Parry. 2002. Rainbow of rocks—mysteries of sandstone colors and concretions in Colorado Plateau canyon country. Public Information Series 77. Utah Geological Survey, Salt Lake City, Utah.

Chan, M. A., B. Beitler, W. T. Parry, J. Ormo, and G. Komatsu. 2004. A possible terrestrial analogue for hematite concretions on Mars. Nature 429:731–734.

Chidsey, Jr., T. C., G. D. Willis, D. A. Sprinkel, and P. B. Anderson. 2000a. Geology of Rainbow Bridge National Monument, Utah. Pages 250–262 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Chidsey, Jr., T. C., D. A. Sprinkel, G. C. Willis, P. B. Anderson. 2000b. Geologic lake guide along Lake Powell, Glen Canyon National Recreation Area and Rainbow Bridge National Monument, Utah-Arizona. Pages 1–76 in P. B. Anderson and D. A. Sprinkel, editors. Geologic road, trail, and lake guides to Utah's Parks and Monuments. Publication 29. Utah Geological Association, Salt Lake City, Utah. http://www.utahgeology.org/road_logs/uga-29_first_edition/NR_guide/lakepowe.pdf (accessed 1 February 2015).

Chidsey, T. C., Jr., D. A. Sprinkel, G. C. Willis, and P. B. Anderson. 2012. Geologic lake guide along Lake Powell, Glen Canyon National Recreation Area and Rainbow Bridge National Monument, Utah-Arizona. In P. B. Anderson and D. A. Sprinkel, editors. Geologic Road, Trail, and Lake Guides to Utah's Parks and Monuments (3rd edition). Utah Geological Association, Salt Lake City, Utah.

Chidsey, T. C., Jr., J. S. DeHammer, E. E. Hartwick, K. R. Johnson, D. D. Schelling, D. A. Sprinkel, D. K. Strickland, J. P. Vrona, and D. A. Wavrek. 2007. Petroleum geology of the Covenant field, central Utah thrust belt. Pages 273–296 in G. C. Willis, M. D. Hylland, D. L. Clark, and T.C. Chidsey, Jr., editors. Central Utah—diverse geology of a dynamic landscape. Publication 36. Utah Geological Association, Salt Lake City, Utah.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier and R. N. Palmer. 2004. The effects of climate change on the hydrology and water resources of the Colorado River basin. Climatic Change 62(1–3):337–363. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.458.1998&rep=rep1&type=pdf (accessed 21 September 2015).

Christiansen, E. II, B. J. Kowallis, and M. D. Barton. 1994. Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior: an alternative record of Mesozoic magmatism. Pages 73–94 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. SEPM (Society for Sedimentary Geology), Rocky Mountain Section, Denver, Colorado.

Colbert, E. H. 1974. Mesozoic vertebrates of northern Arizona. Pages 208–219 in N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, editors. Geology of northern Arizona, with notes on archaeology and paleoclimate, Part 1: Regional studies. Geological Society of America, Rocky Mountain Section, Flagstaff, Arizona.

Colorado Riverkeeper. 2005. The one-dam solution. Report to the Bureau of Reclamation. http://livingrivers.org/pdfs/TheOne-DamSolution.pdf (accessed 16 September 2015).

Condon, S. M. 1997. Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, southeastern Utah and southwestern Colorado. Bulletin 2000-P. US Geological Survey, Washington, DC.

Cook, B. I., T. R. Ault, and J. E. Smerdon. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances 1(1):1–7. http://advances.sciencemag.org/content/1/1/e1400082 (accessed 5 May 2015).

Cook, K. L., K. X. Whipple, A. M. Heimsath, and T. C. Hanks. 2009. Rapid incision of the Colorado River in Glen Canyon: insights from channel profiles, local incision rates, and modeling of lithologic controls. Earth Surface Processes and Landforms 34(7):994–1010.

Dana, G. F., D. J. Sinks, and R. Oliver. 1984. Tar Sand Triangle—largest United States tar sand deposit. American Association of Petroleum Geologists Bulletin 68(7):935.

Davidson, E. S. 1967. Geology of the Circle Cliffs area, Garfield and Kane Counties, Utah. Bulletin 1229. US Geological Survey, Washington, DC.

Davis, J. M. 2013. Physical, chemical, and biological characteristics of weathering pits, Moab, Utah. Dissertation. University of Utah, Salt Lake City, Utah.

DeCelles, P. G. 2004. Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A. American Journal of Science 304 (2):105–168.

Degenhardt, J. J., D. I. Netoff, C. Baldwin, and J. Dohrenwend. 2009. Results of a recent ground penetrating radar (GPR) survey along the Hite Delta, Lake Powell, Utah. Geological Society of America Abstracts with Programs 41(7):133.

DesertUSA. 2015. Lake Powell–Glen Canyon Dam. http://www.desertusa.com/colorado/GlennNRA/du_lpstory.html (accessed 27 January 2015).

De Voto, R. H. 1980. Pennsylvanian stratigraphy and history of Colorado. Pages 71–102 in H. C. Kent and K. W. Porter, editors. Colorado geology. Rocky Mountain Association of Geologists, Denver, Colorado.

Dickinson, W.R., and G. E. Gehrels. 2003. U-Pb ages of detrital zircons from Permian and Jurassic eolian sandstones of the Colorado Plateau, USA—paleogeographic implications. Sedimentary Geology 163(1-2):29–66.

Dickinson, W.R., and G. E. Gehrels. 2009. U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau—evidence for transcontinental dispersal and intraregional recycling of sediment. Geological Society of America Bulletin 121(3 and 4):408–433.

Dionne, J. C. 1973. Monroes: a type of so-called mud volcanoes in tidal flats. Journal of Sedimentary Petrology 43:848–856.

Doelling, H. H. 1968. Southern Utah oddities lure rock hounds. Utah Geological Survey Quarterly Review 2(3):7.

Doelling, H. H. 1975. Geology and mineral resources of Garfield County, Utah. Bulletin 107. Utah Geological and Mineral Survey, Salt Lake City, Utah.

Doelling, H. H. 2010. Geology of Arches National Park, Utah. Pages 11–37 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Doelling, H. H., and F. D. Davis. 1989. Geology of Kane County, Utah. Bulletin 124, Utah Geological Survey, Salt Lake City, Utah.

Doelling, H. H., and G. C. Willis. 2006. Geologic map of the Smoky Mountain 30' x 60' quadrangle, Kane and San Juan Counties, Utah, and Coconino County, Arizona (scale 1:100,000). Map 213. Utah Geological Survey, Salt Lake City, Utah.

Doelling, H. H., and G. C. Willis. 2008. Geologic map of the lower Escalante River area, Glen Canyon National Recreation Area, eastern Kane County, Utah (scale 1:100,000). Miscellaneous Publication 06-3DM. Utah Geological Survey, Salt Lake City, Utah.

Doelling, H. H., R. E. Blackett, A. H. Hamblin, J. D. Powell, and G. L. Pollock. 2010. Geology of Grand Staircase-Escalante National Monument, Utah. Pages 193–237 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Doelling, H. H., D. A. Sprinkel, B. J. Kowallis, and P. A. Kuehne. 2013. Temple Cap and Carmel formations in the Henry Mountains Basin, Wayne and Garfield Counties, Utah. Pages 279–318 in T. H. Morris and R. Ressetar, editors. The San Rafael Swell and Henry Mountains Basin-geologic centerpiece of Utah. Publication 42. Utah Geological Association, Salt Lake City, Utah.

Downs, K. C., and D. J. Wronkiewicz. 2007. Formation of iron-rimmed sandstone nodules; mechanism of formation and terrestrial analogue for Martian blueberries? Geological Society of America Abstracts with Programs 39(6):283.

Dubiel, R. F. 1994. Triassic deposystems, paleogeography, and paleoclimate of the Western Interior. Pages 133–168 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. SEPM (Society for Sedimentary Geology), Rocky Mountain Section, Denver, Colorado.

Dunham, R. J. 1962. Classification of carbonate rocks according to depositional texture. Pages 108–121 in W. E. Ham, editor. Classification of carbonate rocks. Memoir 1. American Association of Petroleum Geologists, Tulsa, Oklahoma.

Elder, W. P., and Kirkland, J. I. 1994. Cretaceous paleogeography of the southern Western Interior region. Pages 415–440 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain Region, USA. Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, Colorado.

Engelmann, G. F. 1999. Stratigraphic and geographic distribution of fossils in the upper part of the Upper Jurassic Morrison Formation of the Rocky Mountain region. Pages 115–120 in D. D. Gillette, editor. Vertebrate paleontology in Utah. Publication 99-1. Utah Geological Survey, Salt Lake City, Utah.

Environmental Protection Agency. 2015. Colorado cleanup sites. http://www2.epa.gov/region8/colorado-cleanup-sites (accessed 22 September 2015).

Everhart, R. E. 1983. Glen Canyon-Lake Powell – the story behind the scenery. KC Publications, Inc., Las Vegas, Nevada.

Fessenden, M. 2015. Utah has the first tar sands mine in the U.S. Smithsonian.com. http://www.smithsonianmag.com/smart-news/utah-has-first-tar-sands-mine-us-180956393/?no-ist (accessed 26 August 2015).

Finnell, T. L., P. C. Franks, and H. A. Hubbard. 1963. Geology, ore deposits, and exploratory drilling in the Deer Flat area, White Canyon District, San Juan County, Utah. Bulletin 1132. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/usgspubs/b/b1132 (accessed 27 March 2015).

Foster, J. R. 2002. Vertebrate track sites in the Chinle Formation (Late Triassic) of the Circle Cliffs area, southern Utah. Abstracts with Programs - Geological Society of America 34(4):6.

Gardner, T. W. 1975. The history of part of the Colorado River and its tributaries-an experimental study in Canyonlands. 8th Field Conference Guidebook. Four Corners Geological Society, Durango, Colorado.

Garvin, C. D., T. C. Hanks, R. C. Finkel, and A. M. Heimsath. 2005. Episodic incision of Colorado River in Glen Canyon, Utah. Geological Society of America Abstracts with Programs 37(7):110.

Geib, P. R., and H. C. Fairley. 1997. Archaeological research in the new monument: lessons from Glen Canyon. Pages 53–63 in L. M. Hill, editor. Learning from the land: Grand Staircase-Escalante national Monument science symposium proceedings. Bureau of Land Management, National Applied Resource Sciences Center, Salt Lake City, Utah.

Gilbert, G. K. 1877. Report on the geology of the Henry Mountains. Rocky Mountain Region, US Geographical and Geological Survey, Denver, Colorado.

Gilland, J. K. 1979. Paleoenvironment of a carbonate lens in the lower Navajo Sandstone near Moab, Utah. Utah Geology 6(1):29–38.

Glazner, A.F., and G.M. Stock. 2010. Geology underfoot in Yosemite National Park. Mountain Press Publishing Company, Missoula, Montana.

Graf, W. L. 1989. Holocene lacustrine deposits and sediment yield in Lake Canyon, southeastern Utah. National Geographic Research 5:146–160.

Graham, J. 2004. Arches National Park geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR–2004/005. National Park Service, Geologic Resources Division, Denver, Colorado. http://go.nps.gov/gripubs (accessed 1 February 2015).

Graham, J. 2006a. Capitol Reef National Park geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2006/005. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs (accessed 26 February 2015).

Graham, J. 2006b. Zion National Park geologic resources evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR–2006/014. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs (accessed 28 February 2015).

Graham, J. 2006c. Dinosaur National Monument geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2006/008. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs (accessed 28 March 2015).

Graham, J. 2007. Navajo National Monument geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR–2007/005. National Park Service, Geologic Resources Division, Denver, Colorado. http://go.nps.gov/gripubs (accessed 3 February 2015).

Graham, J. 2009. Rainbow Bridge National Monument geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR–2009/131. National Park Service, Geologic Resources Division, Denver, Colorado. http://go.nps.gov/gripubs (accessed 26 January 2015).

Grams, P. E., J.C. Schmidt, and D. J. Topping. 2005. A comprehensive history of bed degradation and channel adjustment for the Colorado River within Glen Canyon National Recreation Area downstream from Glen Canyon Dam. Geological Society of America Abstracts with Programs 37(7):331.

Grams, P. E., J.C. Schmidt, and D. J. Topping. 2007. The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000. Geological Society of America Bulletin 119(5/6):556–575.

Grams, P. E., J.C. Schmidt, and D. J. Topping. 2010. Bed incision and channel adjustment of the Colorado River in Glen Canyon National Recreation Area downstream from Glen Canyon Dam. Scientific Investigations Report 2010–5135: Proceedings of the Colorado River Basin science and resource management symposium. US Geological Survey, Scottsdale, Arizona. https://pubs.er.usgs.gov/publication/70029850 (accessed 6 May 2015).

Graversen, O., J. Milan, and D. B. Loope. 2007. Dinosaur tectonics: a structural analysis of theropod undertracks with a reconstruction of theropod walking dynamics. Journal of Geology 115(6):641–654.

Gregory, H. E., and R. C. Moore. 1931. The Kaiparowits region: a geographic and geologic reconnaissance of parts of Utah and Arizona. Professional Paper 164. US Geological Survey, Reston, Virginia.

Gregory, H. E., and R. W. Stone. 1917. Geology of the Navajo country; a reconnaissance of parts of Arizona, New Mexico, and Utah. Profession Paper 0093-P. US Geological Survey, Reston, Virginia.

Gregson, J. D., D. J. Chure, and D. A. Sprinkel. 2010. Geology and paleontology of Dinosaur National Monument, Utah-Colorado. Pages 161–193 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Hamblin, A. H. 1998. Mesozoic vertebrate footprints in the Grand Staircase-Escalante National Monument, Utah. Journal of Vertebrate Paleontology 18(supplement to 3):48A.

Hanks, T. C., I. Lucchitta, S. W. Davis, M. E. Davis, R. C. Finkel, S. A. Lefton, and C. D. Garvin. 2001. The Colorado River and the age of Glen Canyon. Pages 129–134 in R. A. Young and E. E. Spamer, editors. Colorado River origin and evolution: Grand Canyon, Arizona. Symposium Volume. Grand Canyon Association, Grand Canyon, Arizona.

Harshbarger, J. W., C. A. Repenning, and J. H. Irwin. 1957. Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country. Professional Paper 291. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/usgspubs/pp/pp291 (accessed 27 March 2015).

Hasiotis, S. T. 1992. Fossil and ichnological occurrences from the Upper Triassic Chinle Formation of the Canyonlands vicinity: their paleoecological implications. Geological Society of America Abstracts with Programs 24(6):17.

Hettinger, R.D. 2000. A summary of the coal distribution and geology in the Kaiparowits Plateau, Utah, chapter J. Pages J1-J17 in M. A. Kirschbaum, L. N. R. Roberts, and L. R. H. Biewick, editors. Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah, compiled by Colorado Plateau Coal Assessment Group. Professional Paper 1625-B. US Geological Survey, Washington, DC. http://pubs.usgs.gov/pp/p1625b/Reports/Chapters/Chapter_J.pdf (accessed 4 May 2015).

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/ (accessed 30 April 2015).

Hintze, L. F., and B. J. Kowallis. 2009. Geologic history of Utah. Geology Studies Special Publication 9. Brigham Young University, Provo, Utah.

Hite, R. J. 1970. Shelf carbonate sedimentation controlled by salinity in the Paradox Basin, southeast Utah. Pages 48–66 in J. L. Rau and L. F. Dellwig, editors. Third Symposium on Salt. Northern Ohio Geological Society, Cleveland, Ohio.

Hunt, A. P., V. L. Santucci, J. S. Tweet, and S. G. Lucas. 2012. Vertebrate coprolites and other bromalites in National Park Service areas. Pages 343–354 in Hunt, A. P., J. Milàn, S. G. Lucas, and J. A. Spielmann, editors. Vertebrate coprolites. Bulletin 57. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. http://econtent.unm.edu/cdm/ref/collection/bulletins/id/1805 (accessed 24 August 2015).

Hunt, C. B. 1969. Geologic history of the Colorado River. Professional Paper 669-C. US Geological Survey, Washington, DC.

Hunt, C. B. 1980. Structural and igneous geology of the Henry Mountains, Utah. Pages 25–106 in Picard, M.D., editor. Henry Mountain symposium. Publication 8. Utah Geological Association, Salt Lake City, Utah.

Huntoon, J. E., J. C. Dolson, and B. M. Henry. 1994. Seals and migration pathways in paleogeomorphically trapped petroleum occurrences: Permian White Rim Sandstone, Tar Sand triangle area, Utah. Pages 99–118 in J. C. Dolson, M. L. Hendricks, and W. A Wescott, editors. Unconformity-related hydrocarbons in sedimentary sequences. Rocky Mountain Association of Geologists, Denver, Colorado.

Huntoon, J. E., P. L. Hansley, and N. D. Naeser. 1999. The search for a source rock for the giant Tar Sand Triangle accumulation, southeastern Utah. American Association of Petroleum Geologists Bulletin 83(3):467–495.

Huntoon, J. E., J. D. Stanesco, R. F. Dubiel, and J. Dougan. 2010. Geology of Natural Bridges National Monument, Utah. Pages 237–255 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Huuse, M., S. J. Shoulders, D. I. Netoff, and J. Cartwright. 2004. Giant sandstone pipes record basin-scale liquefaction of buried dune sands in the Middle Jurassic of SE Utah. Terra Nova 17(1):80–85.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate change 2014: impacts, adaptation, and vulnerability. Volume II: North America. http://www.ipcc.ch/report/ar5/wg2/ (accessed 5 May 2015)

Irmis, R. 2005. A review of the vertebrate fauna of the Lower Jurassic Navajo Sandstone. Pages 55–71 in R. D. McCord, editor. Vertebrate paleontology of Arizona. Bulletin 11. Mesa Southwest Museum, Mesa, Arizona.

Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. Global climate change impacts in the United States. Cambridge University Press, Cambridge, United Kingdom. http://www.globalchange.gov/usimpacts (accessed 11 June 2014).

Karlstrom, K. E., R. S. Crow, L. Peters, W. McIntosh, J. Raucci, L. J. Crossey, P. Umhoefer, and N. Dunbar. 2007. 40Ar/39Ar and field studies of Quaternary basalts in Grand Canyon and model for carving Grand Canyon–quantifying the interaction of river incision and normal faulting across the western edge of the Colorado Plateau. Geological Society of America Bulletin 119(11/12):1283–1312.

Karlstrom, K. E., R. Crow, L. J. Crossey, D. Coblentz, and J. W. Van Wijk. 2008. Model for tectonically driven incision of the younger than 6 Ma Grand Canyon. Geology 36(11):835–838.

Kauffman, E. G. 1977. Geological and biological overview: Western Interior Cretaceous basin. Mountain Geologist 14: 75–99.

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://go.nps.gov/gripubs (accessed 2 September 2015).

KellerLynn, K. 2010. Petrified Forest National Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/218. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs (accessed 2 September 2015).

Kirkland, J. I., and J. G. Eaton. 2002. Late Cretaceous freshwater fish from southern Utah with emphasis on fossils from Grand Staircase-Escalante National Monument (GSENM). Geological Society of America Abstracts with Programs 34(4):5.

Kirkland, J. I., S. K. Madsen, D. D. DeBlieux, B. Ehler, L. Weaver, and V. L. Santucci. 2010. Final report for paleontological resources inventory and monitoring at Glen Canyon National Recreation Area. Cooperative agreement #H2360097080. Utah Geological Survey, Salt Lake City, Utah.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19:4545–4959.

Kocurek, G., and R. H. Dott, Jr. 1983. Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountain region. Pages 101–118 in M. W. Reynolds and E. D. Dolly, editors. Mesozoic paleogeography of the West-Central United States. Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colorado.

Lageson, D. R., and J. G. Schmitt. 1994. The Sevier orogenic belt of the western United States: recent advances in understanding its structural and sedimentologic framework. Pages 27–65 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado.

Lake Powell Water Database. 2016. Lakepowell.water-data.com. http://lakepowell.water-data.com/ (accessed 2 September 2015).

Land, L., G. Veni, and D. Joop. 2013. Evaluation of cave and karst programs and issues at US national parks. Report of Investigations 4. National Cave and Karst Research Institute, Carlsbad, New Mexico. http://www.nckri.org/about_nckri/nckri_publications.htm (accessed 25 August 2015).

Langford, R. P., and M. A. Chan. 1987. Relationships and scales of three types of eolian bounding surfaces, Permian Cutler and Cedar Mesa formations, SE Utah. Abstracts – SEPM Midyear Meeting. Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma.

Langford, R. P., K. Duncan, and D. Tatum. 2007. Geomorphology and sequence stratigraphy, linking eolian strata to sea level change, Permian Cedar Mesa Sandstone SE, Utah. Geological Society of America Abstracts with Programs 39(6):437.

Lawton, T. F. 1994. Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States. Pages 1–26 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, Colorado.

Livingston, K. M., E. Bogner, S. M. Ireland, E. L. Simpson, T. A. Betts, and E. Laub. 2014. The geomorphic evolution of shallow-sourced methane produced mud volcanoes, Lake Powell, Hite, Utah. Geological Society of America Abstracts with Programs 46(6):766.

Lockley, M. G., and J. Madsen. 1993. Early Permian vertebrate trackways from the Cedar Mesa Sandstone of eastern Utah: evidence of predator-prey interaction. Ichnos 2(2):147–153.

Lockley, M. G., A. P. Hunt, C. Meyer, E. C. Rainforth, and R.J. Schultz. 1998. A survey of fossil footprint sites at Glen Canyon National Recreation Area (western USA): a case study in documentation of trace fossil resources at a national preserve. Ichnos 5(3):177–211.

Lockley, M. G., R. Kukihara, L. J. Mitchell, L. Newcomb, and K. Cart. 2005. Compiling a database for old and new Mesozoic tracksite discoveries from the Lake Powell area (Utah and Arizona). Geological Society of America Abstracts with Programs 37(6):36.

Loehman, R. 2009. Understanding the science of climate change: talking points - impacts to western mountains and forests. Natural Resource Report NPS/NRPC/NRR—2009/090. National Park Service, Fort Collins, Colorado. http://www.nature.nps.gov/publications/NRPM (accessed 23 September 2015).

Loope, D. B. 1979. Fossil wood and probable root casts in the Navajo Sandstone. Geological Society of America Abstracts with Programs 11(6):278.

Loope, D. B. 1984. Eolian origin of upper Paleozoic sandstones, southeastern Utah. Journal of Sedimentary Petrology 54(2):563–580.

Loope, D. B. 2004. Burrows dug by large vertebrates into rain-moistened Middle Jurassic sand dunes. Journal of Geology 114(6):753–762.

Loope, D. B. 2006. Dry-season tracks in dinosaur-triggered grainflows. Palaios 21(2):132–142.

Loope, D., L. Eisenberg, and E. Waiss. 2004. Navajo sand sea of near-equatorial Pangea: tropical westerlies, slumps, and giant stromatolites. Pages 1–13 in E. P. Nelson, and E. A. Erslev, editors. Field trips in the Southern Rocky Mountains, USA. GSA Field Guide 5. Geological Society of America, Boulder, Colorado.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/fluvial_monitoring (accessed 6 May 2015).

Lucas, S. G. 1993. The Chinle Group – revised stratigraphy and chronology of Upper Triassic nonmarine strata in western United States. Museum of Northern Arizona Bulletin 59:27–50.

Lucas, S. G., A. B. Heckert, J. W. Estep, and O. J. Anderson. 1997. Stratigraphy of the Upper Triassic Chinle Group, Four Corners region. Pages 81–107 in O. J. Anderson, B. S. Kues, and S. G. Lucas, editors. Mesozoic geology and paleontology of the Four Corners region. Guidebook for the 48th Field Conference. New Mexico Geological Society, Socorro, New Mexico.

Lucas, S. G., A. B. Heckert, and L. H. Tanner. 2005. Arizona's Jurassic fossil vertebrates and the age of the Glen Canyon Group. Pages 95–104 in A. B. Heckert, and S. G. Lucas, editors. Vertebrate paleontology in Arizona. Bulletin 29. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Lucchitta, I.1989. History of the Grand Canyon and of the Colorado River in Arizona. Pages 701–715 in J. P. Jenney, and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona.

Lyman, A. R. 1963. Memories of the Pagahrit. Desert Magazine, Palm Desert, California.

Martel, S.J. 2004. Formation of exfoliation joints. American Geophysical Union, Annual Meeting, Abstract T31B–1309.

Martel, S.J. 2006. Effect of topographic curvature on near-surface stresses and application to sheeting joints. Geophysical Research Letters 33:L01308.

Martel, S.J. 2011. Mechanics of curved surfaces, with application to surface-parallel cracks. Geophysical Research Letters 38:L20303.

McCombs, B. 2015. 1st US tar sands mine to open for business in Utah. AP: The Big Story. http://bigstory.ap.org/article/4538f6d59b2f44e792ddc4447388d3fb/1st-us-tar-sands-mine-set-open-business-utah (accessed 21 August 2015).

Mead, J. I., and L. D. Agenbroad. 1992. Isotope dating of Pleistocene dung deposits from the Colorado Plateau, Arizona and Utah. Radiocarbon 34(1):1–19.

Mead, J. I., L. D. Agenbroad, P. S. Martin, and O. K. Davis. 1984. The mammoth and sloth dung from Bechan Cave in southern Utah. Current Research in the Pleistocene 1:79–80.

Melillo, J. M., T. C. Richmond, and G. W. Yohe, editors. 2014. Climate change impacts in the United States: the third national climate assessment. US Global Change Research Program, Washington, DC. http://nca2014.globalchange.gov/ (accessed 11 June 2014).

Melton, R. A. 1972. Paleoecology and paleoenvironment of the upper Honaker Trail Formation near Moab, Utah. Brigham Young University Research Studies, Geology Series 19(2):45–88.

Miller, A. No date. Recent geomorphic changes in the Tropic Shale and potential effects to paleontology resources. Internal report. On-file at Glen Canyon National Recreation Area, Page, Arizona.

Milligan, M. 2012. Sizing up titans–Navajo erg vs. Sahara ergs; which was the larger sand box? Utah Geological Survey Notes 44 (3). http://geology.utah.gov/map-pub/survey-notes/glad-you-asked/navajo-erg-vs-sahara-erg/ (accessed 9 January 2016).

Milner, A. R. C., J. I. Kirkland, and T. A. Birthisel. 2006. The geographic distribution and biostratigraphy of Late Triassic-Early Jurassic freshwater fish faunas of the Southwestern United States. Pages 522–529 in J. D. Harris, S. G. Lucas, J. A. Spielmann, M. G. Lockley, A. R. C. Milner, and J. I. Kirkland, editors. The Triassic-Jurassic terrestrial transition. Bulletin 37. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Mickelson, D. L., J. E. Huntoon, and E. P. Kvale. 2005. The diversity and stratigraphic distribution of pre-dinosaurian communities from the Triassic Moenkopi Formation, Capitol Reef National Park and Glen Canyon National Recreation Area, Utah. Geological Society of America Abstracts with Programs 37(7):440.

Mickelson, D. L., J. E. Huntoon, and E. P. Kvale. 2006. The diversity and stratigraphic distribution of pre-dinosaurian communities from the Triassic Moenkopi Formation. Pages 132–137 in S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://www.nps.gov/subjects/fossils/research-volumes.htm (accessed 2 April 2015).

Millberry, K. W. 1983. Tectonic control of Pennsylvanian fan delta deposition, southwestern Colorado. American Association of Petroleum Geologists Bulletin 67(3):514.

Milner, A. R. C., and J. I. Kirkland. 2006. Preliminary review of the Early Jurassic (Hettangian) freshwater Lake Dixie fish fauna in the Whitmore Point Member, Moenave Formation in southwest Utah. Pages 510–521 in J. D. Harris, S. G. Lucas, J. A. Spielmann, M. G. Lockley, A. R. C. Milner, and J. I. Kirkland, editors. Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition. Bulletin 37. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Morris, T. H., V. W. Manning, and S. M. Ritter. 2010. Geology of Capitol Reef National Park, Utah. Pages 85–109 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

National Park Service. 2007. Weather and global warming. http://www.nps.gov/glca/learn/nature/weather.htm (accessed 5 May 2015).

National Park Service. 2010. Foundation Statement: Grand Canyon National Park. National Park Service Intermountain Region, Denver, Colorado. http://www.nps.gov/grca/learn/management/upload/grca-foundation20100414.pdf (accessed 1 October 2015).

National Park Service. 2013. Foundation document overview: Canyonlands National Park. National Park Service Intermountain Region, Denver, Colorado. http://www.nps.gov/cany/learn/management/upload/CANY_Overview_Final_2013.pdf (accessed 23 September 2015).

National Park Service. 2014a. Foundation document: Glen Canyon National Recreation Area–Rainbow Bridge National Monument. NPS/GLCA/RABR/608/125220. Intermountain Region, National Park Service, Denver, Colorado.

National Park Service. 2014b. Recent climate change exposure of Glen Canyon National Recreation Area. Inventory & Monitoring, National Park Service, Fort Collins, Colorado. http://science.nature.nps.gov/im/inventory/climate/recent.cfm (access 21 September 2015).

National Park Service. 2015a. Glen Canyon: people. http://www.nps.gov/glca/historyculture/people.htm (accessed 27 January 2015.

National Park Service. 2015b. Glen Canyon NRA (GLCA) reports: annual park recreation visitation (1904–last calendar year). https://irma.nps.gov/Stats/Reports/Park (accessed 20 June 2016).

National Park Service. 2015c. Glen Canyon: hanging gardens. http://www.nps.gov/glca/naturescience/hanginggardens.htm (accessed 1 February 2015).

National Park Service. 2015d. Arches National Park: geologic formations. http://www.nps.gov/arch/naturescience/geologicformations.htm (accessed 4 February 2015).

National Park Service. 2015e. Weather dangers. http://www.nps.gov/grca/planyourvisit/weather-dangers.htm (accessed 30 April 2015).

National Park Service. 2015f. Glen Canyon photo gallery. http://www.nps.gov/glca/learn/photosmultimedia/photogallery.htm (accessed 30 April 2015).

National Park Service. 2015g. Proposed exploratory petroleum well in Glen Canyon National Recreation Area. http://parkplanning.nps.gov/projectHome.cfm?projectID=12592 (accessed 4 May 2015).

National Park Service. 2015h. Lake Mead National Recreation Area. National Park Service Intermountain Region, Denver, Colorado. https://parkplanning.nps.gov/document.cfm?documentID=63713 (accessed 2 October 2015).

National Park Service and American Geosciences Institute. 2015. America's geologic heritage: An invitation to leadership. NPS 999/129325. National Park Service, Denver, Colorado. http://go.nps.gov/americasgeoheritage (accessed 20 June 2016).

National Park Service Geologic Resources Division and Natural Resources Information Division. 1999. Geologic resources inventory workshop summary Glen Canyon National Recreation Area and Rainbow Bridge National Monument. http://go.nps.gov/gripubs (accessed 4 May 2015).

Natural Arch and Bridge Society. 2015. http://www.naturalarches.org/index.html (accessed 4 January 2016).

Nelson, S. T., M. T. Heizler, and J. P. Davidson. 1992. New $^{40}Ar/^{39}Ar$ ages of intrusive rocks from the Henry and La Sal Mountains. Miscellaneous Publications MP-92-2. Utah Geological Survey, Salt Lake City, Utah.

Netoff, D. I. 1999. Seismogenically-induced fluidization of Jurassic erg sands in a wet eolian-sabkha environment, south-central Utah. Geological Society of America Abstracts with Programs 31(7):A–160.

Netoff, D. I., and M. A. Chan. 2009. Eolian activity at a giant sandstone weathering pit in arid south-central Utah. Earth Surface Processes and Landforms 34:99–108.

Netoff, D. I., and R. R. Shroba. 1993. Morphology and possible origin of giant weathering pits in the Entrada Sandstone, southeastern Utah: preliminary findings. Open-File Report 93-390. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/of/1993/0390/report.pdf (accessed 12 February 2016).

Netoff, D. I., and R. R. Shroba. 1995. Physical weathering processes and probable deflation in the development of giant sandstone weathering pits in southeastern Utah. Geological Society of America Abstracts with Programs 27(3):76.

Netoff, D. I., and R. R. Shroba. 1997. Evidence of deflational removal of sandy sediment from giant weathering pits in southeastern Utah. Geological Society of America Abstracts with Programs 29(6):255.

Netoff, D. I., and R. R. Shroba. 2001. Conical sandstone landforms cored with clastic pipes in Glen Canyon National Recreation Area, southeastern Utah. Geomorphology 39:99–110.

Netoff, D. I., C. Baldwin, and J. Dohrenwend. 2005. Continued activity and geomorphic evolution of fluid/gas escape structures in muddy surficial beds of the recently-exposed Hite Delta, southeastern Utah. Geological Society of America Abstracts with Programs 37(6):7.

Netoff, D., C. T. Baldwin, and J. Dohrenwend. 2010. Non-seismogenic origin of fluid/gas escape structures and lateral spreads on the recently exposed Hite delta, Lake Powell, Utah–preliminary findings. Pages 61–92 in S. M. Carney, D. E. Tabet, and C. L. Johnson, editors. Geology of south-central Utah. Publication 39. Utah Geological Association, Salt Lake City, Utah.

Netoff, D. I., B. J. Cooper, and R. R. Shroba.1994. Origin and development of the giant sandstone weathering pits near Cookie Jar Butte, southeastern Utah. Geological Society of America Abstracts with Programs 26(6):56.

Netoff, D. I., B. J. Cooper, and R. R. Shroba. 1993. Giant sandstone weathering pits near Cookie Jar Butte, southeastern Utah. Pages 25–28 in C. van Ripper III, editor. Proceedings of the second biennial conference on research in Colorado Plateau National Parks, October 1993. NPS/NRNAU/NRTP–95–11. http://sbsc.wr.usgs.gov/cprs/news_info/meetings/biennial/proceedings/1993/physical_resources/Netoff,Cooper,andShroba.pdf (accessed 12 February 2015).

Oldow, J. S., A. W. Bally, H. G. Ave Lallemant, and W. P. Leeman. 1989. Phanerozoic evolution of the North American Cordillera; United States and Canada. Pages 139–232 in A. W. Bally and A. R. Palmer, editors. The Geology of North America: An Overview. Geological Society of America, Boulder, Colorado.

Oliver, J. 1986. Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. Geology 14:99–102.

Parrish, J. M. 1999. Small fossil vertebrates from the Chinle Formation (Upper Triassic) of southern Utah. Pages 45–50 in D. D. Gillette, editor. Vertebrate paleontology in Utah. Miscellaneous Publication 99-1. Utah Geological Survey, Salt Lake City, Utah.

Parrish, J. T., and H. J. Falcon-Lang. 2007. Coniferous trees associated with interdune deposits in the Jurassic Navajo Sandstone Formation, Utah, USA. Palaeontology 50(4):829–843.

Parrish, J. T., H. J. Falcon-Lang, and T. Shipman. 2002. Carbonate and noncarbonate springs and trees in the eolian Navajo Sandstone, near Tenmile Canyon, SE Utah. Geological Society of America Abstracts with Programs 34(6):507.

Pederson, J. L. 2000. Holocene paleolakes of Lake Canyon, Colorado Plateau–paleoclimate and landscape response from sedimentology and allostratigraphy. Geological Society of America Bulletin 112:147–158.

Pederson, J. L. 2009. Lees Ferry, Arizona (surficial geology). Rocky Mountain Friends of the Pleistocene Field Trip Notes. Utah State University, Logan, Utah.

Peterson, F. 1969. Four new members of the Upper Cretaceous Straight Cliffs Formation in the southeastern Kaiparowits region, Kane County, Utah. Bulletin 1274-J. US Geological Survey, Reston, Virginia.

Peterson, F. 1988. Stratigraphy and nomenclature of Middle and Upper Jurassic rocks, western Colorado Plateau, Utah and Arizona. Professional Paper 1633-B. US Geological Survey, Reston, Virginia.

Peterson, F. 1994. Sand dunes, sabkhas, stream, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin. Pages 233–272 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain Region, USA. Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, Colorado.

Peterson, F., and G. N. Pipiringos. 1979. Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona. Professional Paper 1035-B. US Geological Survey, Reston, Virginia.

Phillips, B. G. 1995. Climate change and the lacustrine history of Lake Canyon, Utah. Thesis. Northern Arizona University, Flagstaff, Arizona.

Phoenix, D. A. 1958. Sandstone cylinders as possible guides to paleomovement of ground water. Ninth Field Conference. New Mexico Geological Society, Socorro, New Mexico.

Phoenix, D.A. 1963. Geologic map of part of the Lees Ferry area, Glen Canyon National Recreation Area, Coconino County, Arizona (scale 1:24,000). Bulletin 1137. US Geological Survey, Washington, DC.

Pipiringos, G. N., and R. B. O'Sullivan, R.B. 1978. Principal unconformities in Triassic and Jurassic rocks, western interior United States – a preliminary survey. Professional Paper 1035-A. US Geological Survey, Reston, Virginia.

Potter, L. D., and C. L. Drake. 1989. Lake Powell–virgin flow to dynamo. University of New Mexico Press, Albuquerque, New Mexico.

Pulwarty, R., K. Jacobs, and R. Dole. 2005. The hardest working river: drought and critical water problems on the Colorado. Pages 249–285 in D. Wilhite, editor. Drought and Water Crises: Science, Technology and Management. Taylor and Francis Press, Boca Raton, Florida.

Rahl, J.M., P. W. Reiners, I. H. Campbell, S. Nicolescu, and C. M. Allen. 2003. Combined single-grain (U-Th)/He and U-Pb dating of detrital zircons from the Navajo Sandstone, Utah. Geology 31(9):761–764.

Reineck, H.-E., and I. B. Singh. 1980. Depositional sedimentary environments. Springer-Verlag, New York, New York.

Resolute Energy Corporation. 2013. An update on the Greater Aneth Field, Wyoming CO2 conference. http://www.uwyo.edu/eori/conferences/co2/2013%20presentations/hoppe.pdf (accessed 5 May 2015).

Ritter, S. M., J. E. Barrick, and M. R. Skinner. 2002. Conodont sequence biostratigraphy of the Hermosa Group (Pennsylvanian) at Honaker Trail, Paradox Basin, Utah. Journal of Paleontology 76(3):495–517.

Romboy, D. 2015. Utah wary of future impact as contaminated mine water reaches Lake Powell. Desert News. http://www.deseretnews.com/article/865634777/Utah-wary-of-future-impact-as-contaminated-mine-water-reaches-Lake-Powell.html (accessed 21 September 2015).

Rueger, B. F. 1996. Palynology and its relationship to climatically induced depositional cycles in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of southeastern Utah. Bulletin 2000-K. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/b00K (accessed 24 March 2015).

Sandberg, C. A., and R. C. Gutschick. 1984. Distribution, micro-fauna, and source rock potential of Mississippian Delle Phosphatic Member of the Woodman Formation and equivalents, Utah and adjacent states. Pages 135–178 in J. Woodward, F. F. Meissner, and J. L. Clayton, editors. Hydrocarbon source rocks of the greater Rocky Mountain region. Rocky Mountain Association of Geologists, Denver, Colorado.

Sanford, R. F. 1995. Ground-water flow and migration of hydrocarbons to the Lower Permian White Rim Sandstone, Tar Sand Triangle, southeastern Utah. Bulletin 2000-J. US Geological Survey, Washington, DC.

Santucci, V. L. 2000. A survey of the paleontological resources from the National Parks and Monuments in Utah. Pages 534–556 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28. Utah Geological Association, Salt Lake City, Utah.

Santucci, V. L., and J. I. Kirkland. 2010. An overview of National Park Service paleontological resources from the parks and monuments in Utah. Pages 589–623 in D. A. Sprinkel, T. C. Chidsey, Jr., and P. B. Anderson, editors. Geology of Utah's parks and monuments. Publication 28 (third edition). Utah Geological Association, Salt Lake City, Utah.

Santucci, V. L., J. Kenworthy, and R. Kerbo. 2001. An inventory of paleontological resources associated with National Park Service caves. Technical Report NPS/NRGRD/GRDTR-01/02. TIC# D-2231. NPS Geological Resources Division, Denver, Colorado. Online. https://www.nps.gov/subjects/fossils/thematic-inventories.htm (accessed 31 March 2015).

Santucci, V. L., A. P. Hunt, T. Nyborg, and J. P. Kenworthy. 2006. Additional fossil vertebrate tracks in National Park Service areas. Pages 152–158 in S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://www.nps.gov/subjects/fossils/research-volumes.htm (accessed 24 August 2015).

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://go.nps.gov/paleo_monitoring (accessed 26 February 2015).

Schamel, S. 2013. Tar Sand Triangle bitumen deposit, Garfield and Wayne Counties, Utah. Pages 497–522 in T. H. Morris and R. Ressetar, editors. The San Rafael Swell and Henry Mountains Basin: geologic centerpiece of Utah. Publication 42. Utah Geological Association, Salt Lake City, Utah.

Semken, S. C., and McIntosh, W. C. 1997. $^{40}Ar/^{39}Ar$ age determinations for the Carrizo Mountains laccolith, Navajo Nation, Arizona. Pages 75–80 in O. Anderson, B. S. Kues, and S. G. Lucas, editors. Mesozoic geology and paleontology of the Four Corners region. Guidebook 48. New Mexico Geological Society, Socorro, New Mexico.

Smith, F. J, Jr., L. C. Huff, E. N. Hinrichs, and R. G. Luedke. 1963. Geology of the Capitol Reef Area, Wayne and Garfield Counties, Utah. Professional Paper 102. US Geological Survey, Washington, DC.

Smith, J. A., and V. L. Santucci. 1999. An inventory of vertebrate ichnofossils from Zion National Park, Utah. Journal of Vertebrate Paleontology 19(supplement to 3):77A.

Spears, S. Z., A. R. C. Milner, D. Ferris-Rowley, S. E. Foss, and J. I. Kirkland. 2009. The Nation's first BLM paleontological site stewardship program established in Washington County, Utah. Page 23 in S. E Foss, J. L. Cavin, T. Brown, J. I. Kirkland, and V. L. Santucci, editors. Proceedings of the Eighth Conference on Fossil Resources. Bureau of Land Management, Salt Lake City, Utah.

Spence, J. R. 2001. Climate of the central Colorado Plateau, Utah and Arizona: characterization and recent trends. Pages 187–203 in K. Thomas and C. Van Riper III, editors. Proceedings of the Fifth Biennial Conference on Research on the Colorado Plateau. US Geological Survey Report Ser. USGSFRESC/COPL/2001/24. http://sbsc.wr.usgs.gov/cprs/news_info/meetings/biennial/proceedings/1999/pdf/15_Spence.pdf (accessed 24 January 2016).

Sprinkel, D. A., J. R. Castaño, and G. W. Roth. 1997. Emerging plays in central Utah based on regional geochemical, structural, and stratigraphic evaluation. Abstract, American Association of Petroleum Geologists Bulletin 81(13):A110.

Sprinkel, D. A., B. J. Kowallis, H. H. Doelling, and P. A. Kuehne. 2009. The Middle Jurassic Temple Cap Formation, southern Utah-radiometric age, palynology, and correlation with the Gypsum Spring Member of the Twin Creek Limestone and the Harris Wash Member of the Page Sandstone. Geological Society of America Abstracts with Programs 41(7):690.

Staker, A. R. 2006. The earliest known dinosaur trackers of Zion National Park, Utah. Pages 137–139 in J. D. Harris, S. G. Lucas, J. A. Spielmann, M. G. Lockley, A. R. C. Milner, and J. I. Kirkland, editors. The Triassic–Jurassic terrestrial transition. Bulletin 37. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Steidtmann, J. R. 1993. The Cretaceous foreland basin and its sedimentary record. Pages 250–271 in A. W. Snoke, J. R. Steidtmann, and S. M. Roberts, editors. Memoir 5. Wyoming State Geological Survey, Laramie, Wyoming.

Stewart, J.H., F. G. Poole, and R. F. Wilson. 1972a. Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region with a section on sedimentary petrology by R. A. Cadigan. Profession Paper 691, US Geological Survey, Washington, DC.

Stewart, J.H., F. G. Poole, and R. F. Wilson. 1972b. Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region with a section on sedimentary petrology by R.A. Cadigan and on conglomerate studies by W. Thordarson, H. F. Albee, and J. H. Stewart. Professional Paper 690. US Geological Survey, Washington, DC.

Stock, G.M., S.J. Martel, B.D. Collins, and E.L Harp. 2012. Progressive failure of sheeted rock slopes: the 2009–2010 Rhombus Wall rockfalls in Yosemite 68 NPS Geologic Resources Division Valley, California, USA. Earth Surface Processes and Landforms 37:546-561. http://www.nps.gov/yose/naturescience/rockfall.htm (accessed 8 April 2015).

Stokes, W. L. 1991. Petrified mini-forests of the Navajo Sandstone, east-central Utah. Utah Geological Survey Notes 25(1):14–19.

Stone, D. S. 1986. Seismic and borehole evidence for important pre-Laramide faulting along the axial arch in northwest Colorado. Pages 19–36 in D. S. Stone, editor. New interpretations of northwest Colorado geology. Rocky Mountain Association of Geologists, Denver, Colorado.

Sumida, S. S., J. B. D. Walliser, and R. E. Lombard. 1999. Late Paleozoic amphibian-grade tetrapods of Utah. Pages 21–30 in D. D. Gillette, editor. Vertebrate paleontology in Utah. Miscellaneous Publication 99-1. Utah Geological Survey, Salt Lake City, Utah.

Terrell, F. M. 1972. Lateral facies and paleoecology of Permian Elephant Canyon Formation, Grand County, Utah. Brigham Young University Research Studies, Geology Series 19(2):3–44.

Thomas, K. M. 2000. Paleontological investigations in the Navajo Sandstone near Page, Arizona. Journal of Vertebrate Paleontology 20(supplement to 3):73A.

Thornberry-Ehrlich, T. 2004. Natural Bridges National Monument Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2004/003. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs (accessed 24 August 2015).

Thornberry-Ehrlich, T. 2005. Bryce Canyon National Park Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2005/002. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs(accessed 24 August 2015).

Toomey, R. S., III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/monitor_cavekarst (accessed 1 February 2015).

Tweet, J. S. and V. L. Santucci. 2015. An inventory of Mesozoic mammals and non-mammalian therapsids in National Park Service areas. Pages 297–302 in R. M. Sullivan and S. G. Lucas, editors. Fossil record 4. Bulletin 67. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Tweet, J. S., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring—Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR–2009/245. National Park Service, Fort Collins, Colorado.

Tweet, J. S., V. L. Santucci, and A. P. Hunt. 2012. An inventory of packrat (Neotoma spp.) middens in National Park Service areas. Pages 355–368 in Hunt, A. P., J. Milàn, S. G. Lucas, and J. A. Spielmann, editors. Vertebrate coprolites. Bulletin 57. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. http://econtent.unm.edu/cdm/ref/collection/bulletins/id/1805 (accessed 24 August 2015).

US Department of the Interior. 2008. Glen Canyon Dam quick facts. Upper Colorado Region: Colorado River storage project. http://www.usbr.gov/uc/rm/crsp/gc/gcFacts.html (accessed 27 January 2015).

US Geological Survey. 2010. 2009 earthquake probability mapping. Online information. US Geological Survey, Geologic Hazards Science Center, Washington, DC. http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 5 May 2015).

US Geological Survey. 2014. Utah earthquake information. Online information. US Geological Survey, Earthquake Hazards Program, Washington, DC. http://earthquake.usgs.gov/earthquakes/states/index.php?regionID=44 (accessed 5 May 2015).

Utah Geological Survey. 2013. Utah oil and gas. Public Information Series 71. Utah Geological Survey, Salt Lake City, Utah. http://files.geology.utah.gov/online/pi/pi-71.pdf (accessed 3 June 2015).

Vanden Berg, M. D. 2011. Utah's energy landscape. Circular 113. Utah Geological Survey, Salt Lake City, Utah. http://files.geology.utah.gov/online/c/c-113.pdf (accessed 5 May 2015).

Water Resources Division. 1994. Baseline water quality data inventory and analysis: Glen Canyon National Recreation Area. Technical Report NPS/NRWRD/NRTR-94/33. National Park Service, Water Resources Division, Fort Collins, Colorado. http://www.nature.nps.gov/water/horizon.cfm (accessed 22 September 2015).

Weary, D. J., and D. H. Doctor. 2014. Karst in the United States: A digital map compilation and database. U.S. Geological Survey, Reston, Virginia. Open-File Report 2014–1156. http://dx.doi.org/10.3133/ofr20141156 (accessed 21 June 2016).

Webb, R. H. and J. Hasbargen. 1997. Floods, ground-water levels, and arroyo formation on the Escalante River, south-central Utah. Pages 335–345 in L. M. Hill, editor. Learning from the land: Grand Staircase-Escalante National Monument science symposium proceedings. Bureau of Land Management, National Applied Resource Sciences Center, Salt Lake City, UT.

Welsh, S. L. 1989. On the distribution of Utah's hanging gardens. Great Basin Naturalist 49: 1-30.

Wengerd, S. A. 1962. Pennsylvanian sedimentation in Paradox Basin, Four Corners region. Pennsylvanian System in the United States—a symposium. American Association of Petroleum Geologists, Tulsa, Oklahoma.

Wengerd, S. A., and M. L. Matheny. 1958. Pennsylvanian system of Four Corners region. American Association of Petroleum Geologists Bulletin 42(9):2048–2106.

Wheatley, D. F., M. Chan, M. Hansford, and I. Treat. 2014. Clastic pipe sources and stratigraphic relationships: evidence for multiple liquefaction events in the Middle Jurassic Carmel Formation, southern Utah. Geological Society of America Abstracts with Programs 46(6):352.

Whidden, K.J., P. G. Lillis, L. O. Anna, K. M. Pearson, and R. F. Dubiel. 2014. Geology and total petroleum system of the Paradox Basin, Utah, Colorado, New Mexico, and Arizona. The Mountain Geologist 51(2):119–138.

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://go.nps.gov/monitor_slopes (accessed 30 April 2015).

Wild Backpacker. 2015. Coyote Gulch. http://www.wildbackpacker.com/backpacking-trails/coyote-gulch/ (accessed 4 February 2015).

Wilkens, N. D., J. D. Farmer, and K. B. Pigg. 2005. Exceptional paleobotanical remains preserved in Navajo Sandstone interdune deposits near Moab, Utah. Geological Society of America Abstracts with Programs 37(7):527–528.

Wilkens, N. D., J. D. Farmer, and K. B. Pigg. 2007. Paleoecology of Jurassic Navajo Sandstone interdune environments: an integrated view based on sedimentology, geochemistry, and paleontology. Geological Society of America Abstracts with Programs 39(6):434.

Willis, G. C. 1992. Lava Creek "B" volcanic ash in pediment mantle deposits, Colorado Plateau, east central Utah—implications for Colorado River downcutting and pedogenic carbonate accumulation rates. Geological Society of Abstracts with Program 24(6):68.

Willis, G. C. 2004. Interim geologic map of the lower San Juan River area, eastern Glen Canyon National Recreation Area and vicinity, San Juan County, Utah (scale 1:50,000). Open-File Report 443DM. Utah Geological Survey, Salt Lake City, Utah.

Willis, G. C. 2010a. Geologic map of the Glen Canyon Dam area, Glen Canyon National Recreation Area, Arizona and Utah (scale 1:24,000). Miscellaneous Publication (GIS data). Utah Geological Survey, Salt Lake City, Utah.

Willis, G. C. 2010b. Geologic map of the Hite Crossing— lower Dirty Devil River area, Glen Canyon National Recreation Area, Garfield and San Juan Counties, Utah (scale 1:50,000). Utah Geological Survey Map (GIS data), Salt Lake City, Utah.

Willis, G. C., and R. F. Biek. 2001. Quaternary incision rates of the Colorado River and major tributaries in the Colorado Plateau, Utah. Pages 119–124 in R. A. Young and E. E. Spamer, editors. Colorado River origin and evolution: Grand Canyon, Arizona. Symposium Volume. Grand Canyon Association, Grand Canyon, Arizona.

Willis, G.C., and J. B. Ehler. in preparation. Interim geologic map of Glen Canyon National Recreation Area and vicinity, San Juan, Kane, Garfield, Wayne and Grand Counties, Utah and Coconino County, Arizona (scale 1:24,000 to 1:100,000). Open-File Report. Utah Geological Survey, Salt Lake City, Utah.

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 29 February 2016).

Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of June 2016. 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 (Lakewood, Colorado) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/geology
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientists-in-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- 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://go.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 and Norby 2009): http://go.nps.gov/geomonitoring
- 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 Other Organizations

- Arizona Geological Survey: http://www.azgs.az.gov/
- Utah Geological Association: http://www.utahgeology.org/
- Utah Geological Survey: http://geology.utah.gov/
- 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://pubs.usgs.gov/imap/i272

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Glen Canyon National Recreation Area, held on 23–25 September 1999, or the follow-up report writing conference call, held on 5 March 2015. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

1999 Scoping Meeting Participants

Name	Affiliation	Position
Mark Anderson	NPS Glen Canyon National Recreation Area	Aquatic Ecologist
Pete Biggam	NPS, Natural Resources Information Division	Geologist
George Billingsley	USGS-Flagstaff, AZ	Geologist
Ben Bobowski	NPS Glen Canyon National Recreation Area	Rangeland Management Specialist
Lewis Boobar	NPS Glen Canyon National Recreation Area	Aquatic Ecologist
Tom Chidsey	Utah Geological Association	Geologist
Tim Connors	NPS Geologic Resources Division	Geologist
Joe Gregson	NPS Natural Resources Information Division	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist
Norm Henderson	NPS Glen Canyon National Recreation Area	Research Coordinator
Lex Newcomb	NPS Glen Canyon National Recreation Area	GIS Specialist
Pete Peterson	USGS-Denver, CO	Geologist
Vincent Santucci	NPS Geologic Resources Division, Fossil Butte National Monument, Wyoming	Paleontologist
John Spence	NPS Glen Canyon National Recreation Area	Chief Scientist and Terrestrial Natural Resources Branch Chief
Doug Sprinkel	Utah Geological Association	Geologist
Christine Turner	USGS-Denver, CO	Geologist
Grant Willis	Utah Geological Survey	Geologist

2015 Conference Call Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist
Sarah Doyle	NPS Glen Canyon National Recreation Area	Physical Scientist
John Graham	Colorado State University	Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Tyler Knudsen	Utah Geological Survey	Geologist
John Spence	NPS Glen Canyon National Recreation Area	Chief Scientist and Terrestrial Natural Resources Branch Chief
Grant Willis	Utah Geological Survey	Geologist; Mapping Program Manager

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 NPS 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 June 2016. 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, 54 USC § 100701** 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 (June 2016).	**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	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute.** Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and 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.
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, 54 USC § 100701** 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
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.

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).
Mining Claims	**Mining in the Parks Act of 1976, 54 USC § 100731 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. **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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Individual Park Enabling Statutes:** **16 USC § 230a** (Jean Lafitte NHP & Pres.) **16 USC § 450kk** (Fort Union NM) **16 USC § 459d-3** (Padre Island NS) **16 USC § 459h-3** (Gulf Islands NS) **16 USC § 460ee** (Big South Fork NRRA) **16 USC § 460cc-2(i)** (Gateway NRA) **16 USC § 460m** (Ozark NSR) **16 USC § 698c** (Big Thicket N Pres.) **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B r**equires 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 operation -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751** **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: Glen Canyon NRA (16 USC § 460dd et seq.),** Lake Mead NRA **(16 USC § 460n et seq.),** and Whiskeytown-Shasta-Trinity NRA **(16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. **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 s**tates prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. BLM regulations at **43 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 **Indian 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.
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
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf	None applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 608/133731, August 2016

National Park Service
U.S. Department of the Interior

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www.nature.nps.gov

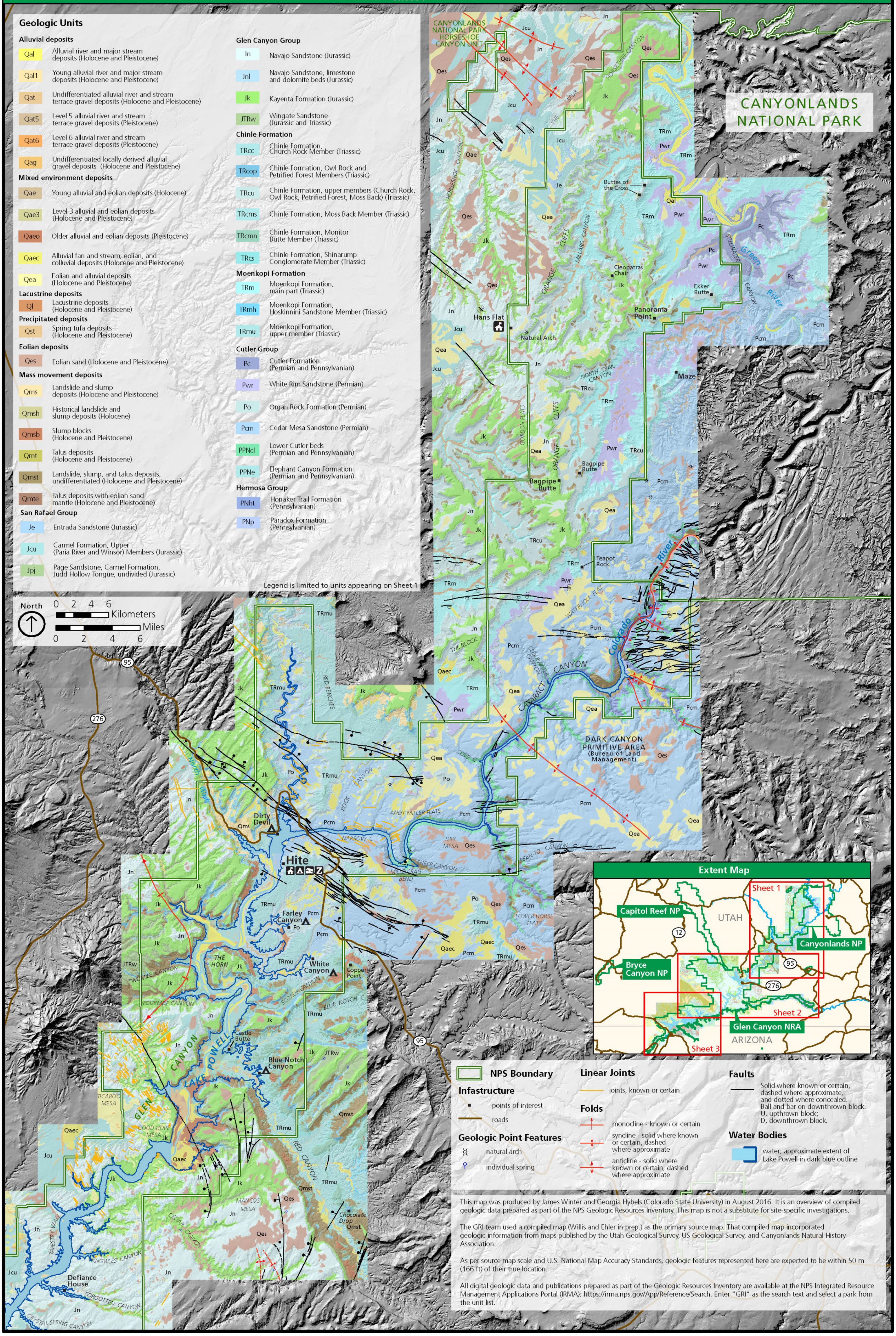
Geologic Map of Glen Canyon National Recreation Area

Arizona and Utah

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 1



This map was produced by James Winter and Georgia Hybels (Colorado State University) in August 2016. 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 GRI team used a compiled map (Willis and Ehler in prep.) as the primary source map. That compiled map incorporated geologic information from maps published by the Utah Geological Survey, US Geological Survey, and Canyonlands Natural History Association.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are expected to be within 50 m (166 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.

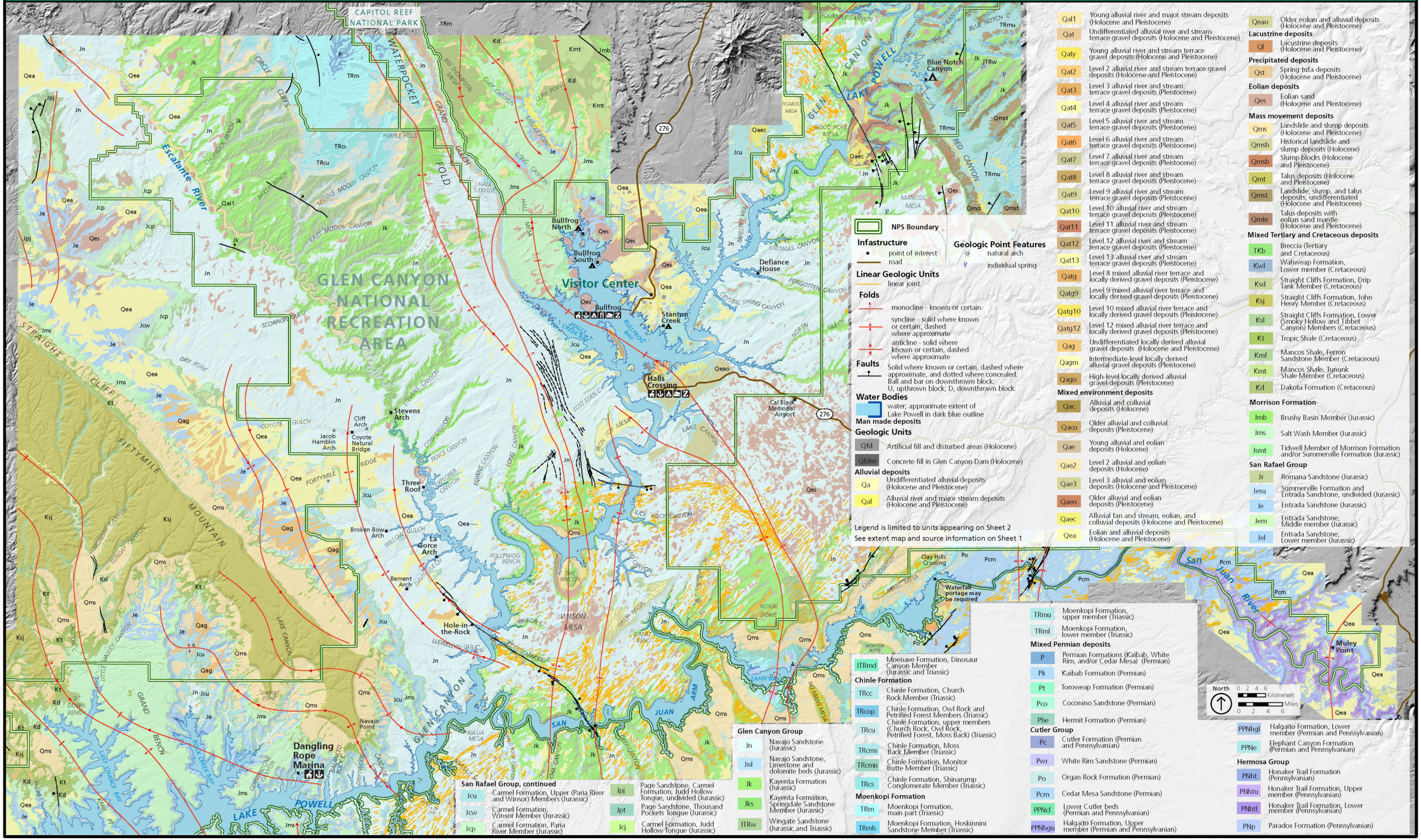
Geologic Map of Glen Canyon National Recreation Area

Arizona and Utah

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 2



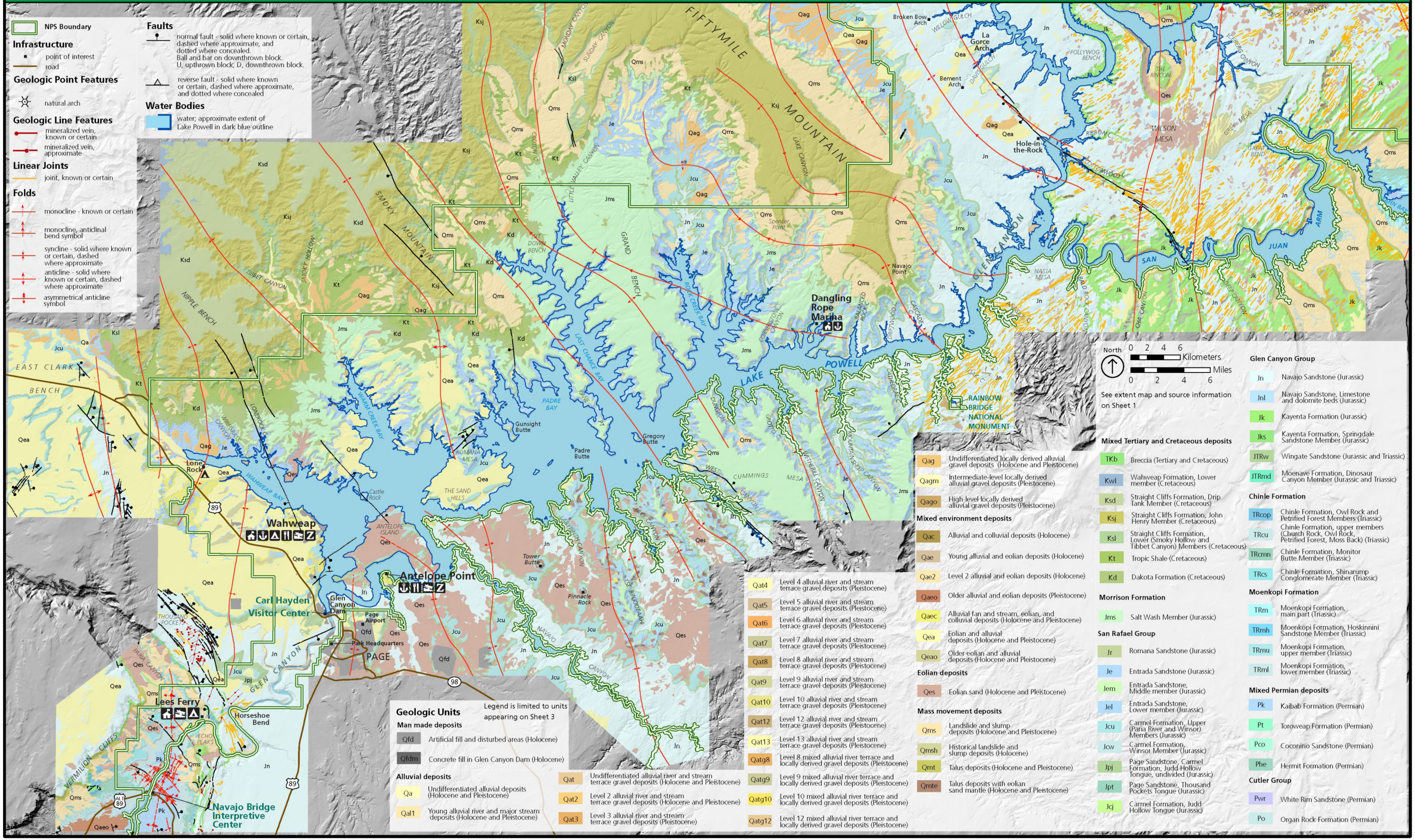
Geologic Map of Glen Canyon National Recreation Area

Arizona and Utah

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 3



Bedrock Map Unit Properties Table: Glen Canyon National Recreation Area

Colored map units are mapped within Glen Canyon National Recreation Area. Bold text refers to sections in report. Refer to the glca_geology.pdf in the GRI GIS data for detailed geologic descriptions and additional information.

Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
UPPER CRETACEOUS to EOCENE (101–34 mya)	Breccia (**TKb**)	Intensely brecciated Navajo Sandstone (**Jn**). Mapped on sheets 2 and 3 (in pocket).	None reported.	None reported.	**Cretaceous–Paleogene Periods: The Laramide Orogeny.** Folding of the Echo Cliffs monocline during the Laramide Orogeny brecciated the Navajo Sandstone and produced **TKb**.
UPPER CRETACEOUS (101–66.0 mya)	Wahweap Formation, Lower Member (**Kwl**)	Yellow-gray and yellow-brown mudstone with variable amounts of trough cross-bedded sandstone, siltstone, and minor carbonaceous shale. Thickness: 76–270 m (250–900 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms slopes with local ledges. **Geologic Type Sections.** No official designated type section, but probably named for exposures along Wahweap Creek.	None reported.	**Cretaceous–Paleogene Periods: The Laramide Orogeny.** The Laramide Orogeny eliminated the Western Interior Seaway and deformed strata on the Colorado Plateau. As sea level fell, **Kwl** was deposited in the recreation area.
UPPER CRETACEOUS (101–66.0 mya)	Straight Cliffs Formation, Drip Tank Member (**Ksd**)	Yellow-gray and yellow-brown, fine- to medium-grained, lenticular sandstone. Minor mudstone and pebble conglomerate. Commonly iron stained and contains iron oxide concretions. Present in westernmost part of the map area. Thickness: 43–170 m (140–550 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms cliffs and benches. **Paleontological Resources.** Turtle and crocodilian fragments in Grand Staircase-Escalante National Monument.	None reported.	**Cretaceous–Paleogene Periods: The Laramide Orogeny.** The Laramide Orogeny eliminated the Western Interior Seaway and deformed strata on the Colorado Plateau. As sea level fell, the shoreface, beach, lagoon, and marsh environments of **Ks** were deposited in the recreation area.
UPPER CRETACEOUS (101–66.0 mya)	Straight Cliffs Formation, John Henry Member (**Ksj**)	Yellow-gray sandstone, gray mudstone, carbonaceous mudstone, shale, and coal. Coal-barren zones are dominated by thick-bedded to massive cliff-forming sandstones. The lower approximately 200 m (600 ft) are preserved in the recreation area. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms slopes and ledges. Sandstone forms cliffs. **Sedimentary Rocks and Sedimentary Rock Features.** Nearshore marine mudstone and coal from coastal marshes. **Paleontological Resources.** Fossils are found in Grand Staircase-Escalante National Monument but not in the recreation area. **Economic Minerals.** Contains the major coal resources of the Kaiparowits Plateau. Coal beds are locally 6 m (20 ft) or more thick.	**Slope Movement Hazards and Risk.** Erosion of the underlying **Kt** results in cliff collapse and rockfalls. **Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from **Ksj** have not yet been documented from Glen Canyon National Recreation Area but could be present. **Abandoned Mineral Lands and Potential Mining Activity. Ksj** contains the major coal resources on the Kaiparowits Plateau. Coal seams may spontaneously combust.	**Cretaceous–Paleogene Periods: The Laramide Orogeny.** The Laramide Orogeny eliminated the Western Interior Seaway and deformed strata on the Colorado Plateau. As sea level fell, the shoreface, beach, lagoon, and marsh environments of **Ks** were deposited in the recreation area.
UPPER CRETACEOUS (101–66.0 mya)	Straight Cliffs Formation, Lower (Smoky Hollow and Tibbet Canyon) Members (**Ksl**)	*Smoky Hollow Member*: white and gray, fine- to medium-grained sandstone, mudstone, carbonaceous mudstone, and coal. Thickness: 7–71 m (24–234 ft). *Tibbet Canyon Member*: yellow-gray to brown sandstone with thin layers of gray mudstone and siltstone. Gradational with Tropic Shale. Thickness: 21–56 m (70–185 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** *Smoky Hollow Member*: ledge- and slope-forming beds. *Tibbet Canyon Member*: forms cliffs. **Sedimentary Rocks and Sedimentary Rock Features.** Cross-bedding. Smoky Hollow features represent fluvial, floodplain, lagoon, and marsh settings. Tibbet Canyon features represent beach and shallow marine environments. **Paleontological Resources.** Abundant in Grand Staircase-Escalante National Monument. Coal is in Glen Canyon National Recreation Area.	**Slope Movement Hazards and Risk.** Erosion of the underlying **Kt** results in cliff collapse and rockfalls. **Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from **Ksl** have not yet been documented from Glen Canyon National Recreation Area but could be present.	**Cretaceous–Paleogene Periods: The Laramide Orogeny.** The Laramide Orogeny eliminated the Western Interior Seaway and deformed strata on the Colorado Plateau. As sea level fell, the shoreface, beach, lagoon, and marsh environments of **Ks** were deposited in the recreation area.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
UPPER CRETACEOUS (101–66.0 mya)	Tropic Shale (**Kt**)	Gray, fossiliferous marine mudstone and shale with some gray sandstone, bentonitic claystone, siltstone, and limestone beds. Approximately equivalent to Tununk Shale (**Kmt**) but Tropic name is used south of Kaiparowits Plateau. Thickness: 150–230 m (500–750 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms slopes, badlands topography and landslide scarps. **Sedimentary Rocks and Sedimentary Rock Features.** Mudstone and marine fossils. **Paleontological Resources.** Ammonites, bivalves, sharks, rays, turtles, and plesiosaurs.	**Slope Movement Hazards and Risk.** The bentonite in **Kt** makes the unit susceptible to slope movements. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Cretaceous Period: Western Interior Seaway.** In the Late Cretaceous, subsidence of the western interior caused by the Sevier Orogeny allowed incursions of the sea from both the north and south. Eventually, the Western Interior Seaway formed, bisecting North America and connecting the Gulf of Mexico with the Arctic Ocean. **Kt** accumulated within this seaway.
UPPER CRETACEOUS (101–66.0 mya)	Mancos Shale, Ferron Sandstone Member (**Kmf**)	Gray to yellowish-brown, fine- to very fine grained sandstone with thin beds of siltstone and coaly shale. Present only northwest of Bullfrog. Thickness: 60–87 m (200–285 ft). Mapped on sheet 2 (in pocket).	**Landscape Features.** Forms a thin resistant cap on small mesas and benches **Sedimentary Rocks and Sedimentary Rock Features.** Cross-bedding.	None reported.	**Cretaceous Period: Western Interior Seaway.** In the Late Cretaceous, subsidence of the western interior caused by the Sevier Orogeny allowed incursions of the sea from both the north and south. Eventually, the Western Interior Seaway formed, bisecting North America and connecting the Gulf of Mexico with the Arctic Ocean. **Kmf** was deposited along the fluctuating coastline of this seaway.
UPPER CRETACEOUS (101–66.0 mya)	Mancos Shale, Tununk Shale Member (**Kmt**)	Dark gray, laminated to very thin bedded shale and silty shale. Weathers to pale gray to pale yellowish gray. Poorly exposed. Approximately equivalent to **Kt**. Present only northwest of Bullfrog. Thickness: 170–200 m (550–650 ft). Mapped on sheet 2 (in pocket).	**Landscape Features.** Forms slope or broad low badlands topography.	None reported.	**Cretaceous Period: Western Interior Seaway.** In the Late Cretaceous, subsidence of the western interior caused by the Sevier Orogeny allowed incursions of the sea from both the north and south. Eventually, the Western Interior Seaway formed, bisecting North America and connecting the Gulf of Mexico with the Arctic Ocean. **Kmt** accumulated within this seaway.
UPPER CRETACEOUS (101–66.0 mya)	Dakota Formation (**Kd**)	Light-brown sandstone, sandy and carbonaceous mudstone, shaley sandstone, conglomerate, dark-brown to black carbonaceous shale and coal. Discontinuous local basal conglomerate in the lower part fills paleotopographic lows. Deposited unconformably above "**Jm**" units, **Jr**, and **Je**. Thickness: highly variable, but generally thickens westward from 1–46 meters (3–150 ft). The lower part of **Kd** may be partly Early Cretaceous in age, which would make it equivalent to the Cedar Mountain Formation in central Utah. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Middle part forms ledges and slopes. **Sedimentary Rocks and Sedimentary Rock Features.** Marine fossils in the upper part. Coal in the middle part. Conglomerate and fluvial channels in lower part. **Paleontological Resources.** Dinosaur tracks, plant fossils, nonmarine fauna, marine invertebrate fossils. Abundant fossils in the Grand Staircase-Escalante National Monument. **Unconformities.** K-0 unconformity at the base of **Kd**. **Folds and Faults.** Exposed on the crest of the Smoky Mountain anticline. **Laccoliths.** Forms the dome of Navajo Mountain.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Abandoned Mineral Lands and Potential Mining Activity.** *Coal Mining*: thin, discontinuous coal seams. *Burning Coal Beds*: potential for coal seams to spontaneously combust.	**Cretaceous Period: Western Interior Seaway.** In the Late Cretaceous, subsidence of the western interior caused by the Sevier Orogeny allowed incursions of the sea from both the north and south. Eventually, the Western Interior Seaway formed, bisecting North America and connecting the Gulf of Mexico with the Arctic Ocean. **Kd** was deposited along the fluctuating coastline of this seaway.
Rocks from the Early Cretaceous Epoch (145–101 million years ago) are not mapped within Glen Canyon National Recreation Area.					

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
UPPER JURASSIC (164–145 mya)	Morrison Formation, Brushy Basin Member (**Jmb**)	Dark-brown to purplish-red, smectitic mudstone. Minor sandstone and conglomerate with gray quartzite and chert clasts. Mapped in the Bullfrog Creek area northwest of Bullfrog Bay. Cut out by a major unconformity near Fiftymile Mountain and in the southwest part of the map area where **Kd** overlies **Jms**. Thickness: about 60 m (200 ft). Mapped on sheet 2 (in pocket).	**Landscape Features.** Forms mostly bare slopes. **Economic Minerals.** Morrison Formation contains uranium.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Jurassic Period: Extensive Dune Fields.** A major transgression of the inland seaway from the north destroys the vast ergs that once covered the Colorado Plateau. **Jr** was deposited in shallow marine, tidal flat, and eolian environments. When sea level fell, the Morrison Formation was deposited across western North America.
UPPER JURASSIC (164–145 mya))	Morrison Formation, Salt Wash Member (**Jms**)	Gray, weathering to dark brown, very fine to medium-grained, pebble conglomerate, and conglomeratic sandstone interbedded with minor purple, green, and reddish-brown mudstone and siltstone. A resistant basal ledge commonly protrudes as an overhanging lip above the ledgy **Je** beds below. Regional thickness ranges from 0 to 94 m (0–310 ft). Cut out by an unconformity in the southwestern corner of the recreation area.. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms ledgy cliffs and mesas and Alcove Arch in Rock Creek Bay. **Sedimentary Rocks and Sedimentary Rock Features.** Cross-bedded sandstone. **Paleontological Resources.** Sauropod tracks in the Lost Spring Wash area. **Folds and Faults.** Forms the crest of Mule Creek anticline. **Economic Minerals.** Morrison Formation contains uranium.	**Landscape Safety Hazards.** Documented fall from **Jms** outcrop. **Slope Movement Hazards and Risk.** Rockfall hazard. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Abandoned Mineral Lands and Potential Mining Activity.** *Uranium Mining*: potential hazard. Uranium occurs in sandstones and conglomerates.	**Jurassic Period: Extensive Dune Fields.** A major transgression of the inland seaway from the north destroys the vast ergs that once covered the Colorado Plateau. **Jr** was deposited in shallow marine, tidal flat, and eolian environments. When sea level fell, the Morrison Formation was deposited across western North America.
UPPER JURASSIC (164–145 mya))	Morrison Formation, Tidwell Member and/or Summerville Formation (**Jsmt**)	Interbedded, gray to brown, very fine to fine-grained sandstone, siltstone, mudstone, and shale. Thickness: 10–26 m (35–85 ft). Along the base of Fiftymile Mountain, the unit has been considered to be either the Summerville Formation or the Tidwell Member of the Morrison Formation. Mapped on sheet 2 (in pocket).	**Landscape Features.** Forms ledgy cliffs to steep ledgy slopes. **Paleontological Resources.** Sauropod tracks with skin impressions. Bone fragments. Termite nests. Pterosaur (*Pteraichnus*).	**Slope Movement Hazards and Risk.** Rockfall hazard. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Jurassic Period: Extensive Dune Fields.** A major transgression of the inland seaway from the north destroys the vast ergs that once covered the Colorado Plateau. **Jr** was deposited in shallow marine, tidal flat, and eolian environments. When sea level fell, the Morrison Formation was deposited across western North America.
UPPER JURASSIC (164–145 mya)	**San Rafael Group** Romana Sandstone (**Jr**)	Yellow, brown, and gray, very fine- to fine-grained, calcareous sandstone with thin beds of reddish-brown sandy siltstone. Mapped in the southwest part of map area. Thickness: 0–45 m (0–145 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms massive to ledgy cliffs. Romana Mesa. **Sedimentary Rocks and Sedimentary Rock Features.** Planar beds of calcareous sandy siltstone and gypsum are characteristic of nearshore, tidal flat, and shallow marine depositional environments. Local high-angle cross-bedding (sand dunes). **Unconformities.** Bounded by the J-3 and J-5 regional unconformities. **Geologic Type Sections.** Romana Mesa north of Wahweap Bay.	**Slope Movement Hazards and Risk.** Rockfall hazard.	**Jurassic Period: Extensive Dune Fields.** A major transgression of the inland seaway from the north destroys the vast ergs that once covered the Colorado Plateau. **Jr** was deposited in shallow marine, tidal flat, and eolian environments.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Entrada Sandstone (**Je**)	Generally consists of upper, middle, and lower (informal) members that are not mapped separately. The 24–122 m (80–400 ft) thick upper member (Escalante Member) has been cut out by the J-3 unconformity throughout most of the map area. Unconformable upper contact. Total thickness of **Je**: 90–300 m (300–1000 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Cliffs, slickrock, arches, natural bridges, hoodoos, sandstone pipes, weathering pits. *Escalante Member*: forms cliffs. *Cannonville Member*: forms slopes. *Gunsight Butte Member*: forms cliffs. **Sedimentary Rocks and Sedimentary Rock Features.** High-angle cross-beds (eolian dunes). **Unusual Sedimentary Rock Features.** Tafoni and contorted bedding. **Paleontological Resources.** Theropod and sauropod tracks, root traces, insect burrows, vertebrate burrows, and sand-swimming traces. **Unconformities.** J-3 unconformity	**Slope Movement Hazards and Risk.** Rockfall hazard. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north, yet **Je** became the most widespread of the preserved ergs on the Colorado Plateau.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Entrada Sandstone, middle member (**Jem**)	Orange to brown, medium- to thick-bedded, cross-bedded, calcareous, very fine grained sandstone with thin partings of siltstone, mudstone, and scarce very thin beds of bentonitic clay. Thickness: about 110 m (360 ft). Formal name is the Cannonville Member. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Generally forms red and white banded ledgy cliffs.	Refer to **Je** for potential management issues.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north, yet **Je** became the most widespread of the preserved ergs on the Colorado Plateau.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Entrada Sandstone, lower member (**Jel**)	Yellow to orange, thick-bedded to massive, calcareous, fine-grained sandstone with thin partings of siltstone and mudstone. Thickness: about 140 m (460 ft). Formal name is the Gunsight Butte Member. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms massive smooth cliffs, rounded bare domes, and broad rolling slickrock swells with common large weathering pits. **Unusual Sedimentary Rock Features.** Contorted bedding, small internal faults, and complex small-scale folds indicate extensive and complex soft-sediment deformation.	Refer to **Je** for potential management issues.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north, yet **Je** became the most widespread of the preserved ergs on the Colorado Plateau.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Carmel Formation, upper (Winsor and Paria River) members (**Jcu**)	*Winsor Member*: reddish-brown, silty sandstone and siltstone with locally gypsiferous sandstone. Overlies the Paria River Member. *Paria River Member*: reddish-brown to gray siltstone and silty sandstone capped by pale-gray to pink, silty to sandy limestone. **Jcu** thickness: 30–50 m (90–150 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Hoodoos. Forms slopes. **Paleontological Resources.** Terrestrial trace fossils are found in the upper part of the Carmel Formation outside of the recreation area. **Sedimentary Rocks and Sedimentary Rock Features.** Features, such as gypsum and silty limestone, that characterize nearshore, tidal flat, or shallow marine depositional environments. Commonly contorted and deformed together with the lower part of the Entrada Formation.	**Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from "**Jc**" units have not yet been documented from Glen Canyon National Recreation Area but could be present.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Carmel Formation, Winsor Member (**Jcw**)	Reddish-brown, silty sandstone and siltstone with locally gypsiferous sandstone. Mapped separate from **Jcu** in the southwest part of the map area. Thickness: 40–46 meters (130–150 ft). Thins to the east. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms slopes. **Paleontological Resources.** Terrestrial trace fossils are found in the upper part of the Carmel Formation outside of the recreation area.	**Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from "**Jc**" units have not yet been documented from Glen Canyon National Recreation Area but could be present.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north.

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MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Carmel Formation, Paria River Member (**Jcp**)	Reddish-brown to gray siltstone and silty sandstone capped by pale-gray to pink, silty to sandy limestone. Mapped separate from **Jcu** in the southwest part of the map area. Thickness: 15–21 m (50–70 ft). Thins to the east. Mapped on sheet 2.	**Paleontological Resources.** Terrestrial trace fossils are found in the upper part of the Carmel Formation outside of the recreation area.	**Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from "**Jc**" units have not yet been documented from Glen Canyon National Recreation Area but could be present.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Carmel Formation, Judd Hollow Tongue and Page Sandstone, undivided (**Jpj**)	*Judd Hollow Tongue*: reddish-brown siltstone and grayish-orange, thin-bedded, fine-grained sandstone. Thickness: 0–90 m (0–300 ft); 18–30 m (60–100 ft) in the Hite area. *Page Sandstone (see note below)*: yellow to gray, thick- to massive-bedded, fine- to medium-grained sandstone. In some areas, divided into two tongues by the Judd Hollow Tongue. **Note:** Recent research recommended restricting the Page Sandstone to areas (mostly Arizona) where the Judd Hollow Member cannot be identified. Many of the mapped areas of "Page Sandstone" in the GRI GIS data should be considered Temple Cap Formation (see "Unconformities" section of report and Doelling et al. 2013). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** *Page Sandstone (see note)*: forms ledges and cliffs. *Judd Hollow Tongue*: forms slopes, **Sedimentary Rocks and Sedimentary Rock Features.** *Page Sandstone*: large-scale, high-angle cross-bedding typical of eolian sand dunes. Quartz grains are very well sorted, well rounded, and frosted from wind abrasion. **Unusual Sedimentary Rock Features.** *Page Sandstone:* tafoni. **Paleontological Resources.** Petrified wood. **Unconformities.** J-1 unconformity marks the base of the Page Sandstone. **Geologic Type Sections.** Just south of the recreation area on Manson Mesa.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Page Sandstone, Thousand Pockets Tongue (**Jpt**)	Gray to brown, thick-bedded, cross-bedded sandstone with thin, red siltstone partings. Forms ledges that overlie the slopes of **Jcj**. Thickness: 27–60 m (90–200 ft). **Note:** Recent research has redefined the Thousand Pockets Tongue as a member of the Carmel Formation (Doelling et al. 2013). Mapped on sheets 2 and 3 (in pocket).	**Sedimentary Rocks and Sedimentary Rock Features.** Large-scale, high-angle cross-bedding typical of eolian sand dunes. Quartz grains are very well sorted, well rounded, and frosted from wind abrasion.	None reported.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north.
MIDDLE JURASSIC (174–164 mya)	**San Rafael Group** Carmel Formation, Judd Hollow Tongue (**Jcj**)	Reddish-brown sandstone, siltstone, and minor red and lavender limestone. Mapped separately only near the southwestern side of map area. Thickness: 0–70 meters (0–230 ft). Pinches out eastward. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms a prominent slope between Page Sandstone tongues northeast of Fiftymile Mountain and in the Bullfrog and Hite areas, where it is mapped as **Jpj**.	None reported.	**Jurassic Period: Extensive Dune Fields.** A sea encroached into west-central Utah from the north, and coastal eolian, sabkha, tidal flat, ephemeral stream, and restricted marine environments developed in the recreation area. The encroaching sea eliminated the sand source from the north.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER JURASSIC (201–174 mya)	**Glen Canyon Group** Navajo Sandstone (**Jn**)	Yellowish-gray, reddish-brown, and reddish-orange, massive, cross-bedded sandstone. Contains thin lenses of gray sandy limestone, dolomite, and calcareous siltstone as much as 15 m (50 ft) thick and 3–5 km (2–3 mi) long with common algae laminae, ripple marks, and mudcracks (**Jnl**). Gradational lower contact with **Jk**. Thickness ranges from about 170 m to 340 m (550–1100 ft) with a maximum of about 340 m (1100 ft) exposed in Glen Canyon below the dam. Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms rounded cliffs, knobs, buttes, mesa rims, slickrock, slot canyons, alcoves, hanging gardens, arches, natural bridges. Entrenched meanders have cut through **Jn**, and the cross-beds in **Jn** are often highlighted by desert varnish. **Sedimentary Rocks and Sedimentary Rock Features.** High-angle cross-bedding, well sorted, rounded, and frosted quartz grains typical of eolian sand dunes. Cross-bed sets range up to 20 meters (60 ft) thick. **Unusual Sedimentary Rock Features.** Moqui (Moki) marbles, contorted bedding from soft-sediment deformation, and tafoni. Features representing oases in the dune field include oscillation ripples, limestone beds, algal layers, and dinosaur tracks. **Paleontological Resources.** Dinosaur tracks include *Eubrontes*, *Anchisauripus*, *Otozoum*, *Batrachopus*, *Brasilichnium*, and *Grallator*. Distinctive unionid clam bed. Petrified trees. Cenozoic fossils collected from Bechan Cave, an alcove formed in **Jn**. **Unconformities.** J-1 unconformity separates **Jn** from overlying strata. **Folds and Faults. Jn** forms most of the crest of the Circle Cliffs anticline. **Joints.** Prominent, parallel to conjugate near-vertical joints.	**Landscape Safety Hazards.** Documented fall from **Jn** cliff at Horseshoe Bend Overlook. **Slope Movement Hazards and Risk.** Rockfall hazard. **Flash Floods and Debris Flows.** Hazard in slot canyons carved in **Jn**. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Navajo Sandstone and Potential Glen Canyon Dam Failure.** Failure of the porous **Jn** at dam spillways could lead to catastrophic consequences for downstream communities and others who rely on Lake Powell water. **Potential Impacts from Global Climate Change.** Decreases in precipitation may adversely affect water availability for the aquifers, springs, and seeps, as well as impact the fragile ecosystems of hanging gardens.	**Jurassic Period: Extensive Dune Fields.** Jurassic deserts began to inundate the Colorado Plateau. Extensive sand deserts (ergs) gradually inundated the fluvial systems of **Jk**, resulting in one of the largest dune fields ever recorded in the history of Earth. The main part of **Jn** was deposited in a large erg with local interdunal playas (oasis-like setting). The basal part of **Jn** represents deposition in a sabkha environment that had abundant wind-blown sand.
LOWER JURASSIC (201–174 mya)	**Glen Canyon Group** Limestone and dolomite beds in Navajo Sandstone (**Jnl**)	Gray, thin-bedded limestone, dolomite, and calcareous siltstone. Thin lenses of **Jnl** are up to about 5 km (3 mi) long. As many as 10 lenses are present in the walls of Navajo Canyon, but 0–3 lenses are more typical. Mapped on sheets 1, 2, and 3 (in pocket).	**Sedimentary Rocks and Sedimentary Rock Features.** Locally contain shallow channels with coarse, angular ripup clasts, algal structures, and dinosaur tracks.	None reported.	**Jurassic Period: Extensive Dune Fields.** Jurassic deserts began to inundate the Colorado Plateau. Extensive sand deserts (ergs) gradually inundated the fluvial systems of **Jk**, resulting in the largest dune fields ever recorded in the history of Earth. Glen Canyon National Recreation Area contains the largest number of **Jnl** lenses known anywhere within the Navajo Sandstone. **Jnl** represent shallow playas or lakes that formed in interdunal areas of the **Jn** erg and provide evidence that **Jn** was deposited in an area with a high water table.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER JURASSIC (201–174 mya)	**Glen Canyon Group** Kayenta Formation (**Jk**)	Brown, reddish-orange, and purplish-red, lenticular, medium- to thick-bedded, locally cross-bedded, fine- to medium-grained sandstone, silty sandstone, and mudstone. A few thin lenses of conglomerate and limestone. **Jk** is divided into a lower Springdale Sandstone Member (**Jks**) and an informal upper member that contains more siltstone than sandstone. **Jks** is exposed only in the Lees Ferry area Thickness: 58–104 meters (190–340 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms alternating cliffs, buttes, slot canyons, and steep ledgy slopes. Hanging gardens at contact with **Jn**. Entrenched meanders have cut through **Jk**. **Sedimentary Rocks and Sedimentary Rock Features.** Cross-bedded sandstone and silt represent braided and meandering streams. **Paleontological Resources.** Dinosaur tracks include *Eubrontes* and *Grallator*. Vertebrate, invertebrate, trace, and plant fossils have been found in many other locations on the Colorado Plateau. **Folds and Faults. Jk** forms the steep slope of the Waterpocket Fold. **Joints.** Large joint sets.	**Slope Movement Hazards and Risk.** Rockfall hazard. **Flash Floods and Debris Flows.** Hazard in slot canyons carved in **Jk**. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Abandoned Mineral Lands and Potential Mining Activity.** Abandoned material (cables, bricks, glass) from an oil and gas well. No natural resource impact. Major tar sands exploration site that was restored in the 1990s. **Potential Impacts from Global Climate Change.** Decreases in precipitation may adversely affect water availability for the aquifers, springs, and seeps, as well as impact the fragile ecosystems of hanging gardens.	**Jurassic Period: Extensive Dune Fields.** Jurassic deserts began to inundate the Colorado Plateau. **Jk** represents rivers that meandered through and eventually overran the **JTRw** dunes.
LOWER JURASSIC (201–174 mya)	**Glen Canyon Group** Kayenta Formation, Springdale Sandstone Member (**Jks**)	Reddish-brown, fine-grained, cross-bedded sandstone and minor siltstone and mudstone. Only recognized in the Lees Ferry area where it is 55–68 m (180–223 ft) thick. Mapped on sheets 2 and 3 (in pocket).	**Sedimentary Rocks and Sedimentary Rock Features.** Horizontal and trough cross-bedding. **Paleontological Resources.** Semionotid (ray-finned) fish and dinosaur tracks.	**Slope Movement Hazards and Risk.** Rockfall hazard. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Jurassic Period: Extensive Dune Fields.** Jurassic deserts began to inundate the Colorado Plateau. **Jks** represents a major fluvial system at the base of **Jk**.
UPPER TRIASSIC to LOWER JURASSIC (237–174 mya)	**Glen Canyon Group** Wingate Sandstone (**JTRw**)	Reddish-orange to reddish-brown, massive, cross-bedded, very fine to fine-grained eolian sandstone. Grains are mostly subangular to subrounded, well-sorted, and frosted. Upper contact varies from sharp to very gradational and is placed at top of highest massive eolian sandstone and below ledgy beds. Thickness: 60–104 meters (200–340 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Massive, vertical to rounded cliffs commonly streaked by desert varnish. Entrenched meanders have cut through **JTRw**. Landscape scarps. **Sedimentary Rocks and Sedimentary Rock Features.** Cross-bedding typical of eolian processes. **Unusual Sedimentary Rock Features.** Tafoni. **Paleontological Resources.** Dinosaur tracks. *Redondasaurus* skull discovered just outside the recreation area. **Unconformities.** Deposited above the TR-5 unconformity, which was called the J-0 unconformity until new research showed that the lower part of the Wingate and equivalent strata are Upper Triassic in age. **Joints.** Strongly cut by near-vertical joints. **Unconsolidated Surficial Deposits.** Slump blocks.	**Slope Movement Hazards and Risk.** Erosion of the underlying Chinle Formation results in cliff collapse, rockfalls, and slides. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Jurassic Period: Extensive Dune Fields.** Jurassic deserts began to inundate the Colorado Plateau. Sand transported from as far north as Montana and Alberta became the dunes preserved in **JTRw**.

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UPPER TRIASSIC to LOWER JURASSIC (237–174 mya)	**Glen Canyon Group** Moenave Formation, Dinosaur Canyon Member (**JTRmd**)	Thick to massive, eolian (Wingate-like) sandstone near the base grades upward into thin- to thick-bedded, reddish-orange to reddish-brown, fine-grained sandstone and siltstone. Some beds near the base are equivalent to **TRcc**. In the recreation area, **JTRmd** is only recognized in the Lees Ferry area. Thickness; about 90–134 m (290–440 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms thin to thick ledgy cliffs and steep slopes. **Sedimentary Rocks and Sedimentary Rock Features.** Lithologic features suggest deposition by fluvial processes.	None reported.	**Jurassic Period: Extensive Dune Fields.** Jurassic deserts began to inundate the Colorado Plateau. **JTRmd** was deposited in a broad coastal plain environment with low energy streams and lakes.
UPPER TRIASSIC (237–201 mya)	Chinle Formation, Church Rock Member (**TRcc**)	Reddish-brown, fine- to coarse-grained sandstone and siltstone. Some conglomerate beds are locally present near the base of the unit. In the Hite area, the upper part of **TRcc** is a thick [6–26 m (20–85 ft)] bed of conglomeratic and purplish-red sandstone called the Hite bed. Surface often contains **JTRw** rockfall debris. Average thickness: 12–20 m (38–60 ft). Mapped on sheets 1 and 2 (in pocket).	**Landscape Features.** Weathers to alternating steep slopes and cliffs. Buttes. **Sedimentary Rocks and Sedimentary Rock Features.** Fluvial features include ripple laminations, mudcracks, and small-scale cross-beds. **Paleontological Resources.** Fossil fish bones and petrified wood (potentially not in situ). Many additional fossils have been found in Grand Staircase-Escalante National Monument.	**Slope Movement Hazards and Risk.** The bentonite in the Chinle Formation makes the unit especially susceptible to slope movements. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Streams cut valleys into the underlying **TRm**, developing a dendritic (tree-like pattern) fluvial system in southeastern Utah. The main trunk stream flowed to the northwest.
UPPER TRIASSIC (237–201 mya)	Chinle Formation, Owl Rock and Petrified Forest Members (**TRcop**)	Gradational contact between the two members. In most areas, it is recognized by a change from strongly colored and banded Petrified Forest Member to grayish-purple to grayish-yellow ledgy beds with abundant paleosols of the overlying Owl Rock. Combined thickness: 85–160 m (280–520 ft). *Owl Rock Member*: calcareous sandstone, mottled and locally brecciated limestone, and siltstone. Commonly covered by talus. Thickness: generally 46–76 m (150–250 ft), but locally thicker [111 m, (365 ft)] at Monitor Butte). *Petrified Forest Member*: variegated smectitic claystone interbedded with siltstone, sandstone, and pebble conglomerate beds. Thickness: 12–160 m (41–520 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** *Owl Rock Member:* forms a steep slope with scattered ledges where protected by the overlying Wingate; elsewhere forms a low ledgy slope. *Petrified Forest Member:* forms a steep, barren "badlands" slope with "popcorn" weathered slopes and sandstone and conglomerate ledges. Landslide scarps. **Paleontological Resources.** Petrified logs. Vertebrate, invertebrate, and plant fossils have been discovered at locations near the recreation area. **Paleosols.** *Owl Creek Member*: stacked alluvial-plain paleosols. **Unconsolidated Surficial Deposits.** Slope movement deposits (rock slides, landslides, and slumps).	**Slope Movement Hazards and Risk.** The bentonite in the Chinle Formation makes the unit susceptible to slope movements, especially where saturated by Lake Powell. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Streams cut valleys into the underlying **TRm**, developing a dendritic (tree-like pattern) fluvial system in southeastern Utah. The main trunk stream flowed to the northwest. The Petrified Forest Member was deposited in a fluvial-lacustrine environment.
UPPER TRIASSIC (237–201 mya)	Chinle Formation, Upper (Church Rock, Owl Rock, Petrified Forest, Moss Back) Members (**TRcu**)	Members are combined into one unit because contacts are not well-defined. Unit thickness: 91–244 m (300–800 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Overall, **TRcu** forms a steep to ledgy slope commonly covered by talus just below the massive **JTRw** cliff. See specific members for other features.	**Slope Movement Hazards and Risk.** The bentonite in the Chinle Formation makes the unit especially susceptible to slope movements.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Streams cut valleys into the underlying **TRm**, developing a dendritic (tree-like pattern) fluvial system in southeastern Utah. The main trunk stream flowed to the northwest.

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UPPER TRIASSIC (237–201 mya)	Chinle Formation, Moss Back Member (**TRcms**)	Brownish-yellow to brown, lenticular, cross-bedded, well cemented, fine- to coarse-grained sandstone and thin lenses and beds of siltstone and pebble conglomerate. **TRcms** is a discontinuous tongue at the base of the Petrified Forest Member in the northern half of the recreation area. Thickness: generally 0–15 m (0–50 ft), but locally as much as 60 m (200 ft). Mapped on sheets 1 and 2 (in pocket).	**Landscape Features.** Forms cliffs to steeply ledgy slopes. **Sedimentary Rocks and Sedimentary Rock Features.** Fluvial features include cross-bedding and rip-up fragments. **Paleontological Resources.** Petrified logs. Possible dicynodont (large mammal-like reptile) *Pentasauropus* tracks. **Unconformities.** TR-4 unconformity is at the base of **TRcms**.	**Slope Movement Hazards and Risk.** The bentonite in the Chinle Formation makes the unit especially susceptible to slope movements. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Streams cut valleys into the underlying **TRm**, developing a dendritic (tree-like pattern) fluvial system in southeastern Utah. The main trunk stream flowed to the northwest.
UPPER TRIASSIC (237–201 mya)	Chinle Formation, Monitor Butte Member (**TRcmn**)	Pale-greenish-gray to reddish-gray to grayish-purple, mottled mudstone with many lenticular, cross-stratified sandstone and conglomeratic sandstone beds. Contains lenses and thin beds of clayey sandstone, limestone-pebble conglomerate, rippled gray mica-rich sandstone, calcareous shale, and coal. Beds at the top of **TRcmn** are locally similar to Petrified Forest strata. Commonly smectitic. Differs from Petrified Forest Member by having more uniform greenish-gray color and larger number of sandstone beds. Thickness: 26–75 meters (85–250 ft); 30 m (97 ft) thick at Monitor Butte. Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms small cliffs to steep slopes, which generally have soft "popcorn" weathering. **Sedimentary Rocks and Sedimentary Rock Features.** Fluvial features include cross-bedding and rip-up fragments. **Paleontological Resources.** Petrified logs, unionids, crocodile relative, and coprolites. Significant lacustrine fossils from Red Canyon include plants, insects, crustaceans, conchostracans, and fish fossils.	**Slope Movement Hazards and Risk.** The bentonite in the Chinle Formation makes the unit especially susceptible to slope movements. **Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Abandoned Mineral Lands and Potential Mining Activity.** Jomac and other uranium mines. High levels of Gamma radiation at the Jomac Mine.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Streams cut valleys into the underlying **TRm**, developing a dendritic (tree-like pattern) fluvial system in southeastern Utah. The main trunk stream flowed to the northwest. Although similar to the Petrified Forest Member, **TRcmn** was deposited under higher energy conditions.
UPPER TRIASSIC (237–201 mya)	Chinle Formation, Shinarump Conglomerate Member (**TRcs**)	Gray to brown, fine- to coarse-grained sandstone and conglomeratic sandstone, with minor lenses of mudstone and siltstone. Fills basal fluvial channels that cut into the underlying Moenkopi Formation. Thickness: generally 0–30 m (0–100 ft), but locally 60 m (200 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms a prominent, discontinuous ledgy cliff with thin slope intervals. **Sedimentary Rocks and Sedimentary Rock Features.** Conglomerate and sandstone fill paleo-channels. These deposits may contain minor uranium and copper, and very minor lead, silver, and cobalt. **Paleontological Resources.** Fossils of fern stems, leaves, and coal. Bone fragments are preserved in cobbles. Fossils include tetrapod footprints, swim traces, invertebrate shells, insect eggs, and beetle feeding traces. **Unconformities.** TR-3 unconformity is at the base of **TRcs**. **Economic Minerals.** Uranium	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Abandoned Mineral Lands and Potential Mining Activity.** *Uranium Mining*: potential hazard. Uranium occurs in sandstones and conglomerates. *Coal Mining*: **TRcs** is the surface formation at the abandoned Spencer coal mine.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Streams cut valleys into the underlying **TRm**, developing a dendritic (tree-like pattern) fluvial system in southeastern Utah. The main trunk stream flowed to the northwest.
Because of erosion at the TR-3 unconformity, Middle Triassic rocks (247–237 million years ago) are not recognized and probably not present within Glen Canyon National Recreation Area.					

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER TRIASSIC (252–247 mya)	Moenkopi Formation (main part) (**TRm**)	Reddish-brown, thinly laminated to medium-bedded, very fine to fine-grained sandstone and siltstone. Distinguished from **TRmh** by color and grain size. **TRmh** is recognized east of Hite and near the San Juan River. Divided into **TRmu** and **TRml** near Lees Ferry. Thickness: 53–114 m (175–375 ft), averaging about 90 m (300 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms buttes and ledges. Contains some arches. Entrenched meanders have cut through **TRm**. **Sedimentary Rocks and Sedimentary Rock Features.** Common ripple marks and mud cracks characteristic of floodplains and low-energy stream flow. **Paleontological Resources.** Vertebrate tracks, swimming claw marks, invertebrate trace fossils, and horsetail molds. **Unconformities.** TR-3 unconformity separates **TRm** from **TRc**. **Unconsolidated Surficial Deposits.** Slope movement deposits (rock slides, landslides, and slumps).	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Tropical climate conditions dominated the region in the Early Triassic. The western part of the Colorado Plateau consisted of a broad continental shelf while nearshore to coastal environments developed in the eastern part of the plateau. Sediments spread into Utah from the erosion of the Ancestral Rocky Mountains in Colorado. **TRm** represents deposition in tidal-flat, sabkha, and low coastal-plain environments.
LOWER TRIASSIC (252–247 mya)	Moenkopi Formation, Hoskinnini Sandstone Member (**TRmh**)	Reddish-brown to grayish-orange, very fine to coarse-grained sandstone. Poorly developed stratification with wavy laminations. Unconformably overlies either **Pwr** or **Po**. Thickness: 0–33 m (0–110 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms knobby cliffs. **Paleontological Resources.** Stromatolites. **Unconformities.** TR-1 unconformity marks the boundary between the Paleozoic Era and deposition of **TRmh** at the beginning of the Mesozoic Era.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Tropical climate conditions dominated the region in the Early Triassic. The western part of the Colorado Plateau consisted of a broad continental shelf while nearshore to coastal environments developed in the eastern part of the plateau. Sediments spread into Utah from the erosion of the Ancestral Rocky Mountains in Colorado. **TRmh** was deposited in a sabkha environment with sediments filling a low area that had been carved into the underlying **Po**.
LOWER TRIASSIC (252–247 mya)	Moenkopi Formation, upper and lower members (**TRmu**, **TRml**)	*Upper unit*: dark-reddish-brown, even-bedded siltstone and sandy siltstone with two to three thin beds of gray sandy limestone. Includes a distinctive 5–12-m (15–40 ft) thick, massive, pale-brown sandstone at the base. Thickness: 0–36 m (0–120 ft). *Lower unit*: pale-brown, thin-bedded to laminated, gypsiferous, shaly siltstone and mudstone. Thickness: 98–130 m (320–430 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Lower part forms ledgy cliff. Upper part forms steep slope with scattered ledges.	**Abandoned Mineral Lands and Potential Mining Activity. TRmu** is at the surface of some abandoned mines.	**Triassic Period: Fluvial Systems in a Tropical Climate.** Tropical climate conditions dominated the region in the Early Triassic. The western part of the Colorado Plateau consisted of a broad continental shelf while nearshore to coastal environments developed in the eastern part of the plateau. Sediments spread into Utah from the erosion of the Ancestral Rocky Mountains in Colorado. **TRm** represents deposition in tidal-flat, sabkha, and low coastal-plain environments.
Rocks from the Middle and Late Permian Epochs (272–252 million years ago) are not mapped within Glen Canyon National Recreation Area.					
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	Permian Formations (P)	In the Circle Cliffs area northeast of the Escalante River, Permian strata are exposed in the bottoms of several deep canyons. See separate descriptions below. Mapped on sheet 2 (in pocket).	See individual Permian units.	See individual Permian units.	See individual Permian units.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	Kaibab Formation (**Pk**)	Gray, thin-bedded dolomite, dolomitic limestone, and sandy dolomitic limestone with thin interbeds of calcareous siltstone. Includes chert nodules and layers in the upper part. Thickness: 70 m (235 ft) at Navajo Bridge near Lees Ferry. **Pk** thins to the east (probably due to erosion prior to deposition of **TRm**). Mapped in the Lees Ferry area. Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms cliffs. **Paleontological Resources.** None reported in the recreation area, but on the Colorado Plateau, **Pk** commonly contains abundant fossils of marine invertebrates including brachiopods, corals, bryozoans, and crinoids.	**Landscape Safety Hazards.** Documented fall from **Pk** cliff. **Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from **Pk** have not yet been documented from Glen Canyon National Recreation Area but could be present.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** By the end of the Permian, the major land masses were suturing together to form the supercontinent Pangea. **Pk** represents a marine transgression across the region.
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	Toroweap Formation (**Pt**)	Gray and brown, fine-grained, silty sandstone, silty mudstone, and cherty limestone. Exposed and mapped only south of Navajo Bridge near Lees Ferry. Thickness: 55–67 m (180–220 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms slopes.	None reported.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** By the end of the Permian, the major land masses were suturing together to form the supercontinent Pangea. **Pt** represents nearshore and shallow marine deposition along the western margin of Pangea
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	Coconino Sandstone (**Pco**)	Yellowish-gray, medium- to fine-grained, cross-bedded sandstone. The uppermost few feet of the formation is exposed and mapped only south of Navajo Bridge near Lees Ferry. Thickness: 0–9 m (0–30 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Cliff- to ledge-forming. **Sedimentary Rocks and Sedimentary Rock Features.** Cross-bedding.	**Abandoned Mineral Lands and Potential Mining Activity.** *Oil and Gas Exploration*: major hydrocarbon reservoir in the Paradox Basin of southeast Utah.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** By the end of the Permian, the major land masses were suturing together to form the supercontinent Pangea. **Pco** represents coastal and nearshore marine deposition along the western margin of Pangea.
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	Hermit Formation (**Phe**)	Dark brownish-red, thin-bedded siltstone and shale with thin beds of lighter colored, fine-grained sandstone. Only the upper part is exposed in the map area south of Navajo Bridge. Thickness: about 195 meters (640 ft). Mapped on sheets 2 and 3 (in pocket).	**Landscape Features.** Forms slopes.	None reported.	Not mapped in Glen Canyon National Recreation Area.
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	**Cutler Group** White Rim Sandstone (**Pwr**)	Gray, fine- to coarse-grained, cross-bedded sandstone, silty sandstone, and locally dolomitic sandstone. Thickness: 0–26 m (0–85 ft) in the Hite area, where it thickens rapidly to the north and northwest and thins and pinches out to the south and east, and 9 m (30 ft) at Nokai Dome along the San Juan arm, where it thins eastward. Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms a cliff and broad bench that makes a prominent marker bed throughout the region. **Sedimentary Rocks and Sedimentary Rock Features.** High-angle cross-bedding. **Unusual Sedimentary Rock Features.** Tafoni. **Paleontological Resources.** Although rare, trace fossils have been reported from Canyonlands National Park. **Unconformities.** TR-1 separates **Pwr** from **TRm**. **Economic Minerals.** Main unit containing tar sands in the Tar Sand Triangle. **Geologic Type Sections.** Designated in Canyonlands National Park adjacent to the northern arm of the recreation area.	**Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from **Pwr** have not yet been documented from Glen Canyon National Recreation Area but could be present. **Abandoned Mineral Lands and Potential Mining Activity.** *Tar Sands Exploration*: contains significant tar sand deposits. Abandoned cabins from the drilling of a tar sands oil well.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **Pwr** was deposited in a mostly eolian environment with some marine influence.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	**Cutler Group** Organ Rock Formation (**Po**)	Brown to grayish-red, horizontally bedded siltstone interbedded with sandstone and mudstone beds. Local lenses of coarse conglomerate in the upper part erode out in relief. Much less resistant than **Pcm**. Thickness: 67–140 m (220–460 ft). Thins to the north. Mapped on sheets 1, 2, and 3 (in pocket).	**Landscape Features.** Forms broad slope or bench that gradually steepens up-section to form steep ledgy slopes and small cliffs. **Sedimentary Rocks and Sedimentary Rock Features.** High-angle cross-bedding (eolian features). Trough-shaped cross-bedding, coarse conglomerate, and mudstone (fluvial features). **Paleontological Resources.** Potential fossils in the stream channel deposits. **Unconformities.** TR-1 separates **Po** from **TRmh**. **Unconsolidated Surficial Deposits.** Slope movement deposits (rock slides, landslides, and slumps).	**Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from **Po** have not yet been documented from Glen Canyon National Recreation Area but could be present.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **Po** was deposited in floodplain, tidal mud-flat, and beach environments that would develop during marine transgressions. Coarse conglomerate lenses are characteristic of high-energy stream channel deposits.
LOWER PERMIAN or Cisuralian Epoch (299–272 mya)	**Cutler Group** Cedar Mesa Sandstone (**Pcm**)	Yellowish-gray, reddish-orange, and reddish-brown, cross-bedded, fine-grained sandstone interbedded with lenses of reddish-brown to grayish-green sandy siltstone. Siltstone increases in upper part. Thickness: 290–335 m (980–1100 ft). Mapped on sheets 1 and 2 (in pocket).	**Landscape Features.** Forms massive cliffs with scattered ledges, mesas, and slickrock. Alcoves. **Sedimentary Rocks and Sedimentary Rock Features.** High-angle cross-bedding (eolian features) and fluvial (floodplain) features. Convoluted bedding common. **Paleontological Resources.** Tracks of the skink, *Anomalopus*, and its prey, the beetle *Stenichus*, as well as tracks of synapsids. **Geologic Type Sections.** Cedar Mesa, which extends north of the San Juan Arm.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **Pcm** was deposited in coastal eolian environments that were occasionally overrun by small rivers or streams, floodplains, and playas (**Po**). Marine incursions occurred in the northern areas.
UPPER PENNSYLVANIAN to LOWER PERMIAN (307–272 mya)	**Cutler Group** Cutler Formation (**Pc**)	Cutler Group strata grade northward into a thick sequence of interbedded arkosic sandstone and mudstone along the Green River in the northeast part of the map area, and individual formations become unrecognizable. In that area, the Cutler Group becomes the Cutler Formation and does not have any formal members. Thickness: about 180 meters (600 ft). Mapped on sheets 1 and 2 (in pocket).	None reported.	None reported.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Erosion of the adjacent Uncompahgre highlands to the northeast shed arkosic (feldspar-rich) sediments into the margins of the Paradox Basin, and these sediments interbedded with marine units. Restricted marine conditions gave way to open-marine environments.
UPPER PENNSYLVANIAN to LOWER PERMIAN (307–272 mya)	**Cutler Group** Lower Cutler beds (**PPNcl**)	Brown, orange, and gray, thin- to thick-bedded, fine- to coarse-grained sandstone interbedded with lesser siltstone, mudstone, conglomerate, and limestone beds. Alternating light (quartzitic) and dark (arkosic) sandstone beds give unit a banded appearance. Best exposed in lower Cataract Canyon from upstream of Hite Crossing to the border of Canyonlands National Park. **PPNcl** are called **PPNe** in Canyonlands National Park and **PPNh** in the San Juan River area. Thickness: 115–140 m (375–460 ft). Mapped on sheets 1 and 2 (in pocket).	**Landscape Features.** Forms a ledgy slope. **Paleontological Resources.** Marine invertebrate fossils of foraminifera, brachiopods, bivalves, gastropods, crinoids, and elasmobranch teeth.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **PPNcl**, **PPNhg**, and **PPNe** record deposition in tidal flat, delta, coastal sand dune, fluvial, and shallow-marine shelf environments.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
UPPER PENNSYLVANIAN to LOWER PERMIAN (307–272 mya)	**Cutler Group** Halgaito Formation, upper and lower members (**PPNhgu**, **PPNhgl**)	Interbedded reddish-brown, grayish-red, and yellowish-red, very fine to medium-grained sandstone, dark-red siltstone. Exposures along the San Juan River are mapped as two informal members. *Upper member*: locally very minor to no carbonate beds exposed on the surface. Thickness: 18–27 m (60–90 ft). *Lower member*: includes thin beds of gray cherty fossiliferous limestone and dolomite. Thickness: about 116 m (380 ft). Thickness: 142 m (465 ft) at Johns Canyon near the San Juan River. Mapped on sheet 2 (in pocket).	**Landscape Features.** Forms steep ledgy slopes. **Sedimentary Rocks and Sedimentary Rock Features.** Cyclic interbeds of fossiliferous marine limestone, siltstone, sandstone, black organic shale, dolomite, and/or gypsum characteristic of fluctuating sea level and nearshore marine depositional environments. **Paleontological Resources.** Marine fossils include foraminifera, crinoids, algal mats, burrows, and bones from fish, amphibians (including the “sail back” *Platyhystrix*), tetrapods, reptiles, and pelycosaurs. **Geologic Type Sections.** Unofficially named for Halgaito Spring, southwest of Mexican Hat.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **PPNcl**, **PPNhg**, and **PPNe** record deposition in tidal flat, delta, coastal sand dune, fluvial, and shallow-marine shelf environments.
UPPER PENNSYLVANIAN to LOWER PERMIAN (307–272 mya)	**Cutler Group** Elephant Canyon Formation (**PPNe**)	Cyclically interbedded gray, planar, medium- to very thick- bedded fossiliferous limestone, poorly exposed brown to gray siltstone, very fine- grained sandstone, and calcareous mudstone. Thickness: about 120 m (400 ft) exposed along the Green River. Mapped on sheets 1 and 2 (in pocket).	**Sedimentary Rocks and Sedimentary Rock Features.** Fossiliferous limestone. **Paleontological Resources.** Marine invertebrate fossils include foraminifera, crinoids, corals, conodonts, bryozoans, brachiopods, trilobites, cephalopods, and echinoderms. **Geologic Type Sections.** Elephant Canyon in Canyonlands National Park.	None reported.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **PPNcl**, **PPNhg**, and **PPNe** record deposition in tidal flat, delta, coastal sand dune, fluvial, and shallow-marine shelf environments.
UPPER PENNSYLVANIAN (307–299 mya)	**Hermosa Group** Honaker Trail Formation (**PNht**)	Cyclically interbedded gray limestone, brown to gray siltstone to very fine grained sandstone, and dark gray to black organic shale. The upper contact is placed at the top of the highest prominent, laterally continuous limestone bed, which can be up to 6 m (20 ft) thick. In the San Juan Arm area, this limestone bed forms a bench beneath slope-forming **PPNcl** beds. A prominent ledge-forming sandstone bed informally called the Goodrich Sandstone directly overlies the upper limestone throughout most of the map area, forming a distinctive double-ledge with the **PNht** contact between the two ledges. Thickness: 218 m (715 ft). Mapped on sheets 1 and 2 (in pocket).	**Landscape Features.** Forms ledges and smaller cliffs separated by short slopes of organic shale. **Sedimentary Rocks and Sedimentary Rock Features.** Cyclic interbeds of fossiliferous marine limestone, siltstone, sandstone, black organic shale, dolomite, and/or gypsum characteristic of fluctuating sea level and nearshore marine depositional environments. **Paleontological Resources.** Marine invertebrate fossils include foraminifera, bryozoans, gastropods, crinoids, and conodonts. Trace fossils include root traces, pellets, and borings. **Unconsolidated Surficial Deposits.** Slope movement deposits (rock slides, landslides, and slumps). **Geologic Type Sections.** Honaker Trail in The Goosenecks section of the San Juan River.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database. **Abandoned Mineral Lands and Potential Mining Activity.** *Oil and Gas Exploration*: major hydrocarbon reservoir in the Paradox Basin of southeast Utah.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **PNht** records deposition in shallow marine, beach, lagoonal, and deltaic environments.

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Age (mya=millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
UPPER PENNSYLVANIAN (307–299 mya)	**Hermosa Group** Honaker Trail Formation, upper and lower members (**PNhtu**, **PNhtl**)	Informal upper (**PNhtu**) and lower (**PNhtl**) members are mapped in the San Juan River Arm. Gradational contact. *Upper member*: red mudstone. Thickness: 49–55 m (160–180 ft). *Lower member*: gray and black shale. Thickness: 163–169 m (535–555 ft). Mapped on sheet 2 (in pocket).	**Landscape Features.** Upper member: forms slopes. Lower member: forms slopes.	None reported.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions gave way to open-marine environments. **PNht** records deposition in shallow marine, beach, lagoonal, and deltaic environments.
MIDDLE PENNSYLVANIAN (315–307 mya)	**Hermosa Group** Paradox Formation (**PNp**)	Gray lime mudstone, spiculiferous wackestone, fossiliferous and peloidal wackestone and packstone, algal boundstone, and cross-bedded ooid grainstone cyclically interbedded with brown to gray siltstone to very fine grained sandstone, dark-gray to black organic shale, and (in Cataract Canyon only) contorted gray gypsum. Sandstone is planar to trough cross-bedded and has fossil fragments. Shale is fossil-poor, laminated to thinly laminated, highly organic, and locally sulfurous. Cycles are typically 2–6 m (6–20 ft) thick. Exposed in the deepest parts of Cataract Canyon and San Juan River Arm and are some of the most studied Pennsylvanian rocks in Utah. The upper contact in San Juan River Arm is placed at the top of a massive blocky cliff known as "The Horn limestone" that forms the most recognizable horizon in the area. Thickness: exposed strata are too contorted to measure, but the estimated thickness is 60 m (200 ft). Mapped on sheets 1 and 2 (in pocket).	**Landscape Features.** Forms cliffs. **Sedimentary Rocks and Sedimentary Rock Features.** Cyclic interbeds of fossiliferous marine limestone, siltstone, sandstone, black organic shale, dolomite, and/or gypsum characteristic of fluctuating sea level and nearshore marine depositional environments. Trough-shaped cross-beds in sandstone beds. **Paleontological Resources.** Potential marine invertebrate fossils include crinoids, bryozoans, brachiopods, fusulinids, corals, foraminifers, and conodonts. Although not found in the recreation area yet, **PNp** also contains sponge spicules, algae, ooids, fish fragments, and scattered distinctive algal boundstone mounds composed of phylloid algal plates that appear like mounds of crushed potato chips. **Unconsolidated Surficial Deposits.** Slope movement deposits (rock slides, landslides, and slumps).	**Paleontological Resources Inventory, Monitoring, and Protection.** Fossils from **PNp** have not yet been documented from Glen Canyon National Recreation Area but could be present. **Abandoned Mineral Lands and Potential Mining Activity.** *Oil and Gas Exploration*: major hydrocarbon reservoir in the Paradox Basin of southeast Utah, and the primary producing reservoir in the Greater Aneth Oil Field of southeastern Utah.	**Pennsylvanian and Permian Periods: Shallow Seas and Assembling Pangea.** Tectonic compression caused the northwest–southeast trending Paradox Basin to subside, resulting in episodes of marine incursions into southeastern Utah. Restricted marine conditions eventually gave way to open-marine environments. **PNp** records cycles of transgressions and regressions, and the subsequent strata of porous limestone, shale, and salt resulted in economic reserves of hydrocarbons in the Paradox Basin.
Rocks older than Middle Pennsylvanian are not mapped within Glen Canyon National Recreation Area.					

Unconsolidated Map Unit Properties Table: Glen Canyon National Recreation Area

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene)	**Man Made Deposits** Artificial fill and disturbed areas (**Qfd**)	Gravel, sand, and earth-fill emplaced by humans and large areas that have been significantly disturbed. Thickness is highly variable, but generally 0–18 m (0–60 ft) thick. Mapped on sheets 2 and 3 (in pocket).	Construction of Glen Canyon Dam and other disturbed areas (not natural geologic features or processes).	**Abandoned Mineral Lands and Potential Mining Activity.** Gravel pits.	**Glen Canyon National Recreation Area And Other NPS Areas Along The Colorado River.** Construction of Glen Canyon Dam and other development in the region resulted in disturbed areas.
QUATERNARY (Holocene)	**Man Made Deposits** Concrete fill in Glen Canyon Dam (**Qfdm**)	Concrete fill (3,745,000 m^3; 4,901,000 yds^3) used to create Glen Canyon Dam. Dam dimensions are in the glca_geology.pdf. Mapped on sheets 2 and 3 (in pocket).	Construction of Glen Canyon Dam and other disturbed areas (not natural geologic features or processes).	None reported.	**Glen Canyon National Recreation Area And Other NPS Areas Along The Colorado River**. Construction of Glen Canyon Dam and other development in the region resulted in disturbed areas.
QUATERNARY (Upper Pleistocene to Holocene)	**Alluvial Deposits** Undifferentiated alluvial deposits (**Qa**)	Boulder to pebble gravel, sand, silt, and clay deposited in small drainages, in stream and wash channels, on broad alluvial fan surfaces, and in terrace remnants. Poorly to moderately well sorted. Thickness: 0–15 m (0–50 ft). Mostly correlates with deposits mapped as **Qal**, **Qal1**, **Qat**, **Qat2-3**, **Qag**, **Qae**, **Qaec**, and **Qea** in other areas. Mapped on sheets 2 and 3 (in pocket).	See individual units.	See individual alluvial units.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.
QUATERNARY (Upper Pleistocene to Holocene)	**Alluvial Deposits** Alluvial river and major stream deposits (**Qal**)	Similar to **Qal1** deposits but more generalized and only found in the northern part of the map area. Locally includes sediments equivalent to **Qat2** and possibly **Qat3**. Mapped on sheets 1 and 2 (in pocket).	**Unconsolidated Surficial Deposits.** With thirty-three mapped alluvial and mixed alluvial units, alluvial deposits are the most diverse surficial deposits in the recreation area.	**Flash Floods and Debris Flows**. Intense thunderstorms may cause flash floods and debris flows, which may threaten visitor safety and damage or destroy infrastructure.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.
QUATERNARY (Upper Pleistocene to Holocene)	**Alluvial Deposits** Young alluvial river and major stream deposits (**Qal1**)	Lenticular, interbedded gravel, sand, silt, and clay deposited by the San Juan and Colorado Rivers and larger tributaries. Generally poor to well sorted. Rounded clasts show evidence of significant transport. May include poorly sorted debris flow deposits and talus derived from side canyons and cliffs. Typically, deposits are up to 6 m (20 ft) above the river and stream channels, but can contain modern human-made debris up to 12 m (40 ft) above the modern river. Thickness: 0–9 m (0–30 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Small-scale trough cross-bedding, climbing ripple laminations, and imbricated cobbles. Forms sand and gravel bars in river channels and point bars on meander bends.	**Slope Movement Hazards and Risk.** Talus indicates where rockfalls have occurred in the past and are likely to occur again. **Flash Floods and Debris Flows**. Intense thunderstorms may cause flash floods and debris flows, which may threaten visitor safety and damage or destroy infrastructure. **Abandoned Mineral Lands and Potential Mining Activity.** Placer gold mines. **Glen Canyon Dam and Downstream Impacts to the Colorado River.** Sandbars and pre-dam flood deposits have been eroded, and the thin point bars that formed at meander bends may eventually disappear.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Upper Pleistocene to Holocene)	**Alluvial Deposits** Young alluvial river and stream terrace gravel deposits (**Qaty**)	Pebble- to cobble-gravel with less common boulders, sand, silt, and clay. River deposits preserved as terraces. Most clasts are moderately to well sorted, rounded, and originated primarily from outside the map area. In the Escalante area, **Qaty** contains many deposits mapped as **Qat2–13**. Mapped on sheet 2 (in pocket).	**Unconsolidated Surficial Deposits.** Remnants of previous terraces.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.
QUATERNARY (Lower Pleistocene to Holocene)	**Alluvial Deposits** Undifferentiated alluvial river and stream terrace gravel deposits (**Qat**, **Qat2–13**, **Qatg8–10**, **Qatg12**)	**Qat**. Terrace deposits of pebble- to cobble-gravel with less common boulders, sand, silt, and clay. Most clasts are moderately to well sorted, rounded, and originated primarily from outside the map area. The many terrace levels range from about 6 m (20 ft) to about 400 m (1,400 ft) above the modern river channel. Lake Powell covers lower deposits. **Qat2.** Level 2 (Holocene; possibly locally late middle Pleistocene) **Qat3**. Level 3 (lower Holocene to upper Pleistocene) **Qat4.** Level 4 (Middle to Upper Pleistocene) **Qat5.** Level 5 (Middle to Upper Pleistocene) **Qat6.** Level 6 (Lower to Middle Pleistocene) **Qat7.** Level 7 (Middle Pleistocene) **Qat8.** Level 8 (Lower to Middle Pleistocene) **Qat9.** Level 9 (Lower to Middle Pleistocene) **Qat10.** Level 10 (Lower to Middle Pleistocene) **Qat11.** Level 11 (Lower to Middle Pleistocene) **Qat12.** Level 12 (Lower to Middle Pleistocene) **Qat13.** Level 13 (Lower to Middle Pleistocene) **Qatg8.** Qat8 and locally derived gravel deposits. (Lower to Middle Pleistocene) **Qatg9.** Qat9 and locally derived gravel deposits. (Lower to Middle Pleistocene) **Qatg10.** Qat10 and locally derived gravel deposits. (Lower to Middle Pleistocene) **Qatg12.** Qat12 and locally derived gravel deposits. (Lower to Middle Pleistocene) **Qat** is mapped on sheets 1, 2, and 3 (in pocket). Numbered alluvial and stream terrace gravel deposits are mapped on sheets 2 and 3. **Qat5** and **Qat6** are both mapped on all three sheets.	**Unconsolidated Surficial Deposits.** Remnants of previous terraces, channel deposits, and alluvial fan-shaped deposits.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.
QUATERNARY (Lower Pleistocene to Holocene)	**Alluvial Deposits** Undifferentiated locally derived alluvial gravel deposits (**Qag**)	Poorly to moderately well sorted, boulder- to clay-sized deposits preserved as remnants above small ephemeral streams and washes, on gentle to moderate slopes, and on broad sloping benches. Some boulders are up to 2 m (6 ft) in diameter. Clasts derived from local bedrock. Eolian silt and sand has accumulated on some older deposits. Generally found at lower levels. Thickness: 0–18 m (0–60 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Remnants of previous terraces, channel deposits, and alluvial fan-shaped deposits.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Middle to Upper Pleistocene)	**Alluvial Deposits** Intermediate-level locally derived alluvial gravel deposits (**Qagm**)	Similar lithology to **Qag**, but **Qagm** is found on benches and slopes 6–30 m (20–100 ft) above the floor of small streams and washes, but still within the canyons. Mapped on sheet 3 (in pocket).	**Unconsolidated Surficial Deposits.** Remnants of previous terraces, channel deposits, and alluvial fan-shaped deposits.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.
QUATERNARY (Lower to Middle Pleistocene)	**Alluvial Deposits** High-level locally derived alluvial gravel deposits (**Qago**)	Similar lithology to **Qag**, but **Qago** deposits cap high, gently sloping benches and knolls up to about 430 m (1,400 ft) above the floor of adjacent small streams and washes. Mapped on sheets 2 and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Remnants of previous terraces, channel deposits, and alluvial fan-shaped deposits.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Clasts in alluvial deposits reflect erosion of local bedrock as well as far-travelled bedrock from western Colorado.
QUATERNARY (Holocene)	**Mixed Environment Deposits** Young alluvial and eolian deposits (**Qae**)	Heterogeneous mixture of boulders- to pebbles, sand, silt, and clay covered by minor to moderate amounts of windblown sand and silt. Similar to **Qa** and **Qac**, **Qae** clasts are composed of local or upslope lithologies. Rockfalls, landslides, and debris flows contribute angular rubble to the deposits. Mapped on broader slopes with less-defined drainages than **Qa** and **Qac**. **Qae** is mapped in small washes where the clasts were deposited in the active part of the wash bottom to about 12 m (40 ft) above the wash floor. Thickness: generally 2–6 m (6–20 ft) thick. Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial and eolian sediments.	**Slope Movement Hazards and Risk.** Angular rubble indicates where slope movements have occurred in the past and are likely to occur again. **Flash Floods and Debris Flows**. Intense thunderstorms may cause flash floods and debris flows, which may threaten visitor safety and damage or destroy infrastructure.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Holocene)	**Mixed Environment Deposits** Level 2 alluvial and eolian deposits (**Qae2**)	Similar lithology to **Qae**, but **Qae2** deposits are 6–12 m (20–40 ft) above the adjacent wash. Mapped on sheets 2 and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial and eolian sediments.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Upper Pleistocene to Holocene)	**Mixed Environment Deposits** Level 3 alluvial and eolian deposits (**Qae3**)	Similar lithology to **Qae**, but **Qae3** deposits are 12–24 m (40–80 ft) above the adjacent wash. Mapped on sheets 1 and 2 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial and eolian sediments.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Upper Pleistocene to Holocene)	**Mixed Environment Deposits** Alluvial and colluvial deposits (**Qac**)	Deposits consisting of boulders to clay-sized sediment. Contains windblown sand and silt and colluvium derived from adjacent slopes. Moderately to poorly sorted. Rockfalls, landslides, and debris flows contribute large angular boulders. Similar to **Qa** and **Qae** except for more colluvium. Thickness: 0–6 m (0–20 ft). Mapped on sheets 2 and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial and colluvial sediments.	**Slope Movement Hazards and Risk.** Colluvium indicates where slope movements have occurred in the past and are likely to occur again. **Flash Floods and Debris Flows**. Intense thunderstorms may cause flash floods and debris flows, which may threaten visitor safety and damage or destroy infrastructure.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Middle Pleistocene to Holocene)	**Mixed Environment Deposits** Alluvial fan, stream, eolian, and colluvial deposits (**Qaec**)	Boulders, sand, to clay deposited as alluvial fan, ephemeral stream, and colluvial deposits on low-relief slopes and benches, especially below cliff- and ledge-forming bedrock units, and in poorly developed terraces along ephemeral streams. Commonly includes talus and rockfall debris. Farthest ends of deposit transition into **Qes**. Thickness: 0–10 m (0–30 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial, colluvial, and eolian sediments.	**Slope Movement Hazards and Risk.** Colluvium and talus indicate where rockfalls have occurred in the past and are likely to occur again. **Flash Floods and Debris Flows**. Intense thunderstorms may cause flash floods and debris flows, which may threaten visitor safety and damage or destroy infrastructure.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Middle Pleistocene to Holocene)	**Mixed Environment Deposits** Eolian and alluvial deposits (**Qea**)	Moderately to very well sorted sand, silt, and clay. Deposited by wind and locally reworked by water. Commonly capped by thick calcic soil (caliche) that forms a resistant bench. Common on broad stable surfaces. Similar to **Qes**, but evidence of alluvial activity is common and dune forms are less common. Thickness: 0–15 m (0–50 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of wind-deposited sand, silt, and clay mixed with stream-deposited pebbles and cobbles.	Human disturbances can lead to migrating windblown sand.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Lower Pleistocene to Holocene)	**Mixed Environment Deposits** Older eolian and alluvial deposits (**Qeao**)	Similar lithology to **Qea** but **Qeao** deposits are mapped on the highest benches and have the thickest calcic soil. Mapped on sheets 2 and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of wind-deposited sand, silt, and clay mixed with stream-deposited pebbles and cobbles.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Middle to Upper Pleistocene)	**Mixed Environment Deposits** Older alluvial and colluvial deposits (**Qaco**)	Similar lithology to **Qac,** but these older deposits are incised by active washes and form inactive terraces and benches 6 m to more than 30 m (20–100+ ft) above washes. Mapped on sheet 2 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial and colluvial sediments.	**Slope Movement Hazards and Risk.** Colluvium indicates where slope movements have occurred in the past and are likely to occur again.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.
QUATERNARY (Lower to Upper Pleistocene)	**Mixed Environment Deposits** Older alluvial and eolian deposits (**Qaeo**)	Similar lithology to **Qae**, but **Qaeo** deposits are 9 to >470 m (30–1,550+ ft) above the adjacent wash. Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Mixture of alluvial and eolian sediments.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. As the Colorado River and associated tributaries continued to incise bedrock, previous channels became elevated terraces. Alluvial deposits mixed with wind-blown sand and silt.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Middle Pleistocene to Holocene)	**Lacustrine deposits** Lacustrine deposits (**Ql**)	Thinly laminated silt, very fine grained sand, peat, and clay. Estimated to be 0–10 m (0–30 ft) thick in the Good Hope Bay area. Thick deposits in Lake Canyon are remnants of a lake that the Piute Indians called Pagahrit, which drained in CE 1915. The lake consists of several lake cycles, the oldest of which has been dated at 5,180 years before present. Mapped on sheets 1 and 2 (in pocket).	**Unconsolidated Surficial Deposits.** Layers of sand, silt, clay, and peat. Several lake cycles record the history of ancient Lake Pagahrit. **Paleontological Resources**. Pollen, peat, and insects that provide paleoclimate information have been retrieved from the Lake Pagahrit site in the Lake Canyon area.	**Paleontological Resources Inventory, Monitoring, and Protection.** Protocols to monitor paleontological resources have been defined and management is in the process of completing an inventory of fossil sites in the recreation area and establishing a systematic monitoring plan and database.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon.
QUATERNARY (Middle Pleistocene to Holocene)	**Precipitated Deposits** Spring tufa deposits (**Qst**)	Pale-gray, yellowish-gray, and reddish-gray tufa (calcium carbonate) deposited by springs. Cements bedrock and talus rubble, colluvium, and other surficial deposits. In many canyons below seeps and springs, tufa can be up to 1–2 m (0.3–0.6 ft) thick. In Red Canyon, deposits are as much as 5 m (15 ft) thick. Mapped on sheets 1 and 2 (in pocket).	**Unconsolidated Surficial Deposits.** Chemical sedimentary rock composed of calcium carbonate. Formed by evaporation.	None reported.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. With exposure of the **Jn**/**Jk** contact, groundwater seeps and springs develop along the canyon walls and calcium carbonate is precipitated.
QUATERNARY (Middle Pleistocene to Holocene)	**Eolian Deposits** Eolian sand (**Qes**)	Very well-sorted, well-rounded, mostly fine- to medium-grained, frosted (translucent) quartz sand derived from the weathering of sandy bedrock, especially Navajo Sandstone (**Jn**). Thickness: 0–15 m (0–45 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Wind-blown sediment deposited in sheets, mounds, and dunes. Primarily derived from weathered **Jn** and **Je**.	Human disturbances can lead to migrating windblown sand.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Uplift continued into the Holocene and eolian processes transported weathered quartz grains from exposed Mesozoic and Paleozoic sandstones and deposited them in sand sheets, mounds, and small dunes in protected areas. Amount of sand generation and transport is probably related to short- and long-term climatic fluctuations.
QUATERNARY (Historical)	**Mass Movement Deposits** Historical landslides and slump deposits (**Qmsh**)	Chaotic, extremely poorly sorted, angular, massive blocks to clay-size material that slumped or flowed down slopes. The deposits range from surficial talus and alluvium to blocks of bedrock several hundred meters across. Thickness is poorly known and highly variable, ranging from 0–75 m (0–250 ft), but locally may exceed 100 m (300 ft). **Qmsh** represents slides and slumps that show evidence of historic movement. Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Variety of slope movement deposits including slides, slumps, earthflows, and toreva blocks, which are landslides that occur when erosion of weaker material, such as shale, undercuts stronger material, such as sandstone.	**Slope Movement Hazards and Risk.** Landslides and slumps occur nearly everywhere the Chinle Formation is exposed above or just below the water line of Lake Powell, but locally may also involve other formations. Landsliding and slumping have been greatly accelerated along the shore of Lake Powell, but have and can impact other areas, as well. Even historical landslides remain unstable and can be reactivated under certain conditions. All landslides and mass movement deposits may continue to move by slow creep and pose a risk of renewed movement.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Entrenched meanders and cliffs developed, along with landslides, slumps, and other slope movement deposits.
QUATERNARY (Lower Pleistocene to Holocene)	**Mass Movement Deposits** Landslides and slump deposits (**Qms**)	Chaotic, extremely poorly sorted, angular, massive blocks to clay-size material that slumped or flowed down slopes. The deposits range from surficial talus and alluvium to blocks of bedrock several hundred meters across. Thickness is poorly known and highly variable, ranging from 0–75 m (0–250 ft), but locally may exceed 100 m (300 ft). May include historic movement. Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Generally forms large coalescing landslide complexes that extend as a continuous apron up to several kilometers. Upper surfaces are typically hummocky.	**Slope Movement Hazards and Risk.** Landslides and slumps occur nearly everywhere the Chinle Formation is exposed above or just below the water line of Lake Powell, but locally may also involve other formations. Even historical landslides remain unstable and can be reactivated under certain conditions. All landslides and mass movement deposits may continue to move by slow creep and pose a risk of renewed movement.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Entrenched meanders and cliffs developed, along with landslides, slumps, and other slope movement deposits.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Lower Pleistocene to Holocene)	**Mass Movement Deposits** Slump blocks (**Qmsb**)	Blocks of bedrock, some as much as 2.7 km (1.5 mi) long, that have slumped downslope, especially blocks of Wingate Sandstone (**JTRw**) that have slumped onto the underlying Chinle Formation (**TRc**). Mapped separately from **Qms** and **Qmst** only in the White Canyon area. Thickness: highly variable. Mapped on sheets 1 and 2 and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Typically, blocks of **Qmsb** have rotated backwards and dip toward the nearby cliff.	**Slope Movement Hazards and Risk.** Weathering and erosion of less resistant material results in cliff collapse, rockfalls, and slides. Probably less active today than in the past except near the lake.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Entrenched meanders and cliffs developed, along with landslides, slumps, and other slope movement deposits.
QUATERNARY (Lower Pleistocene to Holocene)	**Mass Movement Deposits** Talus deposits (**Qmt**)	Angular rockfall debris at the base of steep slopes. Mapped separately from **Qmst** in the Hite Crossing, Bullfrog, Lees Ferry, and San Juan Canyon areas. Thickness: generally less than 10 m (30 ft). Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Jumbled blocks of rock. Commonly at the base of all ledges, cliffs, and steep slopes.	**Slope Movement Hazards and Risk. Qmt** may become unstable and begin to slide down slope with increased precipitation. Rockfalls can occur in any steep area and are highly unpredictable.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Entrenched meanders and cliffs developed, along with landslides, slumps, and other slope movement deposits.
QUATERNARY (Lower Pleistocene to Holocene)	**Mass Movement Deposits** Landslide, slump, and talus deposits, undifferentiated (**Qmst**)	Undifferentiated deposits of **Qms**, **Qmsh**, **Qmsb**, **Qmt**, and **Qmte**. Mapped on sheets 1 and 2 (in pocket).	See individual units.	See individual units.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Entrenched meanders and cliffs developed, along with landslides, slumps, and other slope movement deposits.
QUATERNARY (Lower Pleistocene to Holocene)	**Mass Movement Deposits** Talus deposits with eolian sand mantle (**Qmte**)	**Qmt** deposits that are mostly covered by sand. Sand can be as much as 9 m (30 ft) thick in some areas. Some **Qmte** is not mapped separately from **Qmt**. Mapped on sheets 1, 2, and 3 (in pocket).	**Unconsolidated Surficial Deposits.** Jumbled blocks of rock with a covering of wind-blown sand.	**Slope Movement Hazards and Risk. Qmt** may become unstable and begin to slide down slope with increased precipitation. Talus also indicates where rockfalls have occurred in the past and are likely to occur again.	**Paleogene–Quaternary Periods: Colorado River System And Carving Glen Canyon.** Uplift of the Colorado Plateau during the Paleogene caused widespread erosion. About 5.5 million years ago, the Colorado River began to carve Glen Canyon. Entrenched meanders and cliffs developed, along with landslides, slumps, and other slope movement deposits.