National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Rainbow Bridge National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/131

THIS PAGE:
The view from Cummings Mesa displays the stunning geologic landscape of Rainbow Bridge National Monument. Rainbow Bridge, carved out of Navajo Sandstone, is in the lower center of the image. NPS Photo.

ON THE COVER:
A more conventional view of Rainbow Bridge from the main trail. NPS Photo by Jonathan Parker.

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
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August 2009

U.S. Department of the Interior
National Park Service
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Denver, Colorado

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Please cite this publication as:

Graham, J. 2009. Rainbow Bridge National Monument Geologic Resources Inventory Report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/131. National Park Service, Denver, Colorado.

NPS 118/100151, August 2009

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Executive Summary

This report accompanies the digital geologic map for Rainbow Bridge National Monument in Utah, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Rainbow Bridge ranks as the world's largest known natural bridge. Carved out of Navajo Sandstone, Rainbow Bridge spans 84 m (275 ft) across Bridge Creek, and at 88 m (290 ft) tall, the bridge is nearly as high as the Statue of Liberty. The thick abutments that support the bridge measure 61 m (200 ft) wide on the west and 27 m (90 ft) wide on the east side of the bridge. At the summit, the bridge measures 13 m (42 ft) thick and 10 m (33 ft) wide.

Located approximately 13 km (8 mi) upstream from the confluence of Bridge Creek with the Colorado River in southeastern Utah, Rainbow Bridge lies in some of the most remote country in the conterminous United States. Prior to the construction of Glen Canyon Dam in 1963 and the creation of Lake Powell, visitors experienced a grueling overland route to Rainbow Bridge. Lake Powell provided, and continues to offer, an alternate route. Today, boats bring hundreds of people each day to this 65-ha (160-acre) monument.

The primary management issues related to geology at Rainbow Bridge National Monument include:

- Rainbow Bridge stability
- Maintaining the "sacred integrity" of the bridge
- Rockfalls

The same natural processes that erode the arid Utah landscape act on Rainbow Bridge, yet the stability of the bridge does not seem to be severely impacted by these processes. Rockfall, exfoliation, and freeze-thaw processes have not caused any major decline in bridge stability for thousands of years. Even the man-made impacts from the creation of Lake Powell and the Navajo Power Generating Plant appear to be limited. Barring any natural or unforeseen disaster, Rainbow Bridge should continue to stand for thousands of years.

The increase in visitation to the monument since the creation of Lake Powell has raised management concerns about maintaining the bridge's sacred religious significance. Long before the monument was established, American Indians viewed Rainbow Bridge as a sacred site. Tribal members request visitors approach the bridge with respect and refrain from walking beneath the bridge, an act they consider sacrilegious. Monument managers have addressed this situation in the Rainbow Bridge General Management Plan and now ask visitors to respect the significance of the bridge to American Indians.

Massive rockfalls along the lakeshore pose a potential geologic hazard at Rainbow Bridge National Monument. Undercutting of the Navajo Sandstone cliffs, as well as frost wedging along joints and fractures (a process where water freezes and expands during winter months) both contribute to rockfalls in the area.

The Early Jurassic Navajo Sandstone and Kayenta Formation are the only rock units exposed in the monument. The hard Kayenta Formation sandstone, exposed within the channel of Bridge Creek, forms the base of the bridge. The overlying Navajo Sandstone shapes the impressive cliffs that dominate the landscape. With regional uplift, younger Mesozoic and Cenozoic strata that were once deposited in the region have been eroded from the monument. Talus, comprised of eroded blocks of Navajo Sandstone, has accumulated at the base of the cliffs, and unconsolidated Quaternary terrace deposits now cover Kayenta strata in Bridge Creek canyon. [Note: see Glossary on page 28 for explanations of many technical terms used in this report].

The formation of Rainbow Bridge involved a combination of factors: regional uplift, development of structural fractures and joints in the rock, erosive forces of running water, and lithology. During the Tertiary Period (the beginning of the Cenozoic Era), the Colorado River and its tributaries flowed through meandering channels in wide valleys. Bridge Creek eroded alluvial fan deposits on the flank of Navajo Mountain.

Uplift of the Colorado Plateau rejuvenated the rivers, causing them to vertically incise their channels into the Navajo Sandstone. Joints in the rock helped control Bridge Creek's path. Vertical incision outpaced lateral bank erosion so that the Colorado River and its tributaries, including Bridge Creek, became entrenched, preserving their original meandering patterns with little modification. Where tight meander curves were separated by very short land distances, erosion into the canyon walls created narrow necks, setting the stage for bridge formation.

During the wetter Pleistocene Epoch, stream flow and erosion rates were likely greater than they are today. Cliff collapse, weak bedding layers in the Navajo Sandstone, rockfalls along near-vertical joints, and exfoliation eventually resulted in a hole forming in the narrow wall that would become Rainbow Bridge. Bridge Creek abandoned its old meander around the wall for a new route through the hole. Over time, the channel cut down through the sedimentary rock, widening and expanding the hole into today's Rainbow Bridge.

In addition to the bridge, Rainbow Bridge National Monument preserves part of the largest erg, or extensive sandy desert, ever recorded in Earth's history. During the Jurassic Period, immense sand dunes migrated through western North America. The spectacular large-scale cross-bedding produced by these migrating dunes is preserved in the Navajo Sandstone. Evidence of Jurassic ephemeral streams, called "wadis" and "oases," are encased within the cross-bedded strata.

Sedimentary features in the underlying Kayenta Formation reflect a wetter depositional environment than the arid environment of the Navajo Sandstone. Ripple marks, small-scale cross-beds, rip-up clasts, and dinosaur footprints may be found throughout the Kayenta fluvial (river) and associated floodplain environments including near the base of Rainbow Bridge.

Located on the Colorado Plateau, a physiographic province that includes parts of Utah, Arizona, New Mexico, and Colorado, Rainbow Bridge National Monument and the surrounding region were buffered from the tectonic forces that produced the extreme faulting and folding in the adjacent Rocky Mountains during the Tertiary Period. Subdued structural deformation on the Plateau resulted in broad, regional uplift, gentle folding, fractured and jointed rock, and the emplacement of a unique type of igneous intrusion called a "laccolith." Navajo Mountain, a prominent laccolith southeast of Rainbow Bridge National Monument, influences the drainage patterns in the region and has contributed to increased surface flow and erosion in Bridge Canyon.

Regional deformation produced three types of joints in Rainbow Bridge National Monument: 1) inclined northeasterly-trending joints, 2) near-vertical northeasterly-trending joints, and 3) surficial joints. Surficial joints are nearly parallel to the Navajo Sandstone cliffs and may contribute to massive rockfalls.

Gentle folding in the region is the surface expression of faults that cut Precambrian rocks at great depths, causing the overlying strata to be displaced. The flanks of the folds are inclined at a gradual angle away from the center of the folds. Folding extends for many kilometers (miles) beyond the boundaries of Rainbow Bridge National Monument.

More recent features in Rainbow Bridge National Monument include "alcoves" and "hanging gardens." "Alcoves," arched recesses found in the Navajo Sandstone, formed from a combination of erosion by Bridge Creek's meandering channels, cliff collapse, and groundwater that dissolved the mineral cement holding the sand grains together. In shaded areas where groundwater seeps from the Navajo Sandstone, vegetation appears to be "hanging" from cliffs.

Recent features in Rainbow Bridge National Monument also include the dark mineral coating called "desert varnish" and Quaternary river terrace features. High-level terraces and low-level terraces record Holocene periods of downcutting by Bridge Creek.

The Kayenta Formation and Navajo Sandstone exposed at Rainbow Bridge National Monument represent approximately 24 million years of geologic time during the Early Jurassic Period. Much older rocks are exposed in nearby Glen Canyon National Recreation Area and in Grand Canyon National Park. Precambrian, Paleozoic, Mesozoic, and Cenozoic strata on the Colorado Plateau record a variety of marine and non-marine environments resulting from tectonic plate collisions and climate changes over time. Recent uplift of the Colorado Plateau and vertical incision of the Colorado River and its tributaries has helped shape the region's distinct landscape of plateaus and canyons.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Rainbow Bridge National Monument.

Purpose of the Geologic Resources Inventory

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

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

To realize this goal, the GRI team is systematically working towards providing each of the identified 270 natural area parks with a geologic scoping meeting, a digital geologic map, and a geologic report. These products support the stewardship of park resources and are designed for non-geoscientists. During scoping meetings the GRI team brings together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their innovative Geographic Information Systems (GIS) Data Model. These digital data sets bring an exciting interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. As a companion to the digital geologic maps, the GRI team prepares a park-specific geologic report that aids in use of the maps and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and up to date GRI contact information please refer to the Geologic Resources Inventory Web site (http://www.nature.nps.gov/geology/inventory/).

General Information and Regional Location

Rainbow Bridge National Monument preserves the world's largest known natural bridge. Located in southern Utah near an arm of Lake Powell adjacent to Glen Canyon National Recreation Area, the bridge spans Bridge Creek about 13 km (8 mi) upstream from its confluence with the Colorado River. This region contains some of the most remote country in the conterminous United States (fig. 1). The rugged landscape of plateaus and steep narrow canyons lies within the Colorado Plateau, a physiographic province that encompasses parts of Utah, Arizona, New Mexico, and Colorado. Southeast of Rainbow Bridge, Navajo Mountain, one of the sacred mountains of the Navajo people, rises to an elevation of 3,167 m (10,388 ft).

At 88 m (290 ft) high, Rainbow Bridge stands nearly as tall as the Statue of Liberty (fig. 2). It is 84 m (275 ft) long and is almost symmetrical (National Park Service 1998). The top of the bridge measures 13 m (42 ft) thick and up to 10 m (33 ft) wide.

A natural bridge differs from a natural arch (such as those at Arches National Park) by the way it is formed. Natural bridges span ravines or valleys and form primarily due to the erosive power of stream channels. Arches, on the other hand, do not span ravines or valleys and form by weathering and rockfalls along joints and fractures (Chidsey et al. 2000b). Bridge Creek, fed by springs and runoff from Navajo Mountain, carved Rainbow Bridge by eroding through a thin wall of Navajo Sandstone.

Prior to the construction of Glen Canyon Dam and creation of Lake Powell, access to Rainbow Bridge was by long and difficult trails from the Navajo Mountain Trading Post (39 km; 24 mi) or from Rainbow Lodge (23 km; 14 mi). Today, Lake Powell floods 300 km (186 mi) of Colorado River canyons, and tour boats dock within a 1.8 km (1.25 mi) walking distance of the bridge. Only about 4,000 visitors came to the bridge from 1909 to the early 1970s. Now that boat access is available via Lake Powell, approximately 300,000 people from around the world visit this small 65-ha (160-acre) national monument each year.

General Geology

Rainbow Bridge is composed entirely of Navajo Sandstone, which overlies the Kayenta Formation. The Kayenta Formation is exposed beneath the bridge. The Early Jurassic Navajo Sandstone and Kayenta Formation, both part of the Glen Canyon Group, are the only two bedrock formations exposed in Rainbow Bridge National Monument (fig. 3). The sediments that lithified into the two rock units were deposited between 187 and 200 million years ago (Chidsey et al. 2000b). Cliffs of

Navajo Sandstone dominate the landscape while the Kayenta Formation is exposed only along the channel of Bridge Creek. Older strata beneath the Kayenta Formation have been covered by Lake Powell. Erosion has removed any strata that were deposited above the Navajo Sandstone. Unconsolidated boulders, cobbles, sand, silt, and clay of Quaternary age cover the older bedrock formations in parts of Rainbow Bridge National Monument.

Park History

Long before Anglo-Americans found Rainbow Bridge, American Indians knew about Nonnezoshe, the "rainbow turned to stone." Paleo-Indians occupied the Glen Canyon region between 11,500 B.C.E. and 8,000 B.C.E. (Before Common Era). A 1984 archeological survey showed that ancestral Puebloan people, often called Anasazi, inhabited the Bridge Canyon region during the Puebloan period approximately 700-1300 C.E. (Common Era).

Rainbow Bridge has been a sacred religious site for American Indians for many centuries. Some American Indian religions consider arches and bridges to be gateways through which souls enter or leave the earth. When President Theodore Roosevelt visited Rainbow Bridge in 1913, he noticed that his American Indian guides would say a prayer before going under the bridge or would prefer to ride around the bridge rather than going under it (Kiver and Harris 1999).

Louisa Wetherill and her husband, John Wetherill, ran a trading post at Kayenta in the early days of the 1900s. Louisa heard stories of the sacred bridge from a Navajo elder as well as from a Paiute chief. Both Louisa and John Wetherill were interested in their Indian customers and their culture. John Wetherill, an amateur archeologist, was instrumental in discovering the ruins at Keet Seel (now within Navajo National Monument) and the cliff dwellings at Mesa Verde National Park. In 1909, he joined Professor Byron Cummings and government surveyor William Douglass on an exploratory trip to the bridge led by Paiute guides Nasja Begay and Jim Mike.

Enduring heat, slickrock slopes, treacherous ledges, and sandstone mazes, the men and their horses first saw Rainbow Bridge on August 14, 1909 as they came down what is now Bridge Canyon (Kiver and Harris 1999; http://www.nps.gov/rabr/historyculture/index.htm, accessed December 5, 2007). They found the remains of an ancient Indian altar or shrine at the base of the bridge.

Historians continue the debate over who was the first white man to see Rainbow Bridge. Although both Cummings and Douglass claimed credit for being the first, the Wetherills had visited the bridge before their trip with Cummings and Douglass (Jett 1992). Prospectors, cowboys, and possibly others may have also seen, but not reported, Rainbow Bridge.

The following year, on May 30, 1910, President William Howard Taft established Rainbow Bridge National Monument to preserve this "extraordinary natural bridge, having an arch which is in form and appearance much like a rainbow, and which is of great scientific interest as an example of eccentric stream erosion" (http://www.nps.gov/rabr/historyculture/index.htm, accessed December 5, 2007).

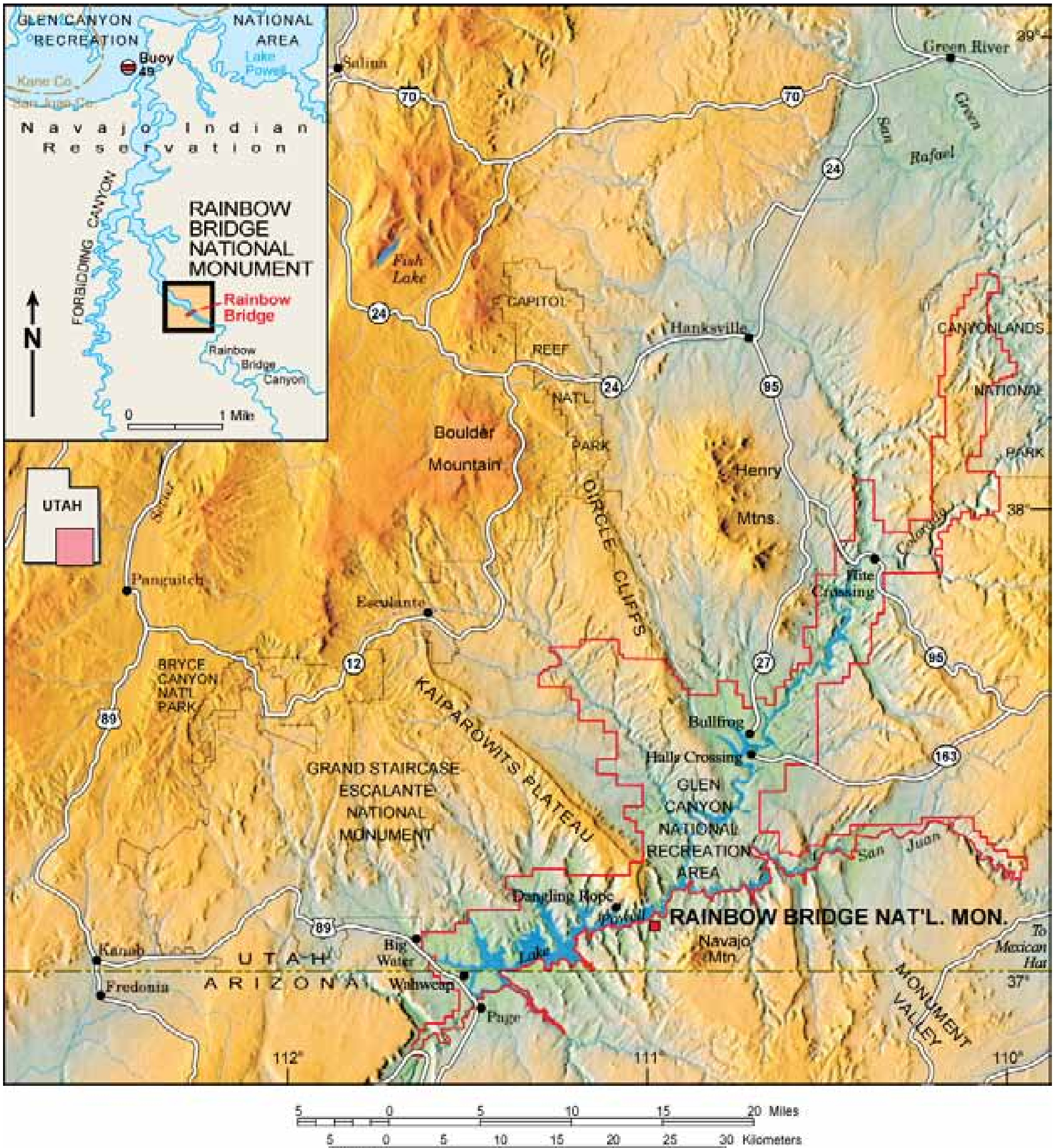

Figure 1. Location map of Rainbow Bridge National Monument (red square) in remote southern Utah, showing surrounding towns, highways, Glen Canyon National Recreation Area (red outline), and other national parks and monuments in southern Utah. Map is Fig. 2 in Chidsey and others (2000b). Utah Geological Association/NPS Map.

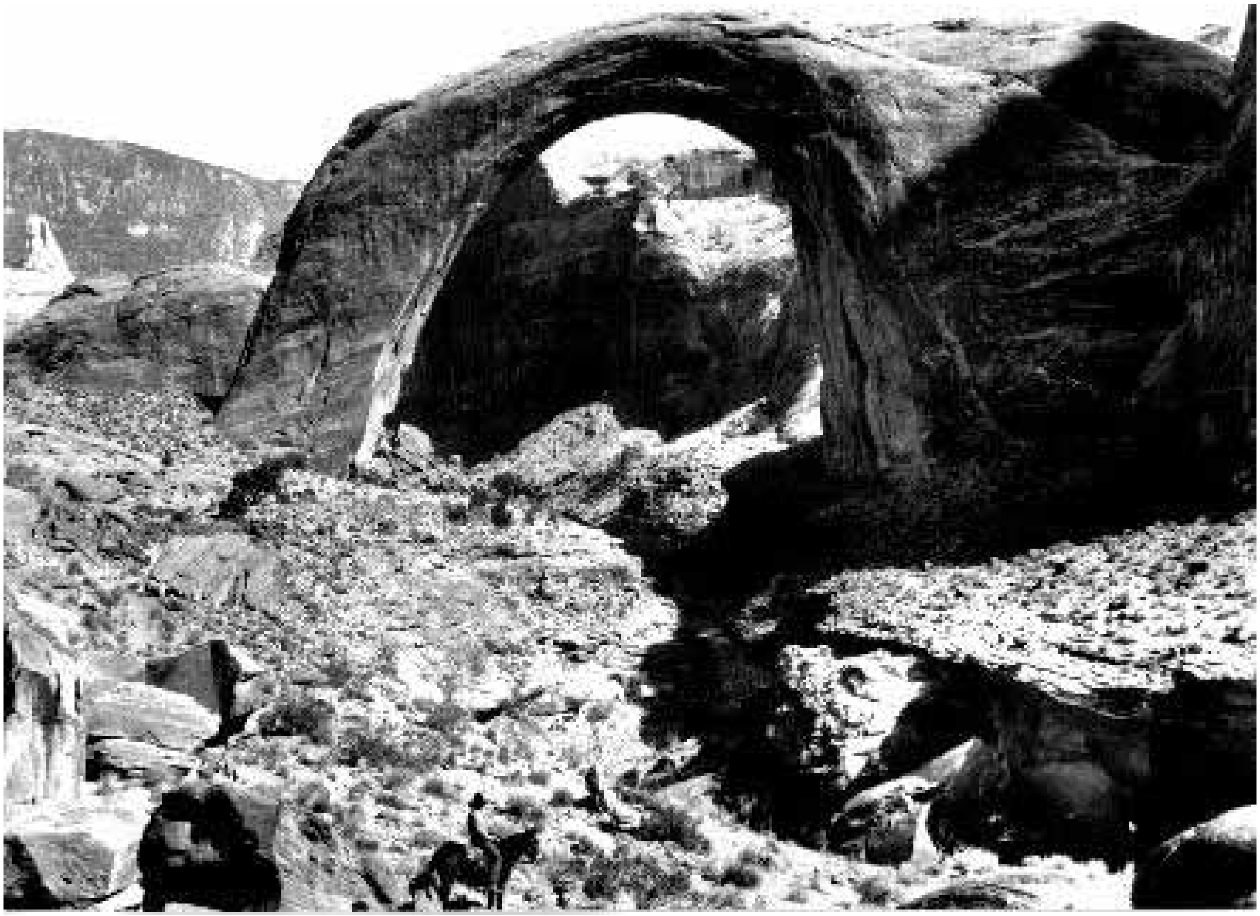

Figure 2. Rainbow Bridge prior to the construction of the Glen Canyon Dam and the creation of Lake Powell. Note the lone horseman in the foreground for scale. NPS Photo courtesy Betsy Scroggs (NPS-Glen Canyon NRA).

System	Age	Formation		Thickness in m (ft)	Lithology	Depositional Environment
QUATERNARY	1.81 – Present	Unconsolidated sediments		Variable	Boulders, sandstone, silt, clay	Terrace deposits, rockfalls, colluvium
	Regional Unconformity (approximately 174 million years are missing)					
JURASSIC (Lower)	199.6 – 175.6	Glen Canyon Group	Navajo Sandstone	357-375 (1170-1230)	Tan to light-reddish brown, fine- to medium-grained sandstone; rounded to subrounded grains; large-scale cross-beds; local limestone.	Interbedded eolian dune, oasis, and wadi deposits
			Kayenta Formation	76-101 (250-330)	Pale-red to dark-orange, moderately hard to hard, fine- to medium-grained sandstone with shale	River and floodplain deposits

Figure 3. Stratigraphic column for the geologic map units exposed in Rainbow Bridge National Monument. Age is in millions of years.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Rainbow Bridge National Monument on September 23–25, 1999, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers.

Issues in this section are identified in relative order of resource management significance with the most critical issues listed first. This section addresses geologic issues that affect the ecosystem, their importance to park management, and the extent to which they are influenced by humans.

Rainbow Bridge Stability

Natural processes that affect the sandstone cliff faces and arches throughout this arid region of Utah raise concern for the stability of Rainbow Bridge. Rockfalls related to tension-formed joints and exfoliation are common occurrences over geologic time. Three types of joints have been recognized in Rainbow Bridge National Monument: 1) inclined joints, 2) near-vertical joints, and 3) surficial joints. Of the three, inclined joints and vertical joints occur on Rainbow Bridge.

Inclined joints are present on the top of the bridge. Along the south side of the bridge, the joints dip 30°-50° to the north and on the western half of the north side of the bridge, they dip 37°-60° to the south. Near-vertical joints are found on the north and south faces of the bridge. These joints trend 65° to the northeast. Due to the weight of the bridge, a joint has developed at a right angle to the axis on the underside of the bridge (Chidsey et al. 2000b).

In winter, moisture in fractures, in cracks, and between sand grains freezes and expands, causing the rock to break apart in a process called 'frost wedging.' Wind abrasion, a common weathering process on the Colorado Plateau, and chemical weathering have had minor impacts on the bridge.

An engineering study in 1972 determined that these natural processes have not caused any major decline in bridge stability over many thousands of years (Dames & Moore Group 1972; Chidsey et al. 2000b). The study also concluded that the bridge is not threatened by its own weight.

In addition, the study evaluated the potential impact of water from Lake Powell that extends under the bridge and increased levels of sulfur dioxide emitted from the Navajo Power Generating Plant located southwest of the Monument in Arizona. At full pool, the surface of Lake Powell lies at an elevation of approximately 1,128 m (3,700 ft) and 14 m (46 ft) of water stands underneath the bridge (http://www.nps.gov/rabr/faqs.htm). In early August 2009, the lake level was approximately 1,110 m (3,640 ft). The Navajo Power Generating Plant is a coal-fired generating station that uses coal from the Peabody Western Coal Company's Kayenta Mine, located 80 km (50 mi) east of the plant. Three scrubbers remove almost all of the sulfur dioxide from the gases emitted through the plant's three chimneys (http://www.srpnet.com/about/stations/navajo.aspx). No significant alteration to the integrity of Rainbow Bridge is expected to occur from these human-induced changes.

According to the Dames & Moore Group (1972) study, over one-half of the foundation rock on each side of the bridge would have to be removed before Rainbow Bridge would collapse. Given the existing conditions, Rainbow Bridge should remain standing for many thousands of years (Chidsey et al. 2000b).

Maintaining the "Sacred Integrity" of Rainbow Bridge

The presence of Lake Powell provides an alternate route to the once grueling overland trek to Rainbow Bridge. Many drastic changes to the ecosystem of the Colorado River and its tributaries began as the waters rose behind Glen Canyon Dam in 1963. As Lake Powell deepened and inundated the region upstream from the dam, about 320 km (200 mi) of spectacular canyon country along the Colorado River were flooded (Reisner 1993; Kiver and Harris 1999). Today, vacationers come by houseboat and hike along a 1.8 km (1.25 mi) trail to visit the bridge (fig. 4).

Many American Indian nations, including the Navajo, Hopi, San Juan Southern Paiute, Kaibab Paiute, and White Mesa Ute consider Rainbow Bridge to be a sacred religious site. American Indian tribes have expressed concern that some visitors have a nonchalant disregard for the sacred bridge. They object to visitors walking under Rainbow Bridge or approaching the bridge in a disrespectful manner.

In 1993, the National Park Service finalized a General Management Plan that offered a long-term plan for mitigating visitor impacts and preserving the resources of Rainbow Bridge National Monument. As part of the plan, the National Park Service asks visitors to approach Rainbow Bridge with respect for its significance, and respect for the people who have long considered Rainbow Bridge sacred.

Rockfalls in the Navajo Sandstone

Throughout the Colorado Plateau, undercut cliffs, vertical joints, exfoliation, and frost-wedging contribute to rockfalls. In the Navajo Sandstone, rainwater dissolves the outer 2.5–7.6 cm (1–3 in) of calcium carbonate cement making it soft and friable. In 1983 at Rainbow Bridge, exfoliation (or spalling) led to a spectacular rockfall in the Navajo Sandstone on the south side of the canyon near the monument's courtesy dock (fig. 5) (Chidsey et al. 2000). Spalling has also occurred near the trail that leads to the #2 viewing area, producing a jumble of talus blocks at the base of the cliff (fig. 6). Rockfall also impacts trails within Rainbow Bridge as evidenced along the South Trail near Redbud Pass. Case (2000) summarized major rockfalls in Utah during the 1980s and 1990s, a number of which occurred within or near NPS units.

Weathering processes such as freeze-thaw or wet-dry cycles, erosion of surrounding rock, root growth, rainfall, and earthquakes typically initiate rockfalls (Case 2000; Lund and Knudson in review). Rockfalls in Utah seem to occur more frequently during spring and summer months although this is not well documented. Spring snowmelt, intense summer rainfall, and daily temperature variations during these months may be contributing factors (Case 2000).

A GIS-based geohazard assessment of the park and neighboring Glen Canyon National Recreation Area would provide additional information for resource management strategies. One such project, produced by the Utah Geological Survey, is currently in progress for Zion National Park (Dave Sharrow, Zion National Park, personal communication, August 2009). NPS Geologic Resources Division serves as a point of contact for technical assistance with geohazards.

Other Issues

Flash Flooding

Precipitation in this area of the Colorado Plateau is generally less than 15 cm (6 in) annually, but intense, late summer thunderstorms may lead to flash flooding in Bridge Creek. Flash floods occur in the narrow canyons of the Colorado Plateau when precipitation falls on exposed or sparsely-vegetated rock. The thin soil and sparse vegetation cannot absorb the precipitation or buffer the impact of the raindrops. Water flows downhill, and the water volume in narrow canyon streams rapidly increases. Flooding occurs with little warning. Narrow portions along both the North and South trails to Rainbow Bridge are particularly susceptible to flash flooding.

Fossil Recognition and Preservation

The first report of dinosaur tracks near Rainbow Bridge came from a 1933 University of California paleontological expedition (Hall 1934; cited in Santucci 2000). At the #2 viewing area, a tridactyl (three-toed) theropod dinosaur left a track in the Kayenta Formation (fig. 7) (Chidsey et al. 2000b). The well-displayed footprint lies about 14 m (45 ft) from the end of the paved trail. The track may be from a *Dilophosaurus*, a Jurassic carnivore approximately 6 m (20 ft) long that weighed about a half ton. Although many tracks are poorly preserved, a paleontological survey of the monument might uncover more evidence of these carnivores and their prey.

The Kayenta Formation in Glen Canyon National Recreation Area preserves similar large theropod tracks, some of which are on exhibit at the Carl Hayden Visitor Center (Santucci 2000). Although fossils are not yet known from within the Navajo Sandstone exposures of Rainbow Bridge National Monument, the sandstone preserves a number of tracksites within Glen Canyon (Lockley et al. 1998).

For a summary of paleontological resources within Rainbow Bridge National Monument and the other parks of the Southern Colorado Plateau Network, refer to Tweet and others (in review).

Petroglyph Recognition and Preservation

Throughout the Colorado Plateau, petroglyphs have been etched into the dark stain ("desert varnish") that covers the surface of the Navajo Sandstone. One petroglyph in Rainbow Bridge National Monument may be of late 19th or early 20th century Navajo origin. An example of historic graffiti (over 50 years old) is located on the canyon wall, approximately 46 m (150 ft) from the end of the trail leading to the #2 viewing area (http://www.nps.gov/rabr/faqs.htm). A bull-shaped animal and a series of numbers are etched into the desert varnish (fig. 8). A survey may reveal additional petroglyphs in the monument.

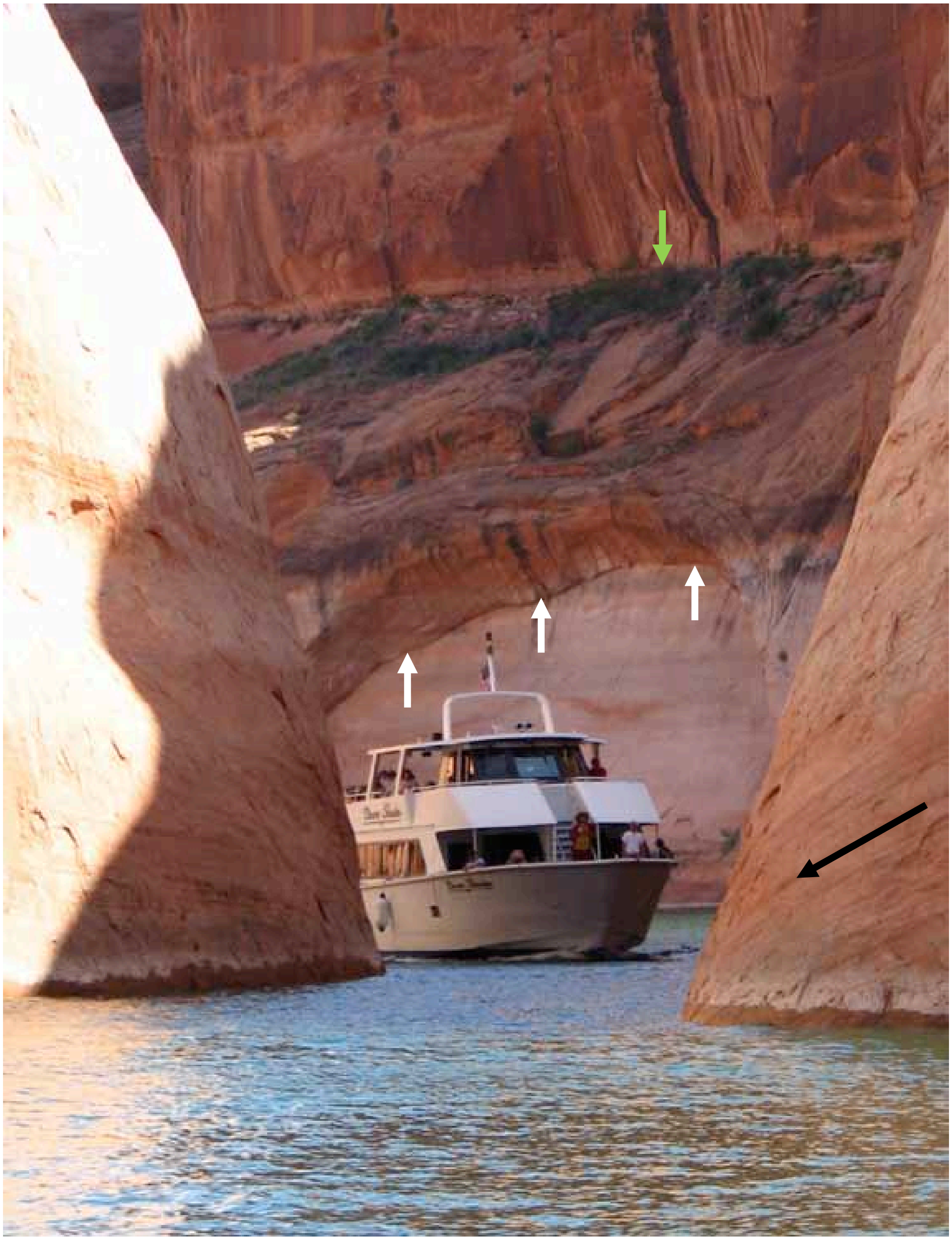

Figure 4. A tour boat on Lake Powell enters (Rainbow) Bridge Canyon. Rainbow Bridge is just a short hike from the floating visitor dock and lake shore. On the Navajo Sandstone cliff face, vegetation grows where groundwater seeps from a nearly horizontal fracture creating a feature called a "hanging garden" (green arrow). Part of the cliff face has spalled off into the lake; white arrows indicate the "scarp" where the spalled material has fallen away. The inclined lines in the sandstone (highlighted by the black arrow) are cross-beds that mark the surfaces of migrating sand dunes formed during the Jurassic Period. Dark streaks on the sandstone are examples of "desert varnish," a surface patina of manganese oxide and iron. Modified from NPS Photo by Jonathan Parker. Available at http://www.nps.gov/rabr/photosmultimedia/photogallery.htm, accessed March 2009.

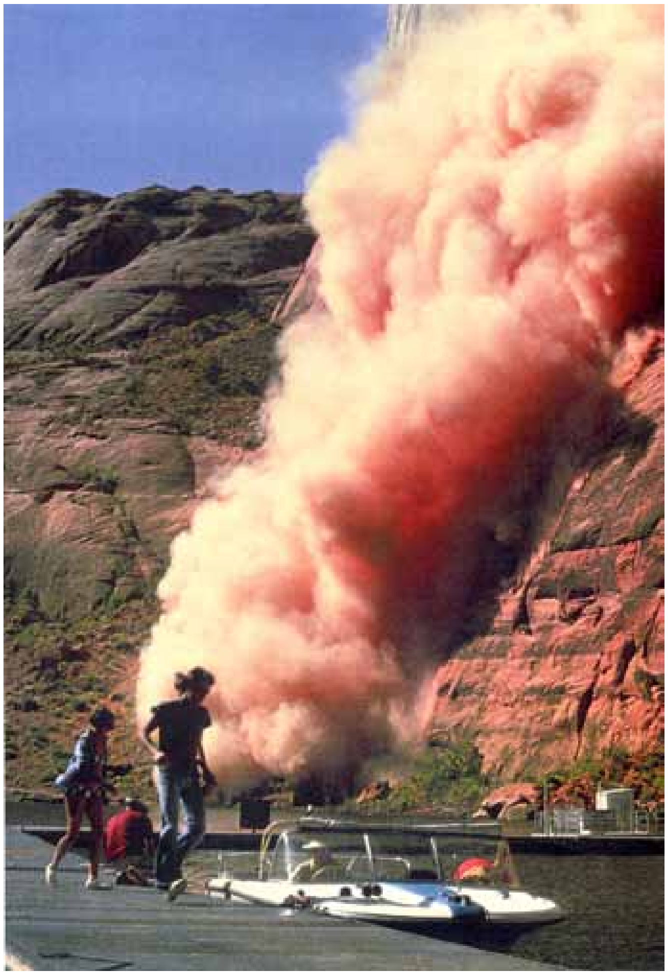

Figure 5. A 1983 rockfall in the Navajo Sandstone on the south side of the canyon near the courtesy dock within Rainbow Bridge National Monument. This dramatic image, captured by park visitor Tom Tyler and donated to the NPS, illustrates the potential for rockfall within the park. NPS Photo.

Figure 6. Rock spall near the trail to #2 viewing area. Exfoliation such as this is common on the Navajo Sandstone cliffs of the Colorado Plateau. The large blocks of rock do not roll far from the base of the cliff. Modified from NPS Photo by Jonathan Parker. Available at http://www.nps.gov/rabr/photosmultimedia/photogallery.htm, accessed March 2009.

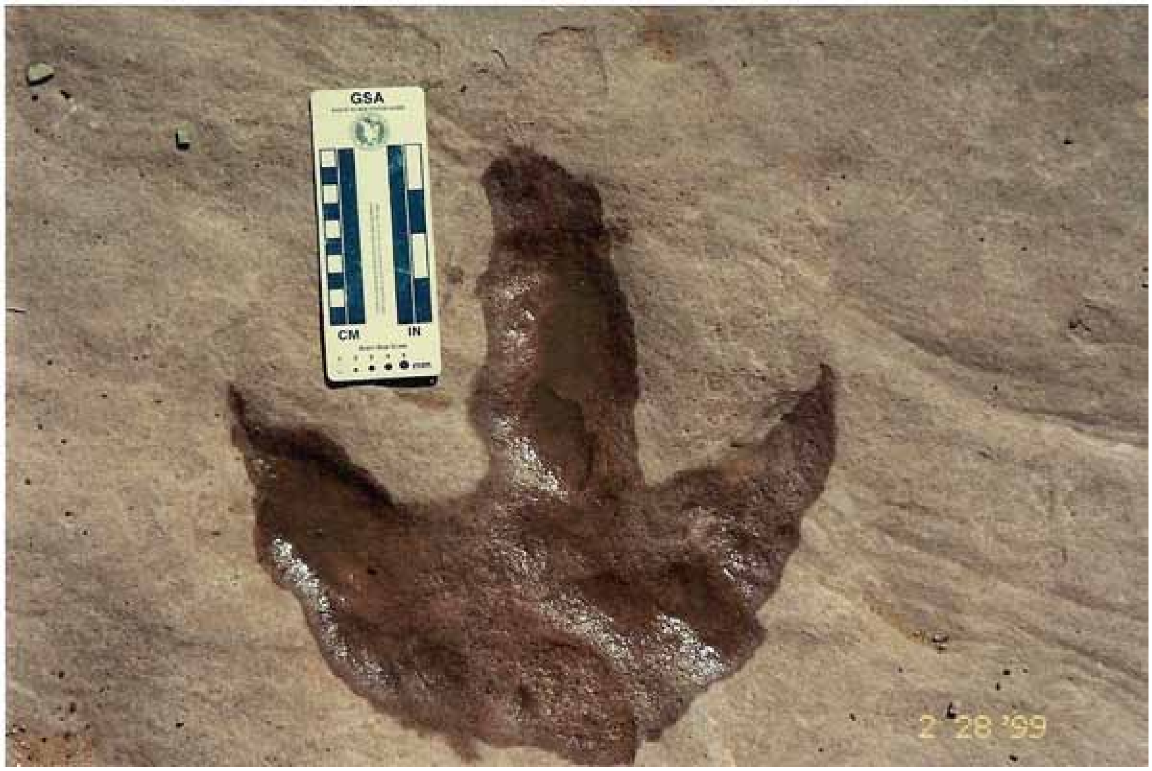

Figure 7. Dinosaur track, easily visible in the Kayenta Formation near the Rainbow Bridge viewing area. The track was made by a large (this image is about one-fourth actual size) theropod dinosaur, perhaps *Dilophosaurus*. Water poured on track to increase visibility. NPS photo courtesy Vincent Santucci (NPS George Washington Memorial Parkway).

Figure 8. Historical graffiti in Rainbow Bridge National Monument. The shape of a bull and the numbers are etched into the dark stain of desert varnish. Cross-bedding in the Navajo Sandstone is indicated by the black arrows, which suggest at least three different directions of dune migration during the Early Jurassic Period. The hole below the bull and the voids opening along the cross-bedding surfaces are examples of "tafoni," or "stonepecker holes." Modified from NPS Photo by Jonathan Parker. Available at http://www.nps.gov/rabr/photosmultimedia/photogallery.htm, accessed March 2009.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Rainbow Bridge National Monument.

This section provides a descriptive list of the most prominent and unique features and processes in Rainbow Bridge National Monument. The most distinctive feature is Rainbow Bridge, but other sedimentary and structural features record a variety of past depositional environments and processes that helped shape the regional landscape. Chidsey and others (2000a) presented a lake guide summarizing geologic features along Lake Powell in Glen Canyon National Recreation Area and within Rainbow Bridge National Monument.

Rainbow Bridge and Bridge Creek

Rainbow Bridge rises to a height of 88 m (290 ft) and spans 84 m (275 ft) (fig. 9). Resting on a foundation of Kayenta Formation, the bridge is composed entirely of Navajo Sandstone. The west abutment is about 61 m (200 ft) wide and the east abutment is about 27 m (90 ft) wide (Chidsey et al. 2000b).

Evolution of Rainbow Bridge began millions of years ago. Long before the region became a maze of canyons and plateaus, the Colorado River meandered across a relatively flat floodplain. Meandering rivers erode laterally, rather than vertically. In these low-gradient rivers, the main current migrates from bank-to-bank, back and forth across the channel, eroding previously deposited unconsolidated sediments. The steep-sided banks that the current actively erodes, or cuts into, are called 'cutbanks.'

When the Colorado Plateau was uplifted and tilted late in the Tertiary Period, the Colorado River began to erode vertically through the bedrock, eventually forming features like Grand Canyon. Rivers that erode downward through bedrock, and maintain their original, sinuous course, are called 'entrenched' rivers, and their meanders become entrenched meanders. Bridge Creek's channel, like the other tributaries to the Colorado River, maintained its meandering profile as it cut down through the bedrock (Kiver and Harris 1999; Chidsey et al 2000b).

As Bridge Creek flowed through its canyon, erosion carved horseshoe-shaped meanders that curved around the ends of a high wall, or 'fins' of Navajo Sandstone (fig. 10). During the Pleistocene Epoch (1.81 million years ago–10,000 years ago), snow accumulated on Navajo Mountain, and glaciers formed on the La Sal and San Juan Mountains. As snow melted and the glaciers thawed, stream flow intensified in the Colorado River drainage system. Erosion at cutbanks carved an ever-wider and deeper trench into the sandstone. As with all streams, wide points in the flow caused eddies to form wherein water tended to swirl back on itself. Higher flow meant stronger eddies and increased erosion.

Abrasive material carried downstream heightened the erosive power of Bridge Creek. Erosion of the fins formed a series of great 'oxbow' meander loops. Seen from the air, an oxbow meander resembles the U-shaped frame that fits an ox's neck. Oxbow meanders have an extreme curvature such that only a thin neck of land is left between two parts of the stream. These meander loops held immense volumes of abrasive-laden water. Remnants of these oxbow meanders can be seen in the amphitheater-like alcove that sits opposite the bridge today.

As the water flowed against the downstream portion of the walls, the walls thinned and formed elongate fins that would not tolerate extended abrasion. About 500,000 to one million years ago, the churning water in Bridge Creek encountered a thick bed of hard Kayenta Formation sandstone, so vertical erosion was reduced. Eddies formed on both the upstream and downstream sides of the fin. These eddies eroded the less resistant Navajo Sandstone above the Kayenta Formation base. Eventually, the swirling eddies eroded a hole in the fin of the Navajo Sandstone (fig. 10).

Bridge Creek then followed the new path of least resistance, plummeting through the widening hole in the fin and abandoning the previous meandering route around the sandstone wall. As Bridge Creek deepened its channel, the hole widened and blocks of Navajo Sandstone collapsed, further widening and lengthening the bridge opening. As the wet period of the Pleistocene subsided, and the region became semi-arid, stream flow decreased. The thinning effect of erosion on the bridge's walls was dramatically reduced, leaving today's stable symmetrical form (Sproul 2001).

Sedimentary Features

Navajo Sandstone

The Navajo Sandstone represents part of the Jurassic desert that covered the Colorado Plateau for roughly 40 million years. This areally-extensive, sandy desert, or 'erg,' contained sand dunes that may be the largest recorded in Earth's history (Kocurek and Dott 1983). In the Rainbow Bridge-Glen Canyon area alone, the Navajo Sandstone is between 357 to 375 m (1,170 to 1,230 ft) thick. The Early Jurassic sand seas inundated vast tracts of land, from Montana to New Mexico. By comparison, in the Sahara, the modern world's largest desert, only 10% of the surface is sand-covered. The Arabian Desert, the Earth's sandiest desert, is only 30% sand-covered.

Typical of eolian (wind) deposits, the Navajo Sandstone contains spectacular, large-scale cross-bedding that preserves the form of the Early Jurassic sand dunes (fig. 11). Blowing primarily from the north and northwest, the Jurassic winds formed cross-bedded dune sets that are up to 8 m (25 ft) thick. Erosion of the sweeping, undulating cross-bedding has shaped the Navajo Sandstone into the characteristic domes seen throughout the Colorado Plateau today.

Moderately- to well-sorted, rounded to subrounded quartz grains dominate the Navajo Sandstone. During deposition, wind energy caused the sand grains to collide against each other, and these collisions left a lusterless, ground-glass-like surface on the rounded grains. This weathering process is called 'frosting.' The tan to light-reddish-brown sandstone is fine– to medium–grained, and most of the grains are cemented together with calcite (calcium carbonate), although silica and iron oxide are also present.

Kayenta Formation

The fluvial (river) depositional environment of the Early Jurassic Kayenta Formation contrasts sharply with the arid sand seas of the Navajo Sandstone. Ripple laminations, current ripples, and small-scale trough cross-beds are some of the sedimentary structures left by the rivers and streams that flowed across this region in a west–northwest direction. Relatively high water flow in the channels produced clay rip-up clasts, and animals dug burrows into the silty banks and floodplains. The theropod dinosaur track at the #2 viewing area suggests that carnivores hunted prey in the region.

Kayenta's pale-red to dark-orange, fine- to medium-grained sandstone is easily distinguished from the massive cliffs of the overlying Navajo Sandstone, and the contact between the two formations is noticeably distinct. The Navajo Sandstone is composed almost entirely of quartz sand, but the Kayenta Formation contains feldspar and mica minerals among the quartz grains. The quartz grains are subrounded to subangular in shape and only moderately sorted. Rather than rounded domes, the hard sandstone of the Kayenta Formation weathers into a series of ledges and low cliffs separated from each other by less resistant shale beds (Chidsey et al. 2000b).

Upper and lower units of the Kayenta Formation are exposed beneath Rainbow Bridge. Two other units now lie below the level of Lake Powell. The upper unit is 1.2–2.1 m (4–7 ft) thick and consists of sandstone beds that tend to split into layers and lenticular, or lens-shaped, beds that are 0.2–0.3 m (0.5–1 ft) thick. The blocky to massively-bedded lower unit is now partially submerged. 'Massive' beds are generally defined as homogeneous units that are more than 1.8 m (6 ft) thick. Before Lake Powell filled, 12–14 m (40–45 ft) of the lower unit were exposed at Rainbow Bridge (Chidsey et al. 2000b).

Dinosaur Tracks

As mentioned in the "Geologic Issues" section, theropod dinosaur tracks are found in the Kayenta Formation at Rainbow Bridge National Monument and were first reported in 1934. Tracks are part of a group of fossils called trace fossils, or 'ichnofossils,' which include impressions made on substrates by organisms. Trace fossils may include trails, tracks, burrows, borings, coprolites (fossilized feces), root cavities, imprints of a body part, resting sites, or any number of impressions left by living or deceased plants or animals. Trace fossils may provide important information about the habitats and ecosystems in which organisms lived.

"Stonepecker holes" (Tafoni)

Small holes, often referred to as "stonepecker holes," weather out of the Navajo Sandstone along cross-beds and bed-set boundaries (fig. 8) (Chidsey et al. 2000b). The geological term for these holes is 'tafoni,' which is a Sicilian term for the honeycomb structures formed in Sicily's coastal granites. Differential erosion in areas where groundwater has weakened the calcium carbonate cement most likely causes these holes to form. Once started, the tafoni become voids where water may accumulate and, if protected from evaporation, promote continued weathering and growth of the openings.

Alcoves and Hanging Gardens

From the north end of the courtesy dock on Lake Powell, a large alcove and hanging garden can be seen on the north side of the canyon. 'Alcoves' are arched recesses in the Navajo Sandstone that formed as a result of erosion by Pleistocene meandering channels and Holocene differential groundwater flow. When percolating groundwater encounters a less permeable zone, often due to a higher silt or clay content, it flows horizontally and forms seeps and springs where it exits the rock. The water dissolves the mineral cement holding sand grains together and, over time, weakens and erodes the rock. Eventually, an alcove forms in the cliff.

The moisture and shade in this area also are ideal for a variety of plants (fig. 4). Root growth further aids in the physical breakup of the rock. Mats of algae, ferns such as maidenhair and bracken, grasses, and sedges often cover the wet surfaces where groundwater seeps from the cliff, forming 'hanging gardens' (Everhart 1983; Anderson et al. 2000; Chidsey et al. 2000b).

Wadis and Oases

A 'wadi' is an ephemeral stream channel that is usually dry in desert regions. In desert environments, an 'oasis' is a vegetated area where springs are present because the water table is close to the surface. Both wadis and oases were present in the Early Jurassic dune fields and have been preserved among the large-scale cross-beds at Rainbow Bridge National Monument.

One wadi deposit is visible on the south side of the canyon from the courtesy dock (Chidsey et al. 2000b). The deposit consists of dark, iron-stained channel sandstones. Some of the channels are about 1.5 m (5 ft) thick. A large block of a wadi deposit fell down about 15 m (50 ft) to the terrace bench near the bridge viewing area. Originally from a channel bed about 0.8–1 m (2.5–3 ft) thick, the block is a mixture of tan to reddish-orange, rounded sandstone clasts and gray to dark-gray, subangular to subrounded dolomitic limestone clasts. The clasts vary in size from gravel to small boulders, and iron-bearing quartz and minor amounts of calcite cement the clasts into a matrix of medium- to coarse-grained sandstone. Most of the stratification in the block is tabular, or planar, although small cross-beds are present. Some of the carbonate clasts were previously part of a muddy surface and have been ripped-up and stacked against each other like dominoes. This type of stacking reflects a current flow that inclined the clasts so that they faced the upstream direction.

An oasis deposit of light-gray, 1.5 m (5 ft) thick, thin-bedded limestone is exposed to the right (west) of Rainbow Bridge as one looks up the wash and across the canyon from the bridge viewing area (Chidsey et al. 2000b). Deposited in a small freshwater lake, the limestone was part of one of many oases that existed in the Navajo Sandstone erg. For oases to develop, whether today or in the Jurassic, fresh groundwater must persist at shallow depths for prolonged periods of time.

Navajo Mountain

Navajo Mountain rises 3,166 m (10,388 ft) above sea level and is a visible expression of the igneous activity that impacted the Colorado Plateau in the Tertiary. Its 10 km (6 mi) diameter, broad, structural dome lies southeast of Rainbow Bridge National Monument (figs. 1 and 9). The mountain is one of several laccoliths on the Colorado Plateau, including the Henry Mountains near the northern end of Lake Powell. These laccoliths formed when magma intruded between bedding planes in the sedimentary strata. The pressure caused overlying sedimentary layers to bow upward, forming the characteristic mushroom-shaped dome of a laccolith. Erosion has exposed the intrusive body within many of the Colorado Plateau laccoliths but not at Navajo Mountain. Consequently, very little is known about the intrusive body that underlies the mountain (Chidsey et al. 2000b).

Jurassic formations are exposed along the flanks and in the canyons of Navajo Mountain. The Cretaceous Dakota Sandstone forms the top of the dome (Chidsey et al. 2000b). Doming at Navajo Mountain is surprisingly localized. Regional dips beyond 8 km (5 mi) from the center of the structure were not affected by the deformation. In Rainbow Bridge National Monument, dips are only 1° to 2° (Chidsey et al. 2000b). However, Navajo Mountain had a major impact on the drainage patterns in the monument area, and may also have influenced the development of joints in the monument.

Joints

Rainbow Bridge National Monument lies in a region of the Colorado Plateau where the strata dip gently, about 2° to 4°, to the northwest. The large sets of joints that provided zones of weakness during the formation of Rainbow Bridge are the dominant structural features in the monument. Because the sandstones of the Navajo and Kayenta formations are brittle, and will therefore shatter more easily than they will bend, joints developed as a response to regional tectonics, local doming at Navajo Mountain, and the release of pressure from the erosion of thousands of meters of overlying rock (Chidsey et al. 2000b). Primary fractures present in Rainbow Bridge National Monument include inclined northeasterly-trending joints, near-vertical northeasterly-trending joints, and surficial joints.

Two sets of joints are included in the inclined joints' category. One set dips 70° to the northwest and the other set is inclined 60° to 70° to the southeast. Conjugate pairs of these joints may be observed in the Navajo Sandstone above the trail that leads to the bridge viewing area. The joints are spaced from 1.5 m (5 ft) to hundreds of meters apart and are as much as several kilometers (miles) in length.

The near-vertical joints are found primarily in the Kayenta Formation, although some prominent examples can also be found in the Navajo Sandstone. These joints are closely spaced, about 0.6–3 m (2–10 ft) apart. Both the near-vertical joints and inclined joints resulted from regional tensional (pull-apart) stresses, including the doming of Navajo Mountain.

Surficial joints are nearly parallel to the Navajo Sandstone cliff face. These joints formed as the sandstone expanded following the rapid erosion and removal of overlying strata. Massive rockfalls may result when large slabs of rock break away from the cliff face along these surficial joints. Closely spaced at the surface, the joints disappear at depth (Chidsey et al. 2000b).

Anticlines and Synclines

Tectonic forces, generated from plate subduction along the western margin of North America during the Late Cretaceous to mid-Tertiary, produced broad folds in the sedimentary strata on the Colorado Plateau. In general, convex folds are called 'anticlines,' and concave folds are called 'synclines.' Dips on the flanks of north– to northwest–trending anticlines and synclines in the Rainbow Bridge region are gentle, up to 7°, but the folds extend for tens of kilometers in length. The northwest-trending Rock Creek anticline crosses the mouth of Forbidding Canyon, north of Rainbow Bridge National Monument (Doelling and Davis 1989; Doelling 1997). The folded sedimentary strata drape over faults that cut Precambrian rock (over 542 million years old) at great depths. Because they are known to trap oil, the anticlines on the Colorado Plateau have been exploration targets for the petroleum industry.

Desert Varnish

One of the more common desert coatings in the southwest, 'desert varnish' forms a lustrous, shiny, and smooth patina on rock surfaces of all sizes, from mere pebbles to massive cliffs (fig. 9). Typically less than 0.25 mm (0.01 in) thick, desert varnish owes its existence to colonies of microscopic bacteria. The bacteria absorb trace amounts of manganese and iron from the atmosphere and precipitate the minerals as a black layer of manganese oxide or reddish iron oxide on rock surfaces. The thin layer of desert varnish also includes clay particles that help shield the bacteria against desiccation, extreme heat, and intense solar radiation.

High-Level Terrace Deposits

High-level terrace deposits cap the high, gently-sloping mesa above Lake Powell to the west of Rainbow Bridge and may provide evidence of extraordinary erosion rates on the Colorado Plateau. The deposits consist of clay, silt, sand, and poorly-sorted boulders that were eroded from the alluvial fan material on the flanks of Navajo Mountain. Some of the boulders are a few meters (several feet) in diameter and would have required an extremely high energy flow regime to transport them so far from the mountain (Chidsey et al. 2000b).

The terrace deposits lie at an elevation of 1,475 m (4,840 ft). The current elevation of Bridge Creek is about 1,114 m (3,655 ft). Incision rates for the Colorado River in the eastern Grand Canyon have been postulated to range from 0.3 m (1 ft) to 0.5 m (1.6 ft) per thousand years (Davis et al. 2001; Hanks et al. 2001; Lucchitta et al. 2001). Based on an average downcutting rate of about 0.4 m (1.3 ft) per thousand years, the terrace deposits can be calculated to be about 900,000 years old (early Pleistocene) (fig. 12). However, field studies of the deposits suggest that they are only 500,000 years old (Chidsey et al. 2000b). If this age is correct, downcutting occurred at a rate of about 0.73 m (2.4 ft) per thousand years, which would be among the highest downcutting rates of any part of the Colorado River system.

Low-Level Terrace Deposits

Terrace deposits adjacent to Bridge Creek are the youngest alluvial sediments exposed in Rainbow Bridge National Monument. These deposits consist of poorly sorted sand, granules, pebbles, and cobbles intermixed with silt and minor amounts of clay deposited by Bridge Creek. The sediments accumulated during periods of high runoff and were derived from Navajo Mountain.

These low-level terraces originally formed in abandoned meanders along Rainbow Bridge Canyon. Most of the deposits are less than 8 m (25 ft) thick and lie from 15 to 30 m (50 to 100 ft) above the active channels. The terraces are probably late Pleistocene in age (Chidsey et al. 2000b).

Talus and Colluvium

Holocene to late Pleistocene talus and colluvium accumulate on the slopes below the Navajo Sandstone cliffs (figs. 6 and 9). ‘Talus’ forms when exfoliation and frost wedging cause slabs of rock to fall from the cliffs and break into rock fragments. ‘Colluvium’ is any unconsolidated soil material or rock fragments deposited by dispersed surface runoff (sheet wash) or by slow, continuous, downslope creep of unconsolidated material. In Rainbow Bridge National Monument, the rockfall blocks, boulders, angular gravel, sand, and silt that form the talus and colluvium are derived primarily from the Navajo Sandstone, older terrace deposits, and windblown sand (Chidsey et al. 2000b).

Petroglyphs and Historic Graffiti

As mentioned in the “Geologic Issues” section, petroglyphs and historic graffiti are present in Rainbow Bridge National Monument. Pecked into the desert varnish that coats parts of the Navajo Sandstone, the petroglyphs likely date from the late 19th or early 20th century and are of Navajo origin (http://www.nps.gov/rabr/faqs.htm).

Figure 9. Features at Rainbow Bridge National Monument. The dark streaks ("A") on the Navajo Sandstone behind Rainbow Bridge are desert varnish. Entrenched meanders ("B") of Bridge Creek are cut into the Kayenta Formation and are visible beneath the bridge. Navajo Mountain is the rounded highland in the distance ("C"). An eroded rock wall, or fin, can be seen behind the bridge's limb in the left part of the photo ("D"). Talus lies in the shadow at the base of the cliff of Navajo Sandstone. U.S. Geological Survey Photo by W. R. Hansen (1959).

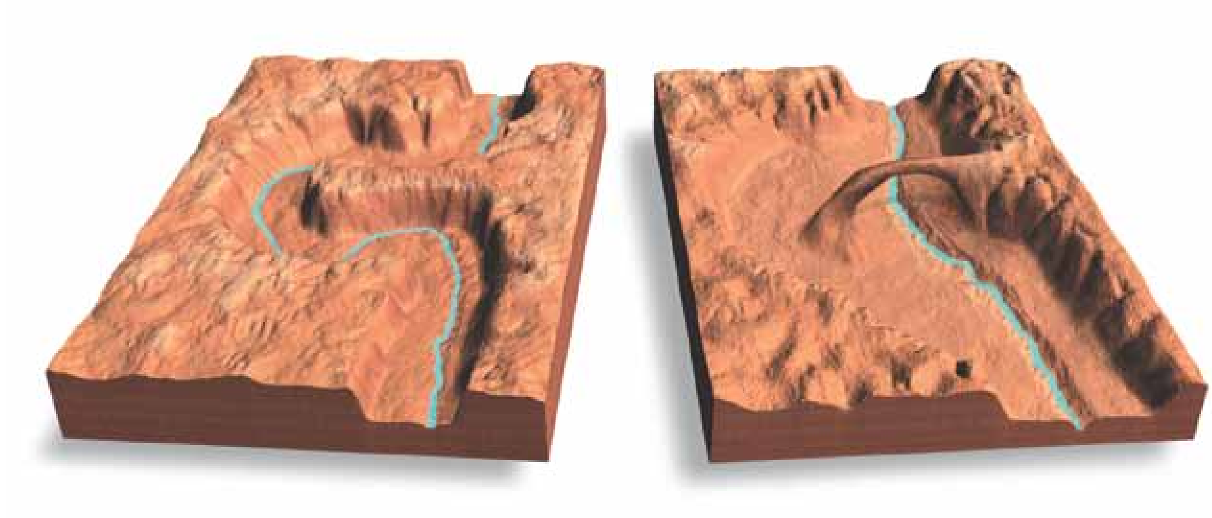

Figure 10. The formation of Rainbow Bridge. Drawing on the left illustrates the meander of Bridge Creek and the development of a narrow wall, or fin, of Navajo Sandstone in the canyon. On the right, the channel has eroded through the narrow fin to create Rainbow Bridge. NPS Graphic courtesy Betsy Scroggs (NPS Glen Canyon NRA).

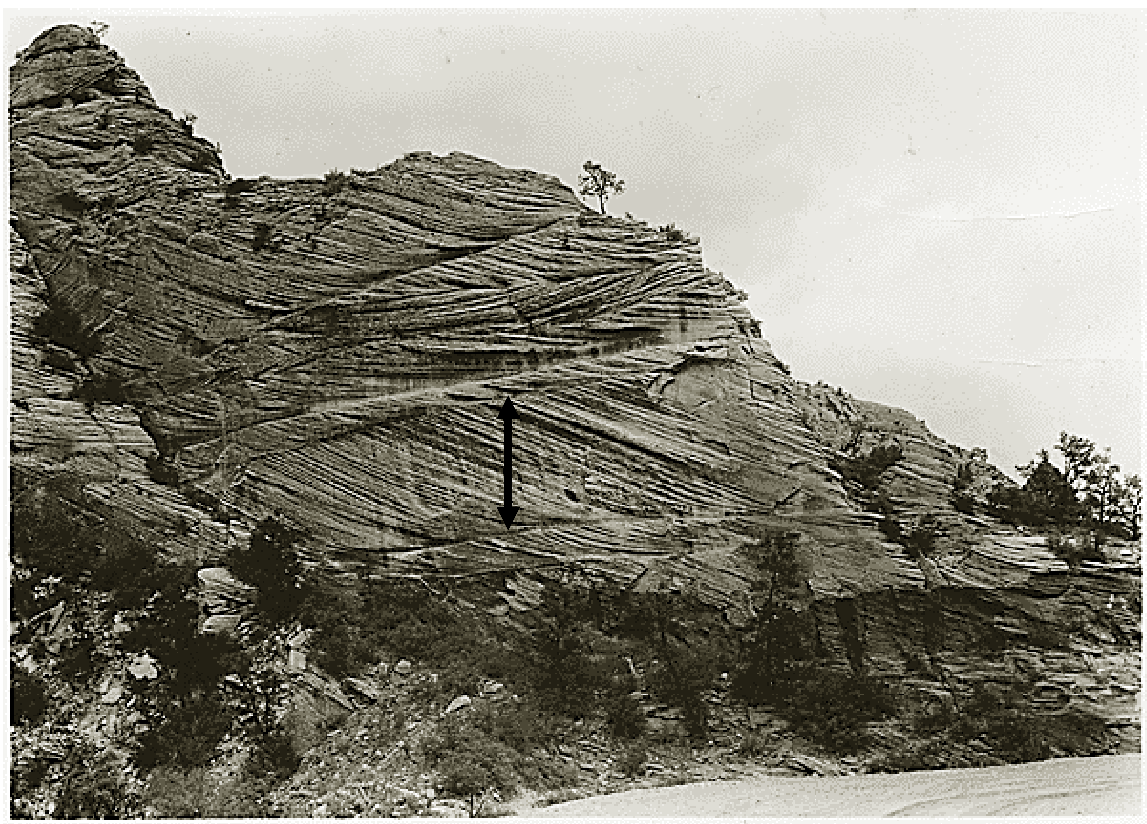

Figure 11. Large-scale cross-stratification in the Navajo Sandstone in Utah's Zion National Park, west of Rainbow Bridge National Monument. Cross-bedding forms when deposition outpaces erosion. The lines dipping to the right at steep angles mark the downwind side of Jurassic sand dunes that are migrating left to right. Trees provide a relative scale with which to compare the height of the dune sets. Individual dune sets (black arrow) may reach 18 m (60 ft) high. The low-angle surfaces dipping to the left are erosion surfaces that truncate the more steeply dipping beds of old dunes. This photograph was taken in 1929 by George A. Grant, the first Chief Photographer of the National Park Service, and is available at http://en.wikipedia.org/wiki/Cross-bedding, accessed March 2009.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Rainbow Bridge National Monument. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of the Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Rainbow Bridge National Monument informed the "Geologic History," "Geologic Features and Processes," and "Geologic Issues" sections of this report. Geologic maps are essentially two-dimensional representations of complex three-dimensional relationships. The various colors on geologic maps illustrate the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships to other natural resources and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps and do not show soil types, but they do show parent material, a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Geologic maps do not show where the next landslide, rockfall, or volcanic eruption will occur, but mapped deposits show areas that have been susceptible to such geologic hazards. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by various geomorphic features that are shown on geologic maps. For example, alluvial terraces may preserve artifacts, and formerly-inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 12) for the age associated with each time period. The table highlights characteristics of map units, such as susceptibility to hazards, the occurrence of fossils, cultural resources, mineral resources, caves, suitability as habitat, and suitability for recreational use.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following reference provides the source data for the GRI digital geologic map of Rainbow Bridge National Monument:

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 1:24,000. Open-File Report 443DM. Salt Lake City, UT: Utah Geological Survey.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software. This increases the overall quality and utility of the data. GRI digital geologic map products include data in ESRI shapefile, geodatabase, and coverage GIS formats, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map with appropriate symbology. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/).

Map Unit Properties Table

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Holocene)	Alluvial and eolian deposits (Qae) Level-2 alluvial and eolian deposits (Qae2)	Qae: Well- to very well sorted, well-rounded sand and silt deposited by wind; locally mixed with sand, silt, and fine gravel deposited by alluvial processes; forms poorly developed dunes, mounds, and sheet-like deposits in depressions and areas protected from erosion for long periods of time; similar in setting and composition to *Qe* deposits except evidence of alluvial activity is more common and dune forms are less developed; mostly derived from, and present on, upper surface of Navajo Sandstone; common residual lag of underlying rock; 0–15 m (0–50 ft) thick. Qae2: Similar in composition and setting to some *Qae* deposits; differentiated where levels are large enough to be mappable at 1:24,000 scale; incised by active washes forming inactive terraces and benches 6–12 m (20–40 ft) above adjacent wash; generally has eolian mantle since upper surface is isolated from most alluvial erosion; 0–6 m (0–20 ft) thick.	Low	High porosity and permeability renders unit unsuitable for waste facilities; buildings constructed within the canyon could prove susceptible to flash floods	Minor slumping possible	None documented	Possible American Indian sites	Sand and gravel	Arid to semi-arid vegetation; sagebrush; few grasses	Short walk to bridge viewing area from Lake Powell	Form most recent river and wind deposits
QUATERNARY (Pleistocene–Holocene)	Talus deposits (Qmt) Talus deposits and eolian sand (Qmte) Eolian sand (Qe) Eolian and alluvial sand and silt (Qea)	<u>Holocene to Upper Pleistocene</u> Qmt: Very poorly sorted, angular blocks mixed with minor fine-grained materials deposited on steep slopes; composed primarily of accumulated rockfall debris; commonly includes minor to moderate amounts of eolian sand; 0–9 m (0–30 ft) thick. Qmte: Similar to *Qmt* deposits except commonly-blanketed by moderate to large amounts of eolian sand that locally completely covers the rockfall debris. <u>Holocene to Middle(?) Pleistocene</u> Qe: Well- to very well sorted, well-rounded sand with minor silt deposited by wind; forms poorly to well developed dunes, mounds, and sheet-like deposits in depressions and areas protected from erosion for long periods of time; locally slightly reworked by alluvial processes and burrowing animals; mostly derived from and present on upper surface of Navajo; residual lag of underlying rock is common; 0–15 m (0–50 ft) thick. Qea: Similar in setting and composition to *Qe* deposits except evidence of alluvial activity is more common and dune forms are less developed.	Variable; rockfall debris more resistant than eolian sand	Infrastructure should avoid talus slopes	Slumps, rock slides, and mass wasting possible	None documented	Possible American Indian sites	Sand	Talus slopes have limited vegetation. Eolian sand may be stabilized by roots	Talus slopes may be unstable; difficult hiking; potentially unsafe to walk next to cliff face	Talus slopes record canyon widening by rockfall
QUATERNARY (Upper to Middle Pleistocene)	Intermediate alluvial gravel deposits (Qagm)	Poorly to moderately sorted boulder to cobble gravel with varying amounts of sand, silt, and clay; clasts are mostly angular to subrounded, well-silicified sandstone and conglomerate boulders up to 2 m (6 ft) in diameter; many clasts were derived from the Jm, and most have a dark-brown weathering patina that gives deposits a dark-brown to brownish-black color; probably mostly reworked from *Qago* deposits; generally on benches and slopes 6–30 m (20–100 ft) above the floor of small streams and washes, but still within the canyons; 0–9 m (0–30 ft) thick.	Variable; finer material is less resistant than boulders and cobbles	Infrastructure within the canyon could prove susceptible to flash floods.	Minor slumping or boulders rolling off benches	None documented	Possible American Indian sites	Sand and gravel	Arid to semi-arid vegetation; sagebrush; few grasses	Suitable for hiking	Terrace-like remnants of alluvium and debris flow deposits in channels draining Navajo Mountain
QUATERNARY (Middle to Lower Pleistocene)	Older alluvial gravel deposits (Qago)	Qago: Similar to *Qagm*, but covers an erosion surface over sloping benches, and commonly has thick carbonate-rich soil accumulation in upper part; cap high, gently-sloping benches and knolls up to about 430 m (1,400 ft) above the floor of adjacent small streams and washes; 0–18 m (0–60 ft) thick.	Variable; finer material is less resistant than boulders and cobbles	Infrastructure should avoid areas with slopes.	Slumps, slides, and mass wasting possible	None documented	Possible American Indian sites	Sand and gravel	Arid to semi-arid vegetation; sagebrush; few grasses	Unstable slopes unsafe for recreational use	May be remnants of an alluvial-fan formed on flanks of Navajo Mountain
QUATERNARY (Middle to Lower Pleistocene)	Level 8 mixed alluvial river terrace and gravel deposits (Qatg8)	Alluvial river terrace deposits; moderately- to well-sorted cobble to pebble gravel and sand; minor silt and clay; major component of large boulders (as described in *Qago*) incorporated into terrace deposits along the Colorado River; includes minor talus and colluvial debris from adjacent bedrock units; includes reworked terrace deposits that drape downslope from the original terrace deposits where the terraces are being eroded; up to 280 m (930 ft) above the modern river channels; mapped levels include *Qat2* to *Qat12*; numbers denote relative heights above the modern channel; 0–9 m (0–30 ft) thick; not all levels are preserved in this area.	Variable; finer material is less resistant than boulders and cobbles	Terrace deposits have relatively limited extent and are relatively unstable; large boulders present problems.	Slumping possible	None documented	Possible American Indian sites	Sand and gravel	Arid to semi-arid vegetation; sagebrush; few grasses	Unstable slopes unsafe for recreational use	Form terrace remnants on benches and slopes near the San Juan and Colorado rivers
QUATERNARY (L. Pleistocene)	Level 9 mixed alluvial river terrace and gravel deposits (Qatg9) Level 12 mixed alluvial river terrace and gravel deposits (Qatg12)	Alluvial river terrace deposits; moderately- to well-sorted cobble to pebble gravel and sand; minor silt and clay; major component of large boulders (as described in *Qago*) incorporated into terrace deposits along the Colorado River; includes minor talus and colluvial debris from adjacent bedrock units; includes reworked terrace deposits that drape downslope from the original terrace deposits where the terraces are being eroded; up to 280 m (930 ft) above the modern river channels; mapped levels include *Qat2* to *Qat12*; numbers denote relative heights above the modern channel; 0–9 m (0–30 ft) thick; not all levels are preserved in this area.	Variable; finer material is less resistant than boulders and cobbles	Terrace deposits have relatively limited extent and are relatively unstable; large boulders present problems.	Slumping possible	None documented	Possible American Indian sites	Sand and gravel	Arid to semi-arid vegetation; sagebrush; few grasses	Unstable slopes unsafe for recreational use	Form terrace remnants on benches and slopes near the San Juan and Colorado rivers

Age	Unit Name (Symbol)		Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
	REGIONAL UNCONFORMTIY in GLEN CANYON NATIONAL RECREATION AREA											
JURASSIC (Upper)	Morrison Formation (Jm)	Salt Wash Member (Jms)	Pale- to medium yellowish-gray, reddish-gray, and greenish-gray, weathering to dark brown, very fine to medium-grained, cross-bedded sandstone, pebble conglomerate, and conglomeratic sandstone, interbedded with minor pale-grayish-green to medium-reddish-brown mudstone and siltstone; forms ledgy cliffs; resistant basal ledge commonly protrudes as an overhanging lip above the ledgy Entrada Formation beds below; only present in one small exposure southwest of Rainbow Bridge where it caps a ridge; regionally, member is about 94 m (310 ft) thick, but only the lower about 60 m (200 ft) is preserved within the Rainbow Bridge area. Not exposed in Rainbow Bridge National Monument.	Ledges of sandstone and conglomerate more resistant than interbedded mudstone and siltstone	Ledges not suitable for development. Not exposed within Rainbow Bridge National Monument	Minor rockfall potential	Dinosaur fossils in other parts of Utah and Colorado. Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Relatively free of vegetation. Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Renowned for its dinosaur fossils and uranium deposits in other western North American localities
	REGIONAL UNCONFORMITY in GLEN CANYON NATIONAL RECREATION AREA											
JURASSIC (Middle)	Entrada Formation (Je)	Middle Member (Jem)	Moderate-reddish-orange to moderate-reddish-brown, medium- to thick-bedded, cross-bedded, calcareous, very fine grained sandstone, interbedded with thin partings of moderate- to dark-reddish-brown siltstone and mudstone, and with scarce, very thin beds of grayish-purple bentonitic clay; forms red and white banded ledgy cliffs; generally less contorted than the Lower Member; upper contact is unconformable; about 110 m (360 ft) thick. Not exposed in Rainbow Bridge National Monument.	Ledges of sandstone and conglomerate are more resistant than mudstone and siltstone	Ledges not suitable for development. Not exposed in Rainbow Bridge National Monument	Minor rockfall potential	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Vegetation scarce. Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Forms the arches in Arches National Park
		Lower Member (Jel)	Pale-reddish-yellow to moderate-reddish-orange, thick-bedded to massive, calcareous, fine-grained sandstone, interbedded with thin partings of moderate reddish-brown siltstone and mudstone; contorted bedding, small internal faults and complex small-scale folds from extensive and complex soft-sediment deformation; fingers and tongues of the Lower Member commonly sag or protrude as pedestals and bulges into the underlying Carmel Formation; forms massive smooth cliffs, rounded bare domes, and broad, rolling slickrock swells with common large weathering pits; abundant secondary alteration and bleaching impart mottled, streaked, and banded appearance to outcrops; about 140 m (460 ft) thick. Not exposed in Rainbow Bridge National Monument.	Sandstone more resistant than interbedded mudstone and siltstone	Cliffs and rounded domes not suitable for development. Not exposed in Rainbow Bridge National Monument	Minor rockfall potential	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Vegetation scarce. Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Most widespread of the preserved late Paleozoic and Mesozoic eolianites (wind derived rocks) on the Colorado Plateau
	Carmel Formation (Jc)		Medium-grayish-red to pale-reddish-gray, interbedded, fine- to very fine-grained sandstone, silty sandstone, siltstone, and mudstone; generally gypsiferous and calcareous; commonly has highly contorted bedding showing a variety of soft-sediment structures produced by loading of the Entrada Formation before Carmel Formation strata were lithified; forms prominent red ledgy slope between the cliff-forming Entrada and Navajo/Page sandstones; 30–42 m (100–140 ft) thick. Not exposed in Rainbow Bridge National Monument.	Less resistant than Entrada Formation and Page Sandstone	Not exposed in Rainbow Bridge National Monument	Minor rockfall potential from ledgy slope	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Gypsum; Not exposed in Rainbow Bridge National Monument	Gypsum limits vegetation	Not exposed in Rainbow Bridge National Monument	Deposited in tidal flats and near-shore environments
	Page Sandstone (Jp)		Moderate-reddish-orange to moderate reddish-brown, fine-grained, very thickly cross-bedded sandstone; locally has very sparse, small angular chert fragments at base; 0–30 m (0–100 ft) thick. Contact with Navajo Sandstone may or may not be an unconformity; if no unconformity, may actually be part of the Navajo Sandstone. Not exposed in Rainbow Bridge National Monument.	Moderate	Not exposed in Rainbow Bridge National Monument	Minor rockfall potential	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Not exposed in Rainbow Bridge National Monument	Sandstone does not retain water; slopes limit vegetation	Not exposed in Rainbow Bridge National Monument	Restricted marine, marginal marine, and eolian (wind) deposits
	REGIONAL UNCONFORMITY in GLEN CANYON NATIONAL RECREATION AREA											
JURASSIC (Lower)	Navajo Sandstone (Jn) limestone beds (Jnl)		Moderate- to pale-reddish-brown to reddish-orange, medium- to thick-bedded, cross-bedded, fine- to medium-grained, poorly sorted sandstone, interbedded with very thin to thin-bedded, moderate- to dark-reddish-brown siltstone and muddy sandstone; grains are subangular to subrounded; calcareous cement; locally contains beds of conglomerate with pebbles of sandstone, siltstone and claystone; forms thick ledges to ledgy cliffs; locally contains thin beds of pinkish-gray limestone; contacts gradational and interlayered with overlying and underlying strata; 60–73 m (200–240 ft) thick.	High except in fractured areas where frost-wedging occurs	Forms cliffs that are not conducive to development	Rockfall potential	None documented in Rainbow Bridge National Monument	Possible American Indian sites in alcoves	Groundwater reservoir in other parts of Colorado Plateau	Cliff-forming units. Some vegetation along groundwater seeps	Rock-climbing potential on cliffs	Forms Rainbow Bridge. Renowned for eolian cross-bedding; extensive ancient erg deposit
	Kayenta Formation (Jk)		Moderate- to pale-reddish-brown to reddish-orange, medium to thick bedded, cross-bedded, fine- to medium-grained, poorly sorted sandstone, interbedded with very thin to thin-bedded, moderate- to dark-reddish-brown siltstone and muddy sandstone; grains are subangular to subrounded; calcareous cement; locally contains beds of conglomerate with pebbles of sandstone, siltstone and claystone; forms thick ledges to ledgy cliffs; locally contains thin beds of pinkish-gray limestone; contacts gradational and interlayered with overlying and underlying strata; 60–73 m (200–240 ft) thick.	Variable. Sandstone more resistant than siltstone and muddy sandstone	Not suitable. Exposed beneath Rainbow Bridge	Minor rockfall associated with ledgy cliffs	Tridactyl (three-toed) theropod dinosaur track at bridge viewing area; locally contains sparse fossil wood	American Indian sacred sites at base of Rainbow Bridge	None documented in Rainbow Bridge National Monument	Forms vertical banks along Bridge Creek and Lake Powell so not conducive to vegetation	Bridge viewing area is located on Kayenta	Deposited in a hot, river floodplain environment

Map source: 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 1:24,000. Utah Geological Survey, Open-File Report 443 DM.

Geologic History

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

Although some of the rocks in the bottom of the Grand Canyon are about two billion years old and upper Paleozoic strata are found in the Glen Canyon National Recreation Area, the oldest rocks exposed in Rainbow Bridge National Monument were deposited during the Lower Jurassic, approximately 200 million years ago (fig. 12). Near the end of the Paleozoic Era, approximately 265 million years ago, explosive volcanoes rose from the sea and formed a north-south trending arc of islands along the border of what is now California and Nevada (fig. 13) (Christiansen et al. 1994; Dubiel 1994; Lawton 1994). South America and Africa collided with North America, causing the growth of mountain ranges from Oklahoma to Maine. The collision of North America with South America also caused the growth of the northwest-trending Uncompahgre Mountains (ancestral Rocky Mountains) in Colorado.

The beginning of the Mesozoic Era saw the major landmasses come together to form a single supercontinent called Pangaea (fig. 14). The Rainbow Bridge area was located approximately 10° north of the equator during this time (Dubiel 1994). Today it is 37° north of the equator.

Late in the Mesozoic, tectonic events began to influence the Rainbow Bridge area. The Late Cretaceous to mid-Tertiary Laramide Orogeny, a mountain-building event responsible for the modern Rocky Mountains, warped the Colorado Plateau into broad folds and basins. Igneous intrusions formed the laccoliths that are responsible for many of the mountains in southern Utah, including Navajo Mountain and the Henry Mountains.

Finally, Tertiary-Quaternary uplift of the Colorado Plateau allowed erosion to aggressively remove much of the strata from the region. As the Colorado Plateau rose, the rivers and streams of the Colorado River drainage system incised their channels into the relatively soft sedimentary strata.

Jurassic Period (199.6–145.5 Ma)

During the Early Jurassic, which extends from 199.6 million years ago (Ma) to 175.6 Ma, the Colorado Plateau region became a broad, low, continental shelf that intermittently accumulated shallow marine to coastal plain sediments. Along the western margin of North America, eastward subduction of the seafloor beneath North America gave rise to volcanic activity. Volcanoes formed a north-south chain of mountains off the coast of western Pangaea in what is now central Nevada. Rivers flowed into the region from highlands to the southeast and east where the ancestral Rocky Mountains remained topographically high.

The Kayenta Formation represents a variety of river, lake, and flood-plain environments (Biek et al. 2000). In contrast to the high-angle, sweeping eolian cross-beds of the overlying Navajo Sandstone, the cross-beds in the Kayenta are only about a meter (~3 ft) in thickness. Evidence of channel and floodplain deposits includes these low-angle cross-beds along with interlayered conglomerates, sandstones, siltstones, and mudstones. Paleocurrent studies show that the Kayenta rivers flowed in a general westward to northwestward direction in the monument area (Chidsey et al. 2000b).

Mountains along the western margin continued to rise in the Early Jurassic as North America collided with the oceanic plate to the west. The mountains created a rain shadow much like today's Sierra Nevada that prevents moist Pacific air from reaching Nevada. During the Jurassic, southern Utah was in the arid, low-latitude climatic belt. Vast sand seas, or ergs, similar to the modern Sahara/Sahel deserts, eventually overwhelmed the region (fig. 15). Sand dune deposits reaching 240–340 m (800–1,100 ft) thick gradually covered the fluvial systems of the Kayenta. Individual high-angle cross-beds in the Navajo may reach 18 m (60 ft) high (fig. 11) (Chidsey et al. 2000b; Morris et al. 2000).

These ergs are preserved as the Navajo Sandstone in southern Utah. Renowned for its uniformity and great thickness, the Navajo Sandstone locally exceeds 610 m (2,000 ft). The preserved dunes consist of moderately well-cemented, well-rounded, fine- to medium-grained quartz grains. Outcrops weather to bold, rounded cliffs. (Blakey 1994; Peterson 1994; Biek et al. 2000; Morris et al. 2000).

Like the Sahara, the Navajo ergs formed a coastal and inland dune field (fig. 15). The Jurassic dune field was located in present-day southern Montana, eastern Utah, westernmost Colorado, southwest Colorado, northeastern Arizona, and northwestern New Mexico (Kocurek and Dott 1983; Peterson 1994).

Although not exposed in the monument, Middle Jurassic (175.6–161.2 Ma) and Late Jurassic (161.2–145.5 Ma) strata record continued deposition near sea level. Broad tidal flats formed along the margins of a shallow sea that lay to the west (Wright et al. 1962). The sea encroached into west-central Utah from the north. Flat-bedded sandstones, siltstones, and limestones filled depressions that had eroded into the underlying strata (Doelling 2000).

Eolian and sabkha-like environments (arid, coastal areas above high-tide) truncated the Navajo Sandstone erg deposits (Blakey 1994). Interbedded sandstones and siltstones, fossil-bearing limestone, and gypsum record a period of intermittent marine flooding and evaporation in the Glen Canyon area (Morris et al. 2000). Sedimentary structures such as mudcracks, ripple marks, and approximately 2.5 cm (1 in)-thick cross-bedding are remnants of the tidal flat conditions that returned to the area.

Fluctuating marine conditions, resulting from increased plate tectonic activity along the western margin of North America, caused a major transgression of an inland seaway from the north. This transgression was one of three transgression/regression cycles that destroyed the extensive eolian sand seas that once covered the Colorado Plateau (Kocurek and Dott 1983). During regressions, braided stream and floodplain deposits spread over the region.

Erosion of the mountains to the west provided sediment to rivers flowing into the area. Increased tectonic activity and marine incursions established lagoons, beaches, and swamps in a landscape that had once supported the Early Jurassic sand seas.

Cretaceous Period (145.5–65.5 Ma)

Cretaceous strata above the Navajo Sandstone have also been eroded in the immediate area of Rainbow Bridge National Monument. Exposed in the nearby Glen Canyon National Recreation Area and throughout the Colorado Plateau, the Cretaceous rocks, like the Jurassic strata, record multiple episodes of marine transgressions and regressions into the Western Interior of North America, the region between the mountains rising on the western margin of North America and the Midwest.

Continued subduction along the west coast of North America initiated the Sevier Orogeny, a mountain-building event that thrust Paleozoic strata from west to east over younger, Mesozoic rocks. The Sevier Orogeny (about 105–75 million years ago) resulted in north-south trending mountain ranges that extended along the entire western margin of North America. As the mountains rose, the Western Interior began to sink, or subside. Rifting between North and South America opened the Gulf of Mexico, and marine water began to transgress northward. At the same time, seawater began to advance onto the continent from the Arctic region.

The seas advanced and retreated many times during the Cretaceous until the most extensive interior seaway ever recorded drowned much of western North America. The elongate Western Interior Seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4,800 km (3,000 mi) (fig. 16).

The Western Interior Seaway was the last marine incursion into the interior of North America. The seaway receded from the continental interior with the onset of the Laramide Orogeny (about 70–35 million years ago). This orogeny marked a pronounced eastward shift in tectonic activity as the angle of the subducting slab of oceanic crust flattened and compressive forces were felt throughout northern Arizona, Utah, and into Colorado. Unlike Sevier thrust faults, Laramide thrust faults moved deeply-buried Precambrian plutonic and metamorphic rocks to the Earth's surface. Sevier thrust faults dip at a low angle, generally 10°–15°, relative to the Earth's surface. In contrast, Laramide thrust faults have steeply-dipping fault planes at the surface that curve and flatten in Precambrian crystalline rocks at depths up to 9 km (5.7 mi or 30,000 ft) below sea level (Gries 1983; Erslev 1993).

During the Laramide Orogeny, tectonic forces folded and faulted Precambrian to Cretaceous age rocks into the Rocky Mountains and adjoining basins, but these compressive forces had comparatively little effect on the rigid Colorado Plateau. The Colorado Plateau was primarily warped into broadly-undulating convex (anticlinal) and concave (synclinal) folds and monoclines with little large-scale faulting (Dickinson and Snyder 1978; Chapin and Cather 1983; Hamilton 1988; Erslev 1993). Laramide features near Rainbow Bridge National Monument include the Circle Cliffs uplift and Rock Creek anticline to the north, the Monument upwarp to the east, and the Kaiparowits structural basin to the west (Chidsey et al. 2000b).

As the seas regressed off the continent in the Late Cretaceous, shoreface, beach, lagoon, and swamp environments returned. Peat beds in the swamps and lagoons were buried and eventually transformed into thick coal deposits throughout the Western Interior region of Utah, Wyoming, and Colorado.

Tertiary Period (65.5–1.8 Ma)

Explosive volcanism dominated the western margin of North America during Oligocene and early Miocene time (fig. 12). Mount St. Helens-type eruptions even exceeded the largest Yellowstone eruptions (Dave Sharrow, Zion National Park, written communication, 2005). Igneous intrusions that produced the mushroom-shaped laccoliths in Utah occurred about 31.2 to 23.3 million years ago, during the late Oligocene (Chidsey et al. 2000b). Bridge Canyon may have originated in the aftermath of Navajo Mountain's laccolithic emplacement. As with most mountains, Navajo Mountain would have created its own weather patterns and attracted storms. Long periods of torrential rain blanketed the Colorado Plateau and the Southwest causing high-velocity water flows that eroded strata from the canyon walls, causing canyons to widen as they deepened (Sproul 2001).

About 15 million years ago, during the Miocene Epoch, the tectonic regime along the southwestern margin of the United States changed from one of compression to one of extension. The crust began to be pulled apart in a process that eventually formed today's Basin-and-Range Province, which is centered primarily in Nevada and

Arizona. The Rainbow Bridge National Monument area was not greatly affected by Basin-and-Range extension, although the large fault systems that parallel the western margin of the Colorado Plateau did impact National Park System units that lie west of Rainbow Bridge and Glen Canyon National Recreation Area (Zion National Park, Cedar Breaks National Monument, and Bryce Canyon National Park in Utah; Grand Canyon National Park and Pipe Spring National Monument in northern Arizona).

Uplift of the Colorado Plateau and the Basin-and-Range Province during the Tertiary Period changed the landscape from one of deposition to one of erosion (Chidsey et al. 2000b; Anderson et al. 2000). Erosive processes of running water and mass wasting (i.e., landslides and cliff collapse) have removed thousands of meters (yards) of sedimentary rock. The Colorado River system carried most of this eroded material to the sea (today the river drains into the Gulf of California).

About 5 million years ago, the Colorado Plateau rose and the Colorado River began downcutting to create the Grand Canyon. Rivers cut their channels downward faster than they cut laterally so that the drainage patterns became entrenched (Anderson et al. 2000; Chidsey et al. 2000b; Huntoon et al. 2000). Countless canyons and entrenched meanders were carved in the Glen Canyon region during this time.

Quaternary Period (1.81 Ma–present)

During the Pleistocene (1.81 million years ago–10,000 years ago), snow accumulated on Navajo Mountain and glaciers from the northern part of the continent moved southward (fig. 17) (Sproul 2001). The flow of water continued to intensify through the Colorado River drainage system, including higher volumes of water in Bridge Creek. During the Wisconsinan glacial stage, about 115,000 to 10,000 years ago, intense cyclonic storms and cold winters impacted the region (Smiley et al. 1991). During the late Wisconsinan stage (28,000–10,000 years ago), summers on the Colorado Plateau were cooler but drier, while winters had increased precipitation relative to today's climate (Patton et al. 1991). The erosive power of Bridge Creek eventually cut a hole in a Navajo Sandstone fin and carved out Rainbow Bridge (fig. 10).

Volcanic activity continued from the Tertiary into the Quaternary along the western margin of the Colorado Plateau (Luedke and Smith 1991; Patton et al. 1991). In the St. George, Utah area, near Zion National Park, Quaternary eruptions may be less than 1,000 years old. During the Pliocene through late Pleistocene epochs, basaltic lava flows and pyroclastics erupted from vents in northwestern Arizona, north of the Colorado River (Patton et al. 1991).

Holocene deposits in the Rainbow Bridge National Monument area consist of fluvial deposits, eolian sand, and landslide accumulations of talus and colluvium. High-level terrace deposits record fluvial activity prior to Bridge Creek's incision to its present channel. Low-level terrace deposits and benches within the canyon record more recent channel patterns, before the most recent downcutting episode. Talus and colluvium are evidence of recent erosion of the Navajo Sandstone cliff face. During wet periods, grassy vegetation tends to stabilize the eolian deposits, but during prolonged dry conditions the eolian deposits are transported by wind activity.

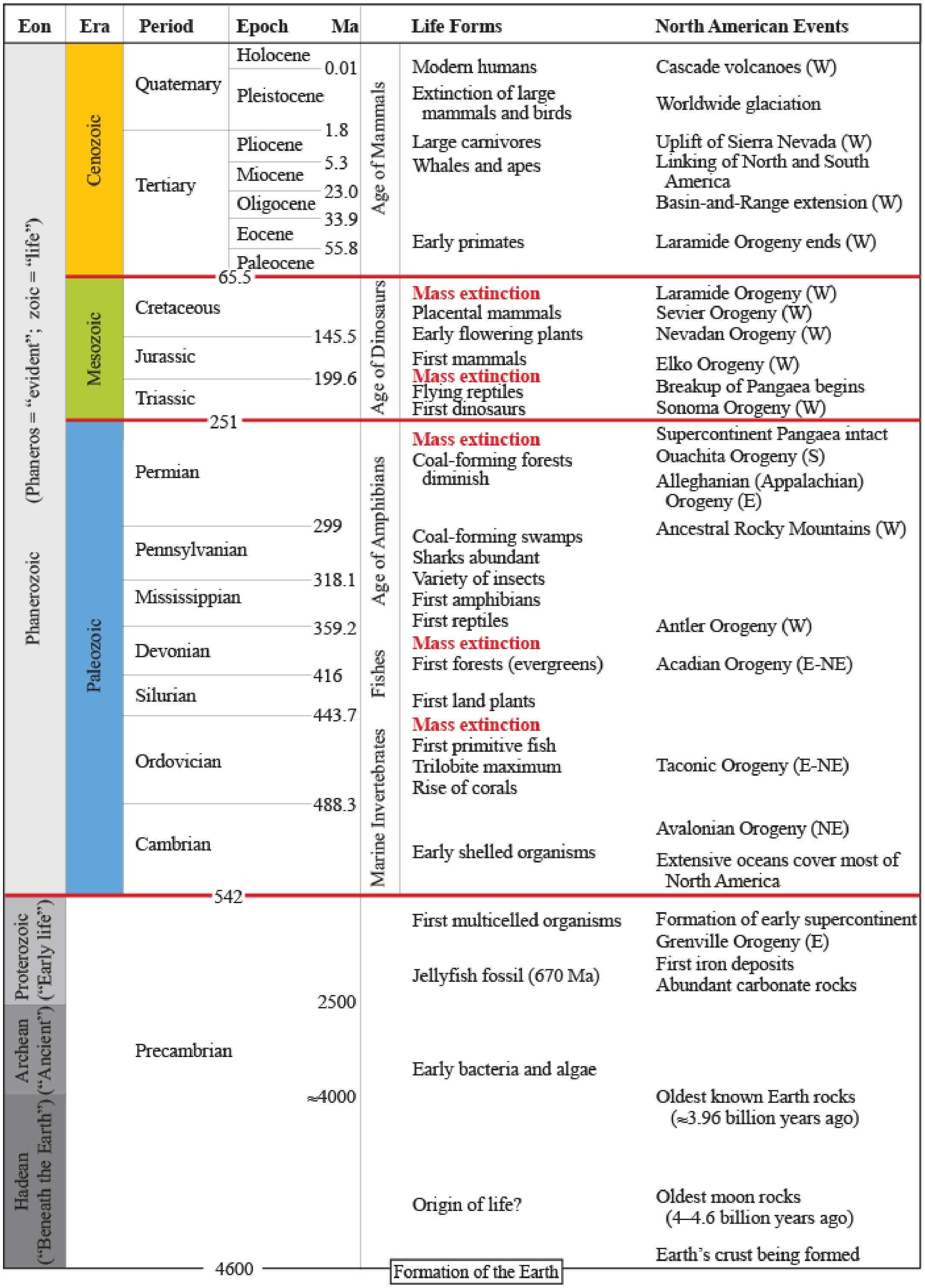

Figure 12. Geologic time scale. Included are major events in life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities (gaps of time in the rock record) between eras. Absolute ages shown are in millions of years (Ma). Compass directions in parentheses indicate the location of individual geologic events with respect to the margin of North America. Adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/).

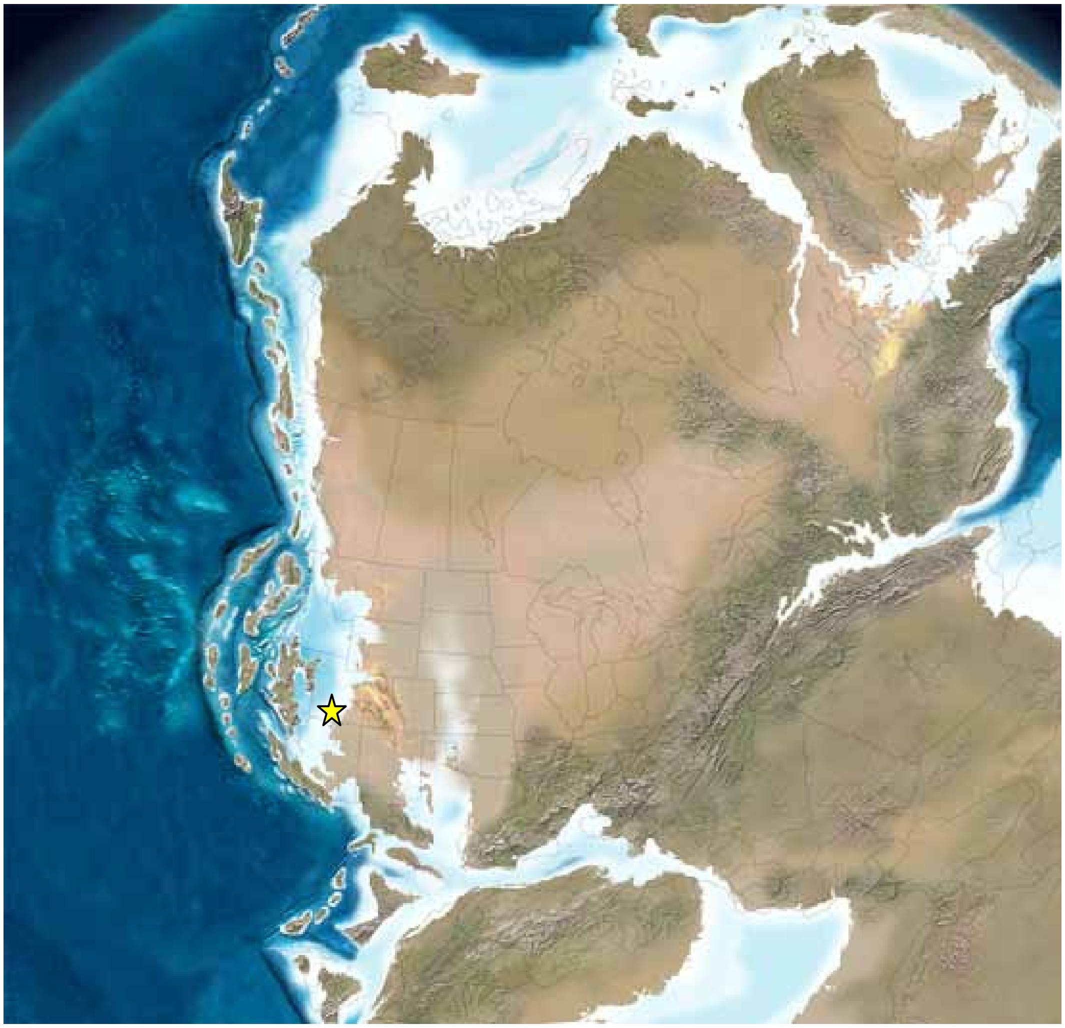

Figure 13. Late Permian paleogeographic map. Approximately 265 million years ago, the landmasses of South America and Africa were attaching themselves to the North American Plate, causing the growth of mountain ranges from Oklahoma to Maine. Subduction along the western margin of North America produced an arc of volcanic islands. The yellow star approximates the location of today's Rainbow Bridge National Monument. Brown-colored areas indicate land with dark brown representing higher elevations. The collision of North America with South America caused the growth of the northwest-trending Uncompahgre Mountains (ancestral Rocky Mountains) in Colorado. Blue colors represent water. Light blue areas represent shallower, near-shore marine environments; dark blue is deeper marine. Modified from Late Permian map created by Dr. Ron Blakey (Northern Arizona University), http://jan.ucc.nau.edu/~rcb7/namP260.jpg, accessed March 2009.

Figure 14. Early Triassic paleogeographic map of the North American region of the supercontinent, Pangaea. Approximately 245 million years ago, Pangaea had reached its greatest extent. The area that would become Rainbow Bridge National Monument (yellow star) lies about 10° north of the equator (white line). Modified from Early Triassic map created by Dr. Ron Blakey (Northern Arizona University), http://jan.ucc.nau.edu/~rcb7/namTr245.jpg, accessed March 2009.

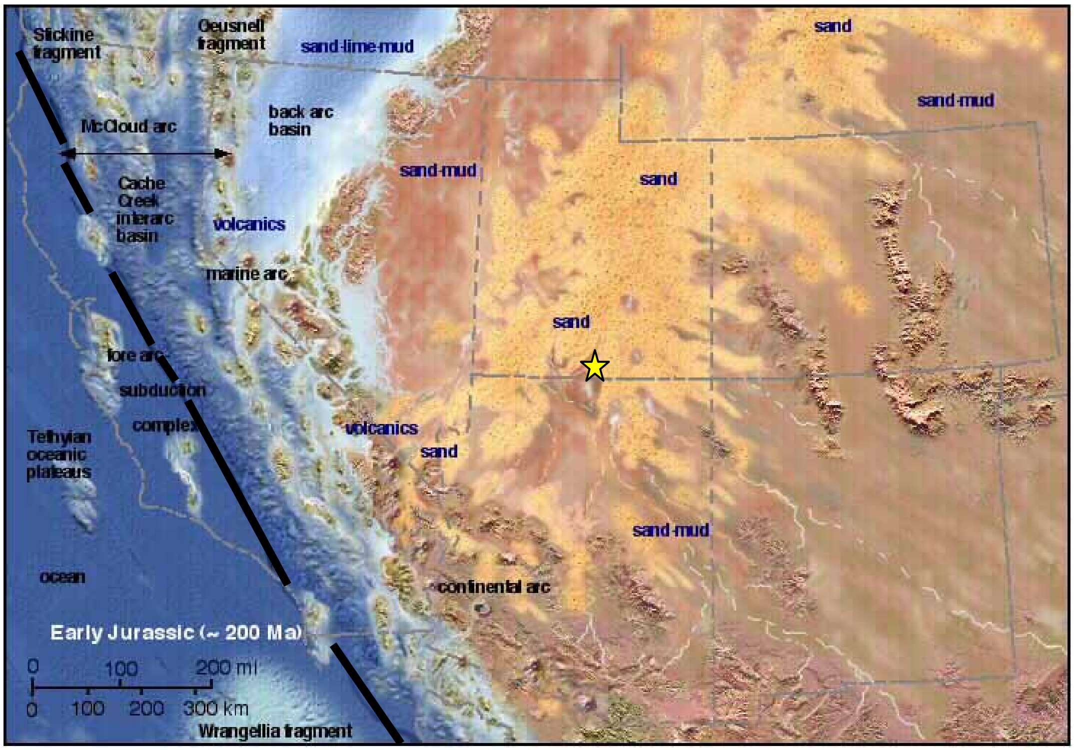

Figure 15. Early Jurassic paleogeographic map of the southwestern United States. Approximately 200 million years ago, the great Navajo sand sea (yellowish tan) had spread across much of the Western Interior. The "continental arc," "marine arc," "volcanic," "fore arc subduction complex," "Cactus Creek interarc basin," "back arc basin," and "McCloud arc" are regions that formed in response to compressive forces related to the subduction zone (thick black line) between the North American Plate and the oceanic plate to the west. The yellow star represents the approximate location of today's Rainbow Bridge National Monument. Modified from the Early Jurassic map created by Dr. Ron Blakey (Northern Arizona University), http://jan.ucc.nau.edu/~rcb7/jurpaleo.html, accessed March 2009.

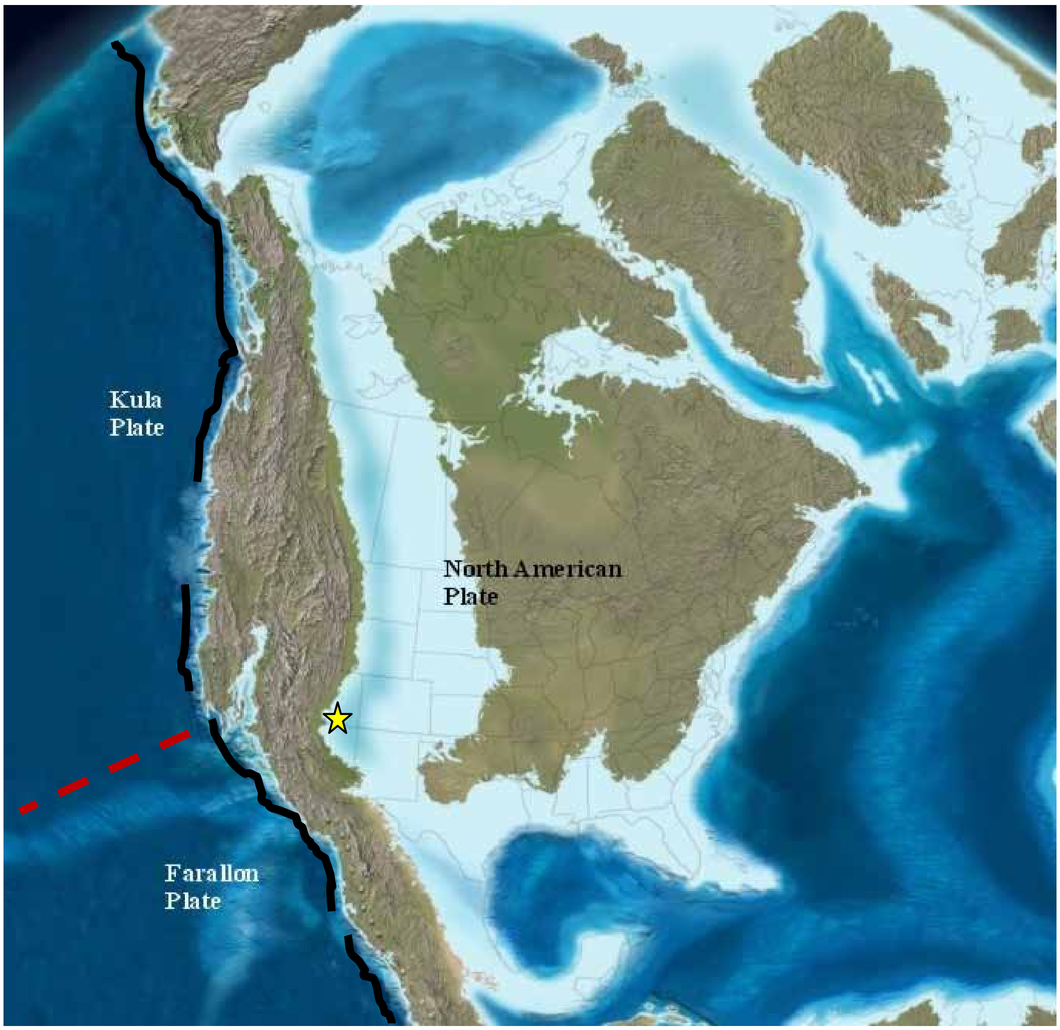

Figure 16. Late Cretaceous paleogeographic map of North America. Approximately 85 million years ago, an inland seaway (light blue) extended from the Gulf of Mexico to the Arctic Ocean. The yellow star is the approximate location of today's Rainbow Bridge National Monument. Mountains formed from compression along the western margin of North America caused by the subduction (convergent boundary) of the Farallon Plate and Kula Plate beneath the North American Plate (thick black line). The dashed red line is the approximate location of the spreading center (divergent boundary) separating the Farallon and Kula plates. Modified from the Late Cretaceous map created by Dr. Ron Blakey (Northern Arizona University), http://jan.ucc.nau.edu/rcb7/namK85.jpg, accessed March 2009.

Figure 17. Pleistocene paleogeographic map of North America. Approximately 126,000 years ago, at the onset of the Wisconsinan stage of the Pleistocene ice age, lakes cover large areas of what is now Utah and Nevada. The yellow star is the approximate location of today's Rainbow Bridge National Monument. Brown is land; blue is water; white is ice and snow. Modified from the Quaternary map created by Dr. Ron Blakey (Northern Arizona University), http://jan.ucc.nau.edu/~rcb7/namQ.jpg, accessed March 2009.

Glossary

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

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

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

alluvium. Stream-deposited sediment.

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

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

basin (structural). A doubly-plunging syncline in which rocks dip inward from all sides (also see "dome").

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

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

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

bedding. Depositional layering or stratification of sediments.

bedset. A relatively conformable succession of beds bounded by surfaces (called bedset surfaces, or bedset boundaries) of erosion or non-deposition.

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

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

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

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

clast. An individual grain or rock fragment in a sedimentary rock, resulting from the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks.

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

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

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

conjugate set (of joints). A pair of intersecting joints related in deformational origin, usually compression, and with angular measurements.

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

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

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

convergent boundary. An active boundary where two tectonic plates are colliding.

coprolite. The fossilized excrement of vertebrates.

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions (e.g., direction and depth).

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

cutbank. A local term in the western U.S. for a steep, bare slope formed by lateral erosion of a meandering stream. Usually opposite a point bar or river bank where sediment is being deposited.

deformation. A general term for the process of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

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

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

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

dome (structural). A doubly-plunging anticline that dips radially in all directions (also see "basin").

downcutting. Stream erosion in which the cutting is directed in a downward direction (as opposed to lateral erosion).

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

entrenched meander. See "meander."

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

ephemeral stream. A stream that flows only in direct response to precipitation.

erg. An extensive tract of sandy desert; a sand sea.

exfoliation. The breakup, spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by differential stresses due to thermal changes or pressure unloading.

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

fold. A curve or bend of a planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

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

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

frost wedging. The breakup of rock due to the expansion of water freezing in fractures.

igneous. Describes a rock or mineral that originated from molten material. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

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

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

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

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

lamination. The finest stratification or bedding, as in shale or siltstone; also the formation of laminae.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through cementation and compaction.

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

lithosphere. The relatively rigid outmost shell of the Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

magma. Molten rock capable of intrusion and extrusion.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The entrenched meander preserves its original pattern with little modification.

mechanical weathering. The physical breakup of rocks without change in composition (syn: physical weathering).

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

metamorphic. Describes the process of metamorphism or its results; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, genesis, and/or recrystallization from increased heat and pressure.

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

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

oceanic crust. The Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

orogeny. A mountain-building event.

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

oxbow. A closely looping stream meander resembling the U-shaped frame embracing an ox's neck; having an extreme curvature such that only a neck of land is left between two parts of the stream.

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

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

parent rock. Rock from which sediments or other rocks are derived.

physical weathering. See "mechanical weathering."

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

pluton. A body of intrusive igneous rock.

porphyry. An igneous rock with abundant coarse crystals (phenocrysts) in a fine-grained matrix.

radiometric age. An age in years determined from radioactive isotopes and their decay products.

red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains.

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

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

rockfall. mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

sabkha. A coastal environment in an arid climate where evaporation rates are high.

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

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

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

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

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

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

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

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

spreading center. A divergent boundary where two tectonic plates are spreading apart. It is a source of new crustal material.

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

strata. Tabular or sheetlike masses or distinct layers of rock.

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

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

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

subangular. Somewhat angular, free from sharp angles but not smoothly rounded.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subrounded. Partially rounded sedimentary particle having many of its edges and corners noticeably rounded off to smooth curves.

syncline. A downward curving (concave up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

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

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

terrace (stream). Step-like bench surrounding the present floodplain of a stream due to dissection of previous floodplain(s), stream bed(s), and/or valley floor(s).

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall. Called a "reverse fault" if the angle of dip is greater than 45°.

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

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

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

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity thus marks a period of missing time.

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

upwarp. Upward flexing of the Earth's crust.

wadi. An ephemeral stream channel, usually dry, in desert regions.

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

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

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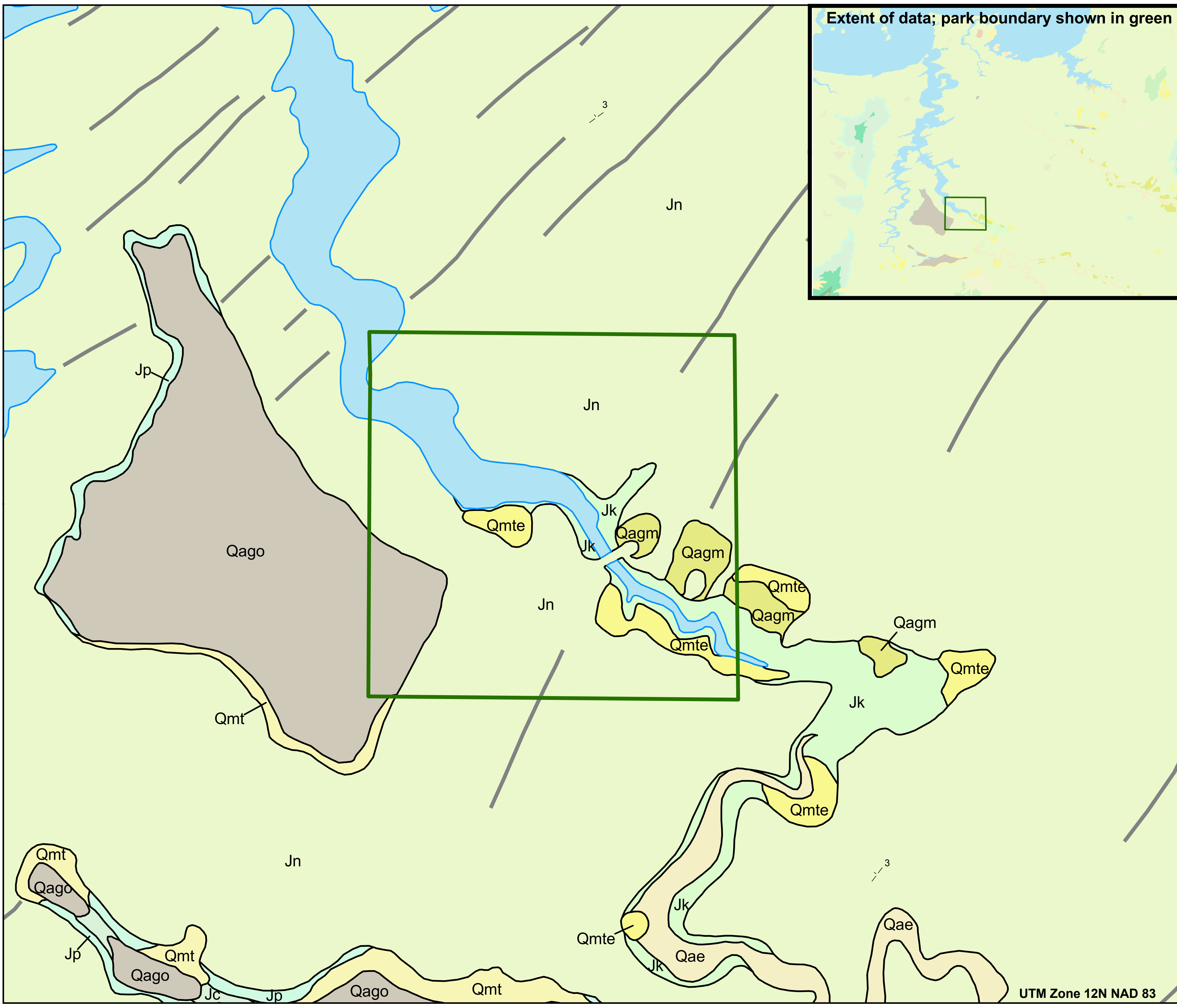
Appendix A: Geologic Map Graphic

The following page is a snapshot of the geologic map for Rainbow Bridge National Monument. For a poster-size PDF of this map or for digital geologic map data, please see the included CD or visit the Geologic Resources Inventory publications Web page (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Map of Rainbow Bridge National Monument



NPS Boundary

Quad Sheet Boundary

Geologic Attitude and Observation Points

approximate strike and dip of inclined beds

Linear Joints

known or certain

Geologic Contacts

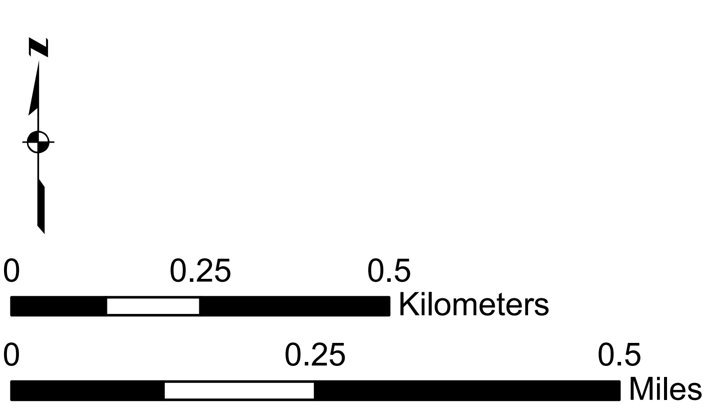
known or certain

map boundary

water or shoreline

Geologic Units

- Water
- Qae, Alluvial and eolian deposits
- Qae2, Level-2 alluvial and eolian deposits
- Qmt, Talus deposits
- Qmte, Talus deposits and eolian sand
- Qe, Eolian sand
- Qea, Eolian and alluvial sand and silt
- Qagm, Intermediate alluvial gravel deposits
- Qago, Older alluvial gravel deposits
- Qatg8, Alluvial river terrace deposits with older alluvial gravel
- Qatg9, Alluvial river terrace deposits with older alluvial gravel
- Qatg12, Alluvial river terrace deposits with older alluvial gravel
- Jms, Salt Wash Member of Morrison Formation
- Jem, Middle member of Entrada Sandstone
- Jel, Lower member of Entrada Sandstone
- Jc, Carmel Formation
- Jp, Page Sandstone
- Jn, Navajo Sandstone
- Jnl, Limestone beds in Navajo Sandstone
- Jk, Kayenta Formation



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

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 1:24000. Utah Geological Survey, Open-File Report 443DM.

Digital geologic data and cross sections for Rainbow Bridge National Monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

Produced by the Geologic Resources Inventory

September 2009

Appendix B: Scoping Summary

The following excerpts are from the GRI scoping summary for Rainbow Bridge National Monument. The contact information and Web addresses in this appendix may be outdated. Please contact the Geologic Resources Division for current information.

An inventory workshop was held at Glen Canyon National Recreation Area and Rainbow Bridge National Monument on September 23-25, 1999. Excerpts that pertain to Rainbow Bridge National Monument are included in this appendix. The purpose of the workshop was:

- To view and discuss the geologic resources,
- To address the status of geologic mapping by both the Utah Geological Survey (UGS) and the United States Geological Survey (USGS) for compiling both paper and digital maps, and
- To assess resource management issues and needs.

Cooperators from the National Park Service Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Glen Canyon National Recreation Area (GLCA), Utah Geological Association (UGA), Utah Geological Survey (UGS), and U.S. Geological Survey (USGS) were present for the two-day workshop.

A field trip to Rainbow Bridge and the southern reaches of Lake Powell was conducted on September 25 and led by UGS geologists Grant Willis, Doug Sprinkel and Tom Chidsey.

UGA guidebook on Utah’s National and State park areas

Doug Sprinkel and Tom Chidsey (UGA) announced that a guidebook treating the geology of Utah's national and state parks and monuments would be compiled for publication in September 2000. This compilation will be a snapshot into the geology of each park and covers most facets of what the Geologic Resource Inventory (GRI) is trying to develop for each park for a final report (i.e. cross sections, simplified geologic map, general discussions of rocks, structure, unique aspects of park geology, classic viewing localities). The only National Park Service unit in Utah that will not be treated will be Golden Spike National Historic Site.

Funding for this publication is coming jointly from the Utah Geological Association (UGA), National Park Service (NPS), Bureau of Land Management, U.S. Forest Service and Utah state parks. Prices for the full-color guidebook are estimated to be approximately $25 per copy, and sales are expected to be high (exact estimates for Capitol Reef National Park were 125 copies per year). A website for the guidebook is forthcoming in October 1999.

Each author will be encouraged to get with NPS staff interpreters to develop a product that aims at a wide audience (the common visitor, the technical audience and the teaching community). Rainbow Bridge National Monument authors will be Doug Sprinkel, Tom Chidsey and Grant Willis.

Park authors are strongly encouraged to get with NPS staff to make sure that any trail logs do follow maintained trails and do not take visitors into unauthorized areas or places where resources are fragile and would be disturbed by increased visitation (i.e. areas with crytptogamic soils).

Also, a CD-ROM will be distributed with the publication featuring road and trail logs for specific parks as well as a photo glossary and gallery. The photo glossary will describe certain geologic features (i.e. what is cross-bedding?). These will also be available as web-downloadable Adobe Acrobat PDF files. The UGA cannot copyright this material because it is funded with state money, so it can be distributed widely and freely, which will also benefit the purposes of the GRI. Additional reprints are not a problem because of the digital nature of the publication and the UGA board is committed to additional printings as needed. UGA normally prints 1,000 copies of their publications because they become dated after about five years; that will probably not be an issue for this publication.

Many other benefits are anticipated from this publication and are enumerated below:

- This type of project could serve as a model for other states to follow to bolster tourism and book sales promoting their state and its geologic features,
- Sandy Eldredge (UGS) will be targeting teaching communities for involvement in the field trips; hopefully teachers will pass on what they have learned to their young audience,
- The language is intended to appeal to someone with a moderate background in geology and yet will be very informative to the educated geologist,
- The publication may be able to serve as a textbook to colleges teaching Geology of National Parks (in Utah),
- A welcomed by-product could be roadlogs between parks in Utah for those visiting multiple parks, perhaps with a regional synthesis summarizing how the overall picture of Utah geology has developed.

Paleontological Resources

Vince Santucci (NPS-GRD Paleontologist) presented an overview of paleontological resources for Glen Canyon National Recreation Area and the NPS in general. GRD provides support on policy and GPRA goals related to

paleontological resources in parks. Paleontology is not currently part of the first level of the Inventory and Monitoring (I&M) program, but this may change in the future. Vince also mentioned the need for a mandate for protecting paleontological resources within federal lands. Vince has participated in refresher training courses for NPS rangers to make them more aware of the importance of realizing and protecting paleontological resources. A first step is to make parks realize if they have significant paleontological resources, and second is to conduct baseline inventories.
Norm Henderson (Glen Canyon NRA, natural resources) is interested in having a Paleontological Survey conducted for Glen Canyon National Recreation Area and Rainbow Bridge National Monument and has already approximately $20,000 in funds designated for this. Similar studies have been done at Zion, Yellowstone and Death Valley. Vince Santucci has offered to conduct such a survey for the park.

Similar surveys have shed valuable new information on previously unrecognized resources. These surveys involve a literature review/bibliography and recognition of type specimens, species lists, and maps (which are unpublished to protect locality information), and also make park-specific recommendations for protecting and preserving the resources.

If a paleontological survey yields significant findings, paleontological resource management plans should be produced for Glen Canyon and Rainbow Bridge involving some inventory and monitoring to identify human and natural threats to these resources. Perhaps someone on the park staff could be assigned to coordinate paleontological resource management and incorporate any findings or suggestions into the park's general management plan (GMP). It would be useful to train park staff (including interpreters and law enforcement) in resource protection, as the fossil trade "black market" has become quite lucrative for sellers and often results in illegal collecting from federal lands.

Collections taken from this area that now reside in outside repositories should be tracked down for inventory purposes. Fossils offer many interpretive themes and combine a geology/biology link and should be utilized as much as possible in interpretive programs.

Geologic Mapping

UGS Perspective: Currently, the UGS is mapping in Utah at three different scales:

- 1:24,000 for high priority areas (i.e. National and State parks),
- 1:100,000 for the rest of the state,
- 1:500,000 for a compiled state geologic map.

The UGS plans to complete mapping for the entire state of Utah within 10-15 years at 1:100,000 scale. For 1:100,000 scale maps, their goal is to produce both paper and digital maps; for 1:24,000 scale maps, the only digital products will be from "special interest" areas (i.e. areas such as Zion and growing metropolitan St. George). Grant Willis mentioned that the UGS simply does not have enough manpower and resources to do more areas at this scale. He also reiterated that UGS mapping goals are coincident with those of the National Geologic Mapping Program.

Current Status

Several (> 50) 7.5-minute quadrangles cover Glen Canyon NRA and Rainbow Bridge NM. The following was proposed with regard to Rainbow Bridge National Monument mapping:

- Jointly fund with the NPS and UGS to complete mapping of the Hites Crossing, Navajo Mountain and Hanksville 100,000 sheet quadrangles to complete the mapping of Glen Canyon Recreation Area. Navajo Mountain-13 quadrangle includes Rainbow Bridge National Monument,
- Rainbow Bridge National Monument would be good to map at 1:6,000 scale; the current quadrangles covering the area are the Cummins Mesa SE and Navajo Mountain-13. Perhaps this would make a good EDMAP project.

Other sources of Natural Resources data

- The UGS has a significant quadrangle database that they have furnished to NRID for the entire state of Utah,
- NRID has compiled a geologic bibliography for numerous parks and monuments, including Glen Canyon NRA and Rainbow Bridge NM. Visit the website at: http://165.83.36.151/biblios/geobib.nsf; user id is "geobib read", password is "anybody,"
- Lex Newcomb (NPS, Glen Canyon National Recreation Area) says he has some 353 maps at 1:4,800 scale with 10 foot contour intervals ranging from elevations of 3140-3750 feet,
- Lex Newcomb also mentioned indexed historical maps along the shoreline showing geologic hazards,
- Abandoned Mineral Land (AML) database by John Burghardt (GRD).

Geologic Hazards

The geologic hazards discussed at the workshop pertained to Glen Canyon National Recreation Area. No issues that were discussed were relevant to Rainbow Bridge National Monument:

Potential research topics for Rainbow Bridge National Monument

A list of potential research topics relevant to Rainbow Bridge National Monument included:

- Paleoclimate change study for the area,
- Paleontological inventory,
- Studies of Rainbow Bridge stability.

Unique Geologic Features

- Rainbow Bridge,
- Hanging gardens; because they are geologically controlled,
- Petrified sand dunes,
- Cross-bedding and other sedimentary structures,
- Unconformities in geologic rock record,
- Alcoves (not caves) in Navajo Sandstone.

Action Items

Many follow-up items were discussed during the course of the scoping session and those pertaining to Rainbow Bridge National Monument are reiterated by category for quick reference.

Interpretation

If desired consult with GRD's Jim Wood (jim_f._wood@nps.gov), UGS Sandy Eldredge(nrugs.seldredge@state.ut.us) or Melanie Moreno at the USGS-Menlo Park, CA (mmoreno@usgs.gov) for additional assistance with various interpretation themes

UGA Guidebook

Attempt to plant the seeds of this concept to other states for similar publications involving local area geology. Such publications are especially useful for the GRI.

Geologic Mapping

- Attempt to locate D.A Phoenix's greenlines to digitize from (Pete Peterson tried to locate but could not),
- Attempt to locate Bureau of Reclamation maps of Glen Canyon Dam from 1960s (10 foot contour intervals).

Natural Resource Data Sources

- Lex Newcomb (GLCA-GIS) would like to obtain a copy of the geologic map of Utah (1:500,000 scale),
- Lex also mentioned historical maps along the shoreline showing geologic hazards; try to incorporate into hazards layer,
- It was mentioned that Martin Lockley has GPS locations of paleo localities that Vince would like to acquire; need to consult Lockley on this.

Miscellaneous

- Review proposed research topics for future studies within Glen Canyon NRA and Rainbow Bridge NM,
- Grant Willis mentioned that someone from the Indian Nation should have been invited to the meetings; Bruce Heise suggested Fernando Blackgoat as possible future contact to better develop ties for mapping on Indian land,
- The UGS will need to develop a proposal for the NPS to get the mapping and digitizing done for Hites Crossing, Navajo Mountain, and Hanksville 1:100,000 sheets.

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Rainbow Bridge National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/131

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NPS 118/100151, August 2009

National Park Service
U.S. Department of the Interior

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