National Park Service
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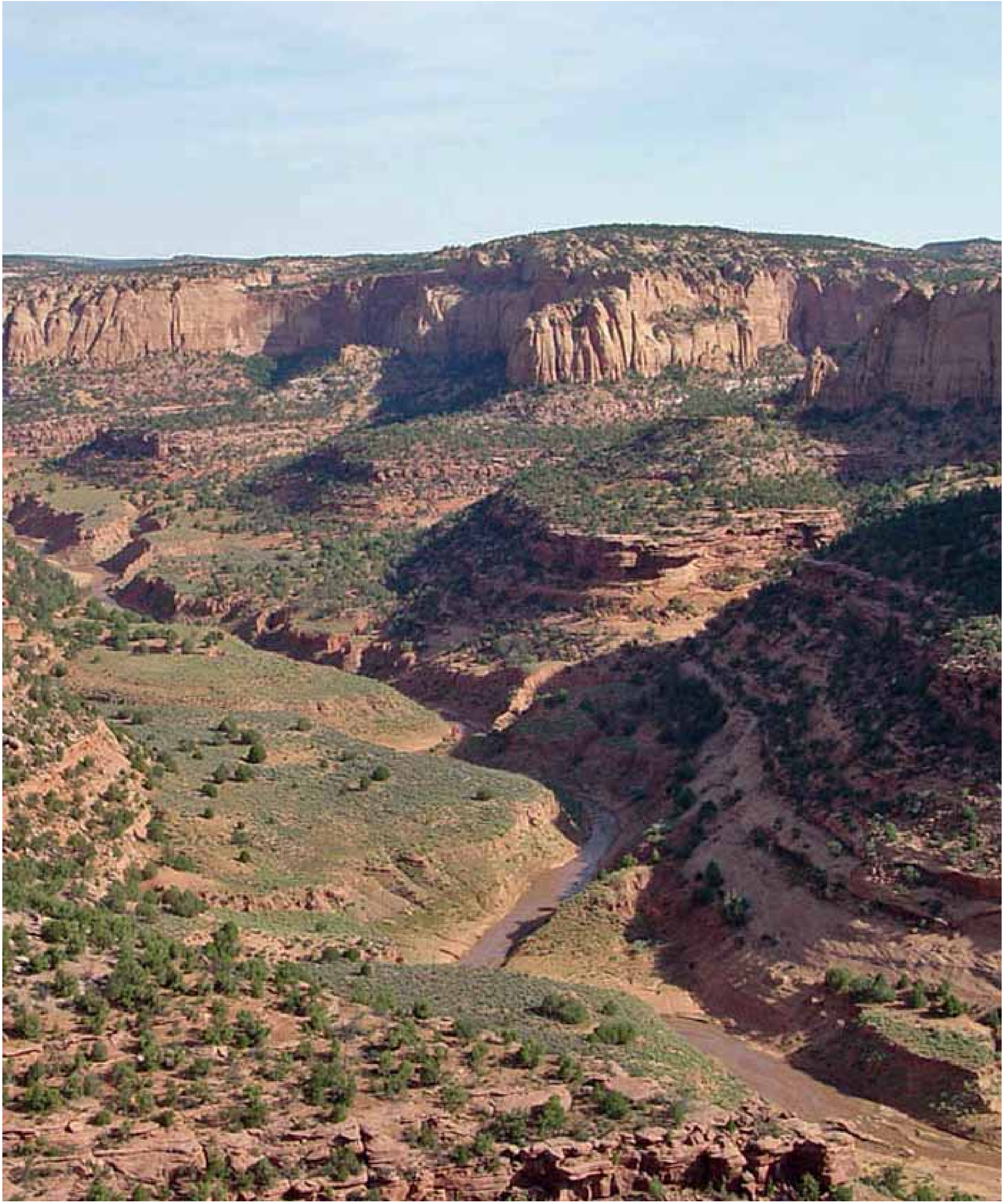
Natural Resource Program Center

Navajo National Monument

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/005



THIS PAGE:
The Navajo Sandstone forms steep cliffs above its contact with the Kayenta Formation in Long Canyon and throughout Navajo NM, AZ.

ON THE COVER:
Photo of the Betatakin Ruins in Navajo NM, AZ .

USGS Photos

Navajo National Monument

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Geologic Resources Division
Natural Resource Program Center
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Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Navajo National Monument in Arizona. It contains information relevant to resource management and scientific research.

Navajo National Monument lies entirely within the Navajo Reservation in northeast Arizona. The monument preserves the most intact cliff dwellings of the Ancestral Puebloan people in three separate units: Betatakin Unit (160 acres), Keet Seel Unit (160 acres), and Inscription House Unit (40 acres). These Pueblo villages, built in natural alcoves eroded into the Navajo Sandstone, date to the late 13th Century.

Navajo National Monument is located on the Shonto Plateau, part of the larger Colorado Plateau Physiographic Province. Uplift and erosion have carved deeply incised canyons into this part of the Colorado Plateau. The Organ Rock Monocline, an uplift underlying U.S. Highway 160 between Cow Springs and Kayenta, Arizona, forms the border between the Shonto Plateau and the Black Mesa region to the south. The Black Mesa region includes about 5,400 square miles (14,000 sq km) in northeastern Arizona and has a diverse topography of flat plains, mesas, and incised drainages.

Navajo National Monument is in the Tsegi Canyon system, the primary drainage of the eastern part of the Shonto Plateau. Tsegi Canyon exposes nearly flat- lying Mesozoic sedimentary strata. Mesozoic strata at Navajo National Monument record marine, nearshore, and continental depositional environments. These environments formed in response to tectonic activity on the western margin of North America. The three main formations exposed in the canyon include, from youngest to oldest, the Navajo Sandstone, the Kayenta Formation, and the Wingate Sandstone. Isolated exposures of the Chinle Formation are found in the canyon bottom, with unconsolidated alluvial deposits overlying bedrock.

Rock- fall and cliff collapse pose the greatest geologic issue for resource management at the monument. Because of the steep canyon walls, significant rock- fall hazards threaten cultural resources in alcoves as well as visitor safety. The Aspen Forest Trail leading to Betatakin Ruins was closed in 1982 due to rock- fall and currently remains closed.

Flash flooding and erosion in the canyon bottoms, groundwater and surface- water quantity and quality, and regolith compaction are also management concerns. Flash flooding threatens cultural resources, erodes stream banks, and promotes vertical incision of the arroyos. Hikers and grazing livestock trample stream banks, compacting the regolith, and accelerating erosion. The Navajo Sandstone is the primary aquifer for the Black Mesa area. As visitation increases at the monument and coal mining activities increase on Black Mesa, groundwater withdrawal from the Navajo aquifer is an increasing concern at Navajo National Monument.

The primary geologic features at Navajo National Monument are the alcoves in which the Ancestral Puebloans built their dwellings. Geologic factors such as the presence of springs and seeps, large sweeping cross-beds in the Navajo Sandstone, and vertical fractures that serve as conduits for water, all contribute to the formation of alcoves. Springs and seeps occur at the contact between the porous and permeable Navajo Sandstone and the less permeable Kayenta Formation. Groundwater flows laterally in the subsurface when it encounters the Kayenta, emerging as springs and seeps along the canyon walls. The discharged water dissolves the carbonate cement holding the sand grains of the Kayenta Formation together and subsequent erosion removes the grains. Undercutting of the Navajo Sandstone controlled by both cross- bedding and vertical fractures, leads to cliff collapse.

Introduction

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

Purpose of the Geologic Resource Evaluation Program

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

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

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

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

Regional Geology

Navajo National Monument is located in the western section of the Navajo Reservation in northeastern Arizona (figures 1a and 1b). The monument consists of three noncontiguous sections: the Betatakin Unit (160 acres), the Keet Seel Unit (160 acres), and Inscription House Unit (40 acres). The elevation of the Betatakin Visitor Center is 7,400 feet (2,220 m). The Keet Seel section is located about 8 miles (13 km) northeast of Betatakin and contains one of the most important large Pueblo ruins in the Southwest. The Inscription House section is located 40 miles (64 km) west of Betatakin in Nitsin Canyon.

Navajo National Monument is part of the Colorado Plateau Physiographic Province, an uplifted area that encompasses portions of Colorado, Utah, Arizona, and New Mexico. Uplift and subsequent erosion have carved deeply incised canyons into relatively horizontal layers of sandstone and exposed colorful, flat- lying sedimentary rock formations in this part of the Colorado Plateau. Navajo National Monument is located north of U.S. Highway 160 on the Shonto Plateau, a subregion of the Colorado Plateau (figure 2). The Organ Rock Monocline, an uplift that underlies U.S. Highway 160, separates the largely Jurassic and Triassic rocks exposed at the surface of the Shonto Plateau from the Cretaceous rocks of Black Mesa. Black Mesa encompasses 5,400 square miles (14,000 sq km) of flat plains, mesa, and incised drainages south of U.S. Highway 160 (Kamilli and Richard 1998; Blakemore and Truini 2000).

Tsegi Canyon is the primary drainage of the eastern part of the Shonto Plateau. It contains three major branches and countless side branches cut deeply into the Navajo sandstone. Betatakin and Keet Seel are located in two of the arteries of the canyon. Side canyons contain numerous other prehistoric ruins (NPS 2001).

Tsegi Canyon has eroded into Triassic- Jurassic strata (figure 3). The primary formations are part of the Jurassic Glen Canyon Group. The formations in the Glen Canyon Group are, from youngest to oldest: the pale salmon-colored, cross- bedded Navajo Sandstone that formed from an ancient sand dune field; the purplish siltstones and cross- bedded sandstones of the Kayenta Formation which record the remnants of a large river delta or floodplain; and the cross- bedded Wingate Sandstone, another preserved sand dune field (Cooley et al. 1969; Chronic 1983; Peterson 1994).

Springs and seeps are associated with the contact between the cliff- forming Navajo Sandstone and the underlying Kayenta Formation. The Navajo Sandstone is porous and permeable and serves as a regional aquifer, while the Kayenta is the confining bed. At the contact, groundwater moves laterally, emerging as springs along the canyon walls.

Three layers of alluvial deposits are present in Tsegi Canyon and comprise the following formations: the Jeddito Formation (late Pleistocene), the Tsegi Formation (early Quaternary about 2000 B.C. to A.D. 1), and the Naha Formation (A.D. 1450- 1880) (Schafer et al. 1974; Karlstrom 1982). A buried paleosol marks the erosional boundary between the Jeddito and Tsegi. The younger Tsegi - Naha boundary is marked by terrace relationships (Karlstrom 1982). The type localities for the Tsegi and Naha Formations are in Tsegi Canyon, which is one of the few places in the southwest where the beginning of arroyo cutting is well documented. Tsegi Canyon is now part of the Tsegi Canyon Navajo Tribal Park (NPS 2003). These formations are represented on the GRE digital geologic map as Quaternary alluvium (map symbol: Qal).

The Colorado Plateau is a relatively rigid lithospheric block that, while uplifted, has not experienced the severe deformation present in the surrounding Rocky Mountain or Basin- and- Range physiographic provinces. While extensive thrust faults deformed the Rocky Mountains during the Laramide Orogeny (Late Cretaceous – Middle Tertiary) and rifts in the earth's crust pulled apart the Basin- and- Range (Miocene Epoch), the Colorado Plateau was bent and folded into broadly warped anticlines and regionally extensive monoclines. The entrance drive to the monument climbs the Organ Rock Monocline that rises from the east to west onto barren outcrops of the Navajo Sandstone. Once on the crest of the monocline, the strata dip only two to three degrees to the southwest (Cooley et al. 1969).

Park History

Four American Indian tribes have cultural associations with the area of Navajo National Monument: Hopi, Navajo, San Juan Paiute, and Zuni (NPS 2003). Each of these tribes has a distinct set of beliefs and a relationship with the sites, geography, and landscapes of the monument.

Ancestors of the Hopi (Hisatsinom) have lived in the Southwest for millennia and in the lands of present- day Navajo National Monument from about A.D. 950 to A.D. 1300 (NPS 2003). Betatakin is known to the Hopi as Talastima, the "Place of the Blue Corn Tassels," and is a Flute and Deer Clan village. Keet Seel (Kawestima) is a Fire Clan village, and Inscription House (Tsu'ovi) is a Rattlesnake, Sand, and Lizard Clan village. For the Hopi, these sites remain active spiritual and physical links to the past, the present, and the future.

Athabaskan- speaking Diné, ancestors of the Navajo, migrated to the Southwest sometime between the 11th and 15th centuries (NPS 2003). Navajo tribal leaders signed a treaty with the United States in 1868, establishing the Navajo Reservation, which encompasses Navajo National Monument. In 1960, the Navajo Tribal Council Advisory Committee created Tsegi Canyon Tribal Park to protect all lands within the Tsegi Canyon System. The Navajo know Betatakin as Bitát'ahkin, which means "ledge house," Keet Seel as Sits'il ("broken pottery"), and Inscription House as Tsah Bii Kin. The Navajo have a long history of using the monument and adjacent lands for both sacred and personal purposes, such as harvesting nuts and berries (NPS 2003).

Several centuries ago, the San Juan Paiute inhabited areas that are now managed by Navajo National Monument, settling along drainages in the Tsegi Canyon System. One group settled in Nitsin Canyon, and the San Juan Paiute still maintain a strong connection to Nitsin Canyon and surrounding areas in the region.

The Zuni also have lived in the Southwest for many centuries, establishing settlements throughout the Four Corners region. Tsegi Canyon is an essential part of their traditions. The Tsegi Canyon Region is known as the "northern canyons" from which several of their clans migrated to their present location at Zuni Pueblo in New Mexico. They traveled through Tsegi Canyon to reach the salt mines located near the Grand Canyon. Today, Zuni elders still visit Batatakin because this site figures prominently in their past.

In the mid- 1850s, trapper, hunter and guide, Captain Joseph Walker, and his party traveled through much of what is now called the Navajo Nation (NPS 2003). The Wetherill brothers, who explored the cliff dwellings at Mesa Verde National Park, also found the Keet Seel dwellings in 1895 (figure 4). Excavation of the site began in 1897. The Wetherills and University of Utah professor Byron Cummings encountered Inscription House and Betatakin ruins in 1909.

President Taft established Navajo National Monument on March 20, 1909, in hopes of protecting Keet Seel, the largest cliff- dwelling in America (Presidential Proclamation No. 873). This proclamation included not only Keet Seel but also sites in Monument Valley; Tsagt- at- sosa canyon; Navajo Creek, Moonlight Creek, and Laguna Creek canyons. Presidential Proclamation No. 1186 on March 14, 1912, provided for a boundary adjustment to its present size of 360 acres. John Wetherill became the first park employee, but the monument entrance road wasn't constructed until 1965.

Figure 1a: Location map for Navajo National Monument.

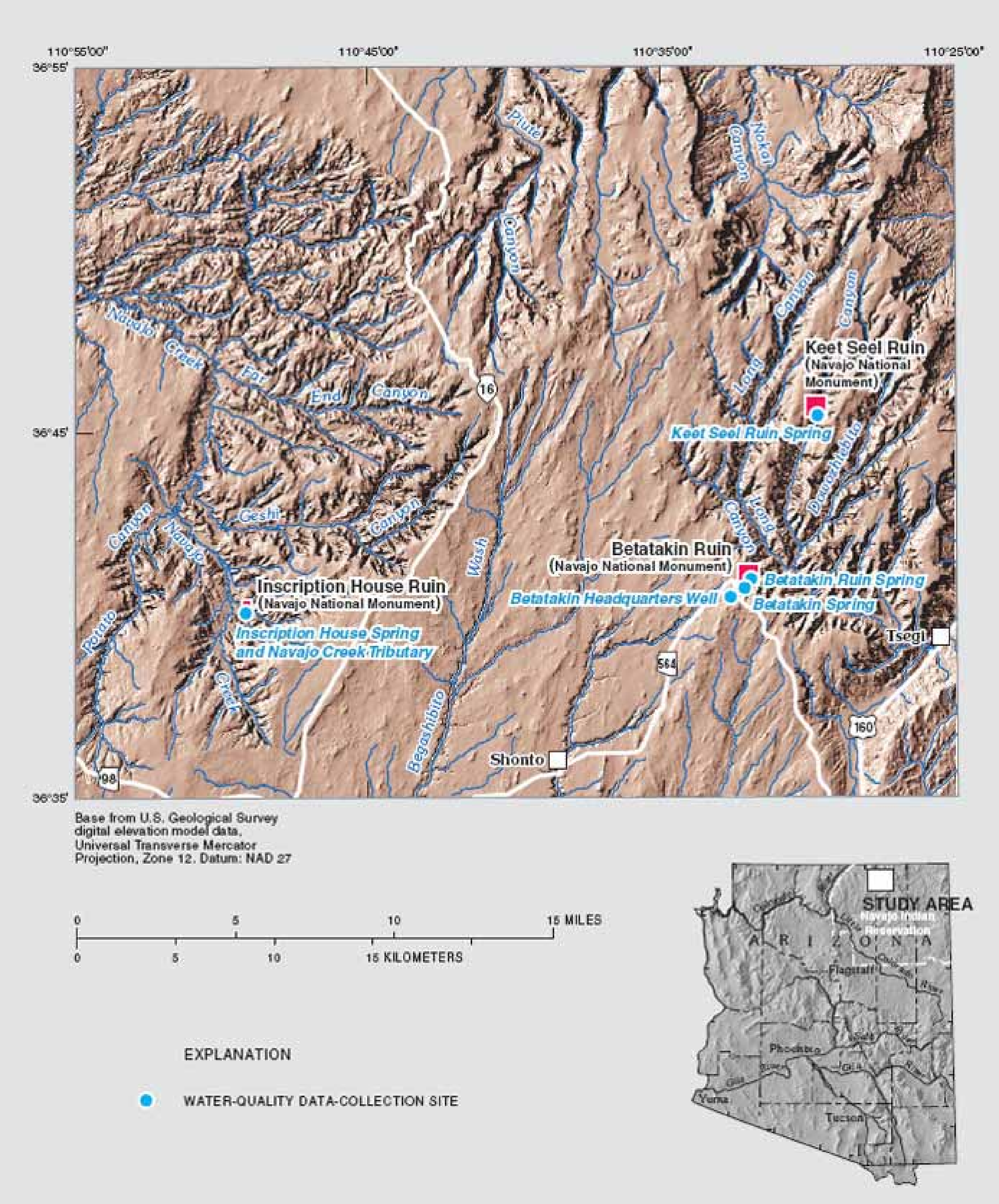


Figure 1b. Detailed location map showing units of Navajo National Monument and water quality data collection sites. Figure reproduced from USGS Open File Report OFR-03-287, Water-Quality Data for Navajo National Monument, Northeastern Arizona--2001-02 by Blakemore E. Thomas.

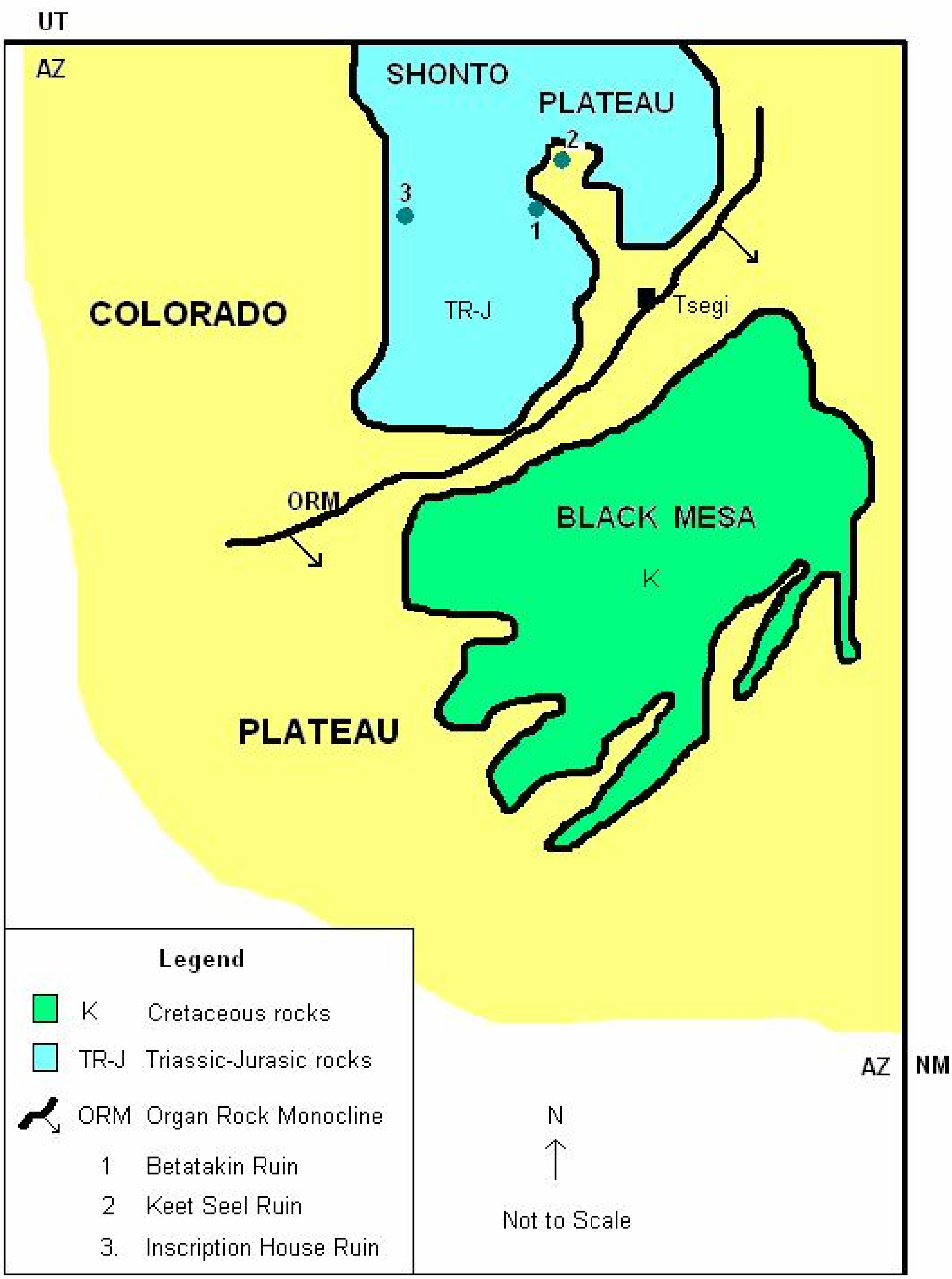


Figure 2. Regional physiographic features associated with Navajo National Monument.

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

Figure 3. Geologic time scale; adapted from the U.S. Geological Survey and International Commission on Stratigraphy. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

Figure 4. Keet Seel ruins. Photo courtesy of the National Park Service, www.nps.gov (12/6/06).

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Navajo National Monument on June 25 and June 28, 2001, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Rockfall Hazards

The most pressing geologic issues facing resource management at the monument are the potential loss of cultural resources in alcoves, from rockfalls and cliff collapse, and visitor safety in these areas. Precipitation, groundwater infiltration, and freeze- thaw cycles, all affect the integrity of the sandstone comprising the cliffs. Significant rock- fall hazards exist on some north- facing walls and within alcoves in the Betatakin unit, as well as along the trail and in alcoves in the Keet Seel and Inscription House units (NPS 2003).

Although the Navajo Sandstone bedrock is weakly cemented by calcite and iron oxides, it is strong enough in some places to form steep- sided canyons such as Betatakin Canyon. The strength of the rock mass, and thus, its susceptibility to failure, is directly related to the number and orientation of joints, fractures, faults, and bedding planes. Local zones of weakness can be generated by the occasional presence of water. The presence of caliche (a carbonate crust) infilling joint systems indicates the frequent passage of groundwater through the steeply dipping joints.

Significant rockslides along the Aspen Forest Trail (figure 5) to Betatakin Ruins made it necessary to close the trail because of visitor safety concerns. Rock- falls on the trail began shortly after construction in 1963, and in 1982, two rock- falls, the first exceeding 9.5 tons and the second estimated at 200- 300 tons, blocked the trail in the steep overhung section just below the locked gate. In 1983, another large rock- fall covered the trail and sent rocky debris to the valley floor near Saucer Cave. The trail was closed in April 1982 and an alternative route to the Betatakin ruins, using the Tsegi Point Road, was initiated in 1985.

The failures noted along the Aspen Forest Trail occurred during wet periods in winter and spring, suggesting that water infiltrating joints may destabilize rock slopes (Wieczorek and Harp 2000). Rockfalls occur more frequently on north- facing walls than on the south- facing walls in Betatakin Canyon.

Along the now closed Aspen Forest Trail, bedding in the Navajo Sandstone generally dips about 26 degrees E- SE. One major joint set (J1) dips about 60 degrees to the north and another major joint set (J2) is nearly vertical. In the section of the trail immediately upslope of the gate, north dipping joint set J1 has the potential for planar sliding (Wieczorek and Harp 2000). Conditions are also favorable for sliding where the joint set J1 intersects other joints sets.

The opposite (south- facing) cliffs of Betatakin Canyon are much more massive and relatively free of rockfalls. The cliffs near the Aspen Forest Trail show “moderate” to “high” susceptibility for failure (Wieczorek and Harp 2000). The area of the trail most at risk for future failure is the overhung section (figure 5). In a 2000 assessment study, the USGS recommended construction of a covered catwalk with anchors emplaced in drill holes on the south- facing canyon wall. If construction of a covered catwalk isn’t feasible, USGS suggested that the logical alternative is using the route into Betatakin Ruins from the Tsegi Point Trail (Wieczorek and Harp 2000). This is the strategy currently employed by the park for providing visitors safe access to the Betatakin Ruins.

Flash Flooding, Floodplain Degradation, and Erosion

Flash flooding, floodplain degradation, and erosion are related geological processes at Navajo National Monument. In arid environments, flash floods cause major erosion damage to stream banks destabilized by a lack of vegetation. An eyewitness hiking in Tseigi Canyon in July 1980 documented a flash flood that washed boulders downstream and eroded a large sandstone block. The main flood event, from the initial wave to the time when travel was once again safe, lasted four hours. However, even after the flood waters passed they reportedly “turned the stream bottom into pockets of mud (quicksand) in which I was sinking up to my waist” (memorandum from Richard M. Bryant, Canaveral National Seashore 1987).

Conditions in the canyons today are similar to the conditions that may have led the Ancestral Puebloans to leave the area 700 years ago. Arroyo- cutting has gouged out the valley floor (figure 6) impacting tributaries and promoting the erosion and destruction of cultural resources (e.g., middens), especially during times of intense thunderstorms.

Floodplain degradation is aggravated by upstream grazing, trampling of stream banks, and subsequent reduction of ground cover outside the monument (NPS 2003). Flash flooding and bank collapse have lead to severe erosion of the alluvial fill at Keet Seel and Inscription House (NPS 1995; NPS 2003). At Inscription House, severe erosion of the alluvial fill in the canyon bottom, flash flooding, bank collapse, and the removal of ground cover allow continued arroyo- cutting. Soil along the stream banks below Inscription House is considered to be “extremely unstable” (NPS 2003, p. 15). The impacts of severe flash flooding and stream bank collapse on monument resources are addressed in the 1995 Resource Management Plan for Navajo National Monument.

Hydrogeology

Groundwater, Springs, and Surface Water

Groundwater, springs, and perennial and intermittent streams are important features in Navajo National Monument. Groundwater from the Betatakin no. 2 well provides drinking water for the monument. Springs and streams provide important habitat for plants and animals as well as drinking water for domestic and wild animals. Springs and streams also were the source of drinking and irrigation water for the Ancestral Puebloans about eight hundred years ago.

Groundwater withdrawal and availability are important issues in the monument and Black Mesa area because of increasing visitation, continued use by plants and wildlife, and a growing population. An average annual precipitation of only about 6 to 14 inches (15- 36 cm) raises concerns about groundwater recharge rate, as well (Truini et al. 2005).

Regional groundwater levels appear to be dropping at Keet Seel and Inscription House (NPS 2003). If the water table drops further, these units could experience, long-term adverse effects on wildlife and the native vegetation. Without plant roots to help stabilize the soil, stream bank instability may increase, accelerating erosion and arroyo- cutting. Continued erosion of the arroyo at Inscription House has the potential to destabilize the entire cliff (NPS 2003).

The strata of Monument Valley and northern part of the Black Mesa area contain several aquifers in one or more formations. The aquifers stack vertically and generally are not hydraulically connected. Primary aquifers used for public, domestic, and livestock use include the lower Triassic C aquifer; Jurassic N aquifer; Jurassic/Cretaceous D aquifer; a Cretaceous aquifer composed of the Yale Point Sandstone, Toreva and Wepo Formations; and the Quaternary alluvium aquifer (Levings and Farrar 1977; Blakemore and Truini 2000; Truini et al. 2005). The N aquifer is the only significant aquifer in the monument region and is the main water source for industry and municipalities in the Black Mesa area. Although water from the C aquifer may be used for domestic purposes, the aquifer is at considerable depth.

Three hydraulically connected formations comprise the N aquifer: the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member of the Wingate Sandstone (figure 3) (Cooley et al. 1969; Levings and Farrar 1977; Christensen 1979; Blakemore and Truini 2000; Truini et al. 2005). The principal industrial user is the Peabody Western Coal Company (PWCC), and the principal municipal users are the Navajo Nation and the Hopi Tribe. Groundwater movement through the aquifer is about 2 to 4 feet (0.6 to 1.2 m) per year (Christensen 1979).

A groundwater monitoring program in Black Mesa designed to determine the long- term effects of groundwater withdrawals from the N aquifer for industrial and municipal uses has been operating since 1971 (Blakemore and Truini 2000; Truini et al. 2005). The monitoring program measures: groundwater pumping rates, groundwater levels, spring discharge, surface water discharge, and groundwater chemistry. Total withdrawals increased by about 12 percent from the mid-1960s to 2003. (Truini et al. 2005).

Betatakin Ruins, Keet Seel Ruins, and Inscription House Ruins all have seeps and springs associated with alcoves and sandstone walls. The seeps and springs appear to be in good condition (NPS 2003). While groundwater discharge to the surface is fairly constant throughout the year, runoff from rainfall and snowmelt varies widely (Blakemore and Truini 2000).

Water Quality

The status of water quality within and around the monument is not well studied or documented (Blakemore 2003; NPS 2003). Livestock grazing within the watershed environment of both Keet Seel and Inscription House contributes to the deterioration of water quality within the monument even though most grazing occurs outside monument boundaries. Trampling of stream banks, by livestock, hikers, and motorized vehicles, promotes erosion and increased sedimentation into surface water. Increased sedimentation combined with accumulations of urine and fecal matter causes deterioration in water quality (NPS 2003).

Keet Seel appears to be the most affected site by all of these outside impacts, especially grazing and trampling. Algae blooms occur throughout the stream system and the stream banks continue to be unstable. Water quality at Betatakin may be impacted by rain and runoff events that transport pollutants from the parking lot to the groundwater table.

Each year, as part of the Black Mesa monitoring program, water samples are collected from selected wells and springs that discharge from the N aquifer. Water samples are analyzed for dissolved solids, specific conductance, chloride, and sulfate. Data are available from the USGS water- quality database (http://waterdata.usgs.gov/az/nwis/qw).

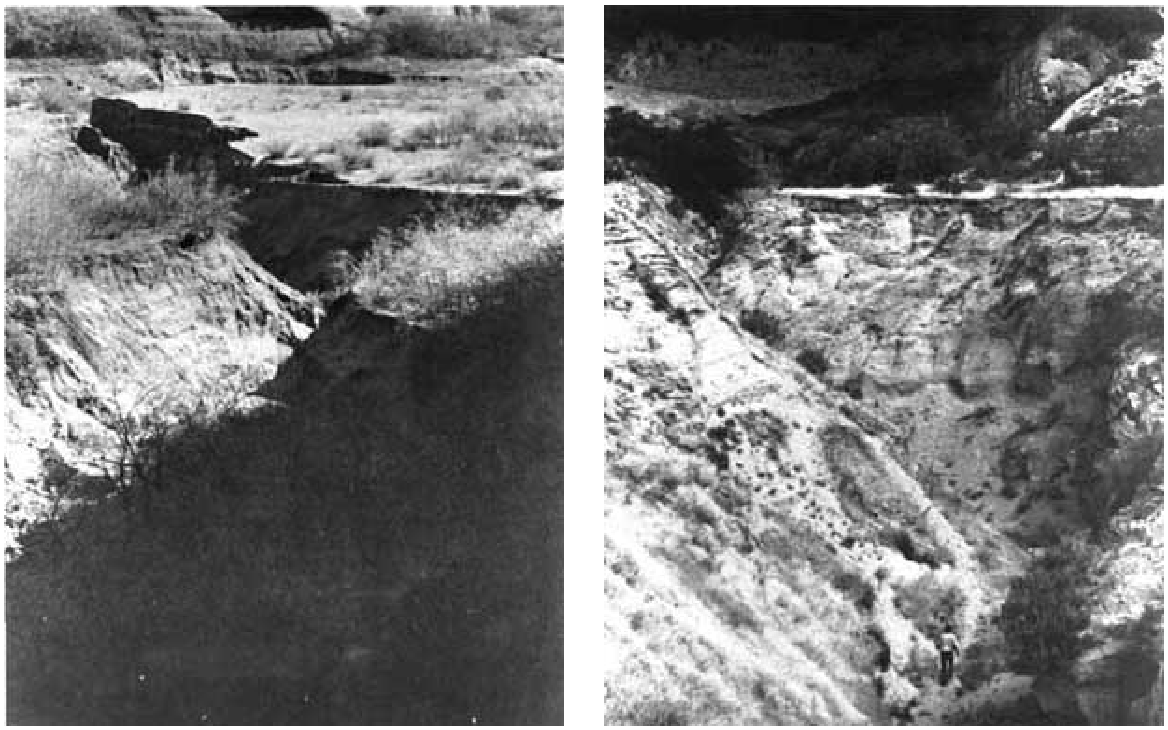
Regolith

At Betatakin hikers compact the regolith (unconsolidated material above bedrock) and break the biological soil crusts. Vibrations from vehicles and from trail and road maintenance lead to rockfalls and to local disturbances of surficial deposits and vegetative cover (NPS 2003). Generally, maintenance, construction, or recreational activities cause minor, short- term adverse effects, but specific construction projects could result in long- term impacts.

To limit these impacts, the monument uses mitigation measures during maintenance and construction projects. Some of these measures include "using previously disturbed sites for staging and stockpiling, returning the disturbed site to its previous grade, salvaging of local plants, and revegetating with native species immediately after a project is finished" (NPS 2003, p. 103). At Betatakin, a boundary fence to eliminate grazing has provided a long- term, beneficial impact by reducing erosion and protecting biotic communities (NPS 1995; NPS 2003).

Hiking, horses, grazing, trampling, and use of motorized vehicles at Keet Seel and Inscription House have adversely affected the regolith around and within the riparian areas. Instability has led to increased erosion and once this unconsolidated surface material becomes unstable, it is difficult, if not impossible, to restore.

Figure 5. Numerous joint discontinuities are found along the overhung section of Aspen Forest Trail. Photograph from Wieczorek and Harp, 2000.



A) 1934 B) 1976

Figure 6. Erosion in front of Keet Seel in 1934 (A) and the arroyo cut by 1976 (B). From Navajo National Monument: An Administrative History; available at http://www.nps.gov/archive/nava/adhi/adhit.htm, access 12/11/2006.

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Navajo National Monument.

Alcoves

The primary geologic features of interest at Navajo National Monument are the alcoves that formed due to groundwater flow, dissolution of carbonate cement, gravity, and wind erosion (figure 7). The Navajo Sandstone is porous and permeable but the underlying Kayenta Formation is not. The Kayenta, therefore, acts as a barrier to vertical groundwater flow. Water infiltrating into the sandstone on the Shonto Plateau moves laterally at the Navajo- Kayenta interface and emerges as springs along the canyon walls.

The carbonate matrix holding the sand grains of the Kayenta Formation together slowly dissolves as a result of ground water flow. Loosened grains destroy the integrity of the rock, undermining the cliffs of Navajo Sandstone lying above. Over time, slabs of the Navajo Sandstone break away into the canyon, eventually forming alcoves. These alcoves, especially ones with a spring at the Navajo/Kayenta interface, were attractive sites for occupation by prehistoric peoples.

A textbook example of alcove formation is found at Betatakin ruins near the visitor center (figure 7). The ruins occupy an alcove that formed as the Navajo Sandstone, undermined by erosion of the less resistant Kayenta Formation, broke away in arching slabs. The arched ceiling of Betatakin ruins offers a unique acoustic experience, as whispers from one end of the ruins can be easily understood at the other. Vibrations off the arched, cross- bedded strata probably contribute to this phenomenon.

Navajo Sandstone

The Navajo Sandstone consists mostly of large- scale cross- bedded, pale salmon- colored, eolian sandstone with minor lenses of pink clay and light gray freshwater limestone that formed in small lakes and ponds during the Jurassic (Peterson 1994). The Navajo Sandstone thickens to the northwest and may reach 1,800 feet (550 m) thick on the Navajo Reservation (Cooley et al. 1969). The Navajo Sandstone is one of the largest preserved eolian systems in the stratigraphic record, and along with its correlatives, the most widespread eolian deposit in North America (Blakey 1994; Peterson 1994). These Lower Jurassic dune sands are distributed from northwestern Wyoming and adjacent Idaho southward to southern Arizona and northern Mexico.

Much of the surface of the Navajo Sandstone is barren of vegetation so that the preserved arcs and swirls of eolian cross- bedding in the preserved dunes are fully exposed. Several sets of vertical joints in the rocks were produced by strains and stresses of deep burial and subsequent uplift. The vertical joints are deeply incised and serve as watercourses for surface flow during rainstorms. Rows of miniature pools mark these watercourses. The pools fill with rainwater and serve as habitats for small plants and animals, many of them microscopic. By- products of these animals and plants include acids that dissolve the limy cement holding the sand grains together. Lichens secrete acids that also loosen grains that are blown away by wind. The barren patches are surrounded by thin soil that is hardly more than wind- blown sand held together by roots of trees, shrubs, and grass.

A surface stain of manganese oxide and/or iron oxide known as desert varnish locally forms a brown or black coat on the bare Navajo Sandstone (figure 7). Ancestral Puebloans used this desert varnish as a backdrop for their petroglyphs. Pictographs were also drawn on the salmon- colored sandstone.

Betatakin Unit

Betatakin Canyon is a side canyon that connects to Tsegi Wash. Tsegi Wash flows into Laguna Wash near US Highway 160. Both of these streams ultimately drain into the San Juan River at Mexican Hat (Chronic 1983). Betatakin Canyon contains the Betatakin cliff dwelling, Kiva Cave cliff dwelling, and the remains of the Wetherill cabin (NPS 2003). Tree- ring dating indicates that the alcove was occupied around A.D. 1250.

Betatakin contains about 135 rooms tucked into a cliff- side alcove 452 feet (138 m) high and 370 feet (113 m) wide (figure 7). Vegetation surrounds a small spring at the Navajo- Kayenta interface at the base of the alcove. The spring has likely accelerated cliff collapse in this area. The natural and cultural resources of the Betatakin Unit are protected from grazing by a boundary fence between the unit and Navajo land.

Betatakin Canyon is visible from the visitor center. Thin beds of freshwater limestone in the Navajo Sandstone cap the highest hillocks near the Visitor Center. These limestones were probably deposited in ephemeral ponds in interdune areas similar to those in modern dune fields (e.g. Great Sand Dunes National Park). There are many small alcoves on switchbacks along the Aspen Forest Trail which is now closed to the public as a result of rockfall hazards. The sandy floors of these alcoves are marked by tracks and droppings of small animals. Cross- bedding in the sandstone controls alcove shape, leading to a sloping ceiling or an arched ceiling like that at Betatakin.

Keet Seel Unit

The Keet Seel site, located up a north- south trending side canyon in the Tsegi Canyon system, contains the largest cliff- dwellings in America: the Keet Seel cliff dwelling (figure 8) and the Turkey Cave cliff dwelling. Many of the features in Betatakin Canyon are present at Keet Seel. Like Betatakin, Keet Seel has a spring at the contact between the Navajo Sandstone and Kayenta Formation. Pictographs of birds are preserved in Turkey Cave.

Pottery and tree- ring dating indicate that the ancient Puebloans lived here as early as A.D. 950. Inhabitants of Keet Seal did not come in groups, as at Betatakin, but arrived and departed randomly. As a result, Keet Seel contains more variation in room design and construction and more kivas than Betatakin.

A surge in building activity in 1272 suggests the arrival of a new group of people. Population growth apparently taxed the capacity of the alcove and people began moving out. Those who remained converted abandoned rooms into granaries; however, they also left around 1300.

Inscription House Unit

Inscription House was named for an inscription on one of the walls noted in 1909 by Byron Cummings and John Wetherill. This cliff dwelling lies at the base of a high-arching sandstone cliff on the north side of an arm of Nitsin Canyon. The site has been closed to the public since 1968 because of urgent stabilization needs and because the local people desire privacy.

The smallest of the three ruins, Inscription House contains about 74 living quarters, granaries, and kivas (figure 9). Other cliff dwellings at the site include Owl House and Snake House. A tree- ring date of 1274 indicates that Inscription House was occupied about the same time as Betatakin and Keet Seel.

As with the other sites, a spring is associated with the ruins. Inscription House Spring flows out of the Navajo Sandstone and into Navajo Creek, which flows northward into Lake Powell (Thomas 2003).

Figure 7. Betatakin ruins in an alcove formed in the Navajo Sandstone, Betatakin Canyon, Navajo National Monument. Photograph from http://3dparks.wr.usgs.gov/2006/navajo/index2.htm, access 02/27/2007.

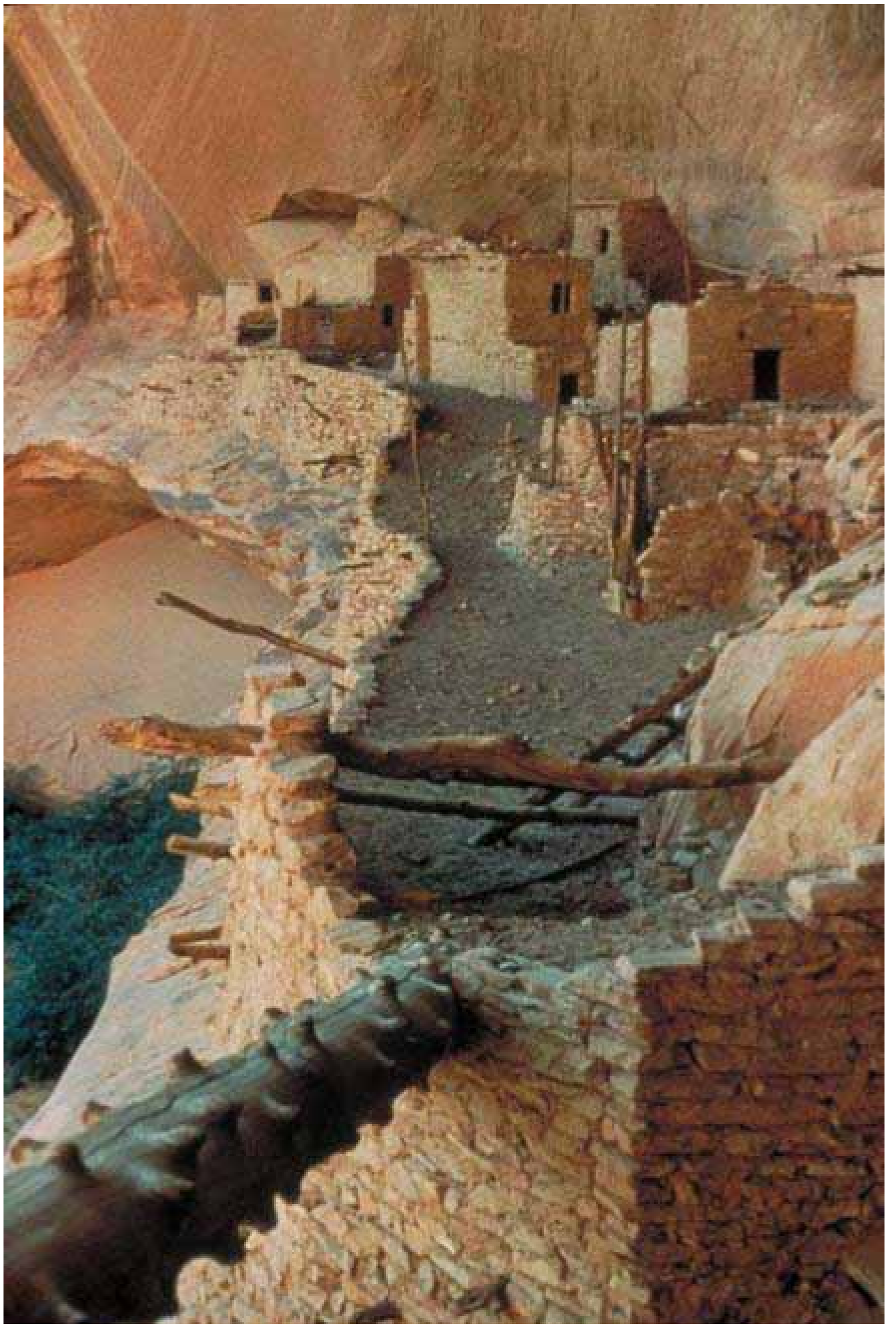


Figure 8. Keet Seel ruins in an alcove cut into the massive Navajo Sandstone. From www.ncdc.noaa.gov, access 12/6/2006.

Figure 9. Inscription House. From the Stuart M. Young Collection, NAU.PH.643.1.59, Cline Library, Northern Arizona University, http://www.nps.gov/rabr/adhi/images/fig14.jpg, access 12/13/06.

Map Unit Properties

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

The following Map Unit Properties Table identifies specific properties of the different map units exposed in Navajo National Monument. Geologic features and processes often occur in or can be restricted to a particular stratigraphic unit (group, formation, or member). This section ties together the geologic features, formation properties, and the accompanying digital geologic map.

Sedimentary rocks exposed at Navajo National Monument are primarily Mesozoic- age sandstones and siltstones. The following table includes several properties specific to each unit in the stratigraphic column including the unit's name, map symbol, a description of lithology, erosion resistance, hazards, potential cultural and paleontologic resources, water potential, mineral resources, and global significance.

Map Unit Properties Table

Age	Map Unit (symbol)	Features and Descriptions	Erosion Resistance	Hazards	Potential Cultural Resources	Paleontological Resources	Water Potential	Global Significance
Quaternary	Alluvium (Qal)	Unconsolidated sand, mud, gravel; river bank deposits	Low	Flash flooding; stream bank collapse; canyon cutting	None documented	Low	Ephemeral surface streams and alluvial aquifers with small amounts of water	None
	Regional Unconformity							
Tertiary	Gravel (tg)	Unconsolidated gravel	Not exposed in monument	NA	NA	NA	NA	NA
	Intrusive rocks (Ti)	Igneous rocks					None in the park; Volcanic rocks are water- bearing in places on Black Mesa	
	Regional Unconformity							
Upper Cretaceous	Yale Point Sandstone (Ky)	Marine sandstone	Not exposed in monument	NA	NA	NA	Aquifer with Toreva and Wepo Fms.	NA
	Wepo Formation (Kw)	Alternating beds of olive- gray siltstone, coal, yellowish- gray sandstone	Not exposed in monument; caps Black Mesa				Aquifer with Toreva Fm; marginal to unsuitable water quality	
	Toreva Formation (Kt)	Basal sandstone member, middle carbonaceous member, upper sandstone member.	Not exposed in monument				Aquifer with Wepo Fm; marginal to unsuitable water quality	
	Mancos Shale (Km)	Black shaly siltstone, shale, and gypsum					Confining bed	
	Dakota Sandstone (Kd)	Interbedded buff sandstone, conglomerate, and siltstone					Part of regional "D" aquifer	
	Regional Unconformity							
Upper Jurassic	Morrison Fm. (Jm)	Red siltstone and fine sandstone	Not exposed in monument	NA	NA	NA	Part of regional "D" aquifer	Dinosaur fossils
	Regional Unconformity							
Middle Jurassic	Cow Springs Sandstone (Jcs)	Eolian sandstone	Not exposed in monument	NA	NA	NA	NA	None
	Summerville Fm (Js)	Red siltstones and mudstones; scattered beds of gypsum; rare limestone; local sandstone					NA	None
	Entrada Sandstone (Je)	White, cross- bedded, eolian sandstone					Part of regional "D" aquifer	Extensive dune field
	Carmel Fm. (Jc)	Red and white, shaly siltstone					Confining bed	None
	Regional Unconformity							
Lower Jurassic	Navajo Sandstone (JTRn*)	Grayish- orange- pink even- grained, highly cross- bedded, eolian sandstone.	High - cliff former	Fractures, rockfalls, cliff failure; rockslides; often undercut	Alcoves contain cultural resources	None documented	"N" aquifer; Primary aquifer on Black Mesa	Records the largest sand sea (erg) in North America
	Kayenta Fm. (TRk*)	Interbedded pale- red sandstone and red mudstone; Cross- bedded sandstones are flood- plain channel deposits; mudstones are overbank deposits; ledgy appearance farther north; may reach 700 ft (213 m) thick on the Navajo Reservation	Moderate - Erosion of mudstone undercuts Navajo cliffs	Erosion of Kayenta leads to rock- falls and cliff collapse in Navajo Sandstone	None documented	Rare dinosaur tracks	Secondary aquifer in "N" regional aquifer	Records rapid uplift of ancestral Rocky Mtns.
	Wingate Sandstone (Lukachutai mbr.) (TRwl*)	Reddish- brown, fine- grained cross- bedded eolian sandstone; calcareous cement; 0- 300 ft (91 m) thick	Moderate - more resistant than Kayenta	Farther north, the Wingate forms prominent cliffs prone to rock- fall	Petroglyphs possible on exposed sandstone	None documented	Secondary aquifer in "N" regional aquifer	Major dune field covering parts of Utah, Arizona, Colorado, and Wyoming
	Regional Unconformity							

Age	Map Unit (symbol)	Features and Descriptions	Erosion Resistance	Hazards	Potential Cultural Resources	Paleontological Resources	Water Potential	Global Significance
Upper Triassic	Chinle Fm. (Church Rock & Owl mbrs.) (TRcco)	Church Rock mbr: reddish- brown siltstone & silty sandstone & grayish- orange- pink mudstone. Owl Rock mbr: mottled light- gray & grayish- pink interbedded limestone & calcareous siltstone. Thins from Utah south into Arizona. Petrified Forest mbr: lavender and brown sandstones, variegated mudstones Two older members of the Chinle Fm found in N. Arizona are not exposed in the park. Chinle Fm. Is 850-1,500 ft (260- 460 m) thick on the Navajo Reservation	Low especially during times of flash flooding. Occupies canyon bottoms.	Mudstones are a potential hazard to any development in the canyon bottoms; bentonite in Petrified Forest member.	Petrified wood and varicolored rocks may have interested ancient Native Americans.	Burrow and root casts, paleosols, petrified wood, and vertebrate remains have been found outside the park.	Upper Chinle shale and siltstone act as confining beds. Basal Shinarump member is part of the regional "C" aquifer about 4,700 ft (1,400 m) below land surface.	Extensive formation found in E, SE, and SW Utah and N Arizona; significant deposits of uranium and petrified wood
	Regional Unconformity							
Lower Triassic	Moenkopi Formation (TRm)	Reddish siltstone, sandstone and gypsum; about 200 ft (61 m) thick	Not exposed in monument	NA	NA	NA	Confining beds	NA
	Regional Unconformity							
Permian	Cutler Formation (Pc)	Interlayered sandstones, mudstones, and limestones representing marine, fluvial, and eolian depositional environments.	Not exposed in monument	NA	NA	NA	NA	NA

* Although the GIS map symbols indicate a Jurassic/Triassic age for the Navajo and a Triassic age for the Kayenta and Wingate Formations, advances in the science of geology since the source map was published reveal that these strata are all Jurassic in age. A regional unconformity separates Triassic strata from Jurassic strata in the region (Peterson, 1994).

Geologic History

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

The strata in Navajo National Monument record Upper Triassic through Lower Jurassic time, but rocks on the adjacent Black Mesa span the entire Mesozoic Era (Map Unit Properties Table; figure 3). The Mesozoic Era followed the most extensive mass extinction preserved in the geologic record - the end of the Permian Period when 96 percent of all species were eliminated (figure 3) (Raup 1991). At the beginning of the Mesozoic, shallow, marine water stretched from Utah to eastern Nevada over a relatively level continental shelf.

Triassic Period (251-200 Ma)

During the Triassic Period, the major land masses came together forming the supercontinent, Pangaea. On the western margin of Pangaea, a subduction zone formed that trended north- northwest to south- southeast with oceanic crust dipping eastward beneath the continental margin. In the Early Triassic, volcanic activity decreased on the western margin of Pangaea and igneous rocks were emplaced along this subduction zone (Saleeby et al. 1992; Christiansen et al. 1994).

Moenkopi Formation:

The reddish siltstone, shales, and sandstones of the Moenkopi Formation were deposited in fluvial, mudflat, sabkha, and shallow marine environments that formed as the shallow sea withdrew from northeastern Arizona. Ripple marks and low- angle cross- bedding in the Moenkopi formed as a result of fluvial processes that leveled the area into a relatively flat plain. The presence of fossilized plants (reeds and *Equiseta*), trackways of reptiles and amphibians, and fossils of warm water marine invertebrates in strata above gypsum zones indicate a shift from a cool, dry climate to a warm, tropical climate in the Early Triassic (Stewart et al. 1972A; Dubiel 1994; Huntoon et al. 2000).

In northern Arizona, red beds of the Holbrook Member of the Moenkopi Formation are lowermost Middle Triassic (235- 240 Ma) based on paleontologic evidence (Dubiel 1994). However, Middle Triassic rocks are generally absent in the Western Interior. Local deposits of lowermost Middle Triassic strata suggest that erosion, rather than nondeposition, is largely responsible for the absence of Middle Jurassic rocks. A regional unconformity separates the Lower Triassic from the Upper Triassic.

Chinle Formation:

Rocks of the Chinle Formation in the Western Interior of North America are a complex assemblage of fluvial, marsh, lacustrine, playa, and eolian deposits from the Late Triassic (208- 235 Ma) (figure 10) (Stewart et al. 1972B). This suggests the Chinle was deposited in a densely vegetated flood plain or mud flat that contained localized shallow ponds and small, shallow, sinuous streams (Scott et al. 2001).

Floodplain mudstones that completely encase fluvial sandstones in the Petrified Forest Member of the Chinle Formation signify deposition by high- sinuosity streams. Altered glass shards and bentonitic mudstones indicate that volcanic ash formed a significant component of the sediment (Dubiel 1994). Fossils of phytosaurs, lungfish, and lacustrine bivalves reflect river, lake, and marsh environments. The Petrified Forest Member grades upward into the Owl Rock Member.

The knobby texture in the Owl Rock Member is thought to result from extensive bioturbation, an interpretation supported by the numerous crayfish burrows found locally in the Owl Rock. Owl Rock sediments were deposited in an extensive lacustrine and marsh environment in response to continued subsidence and to a reduction in clastic and volcanic sediment input (Stewart et al. 1972B; Dubiel 1994). Major fluvial environments, evident in the underlying members of the Chinle, are lacking in the Owl Rock Member, suggesting that the paleoflow in the lower part of the Chinle was disrupted so that rivers and streams backed up and formed ponds during deposition of the Owl Rock. Subaerial exposure in dry periods when lakes and marshes dried up, allowed soil formation processes to modify primary textures (Dubiel 1994). In places, the Owl Rock strata fills valleys eroded into the underlying Petrified Forest Member.

Sandstones and mudstones of the overlying Church Rock Member were deposited by fluvial systems, on lacustrine or playa mudflats traversed by small fluvial systems, and as eolian sand sheets and dunes (Dubiel 1994). The large- scale, eolian cross- stratification and mudcracks found in the Church Rock Member in northern Arizona and the Four Corners area indicate that dry periods became more prevalent during deposition of the uppermost part of the Chinle.

The development of extensive fluvial, lake and marsh systems in the Triassic may be related to uplift associated with converging lithospheric plates along the west coast (Dubiel 1994). As the oceanic plate pushed beneath the overriding North American continent, magma was generated forming linear or arc- shaped belts of volcanoes on the overriding plate, parallel to the subduction zone. Mount St. Helens and the other volcanoes in the Cascade Range formed in a similar way and lie parallel to an active subduction zone that extends from northern California to Canada. Triassic subduction and the evolution of an arc- shaped belt of volcanoes probably influenced the lake systems of the Owl Rock Member, causing drainage reversal in the Church Rock.

Jurassic Period (200-146 Ma)

In the present Four Corners region of Arizona, New Mexico, Colorado, and Utah, the Jurassic Period was a time of extensive dune formation (figure 11). The region was located about 18 degrees north latitude at the beginning of the Jurassic Period and moved to 30- 35 degrees north latitude by the end of the Jurassic (Kocurek and Dott 1983; Peterson 1994). This is the latitude of the present day northeast trade wind belt where cool, dry air descends from the upper atmosphere and sweeps back to the equator in a northeast to southwest direction. The cool, dry air becomes warm, dry air causing intense evaporation. Most modern hot deserts of the world occur within the trade wind belt. The climate of the Colorado Plateau during the Jurassic appears similar to that of the modern Western Sahara of Africa.

The Jurassic deserts that existed for roughly 40 million years (not counting the time represented by erosion) contained sand dunes that may be the largest ever recorded (Kocurek and Dott 1983). Similar to the modern Sahara, these ergs formed on a coastal and inland dune field. These dunes extended from present day southern Montana south and east into eastern Utah, westernmost Colorado, southwestern Colorado, northeastern Arizona, and northwestern New Mexico (Kocurek and Dott 1983; Peterson 1994).

Volcanic islands formed an unknown distance west or southwest of the west coast of North America in the Middle Jurassic. During the Late Jurassic, these islands accreted to the North American plate (Busby- Spera 1988; 1990; Marzoff 1990). Major tectonic plate reorganization in the Late Jurassic followed the Cordilleran magma-generating episode of the Middle Jurassic. At this time, the Gulf of Mexico opened and the North American lithospheric plate rotated counterclockwise. To accommodate the plate motion, a large transform fault zone called the Mojave- Sonora megashear, developed along what is now the Mexico- United States border and truncated the southwestern margin of North America. This northwest- southeast trending megashear zone accommodated approximately 500 to 600 miles (800-1000 km) of left- lateral displacement (Kluth 1983; Stevens et al. 2005; Anderson and Silver 2005; Haenggi and Muehlberger 2005).

Wingate Sandstone:

During the Lower Jurassic, the northern sea in the Arctic region did not encroach onto the continent as it had in the past. Paleozoic sandstones exposed from as far north as Montana and Alberta provided abundant sand transported by wind to the Colorado Plateau (Kocurek and Dott 1983).

Westerly to southwesterly winds transporting sand from Alberta to Arizona may have been diverted to the south by a rising a volcanic arc off the western coast of North America (Kocurek and Dott 1983). Sediments from the volcanic arc to the west are missing from the dune sand on the Colorado Plateau. While the volcanic arc diverted the wind from Alberta, the trade winds probably swept the volcanic ash to the southwest, out to sea. Rivers flowing from the Ancestral Rockies may have provided an additional source of sand to the growing dune fields.

The regional depositional geometry of the Wingate Sandstone, the high- angle cross- bedding and the well-sorted frosted quartz grains indicate that the Wingate was eolian (Peterson 1994). Regionally, six major erg sequences have been mapped in the Wingate (Nation 1990; Blakey 1994). The six erg units vary in detail from one another, but generally, both the overall Wingate Sandstone succession and the individual erg sequences display an upward drying trend with small dunes and sandsheets of large cross- bedded dunes overlying sabkha and lacustrine deposits (Blakey 1994).

Kayenta Formation:

A change from eolian to fluvial deposition is recorded in the sandstones of the Kayenta Formation. In contrast to the sweeping eolian cross- beds of the underlying Wingate and overlying Navajo Sandstones, the cross-beds in the Kayenta are only a few feet thick. Interbedded sandstones, basal conglomerates, siltstones, and mudstones are typical channel and floodplain deposits. Paleocurrent studies show that during deposition of the Kayenta, rivers flowed in a general westward to southwestward direction (Morris et al. 2000). The rocks of the Kayenta Formation display an excellent example of the effects of a climate change resulting in ergs of the Wingate Sandstone being reworked by fluvial processes (Blakey 1994).

Navajo Sandstone:

The Navajo Sandstone records a return to arid conditions and the development of extensive ergs on the Colorado Plateau (figure 11). Sand dune deposits reaching 800 to 1,100 ft (240 to 340 m) high gradually overtook the fluvial systems of the Kayenta. The large- scale (18 m, 60 ft), high- angle, cross- beds of the Navajo attest to the presence of Sahara- like sand dunes during the Early Jurassic (Morris et al. 2000). The paleolatitude of Navajo National Monument during the deposition of the Navajo Sandstone was near 20 degrees north latitude (Parrish and Petersen 1988; Chan and Archer 2000). Paleo- wind directions shifted more northerly giving rise to subtropical and monsoonal circulation patterns in the region. Studies of the cyclicity in Navajo dune sets suggest that the region experienced alternating wetter and drier periods on a decade scale in the Early Jurassic (Chan and Archer 2000).

Lithospheric plate collisions intensified off the western coast in the Middle Jurassic causing rock layers on the continent side of the collision to bulge upward. Weathering and erosion stripped away the exposed rocks and a regional unconformity surface formed on the Navajo Sandstone.

Carmel Formation:

As plate tectonic activity increased, the sea lapped onto the continent from the north. The reddish siltstones and mudstones of the Carmel Formation (Middle Jurassic) were deposited on broad tidal flats marginal to a shallow sea that lay to the west.

Entrada Sandstone:

The Entrada Sandstone (Middle Jurassic) originally covered the entire Colorado Plateau. The Entrada is the most widespread of the preserved late Paleozoic and Mesozoic eolianites. The cross- bedded sandstone was deposited in an extensive dune field in a back- beach area (Kocurek and Dott 1983; Hintze 1988; Peterson 1994; Doelling 2000). Together, the Entrada Sandstone and Carmel Formation record three of the five transgressive-regressive episodes that deposited the Middle Jurassic strata on the Colorado Plateau.

Summerville Formation and Cow Springs Sandstone:

As lithospheric plate collision increased on the western margin, a major transgression of the inland seaway destroyed the vast eolian sand seas that once covered the Colorado Plateau. Tidal flats formed in the area as marine environments encroached from the north. Restricted marine and tidal flat deposits of the Summerville Formation (Middle Jurassic) mark the southern extent of the seaway. The Cow Springs Sandstone (now considered to be a member of the Entrada Sandstone) preserves the remnants of a once vast eolian sand sea (Kocurek and Dott 1983; Peterson 1994).

Morrison Formation:

The Morrison Formation (Upper Jurassic), known for dinosaur fossils and for uranium occurrence (Peterson 1994), was deposited across the western continental United States with the final regression of the Jurassic sea. The stratigraphy of the Morrison Formation reflects a mostly fluvial origin: mudflats, overbank and floodplain deposits, and stream channels, as well as small eolian sand fields, and scattered lakes and ponds. The Morrison with its banded pink, maroon, green, and gray shales is prominent and identifiable over much of the Colorado Plateau.

Cretaceous Period (146-66 Ma)

Fast- flowing streams from highlands to the southwest eroded the softer shales and siltstones of the Morrison Formation, creating a regional unconformity in the rock record between the Jurassic and Cretaceous Periods. However, Lower Cretaceous fluvial, floodplain, and lacustrine deposits, present elsewhere on the Colorado Plateau, have been eroded from the Black Mesa area.

With plate collisions continuing on the western margin, the continental landscape experienced a dramatic change in the Upper Cretaceous. Mountains rose in the west and a north- south trough formed adjacent to the mountains. As the trough subsided, a shallow sea advanced onto the continent from both the Gulf of Mexico and the Arctic Ocean. The sea advanced and retreated many times during the Cretaceous until the most extensive interior seaway to cover the continent drowned much of western North America from about 95 to 64 Ma (figure 12). The advances and retreats of the Cretaceous Sea created a myriad of environments including incised river valley systems, estuaries, coal swamps, lagoons, delta systems, beaches, and shallow marine. These deposits are complex, and the rocks formed from these sediments include alternating and interfingering marine sandstones, shales, and coal beds forming the Dakota Sandstone, Mancos Shale, and the Mesaverde Group.

Dakota Sandstone:

In general, the Dakota Sandstone records shallow marine deposition with some intermittent mud flat and stream deposition. Coal swamps formed in the quiet backwaters of estuaries. Some of the sandstones may have been deposited in paleovalleys incised into the coastal plain during a regressive episode (Gardner and Cross 1994). With burial and increased temperature, the organic material of the Dakota Formation slowly transformed into coal and hydrocarbons. The coarse- grained sandstone layers are today reservoirs for oil and gas as well as and groundwater.

Mancos Shale:

The thick sequence of shale and siltstone with sandstone stringers and minor gypsum and limestone forming the Mancos Shale was deposited in the advancing Cretaceous seaway. For roughly ten million years, clay, silt, sand, and shell debris were deposited in the Cretaceous Interior Sea. At first glance, the formation appears to be 2000+ ft (700 m) of uniform, monotonous black and gray shales. Yet, the history of the Mancos on the Colorado Plateau reflects at least four major changes in depositional systems where shoreline and near- shore environments replaced with new environments created as sea level rose and fell (Aubrey 1991).

Fossil evidence suggests that ocean currents within the Cretaceous Interior Sea were variable. At times, the currents circulated oxygenated water throughout the water column allowing life to prosper at all levels, including within the muddy sea bottom. Conversely, at other times, the circulation in the Seaway was restricted to the upper water layer, and black, organic- rich muds accumulated in the oxygen- poor sea bottom. In those environments, the fossil material includes very few, if any, bottom fauna.

Torevo Formation and Wepo Formation:

The Torevo Formation and Wepo Formation are part of four major transgressive- regressive marine cycles in the Upper Cretaceous (Elder and Kirkland 1994). The formations were deposited from approximately 91- 84

Ma and are slightly younger than the Point Lookout Sandstone at Mesa Verde National Park. The rest of the Cretaceous record, from 84- 66.4 Ma, is missing in the Black Mesa area.

Aggrading fluvial deposits that formed the Toreva Formation record the early phases of transgression. The sediment sources for the Toreva were rifted uplands to the southwest and south (Elder and Kirkland 1994). The rivers flowed to a northwest- southeast trending shoreline that extended from southwest Utah, across northeastern Arizona, and into central New Mexico.

The Wepo Formation resulted from a regressive interval following the transgression that deposited the Toreva Formation. Organic matter accumulated in lagoons and marshes that formed in a coastal- plain depositional system. With burial and elevated temperatures, the organic matter was transformed into coal.

The Yale Point Sandstone is a marine sandstone and refelcts another transgression into the Western Interior Basin. Cretaceous strata deposited above the Yale Point Sandstone have been eroded from the Navajo National Monument area.

Late Cretaceous-Early Tertiary (70-35 Ma)

The North American lithospheric plate collided with the Farallon plate, producing the Laramide Orogeny (about 70- 35 Ma). This event transformed the extensive basin of the Cretaceous Interior Seaway into smaller fault- bounded basins. Thrust faulting during the Laramide Orogeny brought Precambrian plutonic and metamorphic basement rocks to the surface.

Tectonic activity during this time warped the Colorado Plateau region into broad anticlinal and synclinal folds with very little large- scale (kms) faulting (Dickinson and Snyder 1978; Chapin and Cather 1983; Hamilton 1988; Erslev 1993). The Organ Rock Monocline that plunges the Navajo Sandstone beneath Black Mesa is a result of Colorado Plateau deformation during the Laramide Orogeny.

With continued uplift in the late Tertiary and Quaternary, most of the Upper Cretaceous strata was eroded from the Black Mesa area.

Tertiary Period (66-1.8 Ma)

Near the end of the Laramide Orogeny, from about 35- 26 million years ago, in mid- Tertiary time, volcanic activity erupted across the Colorado Plateau. The laccoliths that formed the Sleeping Ute Mountain, La Plata Mountains, Henry Mountains, La Sal Mountains, and Abajo Mountains were emplaced during the mid- Tertiary.

Today, Late Cretaceous shoreline deposits are found on the Colorado Plateau at elevations of several thousand feet. Since the end of the Cretaceous Period 66 million years ago, the Colorado Plateau has risen about 12,000 ft (3,660 m) (Fillmore 2000). Some of this uplift occurred quite rapidly in geologic time. As the rate of uplift increased, so did the rate of erosion. The Colorado River, for example, carved its present course within the last 6 million years.

Quaternary Period (1.8-0.01 Ma)

In the Pleistocene (1.8- 0.01 Ma) ice ages, streams carved deep valleys and river channels into the Colorado Plateau. In the wetter climate, groundwater flow through the permeable Navajo Sandstone was restricted at the contact with less permeable shale and siltstone layers in the Kayenta Formation. The groundwater flowed laterally along the contact to the canyon walls forming seeps and springs. During this time, deep alcoves began to form in the Navajo Sandstone.

The Colorado Plateau as a whole has been subjected to repeated minor uplifts and stream rejuvenation since the end of the last ice age. Today, the climate is drier than during the Pleistocene ice ages yet the intermittent streams in the canyons are still actively downcutting, only at a slower rate than in the past.

The Pleistocene Jeddito Formation and the Holocene Tsegi and Naha Formations are alluvial units in Tsegi Canyon in Navajo National Monument. The Jeddito Formation occurs as remnant high alluvial terraces below Holocene alluvial units. The Tsegi Formation rests on bedrock or locally on the Jeddito Formation (Clay- Poole 1989). The Naha Formation is the youngest unit, forming a terrace 40- 50 feet (12- 15 m) above the stream floor and 10- 15 feet (3- 5 m) below the Tsegi terrace. From carbon- 14 dating of wood fragments near the base of the Tsegi, deposition began around 5,389 years BP and ended about A.D. 1275- 1300. Erosion removed extensive areas of the Tsegi, often to bedrock. Naha deposition began after A.D. 1375 and continued until A.D. 1884. Fresh- water gastropods, pelecypods, and ostracods have been found in the Naha Formation (Briscoe 1974). A new cycle of erosion is in progress today (Clay- Poole 1989).

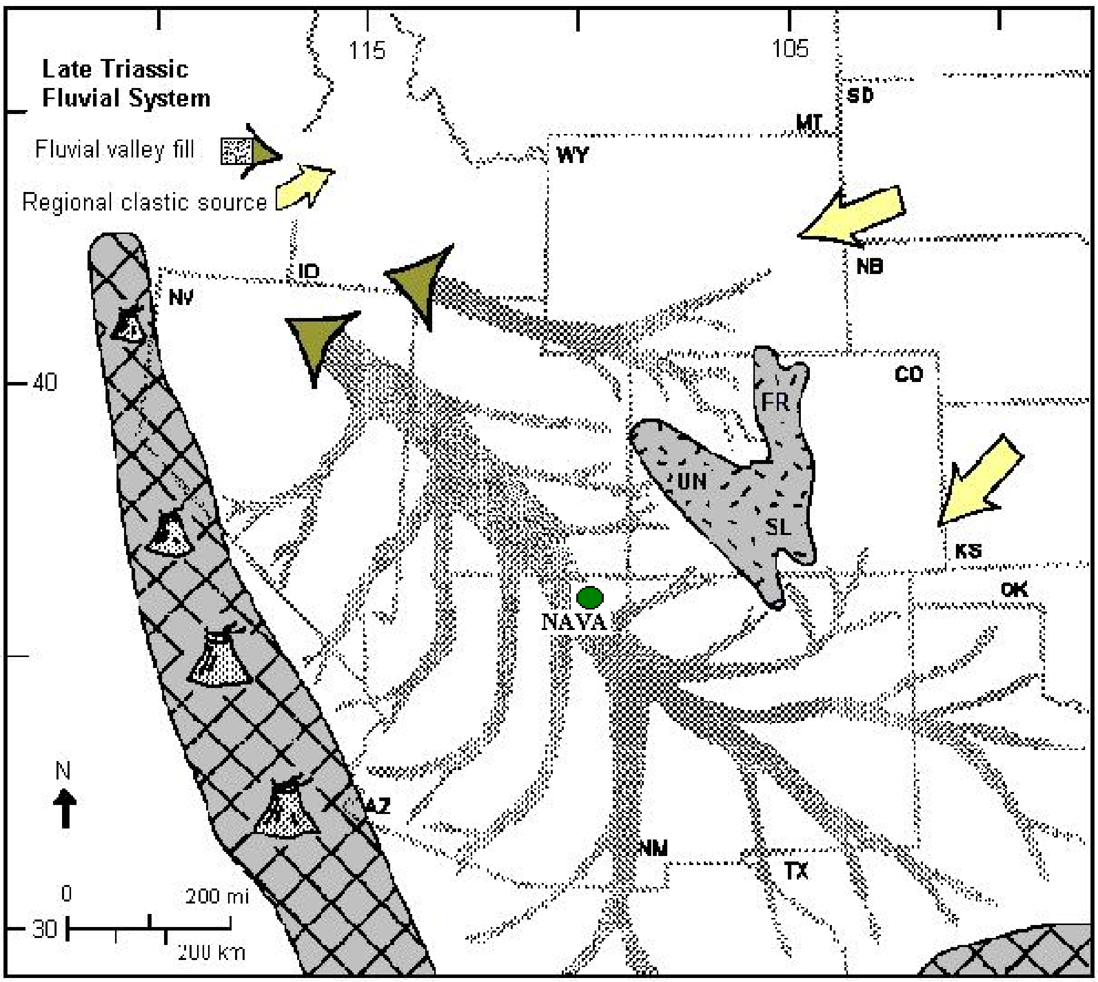


Figure 10. Paleogeography of the southern part of the Western Interior basin during deposition of the Late Triassic Chinle Formation. A volcanic arc has formed along the western margin of North America by this time. NAVA: Navajo National Monument. UN: Uncompahgre Highlands. FR: Front Range Highlands. SL: San Luis uplift. UN, FR, and SL are remnants of the upper Paleozoic Ancestral Rocky Mountains. Modified from Dubiel, 1994.

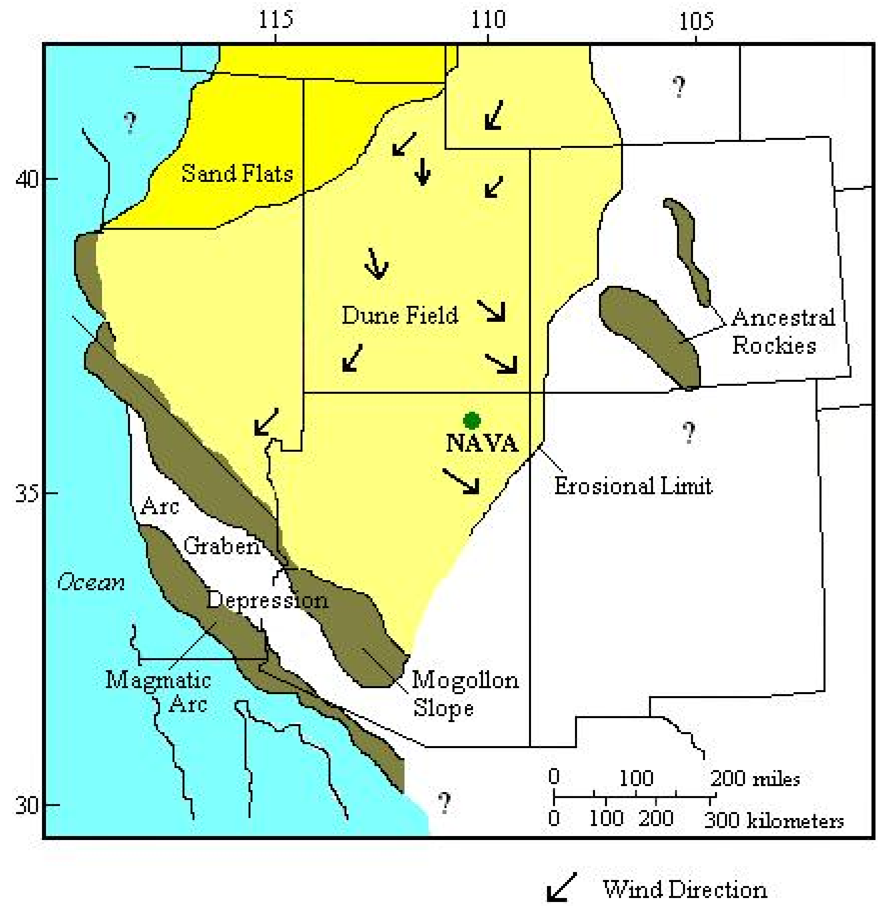


Figure 11. Paleogeography of the southern part of the Western Interior basin during deposition of the Early Jurassic Navajo Sandstone. NAVA: Navajo National Monument. Modified from Peterson, 1994.

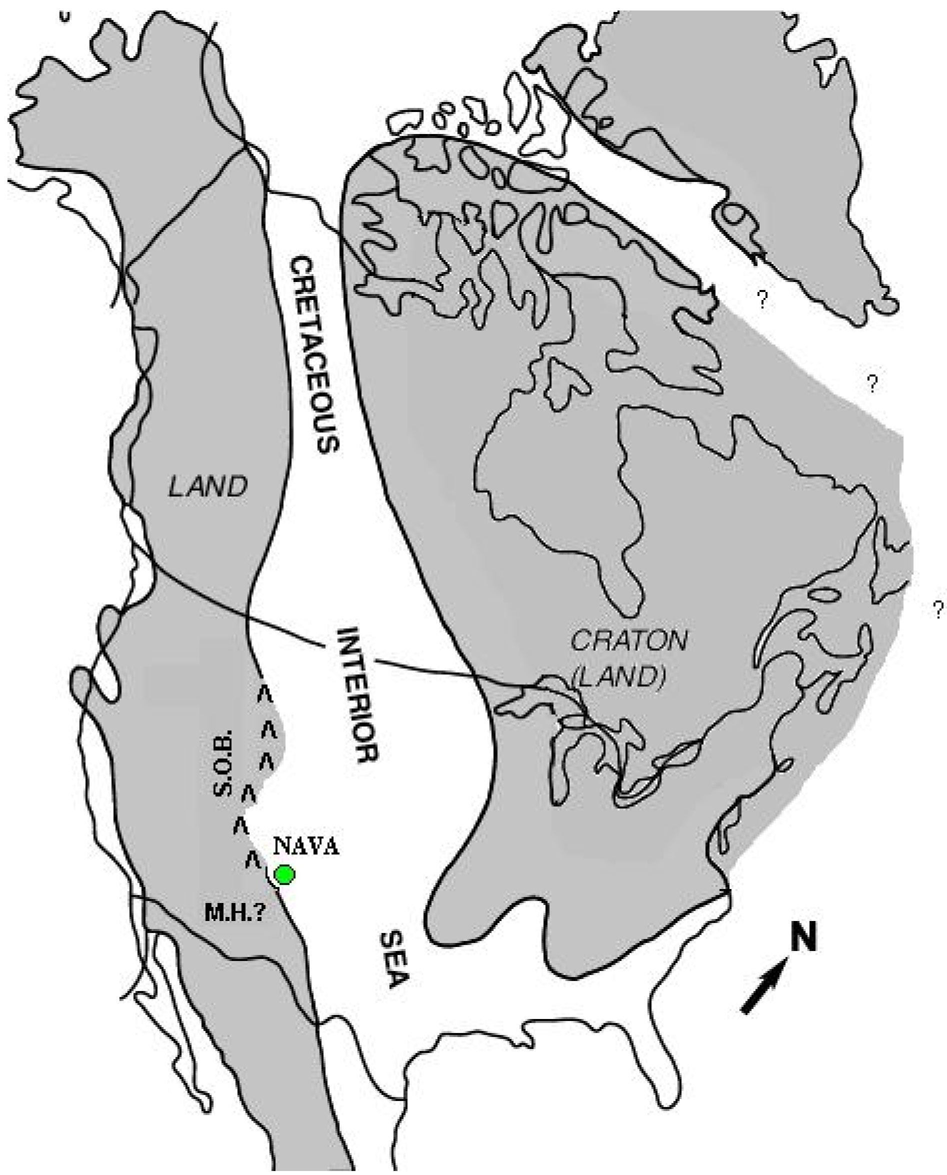


Figure 12. Paleogeographic map showing the extent of the Cretaceous Interior Sea. Shaded areas indicate land above sea level. NAVA: Navajo National Monument. S.O.B.: Sevier Orogenic belt of Mesozoic age. M.H.?: Mogollon Highland of southwestern Arizona. Modified from Rice and Shurr, 1983.

Glossary

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

active margin. A continental margin where significant volcanic and earthquake activity occurs; commonly a convergent plate margin.

alluvial fan. A fan- shaped deposit of sediment that accumulates where a high gradient stream flows out of a mountain front into an area of lesser gradient such as a valley.

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

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

ash (volcanic). Fine pyroclastic material ejected from a volcano (also see tuff).

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie the rocks of interest.

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

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

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

bedding. Depositional layering or stratification of sediments.

calcareous. A rock or sediment containing calcium carbonate.

carbonaceous. A rock or sediment with considerable carbon, esp. organics, hydrocarbons, or coal.

clastic. Rock or sediment made of fragments or pre- existing rocks.

conglomerate. A coarse- grained sedimentary rock with clasts larger than 2 mm in a fine- grained matrix.

continental crust. The type of crustal rocks underlying the continents and continental shelves; having a thickness of 25- 60 km (16- 37 mi) and a density of approximately 2.7 grams per cubic centimeter.

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 (656 ft).

continental slope. The relative 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. A plate boundary where two tectonic plates are moving together (i.e., a zone of subduction or obduction).

craton. The relatively old and geologically stable interior of a continent (also see continental shield).

cross-bedding. Uniform to highly- varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions.

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

dip. The angle between a structural surface and a horizontal reference plane measured normal to their line of intersection.

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include the *barchan dune*, *longitudinal dune*, *parabolic dune*, and *transverse dune* (see respective listings).

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

eolianite. A sedimentary rock consisting of consolidated wind blown (eolian) material; dune sand cemented by calcite.

erg. A large tract of sandy desert; a sand sea.

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

estuary. The seaward end or tidal mouth of a river where fresh and sea water mix; many estuaries are drowned river valleys caused by sea level rise (transgression) or coastal subsidence.

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

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

graben. A down- dropped structural block bounded by steeply- dipping, normal faults (also see horst).

horst. An uplifted structural block bounded by high- angle normal faults.

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

intrusion. A body of igneous rock that invades older rock. The invading rock may be a plastic solid or magma that pushes its way into the older rock.

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 tack head- to arcuate- shaped, concordant pluton that domed or up- arched the overlying country rocks.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.
landslide. Any process or landform resulting from rapid mass movement under relatively dry conditions.
lithification. The conversion of sediment into solid rock.
lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 mi) thick, that encompasses the crust and uppermost mantle.
magma. Molten rock generated within Earth that is the parent of igneous rocks.
magmatic arc. An arcuate line of igneous intrusions; volcanic rocks and/or active volcanoes usually formed by subduction
member. A lithostratigraphic unit with definable contacts that subdivides a formation.
monocline. A one- limbed flexure in strata, which are usually flat- lying except in the flexure itself.
normal fault. A dip- slip fault in which the hanging wall moves down relative to the footwall.
oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6- 7 km (3- 4 mi) thick and generally of basaltic composition.
orogeny. A mountain- building event, particularly a well-recognized event in the geological past (e.g. the Laramide orogeny).
paleogeography. The study, description, and reconstruction of the physical geography from past geologic periods.
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic Periods (also see Laurasia and Gondwana).
permeability. A measure of the ease or rate that fluids move through rocks or sediments.
phytosaurs. Semi- aquatic reptiles resembling the modern crocodile.
plateau. A broad, flat- topped topographic high of great extent and elevation above the surrounding plains, canyons, or valleys (both land and marine landforms).
plate tectonics. The theory that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid aesthenosphere.
pluton. A body of intrusive igneous rock.
plutonic. Describes igneous rock intruded and crystallized at some depth in Earth.
porosity. The proportion of void space (cracks, interstices) in a volume of a rock or sediment.
progradation. The seaward building of land area due to sedimentary deposition.
red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric oxide (hematite) coating individual grains.
regolith. A general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess and eolian deposits, vegetal accumulations and soil.
regression. A long- term seaward retreat of the shoreline or relative fall of sea level.
rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.
ripple marks. The undulating, subparallel, usually small-scale, ridge pattern formed on sediment by the flow of wind or water.
sabkha. A coastal environment in an arid climate where evaporation rates are high.
sequence. A major informal rock- stratigraphic unit that is traceable over large areas and defined by a major sea level transgression- regression sediment package.
slump. A generally large, coherent mass movement with a concave- up failure surface and subsequent backward rotation relative to the slope.
strike. The compass direction of the line of intersection that an inclined surface makes with a horizontal plane.
subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.
subsidence. The gradual sinking or depression of part of Earth's surface.
tectonic. Relating to large- scale movement and deformation of Earth's crust.
tectonics. The geological study of the broad structural architecture and deformational processes of the lithosphere and aesthenosphere (also see structural geology).
terraces (stream). Step- like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).
thrust fault. A contractional, dip- slip fault with a shallowly dipping fault surface ($<45^{\circ}$) where the hanging wall moves up and over relative to the footwall.
transgression. Landward migration of the sea due to a relative rise in sea level.
trend. The direction or azimuth of elongation or a linear geological feature.
unconformity. A surface within sedimentary strata that marks a prolonged period of nondeposition or erosion.
uplift. A structurally high area in the crust, produced by movement that raises the rocks.
weathering. The set of physical, chemical, and biological processes by which rock is broken down in place.

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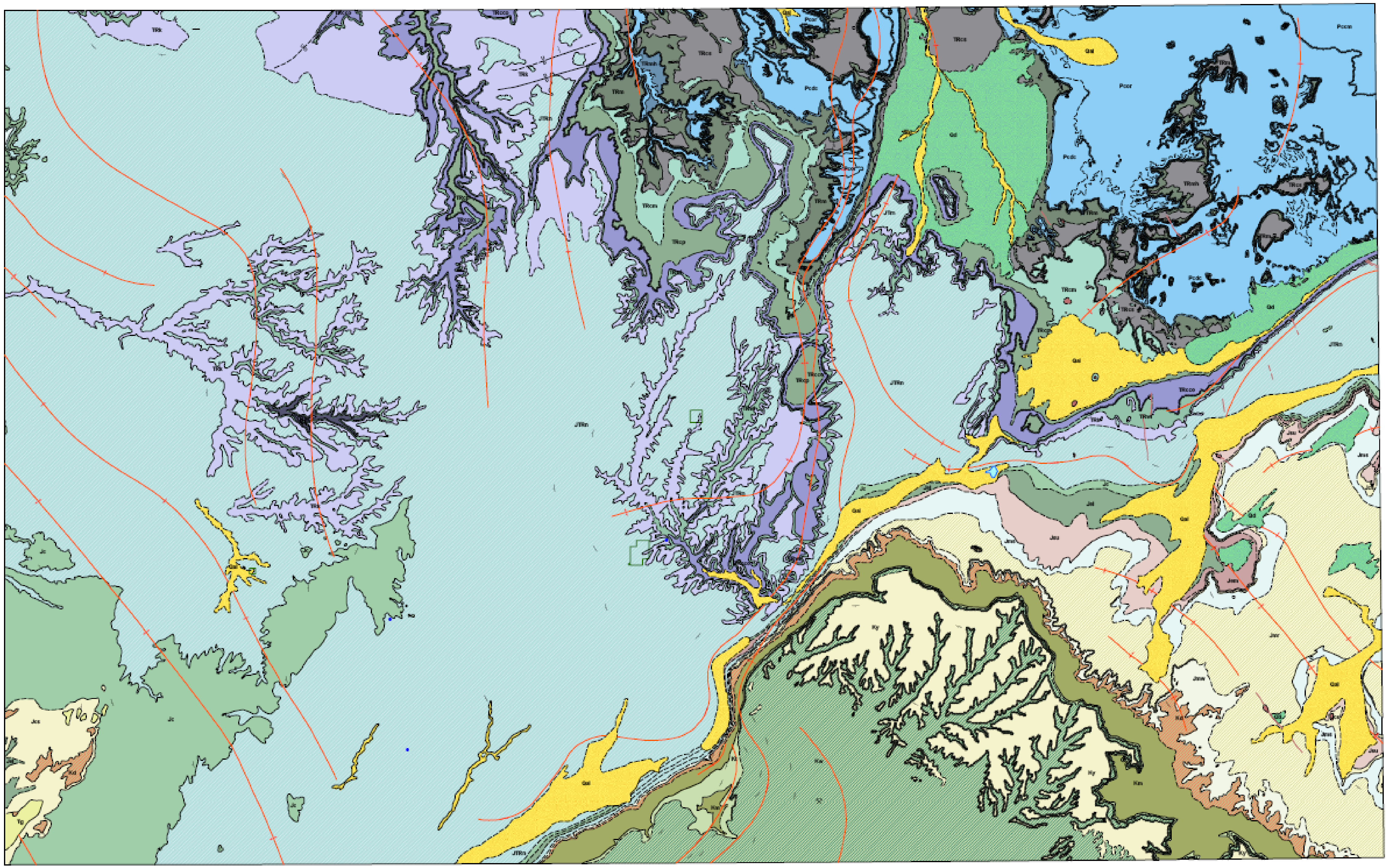
Appendix A: Geologic Map Graphic

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

Geologic Map of Navajo National Monument



Navajo NM Boundary

Geologic Attitude Observation Localities
- strike and dip of beds
- horizontal beds
- upthrown side of fault
- downthrown side of fault
- monocline symbol
- anticline symbol
- syncline symbol

Age-Date Localities
- paleontological

Mine Point Features
- mine

Linear Dikes
- Ti - intrusive igneous rocks

Folds
- know or certain

Faults
- normal fault, known or certain
- normal fault, approximate

Geologic Contacts
- known or certain
- approximate
- gradational
- map boundary
- shoreline

Geologic Units
- Qal - alluvium
- Qd - dune sand
- Tg - gravel
- Ti - intrusive igneous rocks
- Ky - Yale Point Sandstone
- Kw - Wepo Formation
- Kt - Toreva Formation
- Km - Mancos Shale
- Kd - Dakota Sandstone
- Jmw - Morrison Formation, Westwater Canyon Member
- Jmr - Morrison Formation, Recapture Member
- Jms - Morrison Formation, Salt Wash Member
- Jcs - Cow Springs Sandstone
- Jbsu - Summerville Fm., Bluff Sandstone and upper sandy member
- Jsu - Summerville Formation, upper sandy member
- Jem - Entrada Sandstone, middle silty member
- Jel - Entrada Sandstone, lower sandy member
- Jc - Carmel Formation
- JTRn - Navajo Sandstone
- TRk - Kayenta Formation, sandy facies
- TRwl - Wingate Sandstone, Lukachukai Member
- TRwr - Wingate Sandstone, rockpoint member
- TRcco - Chinle Formation, Church Rock and Owl Members
- TRcp - Chinle Formation, Petrified Forest Member
- TRcm - Chinle Formation, Monitor Butte Member
- TRcs - Chinle Formation, Shinarump Member
- TRm - Moenkopi Formation
- TRmh - Moenkopi Formation, Hoskinnini Member
- Pcdc - Cutler Formation, De Chelley Sandstone Member
- Pcor - Cutler Formation, Organ Rock Tongue
- Pccm - Cutler Formation, Cedar Mesa Sandstone
- WATER

0 5 10 20 Kilometers

0 3.75 7.5 15 Miles

Produced by Geologic Resources Division

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

M.E. Cooley, J.W. Harshbarger, J.P. Akers, and W.F. Hardt, 1969, Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico and Utah, U.S. Geological Survey with the cooperation of the Bureau of Indian Affairs and the Navajo Tribe, Professional Paper 521-A, 1:125,000.

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

March 2007

Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Navajo National Monument. The scoping meeting occurred June 25 and June 28, 2001; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

Summary

A geologic resources inventory workshop was held for Navajo NM (NAVA) on June 25th and 28th, 2001 to view and discuss the park's geologic resources, to address the status of geologic mapping for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), NPS Navajo NM, Colorado State University, University of Wyoming and United States Geologic Survey (USGS) were present for the workshop. This was part of a multi- park scoping session also involving Petrified Forest NP, Pipe Spring NM, Sunset Crater NM, Wupatki NM, and Walnut Canyon NM.

On Monday June 25th, scoping involved a half- day field trip to view the geology of the Navajo NM Betatakin Ruin area led by Sherrie Landon (University of Wyoming). Additionally, on June 28th another half- day scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the Geologic Resources Division, and the on- going Geologic Resources Inventory (GRI) took place. Round table discussions involving geologic issues for Navajo NM included interpretation, natural resources, the status of geologic mapping efforts, sources of available data, geologic hazards, and action items generated from this meeting.

Currently, the greatest issue facing park resource management is dealing with the potential threats of resource loss from fractures in the alcove ruins that are causing geologic rockfall and collapse. Because of this, it is desired to increase the scale of existing geologic maps of the area from 1:125,000 scale to larger 1:24,000 scale as it would aid in defining areas at highest risk to resource damage.

For a list of meeting attendees, see the list of attendees at the end of the appendix.

Geologic Mapping

George Billingsley (USGS- Flagstaff, AZ) informed the scoping participants of an existing USGS publication that contains geologic maps covering Navajo NM. (Cooley, M.E., Harshbarger, J.W., Akers, J.P., Hardt, W.F., and Hicks, O.N., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey, Professional Paper 521- A, scale 1:125,000). Unfortunately, these maps are small scale and not necessarily conducive to resource management goals. Additionally, the maps are not on a topographic base. Thus larger scale mapping on a topographic base is desirable for the six quadrangles of interest to NAVA. NAVA contains 3 separate units totaling approximately 500 acres. The quadrangles of interest are as follows:

- Tall Mountain
- Keet Seel Ruin
- Inscription House Ruin
- Shonto NW
- Betatakin Ruin
- Marsh Pass

Sherrie Landon (NAVA- GIP, University of Wyoming), through her work as a volunteer geologist- in- the- park at NAVA and her graduate studies at the University of Wyoming, is interested in doing the large scale mapping for the park. This could probably be funded through a contract or an EDMAP project through her university. It was agreed that she is the most likely person to be able to complete this geologic mapping for NAVA because of her experience in the area and her interest in seeing the project completed. This needs follow- up through GRI staff.

It would be most desirable to have the entire six quadrangles mapped, but that will likely be costly and time consuming. Thus, if the three separate units were mapped in detail to the park boundary, it might suffice in the interim. A scale of 1:24,000 is considered the minimum acceptable scale for any new mapping of the area. Given the size of the monument, perhaps even larger scale 1:12,000 mapping would be best.

Digital Geologic Map coverage

At present, a digital coverage of the 1969 maps has not been found. However, George Billingsley has heard rumors from a Navajo Nation representative that those geologic maps had been digitized, but he is not sure of the source. This information will try to be located as there are numerous sheets, and it would be redundant to re- digitize these maps if the effort has already been undertaken. Tim Connors will attempt to discern if this information is available digitally from the Navajo Nation.

In the event that digitized versions of the existing maps are not found, and until new larger scale mapping can be accomplished for the NAVA area, it is suggested that the existing 1:125,000 scale maps be scanned, registered, rectified and digitized (if necessary) for use in a GIS. While the scale is crude, it can serve as the best "preliminary" baseline geologic map until new, larger scale mapping is completed.

If the mapping for NAVA is completed at the larger scale, it would also be digitized as per the NPS Digital Geologic Map model as demonstrated during the scoping sessions.

Other desired GIS data

Since NAVA does not have a full- time dedicated GIS person at the park, they are dependent on the Intermountain Region GIS staff in Denver for support. They have been receiving assistance to date from Jennifer McCollum.

Miscellaneous Items of interest

- Many of the park trails have had problems with rockslides in the recent past and Betatakin Trail has had to limit hikers because of this problem. A geologic map should help delineate these troublesome areas in the monument.
- Another resource management issue is the effect of deeper canyon cutting in the monument. Arroyo cutting is effecting tributaries and cultural resources (middens) are being washed away and destroyed. According to George Billingsley, Margaret Hiza (USGS- Denver) is currently working with the Navajo Nation on erosion issues and the park may want to contact her for assistance.
- The nearby Black Mesa Coal Mine is interested in pumping more water from the regional aquifer for their industrial uses. This could negatively effect park water quantity and is thus a pressing issue at the current time.
- Current natural resource staff at Navajo NM are Irv Francisco, Kevin Harper, and Brenton White.

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Navajo National Monument

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/005
NPS D-53, June 2007

National Park Service

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Natural Resource Program Center

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